Costs, Impacts, and Benefits of CO2 Mitigation

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Introduction

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Most economic studies of energy systems and their development have focused on the classical question of allocating scarce resources. Over the last few years, however, there has been a shift in emphasis from resource constraints to environmental consequences and limitations. Energy-related emissions – particularly greenhouse gases such as carbon dioxide – are an important contribution to growing concerns about global warming and adverse environmental change in general. Policy measures advanced to alleviate environmental disruption, especially in the energy sector, encompass a broad spectrum of techno-economic adjustments and social-behavioral responses.

Technological and economic measures for achieving environmentally compatible development have been and continue to be studied. Great progress has been achieved in modeling energy-economy interactions, producing greenhouse gas emission scenarios, and estimating the costs of mitigation and emission reduction. On the other hand, there is great uncertainty about the impacts of the anthropogenic global warming, possible adaptation measures, and their associated costs. There are a few studies on the comparative assessment of mitigation and adaptation costs, and the potential benefits of these measures. Since these are all long-term issues ranging into the next century, their assessment also requires a degree of understanding of possible development paths the world may take in the absence of global warming. These development paths could then be used as a reference against which to measure mitigation, impacts and adaptation. Furthermore, it is often difficult to compare studies due to different assumptions, methodology, and temporal and spatial scales.

A three-day international workshop on "Costs, Impacts and Possible Benefits of CO_2 Mitigation" was held in October 1992 to review current research and analysis of economic costs and possible benefits of measures for responding to global climate change, and to critically evaluate knowledge gaps and future research activities. The workshop was co-organized by the Japanese Central Research Institute of the Electric Power Industry (CRIEPI), the International Institute for Applied Systems Analysis (IIASA), the National Science Foundation (NSF), Yale University, and the Energy and Industry Subgroup of the Intergovernmental Panel on Climate Change (EIS/IPCC). Some 80 scientists, mainly economists, from more than 20 countries participated in the workshop, including many of the foremost researchers working in the field. (The workshop was followed by a two-day meeting on technological issues related to climate change organized jointly by IIASA and EIS/IPCC. Many of the participants stayed for the subsequent workshop.)

The workshop was opened by Peter de Jánosi, Director of IIASA and Akira Yajima, Vice-President of CRIEPI. After brief introductory statements by the workshop organizers, Bert Bolin, the Chairman of the IPCC, began the proceedings by stating that in the future the IPCC would undertake economic analyses of climate change with the same vigor that it has demonstrated in its other scientific assessments, and that this workshop marked the beginning of this effort. Subsequently, the new Working Group III of the IPCC was organized and includes economic assessments in its activities.

The workshop was organized in the form of five sessions covering the economics of climate change, its impacts, mitigation costs, policy instruments, and modeling issues. Each of these sessions started with two or three invited papers and contributions by invited discussants, followed by general discussion. The four parts of these proceedings reflect the written contributions and discussions of the five workshop sessions. They are preceded by an introductory paper to this volume that summarizes both these proceedings and the findings and discussions of the workshop.

We would like to extend our thanks to the workshop participants and contributors who provided the essential intellectual substance during the sessions and discussions, and to the co-organizing institutions which provided the financial support to bring such a distinguished group of scientists together. We are also deeply indebted to Lourdes Cornelio, Sarah James, Christina Kugi, and Lieselotte Roggenland for their valuable help and assistance in the preparation of this volume.

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Overview

Measurements for Measures: Current Economic Analyses of Climate Change

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Economic analyses related to various aspects of global climate change have received increasing attention over the past few years from audiences both within and outside the economics profession. The wide range of issues involved in the problem commonly called "global warming" has lured a large variety of studies that seek to clarify specific aspects of the problem. Results have been summarized in a few books so far, but the bulk of the research has been scatteringly reported in numerous journals, institute reports, and mimeos. There is clearly a need from time to time to take stock of the results, sort out knowns and unknowns, and identify promising future research directions.

IIASA's intention with organizing the International Workshop on Cost, Impacts, and Possible Benefits of CO_2 mitigation in September 1992 was precisely this. In retrospect, and looking at the impressive collection of new results embodied in the subsequent papers in this volume, the workshop fulfilled its goals. It has become the latest member of a series of important meetings of which earlier ones were reported in, for example, Dornbusch and Poterba (1991), Wood and Kaya (1991).

The present overview has two major objectives. First, it is intended to provide a short review of the papers included in the volume and explain the logic behind their arrangement. Second, it attempts to put the workshop and its product into the context of the current global warming debate. My summary is explicitly not intended to steal the thunder and present results of individual papers. I think they are all worth reading for their own merits. What is offered here is rather an overview of the variety of approaches, some very new and innovative, the diversity of opinions, views, and value judgements. The summary is hoped to be useful for readers by providing an overall framework for the collection and some background information about each paper.

Section 1 is addressing general issues of global warming economics and policy by reviewing papers in Part 1 of the book. The next section is dealing

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[*] This paper has greatly benefited from the thoughtful comments of Bill Nordhaus. Comments by N. Nakićenović, M. Clark, and G. Klaassen are also gratefully acknowledged.

with impacts and damages largely based on papers in Part 2. There we find three different extensions of damage assessments: one across geographical regions, another one across macroeconomic sectors, and the third covering global agricultural production. Section 3 is devoted to studies estimating costs of a large variety of proposed measures to reduce CO_2 emissions. It is based on global models in Part 3 of the volume. Regional and national estimates of CO_2 abatement costs follow in the next section by reviewing papers in Part 4. Finally, Section 5 provides a short summary of the new developments in the economic analysis related to climate change.

1. General Issues (Part 1)

The primary objective of the workshop was to review what kind of advice can state-of-the-art economic analysis provide in 1992 for present-day GHG policy. The result may appear to be surprising to some: damages from CO_2 doubling are relatively modest while the costs of significantly slowing global warming are relatively high. This conclusion was supported both by comparing results from a variety of empirical studies that assessed potential damages from climate change and costs of different GHG mitigation options, and by several conceptual studies evaluating the economic costs and foregone benefits of early vs. delayed action with a view to different time schedules of information acquisition and learning about the climate system and the magnitude of damages.

This general statement entails two immediate qualifiers. First, it by no means implies the overall inclination of the economics community toward inaction about the potentially serious threats associated with anthropogenic climate change. Mankind as a whole or individual societies may decide to undertake various sorts of actions to mitigate greenhouse-gas (GHG) emissions at any level of costs they find affordable, but proponents should, at least at this point, not rely on economic analysis to supply ammunition. Action based on ecological concerns (nature is fragile), moral principles (it is unethical to plunder nature), or any other a priori consideration might be perfectly legitimate, as they are in numerous other cases ranging from workplace safety to protecting the stratospheric ozone layer which did not pass the test of balancing marginal costs with marginal benefits.

The second qualifier is related to the acknowledged shortcomings of damage and cost assessments conducted so far. I return to these problems later, but it should be noted here that only part of the criticism leveled at these studies stem from purely economic grounds; most objections arise from external, non-economic considerations. There is little room for constructive debate when criticism stems from a different set of axioms.

This topic leads to a more general debate that constitutes the major line of division in economic analysis of environmental problems. It was prevalent at the workshop and it is also apparent in the papers collected in this volume. One approach is rooted in neoclassical mainstream economics and attempts to gradually extend the scope of analysis to include environmental spillovers, in our case the measurable and quantifiable damages of climate change as well as the costs of averting or at least delaying climate change. The starting point of the other approach is an incomplete understanding of ecological systems from which hard constraints are derived and imposed on the economy with little respect for the relative costs and benefits. In the climate case it is ultimately to stop GHG emissions and prevent climate change. A superficial expectation might be that the two viewpoints are approaching each other and will meet sooner or later, but this is only a tempting illusion.

Differences in the attitudes and problem perceptions underlying the above division are apparent in legislative procedures and in economic analyses required to support them in different countries. The precautionary principle has been adopted for environmental politics in many countries. It calls for early actions as opposed to waiting for complete scientific certainty and regards any potential environmental damage intolerable. In our case it implies that climate change must be prevented. If this is the starting point then assessments of potential impacts and damages are practically irrelevant and the scope of analysis is restricted to finding the least expensive policy instruments to reach this objective.

In contrast, if the principle is that policy measures must pass a benefit-cost test then damage estimates become equally important but, unfortunately, the complexity of analysis increases by an order of magnitude. As they gradually evolved over time, benefit-cost analyses proved to be increasingly effective for short-term, local, relatively simple environmental decision problems. It takes a large amount of determination to use this tool for long-term, large-scale, and complex environmental problems like climate change. Yet, in the absence of more appropriate tools, we need to try to improve the ones we have rather than imposing arbitrary constraints on our policy proposals. Some papers in this volume document recent improvements in traditional damage and cost estimates, others propose and demonstrate the viability of profoundly new approaches.

A closer look at the literature of economic analysis about global warming shows major imbalances.

First, the number of studies estimating the costs of GHG/CO_2 mitigation strategies is overwhelming compared to the number of efforts assessing the benefits.

Second, cost studies largely rely on rigorous analytical tools, in most cases a single, sophisticated and thoroughly tested computer model, as opposed to damage estimates that need to rely on a variety of fragmented and in many cases self-contradicting impact assessments to derive an aggregated damage result. Impact assessment studies tend to focus on one specific crop in one region, inundation and property loss from sea level rise in another, and water resources in a third. Moreover, many studies analyze impacts under a $2 \times CO_2$ equivalent climate[1] and, at the same time, carbon fertilization effects of a $2 \times CO_2$ concentration.

Third, the evaluation of mitigation costs over time has proven to be possible by integrating the most important macroeconomic dynamics (GDP growth, productivity improvements, energy use) into the overall framework of analysis. This way, future costs of various abatement strategies are related to projected future GDP values and baseline emission trends. In contrast, impact assessments and thus damage estimates tend to focus on $2 \times CO_2$ climate scenarios and superimpose them on present-day economic and technological conditions.

Finally, and to a large extent explained by the previous points, the spread of results is much larger for damage assessments (in terms of potential GDP losses due to an assumed level of global warming) than for cost estimates (using the same terms to measure economic losses from a specified rate of reduction in CO_2 emissions). This seems to hold despite the apparent gap between results of top-down and bottom-up models applied in cost estimates.

No wonder that these imbalances invite a lot of criticism when the results are integrated into a benefit-cost framework. They also point toward the need for further improvements on both sides, and probably for profoundly new approaches on the damage side.

Beyond obvious differences in the multitude of factors to be considered and in the complexity of the analysis in damage vs. cost estimates, one possible explanation for the above imbalances is that for the latter it was possible to extend earlier energy-economic models (both macroeconomic and engineering types) by incorporating additional constraints in the form of direct emission target levels or incentive-based instruments, like carbon taxes.

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[1] That is, global climate change induced by an elevated concentration of all radiatively active trace gases which corresponds to the effects of doubling the CO_2 concentration in the atmosphere.

Another motivation may have been that cost assessments and studies of different cost reduction schemes (permit trade, tax revenue recycling, etc.) will be important on their own right (and regardless of the damage results) if there will be a policy decision to undertake emission mitigation strategies for other than or beyond purely economic reasons. It is difficult to tell whether due to the convenience of availability of well established models or due to the perceived need for these kinds of results even in the absence of full cost-benefit justification, but cost studies are certainly by far the most advanced area of greenhouse economics and modeling.

Several papers in the volume review the current situation in greenhouse economics and policy. Papers in Part I can be divided into two broad categories. Following an introductory statement by Yajima (this volume), Nordhaus and Cline address practical problems related to climate policy. Peck and Teisberg, and Kolstad shed light on the conceptual problems of decision making under significant amounts of uncertainty but with the possibility of learning.

Nordhaus (this volume) focuses on the level and type of policy interventions that can be proposed on the basis of results from the relatively few systematic benefit/cost analyses completed so far. He also provides a long list of issues where the reduction of our vast ignorance might profoundly change both terms in the cost/benefit balance. His aversion for hasty and overambitious GHG control policies is based on empirical cost/benefit calculations, but it is also supported by a conceptual study presented by Peck and Teisberg (a summary in this volume based on Peck and Teisberg, forthcoming) who explore the relationship between the value of information about impacts and damages and the optimal time path for emission control.

The two-year period before the UN Conference on Environment and Development in Rio de Janeiro in June 1992 was characterized by mixed expectations about the coverage and stringency of a global climate convention that had been expected as a major product of the meeting. Similarly, the post-Rio period has witnessed mixed evaluations of the actual outcome (Parson *et al.*, 1992; Haas *et al.*, 1992). Cline (this volume) evaluates the Framework Convention on Climate Change in a broader context of long-term evolution of efforts to mitigate climate change and with a view to new results in atmospheric sciences and economic analysis.

While Peck and Teisberg use exogenously specified dates of when uncertainty about global warming damages is resolved, Kolstad's model (this volume) includes a dynamic learning process. His study is based on an extended version of the DICE model developed by Nordhaus (1992a) and covers two basic processes considered irreversible over a reasonable time horizon:

emissions (because CO_2 remains in the atmosphere for a long period) and mitigation investments (which are practically lost if they turn out to be unnecessary after they had been committed). His results provide fascinating insights into how relative time-paths of the learning process and major emission reduction commitments might influence the magnitude of economic losses from over-action vs. inaction.

2. Impacts and Damages (Part 2)

The shape and relative position of the damage function synthesizing measurable economic damages of climate change impacts is determined by a broad range of geographical, socioeconomic, and technological factors. The damage function is bound to change over time as those factors change even if the underlying climate change scenario remains the same.

The economic impacts of climate change are generally thought to be negative. Some negative impacts will be offset by positive effects in the same sector or economic activity, e.g. yield losses due to reduced maturation period partly offset by the atmospheric carbon fertilization effect, or part of the increased demand for space cooling in the summer will be offset by reduced costs of space heating in the winter if average temperature increases hold across the whole year evenly. Other negative impacts in one sector might be partly or fully compensated by positive impacts in other sectors in the same national economy. Very few studies dared to estimate the positive impacts of warmer climate, and even fewer the economic benefits associated with them.

Considering the long-term trend of human activities becoming less vulnerable to climatic fluctuations and climate in general (Ausubel 1991, Schelling 1992), actual damages even in 30 but certainly in 50 to 100 years will inevitably be lower than damages calculated by superimposing whatever future climate on today's economy. The general pattern is global although if we assume a saturation pattern in increasing climate-independence as a result of economic development, the autonomous rate of decrease in climatic vulnerability will be higher in developing countries, that is in regions that are thought to be the most vulnerable to climate change today.

A considerable part of the negative impacts can be offset by adaptation. Parallel to decreasing climatic vulnerability, adaptation capacity is also bound to increase with economic development, again in regions where losses associated with global warming are expected to be highest.

There are several aspects of adaptation that make the assessment of this damage reduction potential difficult and largely non-existent up until now. First, the size of adaptation costs depends on the timing of adaptive measures relative to the visibility of impacts. Proactive adaptation is much cheaper than "see and react" adaptation. For example, abandoning long-term programs the results of which might be eliminated or severely degraded by climate change, and supporting social processes that enhance adaptive capacities at the farm, local, and regional level are obviously cheap proactive adaptations.

The second factor to consider is the positive spill-overs from any form (proactive or see and react) of adaptation. If adaptation measures produce benefits in addition just to offsetting the negative impacts (and in many cases there is evidence that they would) these "extra-benefits" should be deducted from the cost accounts which should include direct adaptation costs only, similarly to the "netting-out" the monetary value of positive spillovers from the total abatement costs. Numerous no-regret adaptation strategies can be identified in natural resource management (protective and rehabilitative measures), economic policy (modified price, subsidy, export, and import strategies), institutional mechanisms (legal and government systems), research and development (in agricultural, coastal-protection, and water management technologies), and many other areas (see Toth, 1992).

One major problem with climate impact assessments as practiced today is the apparent contrast between the very detailed climate change scenarios (e.g. daily temperature, precipitation, and other data under 2 × CO_2 equivalent climate) and the very casual treatment of future socioeconomic and technological development patterns. In agriculture, for example, the evolving patterns of climate change will be intertwined with other dynamic processes affecting the resource base (degradation and depletion), with rehabilitation and redevelopment efforts (drainage, land reclamation), and with other factors in the social and economic system (values, laws, technologies, cultural practices).

In general, what are badly needed for the next round of global warming impact and damage assessments are careful and imaginative baseline studies of socioeconomic development in the absence of climate change. Scenarios and assumptions about climate change superimposed on these dynamic baseline scenarios would provide more realistic assessments of the actual threats and potential damages. These studies would also serve as a more realistic basis for evaluating adaptation options, their costs, and their non-climate related benefits. Finally, these scenarios could serve as a more realistic framework for improved cost estimates as future options for more or less aggressive carbon abatement could be simultaneously assessed.

Creating these detailed, long-term scenarios is no mean task. It is relatively easy to construct global and regional scenarios by assuming different rates of change in various macroeconomic indicators, efficiency and diffusion parameters. It is much more difficult to depict what agriculture may look like in the Muda region of Malaysia (currently providing the bulk of the country's rice production) or in Mauritius (currently earning half of the export income from a single commodity, sugar) in the year 2030 or 2050 in terms of land ownership and farm size, level of mechanization and chemical control, types of management practices at the farm level; and the nature of agricultural policy (cheap food, liberal, protectionist) and control tools at the macroeconomic level. Yet, all these and probably much more is needed in order to conduct realistic impact assessments which include the broad future range of adaptation options with their associated costs, and to construct an empirical damage function as a realistic measure of climate impacts. The first attempts have already been made in this direction with moderate success; see for example the MINK Study by Resources for the Future (Rosenberg and Crosson, 1991; Rosenberg *et al.*, 1992) and UNEP's study in Southeast Asia (Parry *et al.*, 1992; Toth, 1992), yet there is a need and plenty of room for further improvements.

The first serious and systematic effort to quantify economic damages from climate change (Nordhaus 1991b) seems to have become a benchmark or reference point to several other studies, results of which were presented at the conference. Many authors criticize the Nordhaus estimates for its omissions and limited scope (see, for example, Cline, 1992 Chapter 3, who also provides his own estimates which are somewhat higher than those of Nordhaus; Ayres and Walter, 1991); others followed its basic principles and extended it to other world regions. One such extension is by Fankhauser (this volume) to the global scale which is interesting because some of his major world regions overlap or are reasonably close to the world regions used in the cost assessment studies (see Part 3.)

The convenient and customary direction of climate impact assessments is "bottom-up". They typically start with one or more agricultural crop(s) in one or more small region(s), then aggregate at the level of economic (sub)sectors and larger regions, and finally, if regional coverage permits, synthesize results at the scale of the national economy (see Parry *et al.*, 1988; Carter *et al.*, 1992). Point estimates of the damage function pegged to the $2 \times CO_2$ and other prominent benchmarks, and the partial equilibrium framework to analyze their economic implications provide useful first grade estimates. Nonetheless, the long-term dynamic interaction between the evolution of the climatic system and economic development calls for a dynamical version of the damage function. Moreover, in addition to direct impacts on sensitive sectors and associated costs, economic impact assessments should also include indirect and induced impacts of climate change. Scheraga *et al.* (this volume) use the dynamic, general equilibrium Jorgenson-Wilcoxen model and present the first "top down", dynamic analysis of total economic impacts of a small set of climate-induced changes (rise in agricultural production costs, rise in electricity costs, and rise in expenditures associated with coastal protection). Despite the numerous caveats suggested by the authors, the approach is a major step towards improved impact and economic damage assessments. Here again, the reader should compare results from this state-of-the-art general equilibrium model with other damage assessments in this volume and elsewhere.

There is a consensus that agriculture will be the economic sector most severely affected by global climate change. Acknowledging all the flaws of past agricultural impact assessments, they provided at least a baseline for a primary economic evaluation of the impacts. While the Scheraga *et al.* study discussed above takes agricultural impacts and calculates cumulative effects within a single economy, Fischer *et al.* (this volume) follow a different approach. They take farm and national level impacts from many countries and several world regions and use a global agricultural-economic model to analyze effects on and adjustment processes within the world food and agricultural system. Given the magnitude of changes in the global food supply projected by this study, global climate change does not appear to be the major threat to feeding this world.

Ever since economists began attempting to formulate a rigorous analysis of the cost and benefit balance involved in global warming, their results have been received with suspicion and criticism. Grubb (this volume) provides an excellent summary of the various kinds of criticisms leveled at damage estimates using the 2 × CO_2 benchmark level. Jansen (this volume) extends this criticism by addressing issues like substitutability between climatic and economic utility and the threats of irreversible ecological changes. Yet, critics have so far failed to present convincing evidence for a systematically prepared damage assessment resulting in much higher damage costs and thus significantly higher benefits from GHG abatement.

One popular and recurring item of criticism leveled at the monetary assessments of climate change induced damages is the neglect of such analyses for non-economic goods, environmental services and amenities outside the national accounts. The problem is, of course, that their current value is in itself difficult to determine, let alone their future value. Attempts to impute some monetary value based on their estimated contribution to past and present economic wealth generation or based on their current management often lead to surprising results. In Malaysia, for example, whatever is left of the mangroves today will have disappeared due to coastal development long before see level rise induced by global warming. Similarly, coral reefs in many regions of the world have been and will continue to be under much more severe threats from illegal fishing methods (poison, dynamite) and other mismanagement than from rising sea level. A proper balancing of our limited resources spent on environment should direct money where it buys the largest amount of protection or prevents the more likely damage. In many cases and in many countries, it is not the mitigation of global warming.

It is clear from both the admittedly imperfect damage estimates and their critical reception that innovative new approaches are badly needed to support economic impact assessments. One such attempt is presented by Mendelsohn *et al.* (this volume). The authors are dissatisfied with the production function approaches based on agronomical crop-development models that tend to bias upwards crop losses and thus significantly overestimate related economic damages by ignoring a broad range of adaptation options. They propose a market-based approach that relates climatic conditions to farm-land prices and thus to (Ricardian) land rents. The Ricardian approach captures all long-term market adaptations and eliminates the upward bias inherent in damage estimates based on production functions. The modelers mobilize huge data sets in order to capture the rich diversity of factors affecting the geographical allocation of agricultural production and land use, and some of their conclusions are clearly instructive. Yet, application of the Ricardian model may prove to be more difficult in other countries and world regions where important assumptions of the model (perfect competition for land and associated equilibrium in land prices, and perfectly competitive input and output markets) do not hold and/or data to estimate the model are simply not available.

Persistent problems in empirical studies, whether traditional or innovative, continue to make conceptual studies an important source of guidelines for greenhouse research and policy. Precise quantification of the damage function is not yet possible and will not be for a foreseeable future. Peck (a summary in this volume based on Peck and Teisberg, 1993) provides valuable insights in how the size of the potentially averted damage can be assessed (and corresponding abatement policies proposed) on the basis of information about the curvature (exponent) of the damage function.

3. Costs of Control: Global Estimates (Part 3)

With the Rio Framework Convention on Climate Change, greenhouse warming moved to a respectable position on the international environmental policy agenda. Despite the increasing number of studies, it is still not clear what the global costs of possible alternative international agreements would be and how these agreements might reshape energy production and consumption, much less overall economic development globally and in major world regions.

The debate is revolving around two main issues. Some model calculations show little long-term effect on atmospheric GHG concentration from rush and aggressive emission reductions. Others argue that at least the low or negative cost options for CO_2 abatement should be utilized and initial price signals should be given to markets and technological development about the possible need for more ambitious emission reductions in the future. The second major issue is still open despite a number of plausible explanations: if studies identifying a negative tail of the cost curves are correct, why are these opportunities to save money and CO_2 emissions not utilized.

Papers in this volume that report results about the potential economic losses associated with a large variety of policies currently proposed or under serious consideration by national or international organizations demonstrate the impressive development in the field of long-term, large-scale modeling of economy-energy interactions in recent years. A survey conducted a few years ago (Toth *et al.*, 1989) could identify only a small number of models that had the necessary geographical coverage and detail, temporal scale and resolution, and economic and energy system disaggregation to become useful tools in studies of various aspects of global environmental change. Despite the then small number of models, their results were difficult to compare because they were based on different baseline assumptions and were driven by different exogenous conditions.

The situation is completely different today. Models are proliferating and there has been an increasing demand for their comparative appraisals from different perspectives and for different purposes and audiences. One would almost be tempted to conduct a review of the review studies covering those like, for example, by Nordhaus (1991a), the OECD Model Comparison Project (Dean, this volume; Dean and Hoeller, 1992; Hoeller *et al.*, 1992), and IIASA's International Energy Workshop (Manne *et al.*, 1992).

Probably the best indicator of the development and usefulness of modeling projects is the activities of the 12th Energy Modeling Forum (EMF12) results of which are reported by Gaskins and Weyant (this volume). EMF12 brings together a large variety of energy-economic models into a common framework of analysis. Participating teams agreed to run a set of standardized scenarios. This approach provided comparable results in the first place, but it is also helpful in understanding to what extent differences in results are due to incorporated or omitted relationships, underlying assumptions, or other reasons.

Despite the overall development in the modeling field, each model is developed with a specific purpose and is intended to investigate a specific range of issues. As a result, each model is better than the others along a specific set of criteria but usually at the price of omitting important relationships. Thus there is still plenty of room for improvements. A new global multi-sector and multi-regional general equilibrium model developed by McKibbin and Wilcoxen (this volume) is designed to address the weakness of current models in dealing with the linkages between national environmental policies and international trade. It will certainly be worth including in the next round of an EMF-like effort.

There seems to be a strongly held general belief about greenhouse mitigation that if one world region acts alone, even if it is a large, economically powerful, and major emitter region, the global benefits of unilateral action will be negligible and the costs for that particular region will be high. Yet, there are contrasting views declaring that short-term and direct losses for the pioneering region will be handsomely compensated by long-term and indirect benefits accruing from being the first.

One of the few concrete GHG/CO_2 emission mitigation proposals seriously considered in policy circles these days is that of the European Community to stabilize its CO_2 emissions by 2000 at the 1990 level. The proposed policy instrument is a gradually phased-in combined carbon and energy tax. Manne and Richels (1993) investigated the economic costs of this proposal and its impact on expected future CO_2 emissions by using an appropriately modified version of their five-region global model Global 2100 (Manne and Richels 1992). Koopman *et al.* (this volume) address the same issue but they use a variety of models (which were developed for different purposes) and their own calculations under different scenarios of carbon/energy tax recycling and off-setting. One important general lesson is worth highlighting here. In the modified Global 2100 model, the EC region is probably the most homogeneous one except for the single-country regions of the USA and China. Yet, the Koopman *et al.* study documents the amazingly wide range of differences among EC member countries in economic development, macroeconomic structure and export composition, household expenditures, and carbon intensity of electricity generation. These differences are likely to be further enhanced by the admission of new applicants over the next few years and imply the necessity for yet another compensation/redistribution scheme among member countries under an EC-wide tax regime.

If there are major differences in economic structure, energy use, and related carbon emissions among countries in a relatively homogeneous region like the EC, then the differences across world regions are even bigger. This suggests that a uniform reduction in CO_2 emissions worldwide might not be the best solution for political and economic reasons. Therefore, many authors propose a global tradable CO_2 emission permit scheme. Three papers analyze various aspects of such trading schemes and they all extend earlier frameworks of analysis by experimenting with innovative ideas. Edmonds *et al.* (this volume) take a modified version of the Edmonds–Reilly–Barns model and investigate the costs of three alternative mechanisms of implementing a hypothetical international protocol: uniform taxes, tradable permits, and individual (regional) targets. Manne and Rutherford (this volume) combine carbon permit trading with oil and gas trade in yet another derivative of the Global 2100 model. The study by Okada and Yamaji (this volume) is based on an extended version of the IEA/ORAU model (Edmonds and Reilly 1985) and incorporates regional CO_2 taxes and carbon fixation options with their associated costs into a global, interregional trade model of carbon emission rights.

Despite the already mentioned improvements in energy-economic modeling, one persistent problem keeps bothering both economists and engineers. This problem is the apparent, and in some cases astonishing, gap in CO_2 abatement cost assessments between macroeconomic (dubbed top-down) and engineering-economic (bottom-up) models. Wene (this volume) offers his explanation from the systems engineer's view. Yet, the final word on this issue, if at all possible, seems to be far away. This is an important research area in the future.

The last paper in Section 3 represents a transition between global and regional models. Matsuoka *et al.* (this volume) present a general GHG emission and absorption model that also includes a simple climate model. The overall model is global with a specific focus on the most dynamic region of the world economy, the Asia-Pacific region. Their results are preliminary but the approach holds the promise of an improved understanding of the costs and benefits of global warming in this extremely diverse part of the world.

4. Costs of Control: National and Regional Estimates (Part 4)

Global assessments of GHG abatement options and associated costs, and especially their distribution across world regions, between energy exporter and energy importer countries, between different MDC and LDC groups are important for negotiators working on the next round of international agreements. They provide insights into the relative merits of various global policy instruments, possible schemes to share the costs and to compensate for losses, leakages resulting from the migration of carbon-intensive activities to non-participating free riders and the like. Though valuable, this information is only a small part of what negotiators at international fora and policymakers responsible for national policy formulation need to know.

The willingness of each state to participate in more or less ambitious international GHG agreements and the stringency of domestic policies will be determined by the costs individual countries need to pay for it and ultimately what national governments can get their voters and influential interest groups to accept. Large number of earlier studies concluded that, for a given national commitment to a specific international agreement, national costs of compliance can be significantly reduced by carefully choosing the appropriate primary policy instrument and a set of offsetting mechanisms. These types of national studies are of special importance for countries who are major players in the international GHG arena either because of their high current contributions to global emissions or because of their large reserves of fossil fuels, mainly inexpensively extractable coal.

The latest vintage of the Jorgenson-Wilcoxen model (this volume) is a useful example of this kind of analysis. By estimating parameters of a highly disaggregated (I would call it "top-to-deep-down") general equilibrium model econometrically from long historical data sets, the authors give their model a respectable memory of long-term evolution processes. This makes all model parameters and especially elasticities more suitable for long-term future analyses than single-point parameterization. Although the perfect substitution assumption used in the model does not permit modeling the depletion of fossil fuel sources, this is not an important limitation as proven geological stocks will not be depleted over the model's time horizon of roughly one century. This powerful tool is then used to evaluate macroeconomic costs of different GHG policy instruments for the US economy.

The model and the results presented by Hourcade (this volume) for France are in a sharp contrast with the Jorgenson-Wilcoxen study. Compared to the US and, in fact, to most other countries in the OECD group, France is a low CO_2 intensive country due to its ambitious nuclear energy program. This characteristic would suggest that further reductions in CO_2 emissions would be difficult, and it even raises the danger of massive future increases. In contrast to the US approach, the French model falls in the category of engineering-type bottom-up models. By analyzing the phenomenon of technological bifurcations, the paper reveals a new way of looking at long-term implications of near-term technological decisions involving very similar set-up or short-term costs and presents an interesting perspective to think about endogenous technologies.

Japan has traditionally been very sensitive to any threat to its high rate of economic growth. Its reliance on imported sources of energy makes the issue of climate change even more important. It is therefore not surprising that several studies have been conducted in Japan to assess the options and costs of CO_2 emission reductions. Amano (this volume) presents a comparative analysis of these studies covering a broad range of multi-sectoral dynamic optimization models and different types of econometric models of the Japanese economy, and series of global models as well.

One of the major sources of uncertainty in all global models is the pace and character of economic development in general, and the evolution of the energy sector in particular over the next two to three decades in countries of Eastern Europe and the former Soviet Union, dubbed as the EEFSU region in most recent global models. In 1986, probably the "last year of peace" before economic decline became evident in most EEFSU countries, their contribution to the global CO_2 emissions was more than impressive. It was 26 percent compared to their population share of 8 percent, and a share in global GDP of about 6 percent.[2] On the "Top 20" list of countries ranked according to their *relative* (percentage) contribution to global CO_2 emissions, the USSR ranked 2nd, Poland 8th, the GDR 13th, Czechoslovakia 15th, and Rumania 17th. In terms of *per capita emissions*, which is probably better at characterizing their distorted economic structures and wasteful use of energy, the GDR was a sovereign leader leaving the US behind by a fair margin, Czechoslovakia ranked 3rd ahead of Canada, the USSR 6th, right

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[2] It is notoriously difficult to prepare comparable GDP estimates for the formal centrally-planned economies. A casual review (Begg *et al.*, 1990) reveals differences on the order of 5 to 7 times between various calculations. The numbers here are based on some middle-ground estimates and the author's calculations.

behind Australia, and Poland 7th ahead of the then smaller FRG. Rank 10 for Rumania in front of Japan is also worth mentioning.

With a view to the importance of the region in past CO_2 emissions and its potential contribution to future emission reductions at the global level, the two contributions from Russia included in this volume are of special interest. First, much of the in-depth data about the FUSSR energy systems have only recently become available to the international expert community. Second, analysis and evaluation of these systems by those who have the most experience with them are most relevant in the phase of economic transformation. Bashmakov (this volume) approaches the CO_2 mitigation problem by taking an inventory of the relative costs and benefits of energy efficiency improvement options in different sectors of the national economy. Kononov (this volume) presents three scenarios of the transition period up to 2010 and estimates energy use and CO_2 emissions under these scenarios. Once again, the reader is invited to compare these papers and draw the conclusions. In my view, both papers hold important lessons for global modelers who probably need to change many parameters in their models to reflect changes in the EEFSU region.

China is by no means less important in the global GHG problem. Jiankun *et al.* (this volume) present results of a major study on the future of the Chinese energy system. Among many others, an important merit of his analysis is that it follows through a wide range of detailed technological options under several macroeconomic development scenarios.

Most studies about global GHG mitigation declare explicitly or assume implicitly that developing countries cannot be expected to undertake costly measures in the short to medium term to reduce their CO_2 emissions. Yet, several studies are underway to estimate costs and benefits of CO_2 abatement options in the LDC region. Pachauri and Khanna (this volume) point out to the special constraints to be considered when analyzing costs of mitigation options in developing countries. In addition, they present cost curves of CO_2 abatement for several Asian countries and for Brazil. Moreira (this volume) discusses a series of economic, institutional, and technological policy options to enhance CO_2 mitigation in Brazil. Biomass-related options, that is slowing deforestation and large-scale afforestation, occupy a prominent place on his list of GHG policies.

Papers in Section 4 reflect the large variance in estimates of GHG/CO_2 mitigation costs produced by national and regional studies to date. The large variety of modeling approaches, the broad range of initial assumptions, and major differences in the principles and techniques of cost accounting has produced such a rich diversity of results that is simply bewildering to policymakers. In order to make these results comparable across countries and regions, some generally agreed standards are needed for national cost studies. Halsnæs and Mackenzie (this volume) report results from a study conducted on the methodological aspects of abatement cost calculations.

The debate among economists about global warming, its impacts and damages, the feasibility and costs of its mitigation, and the diversity of policy recommendations from the economics community is a relatively small part of the overall climate change debate. The summaries prepared from time to time (Houghton and Woodwell 1989, Schneider 1989a, 1989b; White 1990) report progress on individual topics or single components of the problem in atmospheric sciences, but they do not seem to push the overall debate substantially further. Ausubel (this volume) considers a selected set of issues in the general global warming debate and relates them to recent developments in their economic counterpart or equivalent. By relating recent estimates of global warming costs and benefits to a frightening list of other environmental problems which need attention and funding, he creates especially instructive examples about the real size of financial assets that look so negligible in terms of national or world GDP percentages.

5. Summary and Conclusions

Throughout this paper, and in fact throughout the collection that follows, one item recurrently emerges and it is the issue of spatial and regional aspects in both impacts and prevention of global climate change. The magnitude of economic damage and the range of possible adaptation options depends on the regional level of aggregation. Impacts on a single farm and adaptation possibilities for an isolated farmer are very different from what we see at the scale of a regional economy or at the national level. Similarly, incentives and opportunities for shorter and longer term CO_2 abatement at a specific power plant, industrial unit, or residential heat supply system might be very different from the broad range of legal, technological, and economic options available at the regional or national scale.

All this points toward the need for an iterative type of analysis where results of many more and improved regional and national studies are integrated into a global framework. Conclusions from the global analysis should then be fed back into the next round of national and regional studies. Both national studies and the global synthesis should consider various aspects of mitigation and adaptation simultaneously. Mitigation and adaptation studies should be based on the same baseline scenarios of socioeconomic and technological development. This approach offers hope for more consistent and reliable results. These results are, in turn, badly needed for formulating national GHG policies (based on the national impacts, costs, and benefits) and for negotiating international agreements (based on an improved understanding of national stakes and interests).

Recent studies about the economic aspects of global climate change have produced major developments in several areas. A variety of new ideas and new results were first presented at this Workshop. An incomplete list of new developments includes the following.

- Many features of the global warming problem make traditional methods of analysis difficult to apply or even inadequate. New ideas and innovative approaches are in great demand in order to make our economic, social, and technological analyses of climate change more relevant for policy makers. The approach to estimating agricultural impacts based on Ricardian rents by Mendelsohn *et al.* or the technological bifurcation analysis by Hourcade (both this volume) are excellent examples of the kinds of creative thinking necessary to overcome barriers of traditional analytical tools.
- There has been a gradual increase in the geographical coverage of damage estimates. This was made possible by the proliferating regional and national climate impact assessments conducted in many world regions. Although the methodological underpinnings of these studies are, at best, mixed and many of them do not permit us to derive monetary estimates, we now have a substantially improved knowledge base for damage assessments than the initial attempts which applied a simple multiplier to derive damage estimates for LDCs from those calculated for MDCs.
- The time horizon of the analysis has been dramatically extended. Economists have traditionally considered time horizons of 20 to 30 years at most. The very long-term nature of climate change demands analyses at much longer time scales. Recent analyses face this challenge: Cline's (1992) analysis covers 300 years, some of Nordhaus' analyses with the DICE model extend over 400 years. These time scales, of course, raise new problems especially about the parameters affecting the intertemporal allocation of resources, notably the discount rate.
- Parallel to the increasing time horizons, there is a clear tendency away from the comparative static analyses based on 2 × CO_2 equivalent impact and damage assessments towards truly dynamic analyses. Various types of dynamic energy-economy models have been used to prepare cost estimates for many years, but dynamic approaches have only recently

been applied in the benefit calculations. Scheraga *et al.* and Fischer *et al.* (both this volume) present very different but promising advances in this direction.

- Probably the most significant breakthrough in the economic analysis of global warming has been the integrated analysis of impacts of climate change and costs of mitigation in a single dynamic framework. The DICE model by Nordhaus (1992b) integrates the dynamics of emissions, atmospheric processes, climate change, its impacts, as well as costs and benefits for the first time into a single, albeit simple, synoptic model. *Alea iacta est*, and although this was not the last roll of the DICE, the results are worth thorough consideration.

Some results presented at the conference also point toward the next, more detailed modeling framework integrating both cost and benefit calculations, at least for the U.S. economy. Two separate papers make use of the Jorgenson-Wilcoxen model. Scheraga *et al.* (this volume) use it to prepare a full-scale economy-wide damage estimate while Jorgenson and Wilcoxen (also this volume) calculate costs of various CO_2 abatement strategies. Closing the loop both at the atmosphere/climate side (which will require estimates of non-US and other non-CO_2 emissions) and at the optimal resource allocation side, similarly to DICE, will be by no means a straightforward task, but it is not difficult to envision that it will be done soon. The result will be a powerful tool for integrated cost/benefit assessments, at least for the American economy. The G-Cubed model by McKibbin and Wilcoxen (this volume) holds the promise of the possibility of extension for similar analyses at the global scale.

All these results and new developments suggest that even in the short-term

- the reliability of economic analyses will continue improving even in the absence of major improvements in the scientific understanding and prediction of climate change on the natural science side;
- methodological approaches, modeling techniques, and other analytical tools available for economic analyses of global climate change will be more sophisticated, better tied to the special characteristics of the global warming problem, and more appropriate to handle results from the next cycle of atmospheric and climate research.

Several papers presented at the workshop and included in this volume support these expected short-term improvements in our economic assessments. Plenty of evidence is provided by historical examples, by conceptual and empirical studies, by cost and benefit assessments, by mathematical models and simple reasoning, that the globe may lose more by premature action than by losing a few years from inaction while details of sound and economically efficient action can be developed. This suggests that in the short run investment in information is likely to result in better pay-offs than investment in mitigation.

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Part 1
General Issues

Global Climate Change on the Policy Agenda

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On global environment issues, lots of information, sometimes excessive, have been showering on us. People understand these appeals to save the Earth fairly well by now. But do they really feel it in their hearts? As you may agree, it seems that we fail in transforming the understanding into a feeling of impending perils which need immediate policy measures and actions.

It may be asked why have people so neglected to prevent the worsening conditions of the Earth? Because we have been trapped by that familiar way of thinking, "OK, it is indeed important, but we have a lot to finish before that!" This is what I call a moratorium of thought or state of inaction.

Then what factors underlie this moratory attitude of people? I believe there are four.

First, as in every age, many people innocently believe in human abilities; in general, people place too great a faith in the ability of technology and market mechanisms to solve problems. They believe that the market will be formed whenever necessity arises, and technologies will break through the impasse. Such optimistic, one hundred percent belief in markets and technologies cannot be a convincing argument for environmental issues involving irreversible phenomena.

Second, the environmental and energy resource issues are typically interregional and intertemporal. So far, however, under the conventional socioeconomic regimes, what has almost always been pursued is a partial optimization for a specific region or nation or generation. Current consumption or today's self-interest has been favored over a more optimal allocation of resources.

For example, Japan, a resource-poor country, has benefitted enormously from a relatively free access to the resources of other nations, often in ways that worsened conditions elsewhere. It now has a responsibility to ease and improve the plight of others.

Third, until relatively recently, environmental resources have been considered external in the process of industrialization. The environmental costs were not part of cost calculations; hence there was little incentive to use environmental resources efficiently. Now we face the challenge of how to internalize and how to allocate these environmental costs. The environmental costs, such as those of greenhouse effects, are yet difficult to estimate with accuracy. But I believe that even if this is the case, at least part of the costs should be immediately internalized so that people recognize it as clearly as possible. Both business and consumers should be prepared to bear the present and future burden of this kind of cost internalization. This, I suppose, is a necessary, but not necessarily sufficient, condition for all policy measures to become effective. Perhaps I should stress that the cost of recovering environmental destruction is far higher than the cost of preventing it.

This leads to my fourth point, that is, the uncertainties in the data concerning environmental impacts. These data are composed of quite diverse factors and tend to accumulate uncertainties. Furthermore, even the values claimed to be critical for the global environment and human life are often difficult to prove objectively. So, people are apt to take the ambiguities due to such uncertainties as a kind of leeway or time to spare before taking action. It is often emphasized from a short-term viewpoint to avoid overshooting in environmental policies using the uncertainties as an excuse. But I would like to stress that it is essential to underline the "minimum regret policy" taking into consideration the long-term irreversibility in environmental destruction.

To solve fundamentally the problems associated with global resource scarcity and negative environmental impacts, we need a breakthrough in technological development. However, it often takes many years before innovative technologies can be practically applied, even if we start development immediately. Until then we have to gain time by adopting policy measures like action plans, funding plans and agreements, one by one, and steadily build up achievements. Of course, enormous time will be required here too, before all the nations and economies jointly act along the line of a prescription. Every participant has his own interests, sense of value, and culture. This often produces conflict.

There is no time to spare, yet time is slipping by. We must move away from the tendency to delay taking decisive action. We must get a common recognition or common sense of the plight of the Earth as an objective fact.

What we should do first of all for this purpose is to construct quickly an open environmental database and an integrated network to collect and distribute information on a global scale, in order to foster a common recognition of crisis of the Earth.

Various difficulties will lie along the way; violation of political secrets, funds too enormous to raise, existence of technical barriers, and so on. Yet, no action plan can become effective unless the common recognition overcomes national self-interests.

I believe that IIASA is, and will continue to be, one of the very important nodes in this global information network. I also believe that this international workshop is an important step in this direction. Through excellent presentations, animated discussions, and further cooperation of all the distinguished participants here, this workshop will make a substantial contribution toward our common target.

The Economics of Greenhouse Warming: What are the Issues?

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1. Introduction

The globe faces a profound challenge in the years ahead in addressing the problem of global warming in an efficient and equitable manner. Some would argue that inaction holds perils for our economies and ecological systems, while others hold that the most serious dangers arise from zealous and overambitious government regulation. The perspectives on this issue will differ depending upon one's professional focus or national interest. An ecologist will worry about the loss of precious coral reefs while an economist will fret about the loss of precious national output. Americans look at the prospect of regulation slowing growth in living standards, while Japanese might see regulation as allowing faster growth of exports. A coal producer would be threatened by the tendency of carbon taxes to reduce demand, while a low-lying country would be threatened by the tendency of global warming to raise sea level. Large, rich, and mobile countries might feel they could easily adapt by moving poleward or installing more air conditioners, while small, poor, low-lying, and immobile groups see nothing but misery piled on misery. There is ample room for debate and alternative viewpoints here.

Much economic analysis today has come from the perspective of the rich, adaptive, and mobile countries, a perspective that is hardly representative of the late 20th century. But we are speaking of impacts in the 21st and 22nd century, so it might be that this perspective will apply to many more regions in the future than it does now. In these remarks, I will focus on efficient mechanisms for coping with the threat of global warming. Recent studies suggest that these mechanisms will only be used in high-income countries which have ample resources to devote to longer-term objectives. Moreover, I will concentrate on issues of efficiency and will leave for another day issues of the distributional burden of policies.

2. Choices for Efficient Regulation

The efficient choice of policies poses thorny issues for governments because it requires difficult choices in five distinct areas: selecting the appropriate areas for intervention, finding the right level of intervention, choosing the most efficient tools for minimizing the net economic harm from externalities, coordinating policies where there are international spillovers, and because greenhouse warming poses serious issues of decisionmaking under uncertainty. Because governments operate as monopolists in the industry of regulating environmental protection, there is no market test on any of the four choices. Governments can make many sound or foolish decisions on regulating externalities without bankrupting the country or being driven from office. In some cases, such an overregulating acrylonitrile, the political and economic effect of excessively zealous regulation are trifling; in others, such as regulating health and safety of nuclear power plants, an industry can be sent to its grave. The issues involved in greenhouse warming are a fine example of these issues.

1. To intervene or not to intervene? Government must decide whether greenhouse warming is sufficiently serious as to warrant the setup costs of establishing a new regulatory mechanism; the Bush administration has argued that doing so is premature, while many European governments have made commitments or even imposed carbon taxes. The preponderance of scientific opinion is that this is a sufficiently serious problem to warrant intervention, and economists are coming to that point of view as well. But this leaves the kind of intervention and the stringency of interventions to be determined.

2. Finding the right level of intervention has proven extremely elusive even amongst those who argue for taking steps to slow climate change. Should governments take "no-regret" policies or impose light or heavy tax or regulatory steps? A good measure of the stringency of global-warming policies is the level of "carbon taxes", which are taxes on emissions of greenhouse gases like CO_2. The European Community (EC) has proposed a carbon tax of around $100 per ton carbon (which would more than triple the price of coal in the USA); by contrast, my studies suggest that a carbon tax of $5 to $10 per ton carbon is the maximum that is justified by a cost-benefit comparison, and the $100 carbon tax would be much worse than nothing; and the US government has argued for doing nothing. There is much room for constructive analysis and debate here.

3. The third design issue in this area is the policy instrument. In the United States, command-and-control approaches have been the major tools for accomplishing our regulatory objectives. Academic studies have found

that US regulations have tended to be between modestly and enormously cost-ineffective. Only recently and rarely have market instruments been employed, although there is increasing recognition in the policy community of the importance of cost-effective instruments. The use of taxes on ozone-depleting chemicals, the experiment with tradable CO_2 permits, and the EC's contemplating of carbon taxes are hopeful signs of a trend toward using more efficient regulatory tools.

4. Combatting greenhouse warming will require international coordination of policy in much the same way as do trade policies or exchange-rate mechanisms. There has been much criticism of the slow progress in reaching international agreements with meaningful and binding targets, and mechanisms for ensuring that targets are reached. While some deplore the snail's pace in reaching international agreements in global warming, a more cautious view would recall the fate of the first four cholera conventions, the League of Nations, the Treaty of Versailles, the Gold Standard, Bretton Woods, and the European Exchange Rate Mechanism, the interwar disarmament treaties, SALT II, and the Maastricht Treaty.[1] The cautious would suggest that a slow movement toward consensus may be preferable to a questionable, fragile, and ambitious agreement crammed down the throats of reluctant legislators and voters. All these difficulties should not drive us to the Sununist conclusion that nothing is better than anything, but it surely would forewarn us that temporary inaction is sometimes preferable to makeshifts.

5. An additional thorny issue concerns uncertainty. As scientists, we must admit that our estimates are crude, the models are primitive, the future is uncertain, and our ignorance is vast. Faced with our profound ignorance, should we respond like the Bush Administration on the environment, waiting until the uncertainties are resolved before acting? Or like the Reagan Administration on defense, pursuing spending programs because of the uncertainties about future political developments? Should we assume the worst case on climate change and species losses as we traditionally have with ballistic missiles and at the Fulda Gap?

Modern decision sciences would argue that none of these are correct. An appropriate approach to uncertainty is to weigh the consequences and likelihoods of potential outcomes and to take actions which would maximize the net benefits of expected policies. To wait for uncertainties to be resolved may involve forgoing inexpensive steps that will prove highly beneficial if the dice rolls unfavorably; to wait until uncertainties are resolved is likely to

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[1] The perils of the Treaty of Versailles were foreseen in J.M. Keynes, *Economic Consequences of the Peace* (1920) while a history of international agreements in cholera is contained in R.N. Cooper's *Can Nations Agree?* (1988).

mean waiting forever; literally to defend against the worst case will quickly bankrupt any imaginative government. In games against nature, a best-guess strategy is likely to come tolerably close to an optimal policy – the exceptions being where the stakes are very large, the outcomes are highly asymmetrical, or learning takes place over time.

While the appropriate treatment of uncertainty is not a controversial theoretical issue, it often poses daunting problems of estimation and implementation. The sheer complexity of problems of decisionmaking under uncertainty will overwhelm most analysts and decision makers, for the already-complex issues surrounding greenhouse warming are further complicated by branching of probability, learning, and decision trees. Data problems are compounded because the trees depend on subjective probabilities, future values, and evolving technologies that cannot be found in any handbook of economics or physics. Coping with uncertainty pushes our analysis to the limit.

3. Science as the Handmaiden of Government

I have described some of the issues that governments face in designing efficient approaches to greenhouse warming. I next turn to the role of economic and other sciences as handmaidens to governments. Government leaders clearly will have their own views about the issues – as is clear from this year's American Presidential election – but scientists can properly help frame the issues so that the goals of governments are effectively attained. In this final section, I will lay out five areas where governments need careful analytical work in the economics of greenhouse warming.

1. At the synoptic level, economists rely upon cost-benefit analyses (CBA) to determine the answers to the first two issues above – whether to intervene and at what level of stringency. (In a formal sense, of course, the first is subsumed under the second as deciding whether the level of regulation should be zero or not.) Cost-benefit analysis involves weighing the costs and benefits of interventions and choosing that level of intervention where the incremental benefits no longer exceed the incremental costs. It is often forgotten that CBA can be either quantitative or qualitative. For many areas – such as constitutional decision on free speech, custody decisions on children, or making medical mistakes[2] – a qualitative CBA underlies the decision because quantification is impossible. In greenhouse warming, by

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[2] Recall T.H. Huxley's qualitative cost-benefit analysis on medical education: "There is the greatest practical benefit in making a few failures early in life."

contrast, much is quantifiable and we should insist that policies pass a cost-benefit test as we would for hospital or road construction, defense, or training programs. Therefore a first area where we need much more attention if we are to design efficient policies is to construct careful, empirically based cost-benefit analyses.

2. To construct meaningful CBA, we must have measures of costs and benefits over time that are reasonably reliable. The major uncertainty today lies in the area of benefits, where quantification of the benefits (or damages averted) has been extremely difficult and equally controversial. Nonetheless, to ensure that our policies are efficient, it is absolutely critical that more attention be paid to the impacts side of the equation. In a rough calculation of the value of information in global warming, I found that for studies of greenhouse-warming policies, reducing uncertainty about the impacts of climate change appears to have the largest single payoff and, at the same time, to receive only modest government support. Up to 1990, there was no general support for research on the impacts of climate change. Virtually all the support of research in the USA into the impacts of climate change has been a spinoff of research on agriculture; yet 97 percent of economic activity in the USA today is in the nonfarm sector. The result of this is that we know very little about the impacts of climate change in the nonfarm sector and even less about the impacts in developing countries. There is much fruitful research to do in these areas.

3. In the area of greenhouse warming, there has been good progress on the study of costs, and, while not without controversy, we have several alternative approaches and estimates of the costs of reducing greenhouse gas emissions. Figure 1 shows the results of a survey I undertook two years ago, collecting the costs of reduing GHG as compared to the marginal cost of reduction (or implicit tax rate). Figure 2 adds to this figure the results of a recent model comparison undertaken by the OECD. There is clearly a substantial difference in opinion of the models, and there is no convergence in the most recent studies. I believe that, notwithstanding the remaining dispersion in results, we have learned a great deal from economic models of the costs.

There is, however, one major open issue in cost studies which does not emerge from the surveys shown in Figures 1 and 2. This involves what is sometimes called the difference between the "top-down" and the "bottom-up" approach. More precisely, the difference is between economic-equilibrium models and engineering-optimization models. In economic equilibrium models, markets and decisions are assumed to be efficient and there

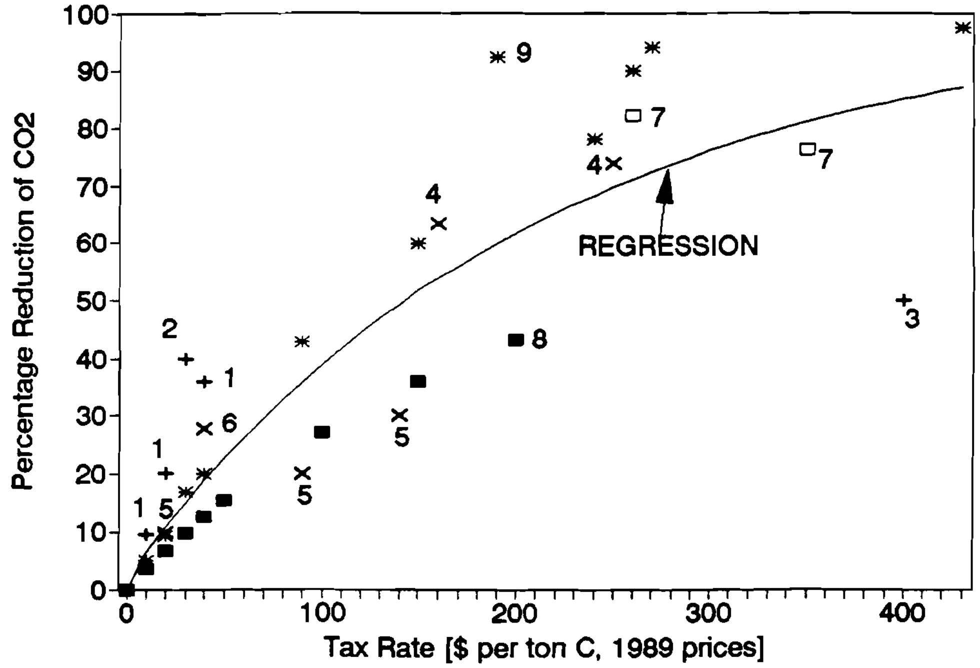

Figure 1. Marginal cost of CO_2 reduction (cost per ton CO_2, 1989 prices).

are no costless GHG reductions (except in situations with classical externalities). By contrast, engineering-optimization models contain technological possibilities for zero-cost or even negative-cost reductions in GHGs. An example often cited is energy conservation, in which it is claimed that there is insufficient investment in energy conservation because of incomplete information, defective incentive structures, or too high a discount rate of consumers. In the colloquialism of economics, this view is not only that there are free lunches, but that in a selected set of restaurants you can get paid to eat.

An example of the contrast between these two approaches is contained in the recent US National Academy of Sciences Report on greenhouse warming (see Figure 3).[3] The step functions show the results of the engineering-optimization studies undertaken by the Panel while the shaded region is a representation of the dispersion of the economic-equilibrium models shown in Figures 1 and 2. The latter approach finds a sharply increasing and positive cost function while the engineering-optimization finds that between 10 and 40 percent of US GHG emissions can be reduced at negative or zero

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[3] National Academy of Sciences Press, 1991, hereafter *Policy Implications*.

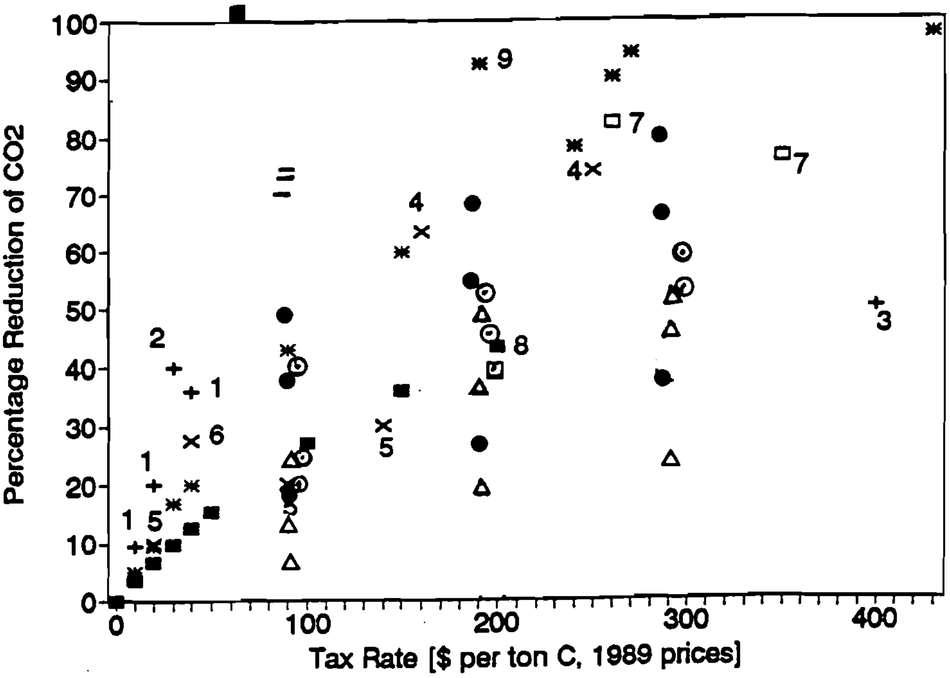

Figure 2. Marginal cost of CO_2 reduction (cost per ton CO_2, 1989 prices).

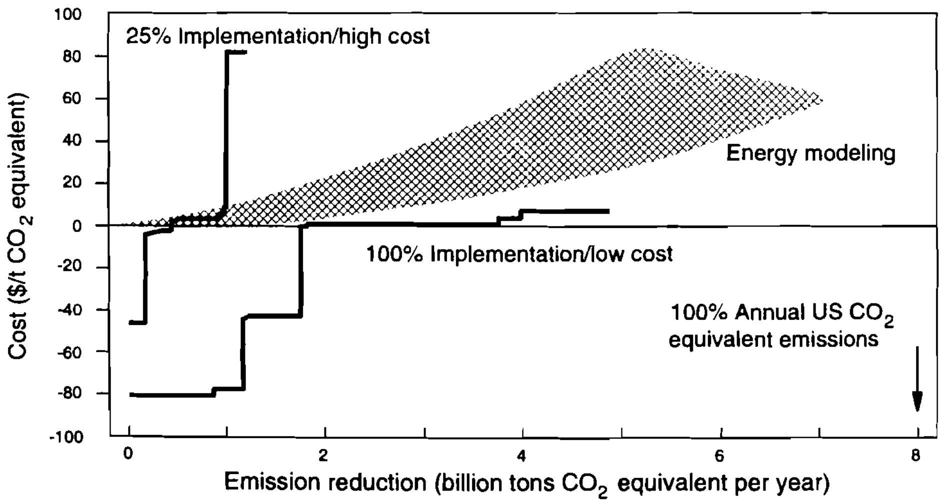

Figure 3. Emission reduction (billion tons CO_2 equivalent per year).

costs. One of the major issues facing modelers is to reconcile the discrepancy between these two approaches.

4. Many who analyze the perils of future climate change argue that the major concern is not the smooth and linear projection that comes out of mainstream climate and economic models. Rather, it is the low-probability, high-consequence events – possibly even catastrophic changes that are difficult or impossible to foresee – which cause the most concern about greenhouse warming. One statement of this point of view is the following from the National Academy *Policy Implications of Greenhouse Warming*:[4]

> Large changes in climate have happened in the past. Desperate masses of people have fled drought or flood in places with marginal farming and growing population. These disasters occurred before greenhouse gases began increasing, and they could occur again. The panel knows of no convincing attempt, however, to compute the probability of cataclysmic changes such as the stopping of the current that warms Europe. Because the probability and nature of such unexpected changes are unknown, the panel cannot project their impacts or devise adaptations to them.

If we heed the words of the National Academy panel, then we at the same time are advised that one of the major concerns is the potential for major ecological disruptions yet we have no systematic way of assessing the likelihood of those events. My own research comes to much the same conclusion: while we can assess the impacts of modest changes in climate, the impact of major, rapid, and discontinuous system shifts is so far outside the range of historical experience that we can hardly expect to pull a reliable economic model out of the tool box to appraise the damages.

I will not attempt to lay out an answer as to the right way to model the economics of decisionmaking with uncertainty and learning although I admit to having a few ideas. Rather, I would urge a collaborative effort of physical scientists, economists, and decision scientists to develop both the tools and empirical distributions that will help our governments come to grips with these difficult issues.

5. The final issue involves the question of institution design. It is easy to become pessimistic about the likelihood of reaching sensible policy responses to the threat of global warming. The need to address the potential issues raised by future climate change is daunting for those who take policy analysis seriously. It raises formidable issues of data, modeling, uncertainty, international coordination, and institutional design. Because the economic stakes are enormous, involving investments on the order of hundreds of billions of

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[4] *Policy Implications*. p. 45.

dollars a year to slow or prevent climate change, we can hardly expect interested parties in the coal, oil, or forest industries to leave argumentation to scholarly studies in the Journal of Economic Theory. Moreover, any efficient policy must be adopted by all major countries and have appropriate incentives for billions of consumers and firms.

All these somber thoughts should not lead to despair. Rather, they emphasize the importance of careful scientific and policy analysis and establishing or strengthening institutions which contain incentives that are compatible with thoughtful balancing of long-run costs and benefits of social investments. The key concept here is incentive-compatible mechanisms or decision processes – ones in which the incentives would lead individuals to actions that are in the long-run interests of society as a whole. The attractiveness of markets is exactly the incentive compatibility of Adam Smith in which profit-maximizing firms and utility-maximizing individuals are led in perfectly competitive markets "as if by an invisible hand" to behavior that serves society.

At the outer limit of incentive-incompatible mechanisms are markets in which there are extensive externalities over space and time and no externality is more pervasive than global warming. One proposal for an incentive-compatible mechanism is a carbon tax system in which carbon taxes are levied at the cost-beneficial level. Such taxes would be preferable to regulatory interventions because taxes provide incentives to minimize the costs of attaining a given level of GHG reduction while regulations often do not; in addition, raising the prices of fossil fuels will give a boost to private-sector efforts on vital new low-GHG technologies; and for countries starved for low-dead-weight-cost revenues, the taxes would allow reductions in deficit reductions or other burdensome taxes.

However, while carbon taxes are a near-ideal incentive-compatible mechanism for harnessing private interests to public uses, there is no comparable mechanism to ensure that governments set the correct level of the tax. As I suggested above, governments can be overzealous or slackers in setting their carbon taxes, and there is no market in governments that will guarantee sound decisions. Among the major challenges that face social sciences is to devise mechanisms that give governments appropriate incentives to set their national policies at levels that will balance long-run global costs and benefits of actions to slow climate change. This is a worthy challenge.

Greenhouse Policy After Rio: Economics, Science, and Politics

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1. Introduction

At the Earth summit in Rio de Janeiro in June, 1992, most nations signed the international framework convention on climate change. The agreement committed signatories to develop plans for limiting emissions of greenhouse gases. For the industrial countries, it provided that by the year 2000 emissions would be reduced to "earlier levels", and a subsequent paragraph in the text cited 1990 levels as a benchmark. Whereas much of the publicity on the treaty focused on its failure to establish binding commitments, in practice it amounts to a relatively strong regime for best efforts toward limiting emissions to 1990 levels by the year 2000. Notably, as an initial framework convention the climate change is considerably tougher than its counterpart for stratospheric ozone depletion, the 1985 Vienna convention.

This essay first reviews recent debates in economic analysis of global warming, and notes perplexing implications of certain recent scientific findings. It then turns to the issue of the international policy strategy for the 1990s. The discussion places considerable emphasis on the role of the developing countries.

2. Recent Economic Analysis

Benefits and Costs of Action. Cline (1992b) provides a benefit-cost analysis for an aggressive international program of limiting carbon emissions to four gigatons of carbon (GtC) annually (and restraining other greenhouse gas emissions commensurately). This program, equivalent to the most ambitious considered by the Intergovernmental Panel on Climate Change (IPCC), amounts to an initial reduction of emissions by about one-third. Because of likely future growth of the world economy and emissions, the cutback from baseline is on the order of 80 percent by 2100 and even greater thereafter.

My analysis adopts a 300–year horizon, because only by that time will deep-ocean mixing begin to limit atmospheric buildup of carbon dioxide. I estimate that under business as usual, the central estimate for global warming amounts to 10 °C by late in the 23rd century, with an upper bound of 18 °C. Damages in agriculture, from sea level rise, in higher electricity requirements for air conditioning, in water scarcity, human health, and numerous other categories could be large. With 2-1/2 °C warming by 2050 (the conventional 2 × CO_2 benchmark), a moderate central estimate would place damages at one percent of GDP, but damages could easily reach two percent of GDP with plausible higher estimates for species loss and including air pollution effects.[1] If warming turns out to be at the upper-bound of 4-1/2 °C for 2 × CO_2, economic damage by 2050 could exceed four percent of GDP. Moreover, these estimates are calibrated for the US economy, and could be greater for more vulnerable countries (but lesser for other, presumably high- latitude, countries). For very-long-term warming, my estimates suggest that economic damages could be in the range of 6 to 20 percent of GDP, depending on the severity of warming and the degree of nonlinearity assumed in the damage function.

The analysis compares the benefit of avoiding the bulk of these damages against the costs of doing so, and uses existing energy-economic-carbon models to estimate those costs. Typically these models find that it costs on the order of one to three percent of GDP to reduce carbon emissions by 50 percent from baseline by the middle of the next century. My estimates assume that an initial reduction in emissions by about one-fifth can be achieved at zero cost, based on the engineering estimates of gains from movement to best practices. The calculations also include emphasis on low-cost forestry measures over the first 30 years, as discussed below. The overall analysis concludes that the benefit-cost ratio comfortably exceeds unity for the aggressive action program, if a risk-averse approach is taken and greater weight is placed on the high-damage variants than on low-damage outcomes.[2]

The Discount Rate Debate. The benefit-cost analysis applies state of the art discounting methodology (Arrow-Kurz-Bradford-Feldstein; see e.g. Gramlich, 1990). All investment effects are converted to consumption equivalents with a shadow price on capital, and then the social rate of time preference

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[1] Measures to reduce global warming would reduce air pollution as well, so their "benefit" would include not only the greenhouse damage avoided but also the gains from lower air pollution.

[2] The full analysis is given in Cline (1992b). A policy-oriented synthesis appears in Cline (1992a).

(SRTP) is used for discounting. Following Ramsey (1928), I argue that the rate of "pure time preference", for myopic preference of earlier consumption regardless of income level, should be zero, an especially appropriate assumption for inter-generational comparison. That leaves discounting only for utility growth. I apply a constant relative risk aversion utility function with the elasticity of marginal utility set at -1.5 (faster decay of marginal utility than under the unitary elasticity of the more conventional logarithmic utility function). With average per capita income growth of one percent, the result is an SRTP of 1.5 percent, and an effective discount rate on the order of two percent once capital shadow pricing and capital productivity are taken into account.

Lawrence Summers of the World Bank and Thomas Schelling of Harvard and the University of Maryland have criticized this approach as applying too low a discount rate; James Tobin of Yale University has endorsed it (Summers, 1992; Stokes, 1992). It would seem useful at this juncture to seek at least greater agreement on the nature of the disagreement.

With Nordhaus (1992a, 1992b), I concur that the discount rate may usefully be separated into what he calls "growth discounting" and pure time preference. Growth discounting is the component associated with declining marginal utility as income rises. In my benefit-cost approach, it is the SRTP. In approaches optimizing a stream of utility, growth discounting is taken care of directly in the utility function, whereas the return on capital investment is incorporated in the optimal choice of savings rates over time. For example, with rising per capita consumption, the logarithmic utility function already shrinks the contribution of additional future consumption by a degree comparable to that from time discounting at the rate of per capita consumption growth (Cline, 1992b, ch. 6).[3] Any discounting beyond the amount already implicit in this shrinkage for declining marginal utility is pure time preference discounting. It would clarify matters, then, if economists could agree that essentially they disagree about the rate to use for pure time preference, or myopia.

It is important to recognize that the disagreement is not about the rate of return on capital. The question is not whether lower rates of return should be permitted on environmental projects (Summers, 1992). Within a given capital budget, the projects with the highest return should be adopted, environmental or otherwise. The point, however, is that in evaluating the

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[3] With a logarithmic utility function, a given percentage change in consumption in the future is equivalent in utility to the same percentage change today, even though the absolute change in the future is far greater because it applies to a higher per capita income.

output of the project, there should be shadow pricing of environmental effects. In particular, there should probably be a shadow price for damage from carbon emissions. In arriving at this shadow or accounting price, it is necessary to use an appropriate SRTP as described above in an overall evaluation of greenhouse policy. But with the carbon shadow price in hand, normal discount rates should be applied at the level of development project analysis.

A final word on the discount rate. Some imply that the alternative to action on greenhouse gases is to take the resources and place them wholly into investment, and then after decades or centuries compensate the future generations for greenhouse damage by endowing them with the massive proceeds of other goods and services resulting from this investment. Advocates of this approach should recognize that it requires explicit political action to levy a tax for the compensatory investment fund, rather than merely the argument that such compensation could be implemented. They should also recognize that it may prove physically impossible to make an intertemporal investment transfer over decades and centuries. We do not know what consumption goods will be desired in the distant future, nor how to construct investment goods that produce only second-stage investment goods for an unbroken chain of investment until that time. In short, the "full investment opportunity cost" argument is implausible and an inappropriate basis for applying the capital investment rate of return as the discount rate in greenhouse benefit-cost analysis.[4]

Optimal Emissions Paths. Nordhaus (1992a, 1992b) has constructed a Dynamic Integrated Climate-Economy (DICE) model to examine optimal emissions over time. His initial results with DICE resemble his earlier conclusions with a comparative static model: only modest reductions in emissions are optimal, on the order of 10 percent cut from baseline in the initial decades and only 15 percent by 2100 (leaving absolute emissions far higher at that time than now). The DICE model has important improvements, including a 400 year horizon that makes it possible to consider the much higher "very-long-term warming" that I have emphasized.

I have conducted alternative experiments using the DICE model (Cline, 1992c). Although my results are preliminary, they show several key results. First, Nordhaus has a much lower baseline of carbon emissions by late in

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[4] The consumption-equivalent method, in contrast, does give weight to the capital rate of return, but assumes instead that only a portion of the resources diverted for greenhouse avoidance come out of investment, whereas the bulk come out of consumption.

the 23rd century than those in my projections, primarily because he has a decelerating rate of total factor productivity growth that leads to lower world GDP and emissions. With a lower baseline of emissions, global warming is less of a problem (reaching only about 5-1/2 °C by the late 23rd century), and given levels of target emissions constitute smaller reported percentage cutbacks from baseline. Second, even using Nordhaus' optimization model, the optimal path for carbon emissions cutbacks is far more aggressive if a low rate is assigned to pure time preference. Thus, at a pure time preference rate of 0.5 percent but assumptions otherwise as in the Nordhaus estimates,[5] the optimal path for reduction of carbon emissions is about 30 percent from baseline in the initial decade, rising to 50 percent by 2100 and 85 percent by 2200. Moreover, this outcome is obtained even without incorporating high-damage variants into the analysis.[6]

In short, the DICE model offers important advances in merging greenhouse climate analysis with economic optimization. However, my initial experiments with the model suggest that its policy implications may be far closer to those from my simpler benefit-cost evaluation than suggested by the preliminary findings reported by Nordhaus, if appropriate modifications are made for baseline, pure time preference, and other parameters.

There are more general points to be made about studies of optimal emission paths. First, especially with intermediate or high discount rates they will tend to defer carbon abatement until relatively late in the horizon. Yet as a matter of political economy, we should be skeptical of a global strategy that assumes later generations will be prepared to take extreme measures whereas the present generation is unwilling to take mild ones. Because of an optimization model's alternative of investing, it can easily reach a flip-flop solution in which there is minimal abatement for several decades and then a switch to nearly complete carbon elimination. The politics of the first phase are easy to imagine, but those of the second phase would seem nearly impossible. Second, such scenarios seem likely to miss the steeply rising trade-off between the usual basket of goods and services and the scarcity value of environmental goods, although in principle this trade-off should be captured in the warming damage function.

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[5] As Nordhaus uses the logarithmic utility function, which has "utility growth discounting" of one percent per annum when per capita income is growing at one percent, the approach most comparable to my SRTP of 1.5 percent is to set the pure time preference rate at 0.5 percent.

[6] In addition, other experiments with the model indicate that optimal abatement may be understated by the model's additive rather than multiplicative treatment of radiative forcing from non-carbon greenhouse gases.

3. Recent Scientific Findings

Two scientific studies published in recent months raise a fundamental paradox about the amount of greenhouse warming to date. The first (Charlson *et al.*, 1992) reports that:

> Current climate forcing due to anthropogenic sulfate is estimated to be -1 to -2 watts per square meter, globally averaged. This perturbation is comparable in magnitude to current anthropogenic greenhouse gas forcing but opposite in sign (p. 423).

Anthropogenic sulfate refers to sulfate aerosols emitted to the atmosphere from urban pollution. Incoming solar radiation reflects from these particles, which increase the earth's "albedo" or reflectivity, both directly and indirectly through their stimulation of the formation of low clouds (whose impact is primarily to reflect incoming shortwave radiation rather than to further trap outgoing longwave radiation).

The Charlson *et al.* finding is remarkable by itself, because it implies that we should have observed no greenhouse warming to date. Aerosols from urban pollution should have fully neutralized radiative forcing from increased carbon dioxide concentrations. There has been "masking" of greenhouse warming that would be unveiled if urban pollution were reduced, or even if its albedo effect failed to rise sufficiently in the future to offset rising carbon concentrations.

This paradox was compounded with the publication of a second recent study (Penner *et al.*, 1992), which found that:

> ... smoke particles from biomass burning ... act to reflect solar radiation directly [and] also can act as cloud condensation nuclei, increasing the reflectivity of clouds. Together these effects ... may add up globally to a cooling effect as large as two watts per square meter, comparable to the estimated contribution of sulfate aerosol (p. 1432).

In other words, the burning of (primarily tropical) forests is emitting smoke aerosols that have an impact comparable to urban pollution in masking greenhouse warming. Indeed, taken together, the two effects provide twice as much negative radiative forcing as the estimated positive radiative forcing from greenhouse gas buildup to date. We should have been observing global cooling over the past few decades, rather than warming.[7]

My interpretation of these two studies is that they seriously increase the likely greenhouse warming that is in the pipeline but presently being

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[7] Note that there was indeed cooling in the Northern hemisphere from the 1940s to the 1970s.

masked by anthropogenic aerosols. Together, they provide a compelling explanation for any shortfall of observed past warming from the amount of transient warming predicted by the General Circulation Models. For this reason, the 1990 IPCC judgement placing the "best guess" estimate for the climate sensitivity parameter (Λ) at 2.5 °C for a doubling of carbon dioxide equivalent above preindustrial levels would seem downward biased. The IPCC chose this level, which is below the midpoint of the previously accepted range of 1.5 °C to 4.5 °C, because of the shortfall of observed transient warming from levels predicted by the general circulation models (GCMs). Yet the most recent GCM runs had tended to predict a climate sensitivity parameter on the order of 3-1/2 to 4 °C. The double-masking effect of sulfate and smoke aerosols suggests the recent, hotter GCM runs may have been right after all.[8]

Another recent scientific development is the natural laboratory experiment provided by the eruption of the Philippine volcano Pinatubo. Sulfate aerosols from the eruption were expected to cause global cooling of about 1/2 °C for two years or so from the increased albedo, based on estimates of the GCMs (Kerr, 1992; Washington Post, 19 May, 1992). By the first several months of 1992, global cooling was occurring by about the amount predicted (*ibid*). The eruption thus provided verification of the GCMs that, if it holds up, will be another basis for confirming their estimates of the climate sensitivity parameter.

As the findings on aerosol masking illustrate, the scientific understanding of global warming is evolving. The Rio framework convention was judicious in explicitly providing that scientific uncertainty is not a basis for postponing action. At the same time, however, remaining scientific uncertainty does seem to warrant a "best efforts" approach rather than legally binding emissions limits by the end of the decade, essentially the strategy adopted at Rio.

4. North-South Cooperation

The current state of both the science and economics points toward a decade or so of cautious but meaningful action to begin limiting emissions of carbon dioxide and other greenhouse gases while carrying out intensive research to verify the severity of the problem and identify the proper extent of future action. The Rio Summit showed, however, that it will be a major challenge

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[8] The evidence in the ice core data is also more consistent with the higher range for Λ. See Cline (1992b, p. 27).

to mobilize participation by all countries. Many would say that US refusal to adopt binding limits was a major instance of such difficulty, although US representatives contended that the American action plan was one of the most concrete in the world.

Regardless of the degree of cooperation among the industrial countries, it was evident at Rio that there is even more doubt about whether, and on what terms, the developing countries would be prepared to participate in greenhouse restraint. There was a strong tone at Rio of reviving the "North-South conflict" from the 1970s, with a focus on the transfer of resources from rich to poor countries. The implicit theme was that whereas previous "threats" from the South (oil and commodity power) had failed to mobilize large resource transfers, perhaps the environmental threat would provide the leverage to do so.

Mutual Interests. This orientation of the negotiations was unfortunate. It tended to relegate the substance of greenhouse risk to secondary importance and focus attention on bargaining over the traditional problem of sharing global income. Yet global warming is a new problem with concrete stakes for the South as well as the North.

There has been some tendency to depict the greenhouse problem as a new infatuation of environmentalists in rich countries, a concern that is a luxury the poor countries cannot afford. Indeed, the World Bank's review of environmental problems in developing countries had the overall tone that global warming was far down the list in importance (World Bank, 1992). In fact, Lawrence Summers of the World Bank has been quoted as arguing essentially that any diversion of developing country resources to greenhouse abatement would be a mistake considering that tens of millions of people die annually from poverty, and that such life-saving measures as providing safe drinking water should have much higher priority than limiting global warming (New York Times, 31 May 1992).[9]

Suppose for the moment, however, that scientific uncertainty were removed, and that global warming was indeed demonstrated to be extremely likely to reach the dimensions outlined above over the long term. Under these conditions, it would be a serious mistake for the developing countries to consider the greenhouse problem to be a luxury for only the North to worry about. The fact is that some of the most severe consequences would

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[9] The same argument would seem to imply more broadly that investments in electricity, steel, and certainly television sets or other luxuries should be postponed until safe water and other life-saving infrastructure are available for all.

be likely to occur in developing countries. The risk of damage from sea-level rise for Bangladesh is well known, but sea level damages could also be high in such countries as Egypt, China, Brazil, and numerous other developing countries. For example, one study indicates that in China, Shanghai and other important cities could be submerged (Cline, 1992b, p. 112). Similarly, an international team of agricultural researchers coordinated by the US Environmental Protection Agency has concluded that agricultural damages from global warming would tend to be the most severe in developing countries, in part because their ability to adapt would be relatively limited (Rosenzweig and Parry, 1992). Recent work by EPA also seems to suggest that health damages from global warming would tend to be more severe in developing countries.[10]

The real issue, then, is not that greenhouse warming involves a trade-off between the interests of the North and the South, but instead that it involves a trade-off between the present generation and the future generation in both the North and the South. There is a modicum of analytical validity to greater emphasis on the present in the South, because of lower per capita income relative to expected future levels and thus a higher (utility-based) time discount rate.[11] Broadly, however, responsible leaders in developing countries should consider their descendants just as much as leaders in the industrial countries should.

Recognition that developing countries are likely to experience greenhouse damages at least as severe as those in industrial countries should help return the question from one perceived of as a zero sum game, involving threats from the South to elicit bribes from the North, to a positive-sum game where broad participation can minimize damage in both areas.

The Rio Blame Game. Nor is it helpful to blame the North because the rich countries have emitted the most carbon historically. Almost all of past emissions occurred without awareness of any global warming damage. More importantly, it is the large increases in future emissions – rising to some ten times today's levels – that threaten to impose high warming, not the stock of carbon from past emissions. The developing countries are expected to contribute the lion's share of future emissions, because they will account for nearly 90 percent of world population and the largest increases in per

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[10] In these various dimensions, more severe damage occurs in the developing countries despite the fact that their geographical concentration in the lower latitudes would suggest warming by less than global means.

[11] Even this justification is shaky, however, in view of the near-zero increase in per capita income in sub-Saharan Africa over the past three decades (World Bank, 1992, p. 219).

capita income. Even today, developing countries are responsible for 45 percent of carbon emissions if deforestation is included (29 percent excluding deforestation; Cline, 1992b, pp. 331-34).

Action Stages for Developing Countries. Because considerable scientific uncertainty remains, it is reasonable to expect the industrial countries to undertake relatively greater abatement efforts at first, just as the rich tend to spend relatively more on insurance than the poor. When and if a new phase of sharply increased scientific certainty begins, more energetic measures by the South would be appropriate. Even then, the objective would likely be limiting future emissions increases in the South (to perhaps no more than twice current levels), rather than seeking absolute reductions below present rates. In both phases, additional financial assistance from North to South is appropriate to cover a major portion of the cost of abatement.

5. An Action Program for the 1990s

The implicit and nearly explicit consensus coming out of Rio was that in industrial countries, by the year 2000 greenhouse gas emissions (chiefly carbon dioxide) should be no higher than in 1990; moreover, developing countries should also be attentive to limiting emissions. Ideally the implementation of this broad objective should be on an efficient basis. Technically, that would require different proportionate cutbacks from baseline in different countries in view of varying marginal cost of emissions reduction. Efficiency would also require credit for sinks (planting trees) and cross-border efforts (e.g. payments by the Netherlands to Poland to reduce Polish carbon emissions for purposes of meeting Dutch reduction targets).

Efficiency Campaigns. The place to start is probably public campaigns to move toward the best-practices frontier. In the United States, public utility rate structures should be revised to create incentives to conserve energy. Reasonable revisions in standards for buildings and automobile fuel efficiency should be pursued. Information pooling should be pursued through coordinated "model home energy configuration" programs that help overcome the "public good" nature of investment in information.

Carbon Tax. It is difficult to see how much real progress will be made in limiting carbon emissions until a price penalty is attached to them. My own preference is for an initial tax on the order of $5 per ton of carbon, rising to $40 by the year 2000 (still only 12 cents per gallon of gasoline). Others would prefer keeping the tax toward the low end of this range (Nordhaus, 1992a), but even implementing a tax on that level would send an important signal to firms that economizing on carbon emissions in the future will be important. The hybrid carbon and energy tax proposed in the European Community is an important political breakthrough, but it is less efficient for purposes of greenhouse policy than a pure carbon tax.

In the US context, the excess burden of the existing tax structure from disincentive effects means that about 30 cents of each dollar collected is a deadweight loss to society (Jorgenson and Wun, 1990). Shifting the composition of taxes toward carbon taxes should therefore provide an important partial offset to abatement costs through reduction of this loss. Moreover, in the United States the need to restore fiscal balance places a further premium on the identification of politically feasible taxes.

During the 1990s, it seems highly un likely that a carbon tax could (or perhaps even should) be levied internationally. The sums are potentially too large for countries to entrust to international entities. Nonetheless, nationally imposed and collected taxes would broadly have the effect of leading toward efficient abatement, especially if set at comparable rates among countries.

In the first decade, some fraction (at least 10 percent) of carbon tax revenue in industrial countries would appropriately be channeled to developing countries to support specific programs to limit greenhouse gas emissions (such as the adoption of non-carbon energy technologies or the reduction of deforestation). Because a carbon tax will have a disproportionately large impact on coal production (as coal has a higher carbon content per unit of energy), it would be fair to allocate some of the carbon tax revenue toward relocation and retraining of affected workers in the coal industry.

Research. By late in the next century the world economy may have to be largely carbon-free, if cutbacks from baseline on the order of 80 percent prove warranted as in my analysis. That outcome is difficult to envision without important technological breakthroughs.

Analyses of technological change argue that in some areas such as solar energy and especially biomass, there is potential for massive departure from carbon-based technology but there is also a need to make an initial breakthrough in such aspects as infrastructure as well as production technology. Essentially, such observers are arguing that we face the type of problem illustrated in Figure 1. At time 0 (today), unit cost of this technology (on

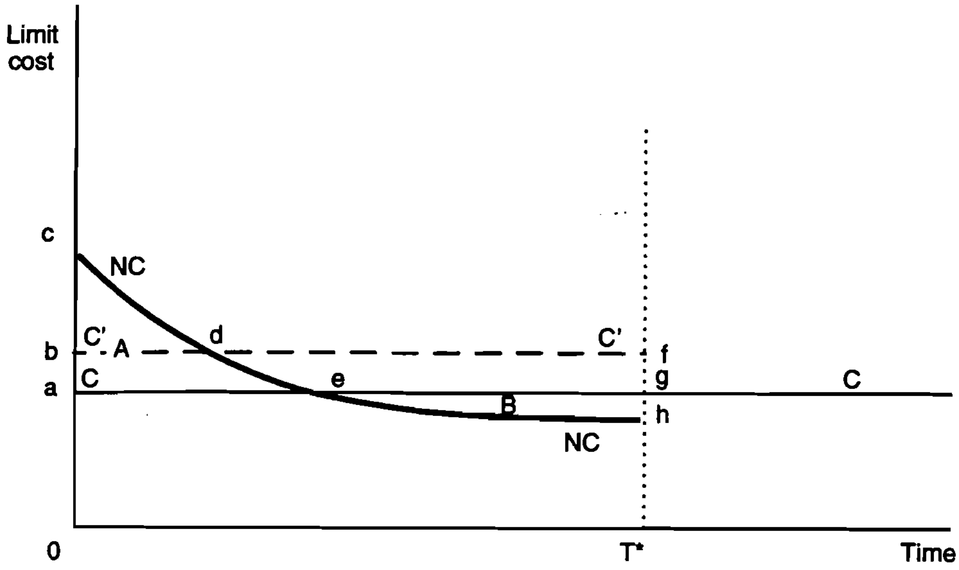

Figure 1. Efficient infant-industry subsidy under environmental externality.

curve NC) exceeds that of carbon alternatives (curve CC). Technical change is expected to reduce unit cost to levels at or below that of non-carbon technologies over time. However, the amount of any such future cost advantage is likely to be sufficiently limited that there is insufficient compensation to adopting the non-carbon strategy today. That is, the future savings represented by area B over the planning horizon are too small to warrant the initial excess cost as represented by area A (especially after discounting).

Explicit inclusion of the negative externality of the carbon-based technology would increase its social cost curve, to C'C'. With this evaluation, the initial excess cost area would shrink from A (=ace) to bcd, whereas the area of future savings would expand from B (= egh) to dfh. The calculus would now favor an initial subsidy to the non-carbon technology because future savings would more than compensate.

Greenhouse policy in the 1990s should include some stimulus to research, development, and adoption of non-carbon energy technologies (including biomass because of its closed-cycle, zero net-emissions nature). [12] In the United States, public funding for research for renewable energy has fallen sharply over the past decade. This trend should be reversed.

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[12] Biomass grown for fuel absorbs the same amount of carbon from the atmosphere that it releases when burned.

There is a key interaction between research and the carbon tax. The tax provides an incentive to focus research efforts on carbon-saving methods, and is thus likely to increase the rate of technical change in these technologies. Moreover, part of the carbon tax revenue can be used to fund research.

Forestry Measures. Carbon can be removed at some $15 per ton through afforestation and at less than $10 per ton through reduced deforestation, compared with costs reaching $100-$250 per ton through cutbacks in industrial emissions at levels on the order of 50 percent or so from baseline. Curbs on deforestation and programs of afforestation should be included in the initial decade of greenhouse policy. Reduced deforestation in developing countries should receive financial support from the North. My program of aggressive action includes an international afforestation effort to plant 260 million hectares in forest (of which 150 million would be in developing countries). An efficient long-term strategy would emphasize the use of new forested area for the production of biomass energy.

Removal of Carbon Subsidies. Many countries subsidize coal and oil. Shah and Larsen (1991) estimate that nine large developing and Eastern European countries spend $40 billion annually on energy subsidies, and the former Soviet Union another $90 billion; the removal of these subsidies would reduce global carbon emissions by an estimated eight percent. MacKenzie *et al.* (1992) have estimated that US drivers receive an implicit subsidy of as much as $300 billion per year, or $2.25 per gallon of gasoline. Even if their estimates are pared down to eliminate costs that would persist even with non-carbon fuel (road construction and maintenance, police, value of untaxed parking, accidents, noise) and to omit direct evaluation of carbon damage (which they place at $27 billion annually or more), a subsidy of about 26 cents per gallon remains ($25 billion as motorists' share of security in the Middle East and $10 billion in air pollution). Outright subsidies to coal in Germany and, arguably, the oil depletion tax allowance in the United States, are further examples of carbon subsidies. At the very least, an internationally coordinated greenhouse strategy can ask that nations stop subsidizing the use of carbon, even if they are unwilling to begin taxing it. Subsidy removal should be directly in the economic interests of the nation in question (though not politically palatable to the interest groups that have enjoyed the subsidies).

Population. One of the most notable shortcomings of Rio was the absence of a hard-hitting position on population growth. It is evident that over the long term, emissions will depend on economic scale, and thus on population. In an aggressive carbon limit program, the carbon budget will be about 0.4 tons per person per year if population stabilizes at 10 billion, but about half that or less if some of the pessimistic population scenarios materialize. In view of eventual carbon abatement costs of at least $10 per ton annually and more probably $100 to $250 per ton, it is likely to be worth an investment on the order of $1,000 or more to secure a steady-state population that is lower by one person. That much money should go far toward reducing population growth (e.g. through educating young women, strengthening social security programs, etc.). What is needed is an ideological breakthrough, considering that it is already known that living standards can improve more rapidly with slower population growth.

6. Beyond 2000

The Rio agreement appropriately provides for at least two international reviews of greenhouse strategy by the year 2000. Let us suppose that by that year the scientific evidence is considerably more certain and substantially confirms the warming prospects outlined above, including the likelihood of high very-long-term warming. Under those circumstances, it will be appropriate to shift to a more intense international regime to limit and reduce greenhouse gas emissions.

In this second phase, a logical first step would be widespread application of carbon taxes at stiffer rates. The taxes could still be levied and collected at the national level, but with greater international coordination on rates, and with an explicit international program to channel some of the revenue to those developing countries that adopt aggressive greenhouse abatement programs of their own. If such an internationally coordinated tax program failed to achieve substantial limitation of emissions within a reasonable period (e.g. 5 to 10 years), it could be necessary to move to a regime of international carbon quotas with tradable permits.

The tradable permit approach would ensure closer adherence to target emissions. However, it would directly raise the equity and efficiency issues associated with determining the initial allocation of the quotas. A reasonable point of departure would be to set initial quotas based equally on three shares in world aggregates: base year population (for equity), GDP (for production needs), and carbon use (for realism at the outset). Over time, the weights would be phased down for carbon use (sooner) and GDP (later), eventually leaving base year population (not contemporaneous, lest there be an incentive to population growth) as a solely equity-based criterion for allocation. Such an approach would automatically provide resource flows to the developing countries, as their shares in carbon quotas would exceed their shares in use, so that they could sell permits to industrial countries and receive revenue thereby.

The second-phase regime would ideally rely on positive incentives to countries to participate in emissions restraint, in the form of revenue-sharing of carbon taxes channeled to developing countries that adopt abatement programs. If positive incentives proved inadequate, then at some point it would be appropriate to impose negative incentives, probably in the form of trade penalties on countries that make little or no effort to limit carbon emissions. The Montreal Protocol on stratospheric ozone depletion provides a precedent for such penalties.

7. Conclusion

Despite its bad press, the Rio agreement marks a significant beginning and workable initial framework for serious greenhouse policy. Recent scientific developments if anything reinforce the prospect of future global warming by increasing the estimated masking currently hiding the warming already in the pipeline (from urban pollution and smoke particles from deforestation). The evolving economic literature on the issue seems amply capable of leading to the conclusion that the abatement game is worth the candle, although here the verdict is likely to turn on whether a substantial time discount factor should be permitted for pure myopia (and in intergenerational analysis). Much scientific work remains to be done, however, including examination of warming and its damage over the very long term (some three centuries).

In the meantime, a whole array of initial measures would seem to make eminent sense, as outlined above. The principal area for debate in the initial phase would seem to be just how high to set a carbon tax and how much incentive to provide to technical advance in carbon-saving technologies. Action in the other areas (movement toward best practices, subsidy removal, forestry measures, population measures) should largely make sense even with a relatively low assessment of the optimal carbon penalty.

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Summary of Global Warming Uncertainties and the Value of Information: An Analysis Using CETA[1]

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1. Introduction

In this paper, we use the Carbon Emissions Trajectory Assessment (CETA) Model to investigate the value of information about global warming. The CETA model represents world-wide economic growth, energy consumption, energy technology choice, global warming, and global warming costs over a time horizon of more than 200 years. In CETA, energy technologies and the oil, gas, and coal resource bases are inputs to an energy submodel, which supplies energy inputs to a production submodel, and the CO_2 by-product to the warming submodel. In the production submodel, energy, labor, and capital inputs are used to produce output which is then allocated to consumption, investment, energy costs, and damage costs of warming. Because energy costs (and energy technology choices) are considered together with warming damage costs, the time paths of CO_2 emissions and carbon taxes in our model reflect an optimal balancing of the cost of emission reduction and the benefit of reduced global warming.

2. Parameter Sensitivities

We begin our investigation of the value of information by exploring the sensitivity of optimal policies to variations in key parameters. We do this at two points in time: 2030 (before a major transition to coal based synthetic fuels has occurred) and 2100 (well into this transition). We find that optimal emissions tend to be insensitive to parameter variation in 2030, but not in 2100. This implies that resolving uncertainty about these parameters before 2030 is not likely to have high value – if roughly the same policy is optimal in

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[1] This paper does not represent the views of EPRI or of its members.

this time frame regardless of parameter values, little is gained by resolving uncertainty about these values. Second, and conversely, the sensitivity of optimal emissions in 2100 implies that resolving uncertainty well before 2100 is likely to have relatively high value.

Our sensitivity results also suggest a subset of key parameters on which we focus in our subsequent value of information analysis. These are parameters which have significant effects on optimal emissions, and which (for technical reasons) affect the benefits rather than the cost of CO_2 emission control. These key parameters are the warming rate per CO_2 doubling and the parameters specifying the warming damage function.

3. Valuing Information

To investigate the value of information about uncertain parameters, we use the paradigm suggested by decision analysis. In this paradigm, information is valued as the difference between (1) the expected value obtained if the state of the world is known before a policy must be adopted, thereby allowing a potentially different policy to be applied in every possible state of the world, and (2) the expected value obtained if a single policy must be adopted (without knowledge of the state of the world) and then applied across all possible states of the world.

In using this approach, a central issue concerns how the emissions control policy under uncertainty in chosen. In the standard decision analysis approach, this policy is set so as to maximize expected net benefits. However, the global warming problem is being considered in a highly political context involving governments of many countries with differing perspectives and interests. In this context, emissions control policies chosen in the absence of good information may be far from the optimal policy. Thus we present results assuming both that the policy under uncertainty is optimal, and that the policy is arbitrarily chosen in the political process.

There are numerous challenges in valuing information in the context of the global warming problem. First, there is a very large number of uncertainties involved in global warming. Second, available assessments of parameter uncertainties are typically limited to possible ranges at most, while information on distributional shapes and possible correlations among uncertain parameters is not available. Third, perfect information rarely becomes available all at once – instead, there is a continuing process of updating "best estimates" over time as information is developed. Finally, even without uncertainty, modeling of global warming is computationally demanding, since warming involves complex natural and human systems over a time scale measured in centuries.

In the face of these difficulties, we adopt certain simplifications in this paper. First, based on our parameter sensitivity results, we limit our consideration to three key parameters affecting the benefits of emission reductions. Second, for most of our analysis we treat each parameter in turn as the only uncertain parameter, and represent its probability distribution using three points, with probabilities 1/6, 2/3, 1/6 for the Low case, Central case, and High case, respectively. However, we do conduct an experiment to explore the implications of joint uncertainty about more than one parameter. For this experiment, we simplify our problem even further by assuming that the two parameters are independently distributed and that these parameters can take on only a High or Low value, each with probability 1/2. Finally, in all the cases we consider, we assume that information perfectly reveals parameter values.

4. Results Assuming Optimal Policy Under Uncertainty

When we consider *single parameter uncertainty* assuming that policy under uncertainty is chosen to maximize expected net benefits, our results suggest that the value of information can be up to hundreds of billions of dollars. For the key parameters we consider, we find that the value of information is greatest for information regarding the potential warming anticipated from a given increase in CO_2 concentration; however, the value of information regarding the future damage costs of warming is nearly as great.

In general, these value of information numbers seem to justify devoting substantial resources to resolving global warming uncertainties. Also, since global warming research budgets are now directed primarily at resolving scientific uncertainties like that about the extent of potential warming, our results provide some support for the position that budgets for research on impacts and adaptation are relatively under-funded, and should be given more resources.

Although resolving uncertainty produces a large benefit relative to not resolving uncertainty, the benefit of resolving uncertainty quickly is surprisingly low. Specifically, we find that the benefit of resolving uncertainty now instead of 20 years from now is roughly 2 percent of the overall benefit of resolving uncertainty. This result is due to the fact that the optimal energy use policy in our model would be about the same over the next couple of decades, for any resolution of uncertainty about the key model parameters. However, by the middle of the next century, optimal energy use policies will become more sensitive to the key model parameters. Consequently, the benefits of accelerating uncertainty resolution by 20 years would be much higher later on.

To obtain a rough sense of the implications of *joint uncertainty* about two or more model parameters, we conduct an experiment in which we treat two parameters as jointly uncertain and independently distributed. Our results from this experiment are generally consistent with those for single parameter uncertainty. However, there are some noteworthy differences. First, the value of information about either uncertain parameter is higher when the other parameter is treated as uncertain, rather than treated as known and equal to its Central case value. Second, the value of resolving uncertainty about both parameters simultaneously is well in excess of the sum of the values of resolving information for each of the two parameters treated as the only uncertain parameter. This result suggests that the sum of the values of information for two or more parameters each treated as the only uncertain parameter understates the value of resolving uncertainty about all those parameters at once.

5. Results Assuming Arbitrary Policy Under Uncertainty

In the forgoing analysis, we assumed that emissions control policy under uncertainty is based on an optimal balancing of the expected costs and benefits of emissions reduction. We also present some results assuming that policy under uncertainty is arbitrarily determined by a real world political process involving the governments of many countries with differing perspectives and interests.

While it is difficult to forecast what kind of emissions reduction policy might emerge from the political process, whatever policy emerges is unlikely to be the optimal one. We consider two possible suboptimal policies that might emerge: one is a policy of no emissions reduction before uncertainty is resolved, and the other is a policy of limiting emissions to the 1990 level until uncertainty is resolved. In either case, we assume that when uncertainty is resolved, the policy will revert to the optimal one for whatever state of the world is revealed.

When policy under uncertainty is arbitrarily chosen, we find that the value of resolving uncertainty now instead of twenty years from now is much greater than when policy under uncertainty is optimal. Specifically, if the arbitrary policy under uncertainty were to be no emissions reduction, the benefit of resolving uncertainty is an order of magnitude greater; and if the arbitrary policy were to be an emissions limit at the 1990 level, the benefit is three orders of magnitude greater.

These results contrast sharply with our earlier ones that suggested there was not a great deal of urgency in resolving global warming uncertainties when an optimal policy is used under uncertainty. Evidently, if early resolution of uncertainty can head-off implementation of inappropriate CO_2 control policies, early resolution has huge benefits.

6. Conclusions

The global warming problem is a complicated one, and placing a value on resolution of global warming uncertainties is a difficult task. In this paper, we present a first effort at such an analysis. Obviously, there are important caveats that should be attached to our analysis.

First, the CETA model cannot perfectly represent the future for the next 200 years, even if the key parameters of the model are completely known. Both the climate model and the economic growth model in CETA are very simple representations of extremely complex systems over a very long period of time; these simple representations necessarily omit many real world factors that bear on the warming problem.

Second, our representation of uncertainty and learning is both limited and simplified. We limit the number of parameters that we treat as uncertain at a given time, we limit the number of possible values that each may take, and we assume that these parameter values are either completely unknown or perfectly known. In addition, the possible values that parameters may take are in most cases just our own estimates of 5 and 95 percent probability points for these parameters.

However, we have conducted a self-consistent exercise to identify important driving variables and to estimate the value of information for a selected subset of these variables. Caveats notwithstanding, we believe that our results support the following tentative conclusions:

1. If an optimal policy is used under uncertainty, the value of information is large enough to justify current research efforts, and perhaps to justify increased emphasis on research into the impacts of warming and cost of adaptation to warming.

2. If an optimal policy is used under uncertainty, ample time is available to plan and execute a well-designed research program to resolve uncertainties.
3. However, if the political process will choose suboptimal policies and this choice could be prevented by early resolution of uncertainty, the urgency of resolving uncertainty is dramatically increased.

Looking vs. Leaping: The Timing of CO_2 Control in the Face of Uncertainty and Learning

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Abstract

This paper concerns the optimal regulation of greenhouse gases that lead to global climate change. In particular, we focus on uncertainty and learning (which, over time, resolves uncertainty). We present an empirical stochastic model of climate-economy interactions and present results on the tension between postponing control until more is known vs. acting now before irreversible climate change takes place.

1. Introduction

Uncertainty is a dominant characteristic of environmental externalities, including the accumulation of greenhouse gases leading to climate change. We understand well neither the effects of climate change nor the costs of controlling greenhouse gases. This is one reason considerable sums are expended in trying to better understand this problem. An additional factor frequently comes into play having to do with the cumulative or stock effects of greenhouse gases. It is not the emissions of greenhouse gases that directly cause adverse effects; rather it is the stock of these gases that may lead to climate change and these stocks change slowly with a great deal of momentum. These two aspects of the problem – stock effects and uncertainty – lead to a tension between instituting control and delaying control.[1] Some in society will desire control of greenhouse gases before climate change is well understood. Others in society may urge delaying control until the problem

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[1] There are other examples with these basic characteristics: hazardous wastes and groundwater, acid rain, species extinction, pesticide accumulation, and the list could go on.

is clearly delineated. If, *ex post*, the problem turns out to be less severe than expected then those urging delay will have been proved correct (*ex post*). If on the other hand, the problem turns out to be more severe than expected, then delay can be very costly indeed.

This paper concerns one of the most fundamental questions in the climate change/greenhouse gas control policy arena: when and to what extent to regulate the generation of greenhouse gases when uncertainty exists and learning is taking place. Thus this paper seeks to determine how the *fact* that we are learning about climate change influences our actions *today* to control greenhouse gases. In our application, there is uncertainty on the damage from climate change. While there has been some work related to this question (Manne and Richels, 1992; Peck and Teisberg, 1992; Nordhaus, 1991a), explicit treatment of the learning process has yet to appear in the empirical literature on climate change.[2] Our approach to the problem is to adapt a simple optimal growth economy-climate model (Nordhaus, 1992) to include uncertainty and learning.

Two primary results emerge from our analysis. If emission control is perfectly reversible (no sunk capital), then the fact that one is learning does not appreciably affect today's emission control policies. This is because of the long lags in emissions contributing to temperature change. In the case where emission control investments, once made, become sunk costs, then rapid learning does tend to *modestly* reduce optimal current period emissions.

The next section of the paper reviews some important contributions to the theoretical literature on learning, as well as existing empirical analyses of climate change and learning. The subsequent section presents our model of optimal regulation. We examine the case of uncertainty in the disutility of pollution. We then consider results.

2. Background

Irreversibilities and Stock Externalities

A major literature has developed in the area of investment under uncertainty in the presence of externalities. Arrow and Fisher (1974) initiated much of the work in this area by focusing on a two period model with uncertainty about the benefits of an environmental asset that is to be exploited (e.g.,

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[2] See Kolstad (1992), and Cunha-e-sa and Kolstad (1992) for a discussion of theoretical issues surrounding learning and stock externalities.

a canyon flooded to make electricity). With some uncertainty resolved between the two periods and the impossibility of undoing development of the environmental asset, it turns out to be optimal to bias development in favor of preservation of the environmental asset. Henry (1974a, 1974b) published similar results. In essence, taking an irreversible action has a cost in terms of reducing the value of information. Arrow and Fisher (1974) introduced the notion of quasi-option value, the value of the information gained by waiting before exploiting the environmental asset. Since then, there has been a considerable literature on irreversibilities and on quasi-option value (e.g., see Fisher and Hanemann, 1987, 1990; Freeman, 1984; Olson, 1990; Conrad 1980; Miller and Lad, 1984). Of course there is also a large literature in finance on option value. In particular, a number of recent papers concern the optimal timing of capital investments (e.g., oil field development) when learning is taking place (e.g., oil field exploration); see Paddock *et al.*, (1988).

Another related literature, primarily from the early 1970s, concerns optimal growth in the presence of environmental externalities, particularly stock externalities. This was a natural extension of the optimal growth models that were popular in the 1960s and early 1970s. An important and characteristic paper in this genre is that of Keeler *et al.*, (1971). In that paper a simple optimal growth model is posited where utility is a function of consumption and a stock of pollution. Optimal paths for accumulation of capital and pollution are developed for several different types of pollution control. Other papers of this type include Plourde (1972), d'Arge and Kogiku (1973), Smith (1972), Plourde and Yeung (1989) and Forster (1973). Cropper (1976) also considers such a model of optimal growth, but focuses on catastrophic environmental effects – the ultimate in irreversibilities.

Learning

There are three basic types of learning which are potentially applicable to global warming. One is active learning whereby observations on the state of the economy/climate conveys information about uncertainty. Thus by perturbing emissions, one can obtain information about uncertain parameters. A second type of learning is purchased learning whereby knowledge is purchased and the amount of knowledge purchased (R&D expenditures) depends on its cost and benefits. A third type of learning can be called autonomous learning where the mere passage of time reduces uncertainty. It is this third type of learning that we examine in this paper.

1. *Information Structures.* The typical approach to including autonomous learning in models of irreversibility is to posit a two or three period model where uncertainty changes from one period to the next. Miller and Lad (1984) use a two period model with an *ex ante* probability distribution on period i benefits (b_i) of $f(b_1,b_2)$. After observing period one benefits, the *ex post* marginal distribution is obtained: $f(b_1,b_2|b_1)$. While this is clearly learning, we need a way to parameterize the *rate* of learning so that the effects of the rate of learning can be deduced. Jones and Ostroy (1984), Olson (1990), and Marshak and Miyasawa (1968) provide such a framework through the concept of an ordering on information structures. Starting with a set of states of nature and an informative message, an information structure consists of a prior on the probabilities of receiving specific messages, along with a conditional probability on states of nature, given a specific message. Of two information structures with the same prior on states of nature, the one that has the greater variability in terms of possible posteriors is viewed as being "more informative." This is equivalent to the more informative structure yielding a higher attainable expected utility when the consumption bundle depends on the state of nature (Jones and Ostroy, 1984 – more flexibility can only be advantageous). Thus if two learning processes yield two comparable information structures, then the structure that is more informative corresponds to greater learning.

To quantify this concept of learning further, suppose there is a set of possible states of nature, indexed by $s=1, \ldots, S$. Furthermore, suppose there is a finite set, Y, of possible "messages" containing information on the state of nature. Suppose the prior on receiving particular messages is q (dimension equal to the size of Y) and the conditional probability on states of nature (after the message $y \epsilon Y$ has been received) is $\pi(y)$. We use the term "prior" to refer to a probability distribution on states, before the message is received and posterior to refer to distributions assuming a message has been received. Let Π be a matrix with columns consisting of $\pi(y)$ with a different column for each y. Thus Π has S rows and the same number of columns as members of Y. (Π,q) is an information structure. A first goal is to develop an economically relevant ordering on information structures. A standard definition of the comparative value of information is provided by Jones and Ostroy (1984) (see also Laffont, 1989).

2. *A Special Parameterization of Learning.* We consider a special restriction on the set of comparable information structures. In particular, if there are S possible states of nature, we assume a message consists of a noisy signal as

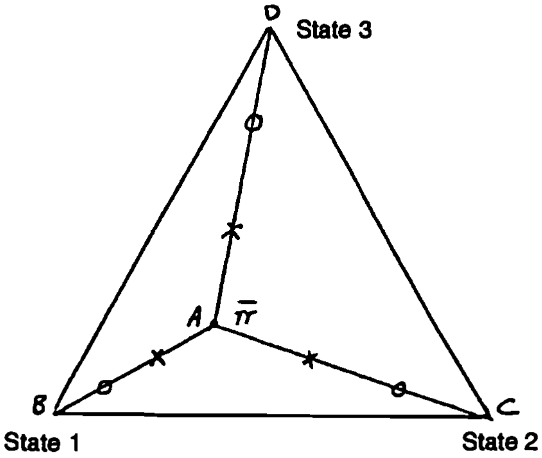

Figure 1. Star-shaped spreading of beliefs from $\bar{\pi}$.

to the true state of nature and there are S possible noisy signals. Let $\lambda \epsilon [0,1]$ reflect the level of information in the signal with 0 being no information and 1 being perfect information. Thus given a prior $\bar{\pi}$ we define the ***star-shaped*** information structure (Π,q) where q$\equiv$ $\bar{\pi}$ and the s^{th} column of Π is

$$\pi^s = (1-\lambda)\bar{\pi} + \lambda e_s \tag{1}$$

where e_s consists of all zeros except with a one in the s^{th} position. Clearly $\pi_q = \Pi\bar{\pi} = \bar{\pi}$. Furthermore if $\lambda=0$, each column of Π is $\bar{\pi}$ and if $\lambda=1$, $\Pi=I$.

As an example, suppose you can receive one of three messages indicating whether the state of nature is 1, 2 or 3. We thus assume that the number of possible messages equals the number of possible states-of-nature, which need not be the case. A message that conveyed the maximum amount of information would resolve all uncertainty on the state of nature. If the message is too noisy to contain any information, then the posterior on states of nature is the same as the prior. This is illustrated in Figure 1 where the simplex of probabilities on states of nature is shown. The prior is $\bar{\pi}$. The set of posteriors associated with a star-shaped spreading of beliefs, spread all the way out to the vertices, is shown by the three lines radiating out from $\bar{\pi}$. Perfect learning would move you to one of the three vertices following receipt of the message. Less perfect learning would move you to one of the three points marked with circles. Even less perfect learning would move you to one of the three points marked with x's after receiving the message.

The advantage of representing learning by this star-shaped spreading of beliefs is that the process can be parameterized by the λ in equation (1). The disadvantage is that we have eliminated perfectly legitimate and orderable learning processes (emanating from $\bar{\pi}$ in Figure 1).

Economy-Climate Models

Economic models have played a critical role in the formulation of environmental policy in the US over the past three decades. The main function of these models has been to simulate the economy's response to particular environmental regulations. Before putting a regulation in place, Congress or regulatory bodies desire to estimate the economic effects as well as the environmental effects of these regulations. That is precisely what an economic model can do, at least in theory.

One of the first economics papers in the global warming area is by Nordhaus (1977) and one of the earliest models is due to Nordhaus and Yohe (1983). They utilize a highly aggregated model, specifying in a single equation the relationship between world GNP and inputs of non-energy factors (such as labor), fossil fuels and nonfossil fuels. Technical change is explicitly represented. Using this highly simplified representation of the world economy, the authors focus on the effect of uncertainty in the underlying parameters on levels of CO_2 over the next 125 years. They are also able to infer which aspects of their model most affect atmospheric CO_2 levels.

William Nordhaus' work has also evolved considerably since the early 1980s. In a recent paper, Nordhaus (1992) augments his economic model by incorporating equations representing the evolution of the atmosphere in response to greenhouse gas emissions. He has also conducted a useful and thorough review of the costs of control of greenhouse gas emissions (Nordhaus, 1991b). Also in the early 1980s a much more detailed model of the relationship between CO_2 and world energy demand was developed at Oak Ridge Associated Universities (Edmonds and Reilly, 1983). The model divides the world into nine regions. In each region aggregate energy demand is a function of prices and income. Supply of energy is represented in some detail, with various technological options represented separately. Using the model, they demonstrate the effect of carbon taxes, either on a worldwide basis or just for the US. Thus they are able to demonstrate the effect of regulation as well as the difficulty in controlling the problem at the sub-global level.

Edmonds and Reilly have developed their model further in recent years (Edmonds *et al.*, 1986). In a recent paper (Darmstadter and Edmonds, 1989), they demonstrate the dramatic effect uncertainty can have on future CO_2 emissions. For example, they show that there is a 5% probability that CO_2 emissions will actually be substantially lower in 2050 than at present, at least given the probability distributions they assume for their exogenous parameters.

Recent entrants into the greenhouse gas analysis arena, though not newcomers to energy modeling, are Alan Manne and Richard Richels. They extend Manne's ETA-Macro model (Manne, 1981) to include the generation of greenhouse gases (Manne and Richels, 1990). The model is used to determine the level of a carbon tax that would be necessary to support particular CO_2 emission goals for the US. Related to this question, they have used their model to look at the value of R&D in climate change by looking at the payoff from resolving uncertainty (Manne and Richels, 1991b; 1992).

The Manne and Richels framework has proved to be very popular in greenhouse policy circles. Peck and Teisberg (1992) have introduced a damage function into the Manne and Richels model to examine the influence of the curvature of the greenhouse gas damage function on optimal control policies. Manne and Richels (1991a) have substantially extended their model by considering several distinct regions of the world. This model they term the "Global 2100" model.

There are several other models of the economics of CO_2 generation that should be mentioned. Marks *et al.*, and Dixon and Johnson have examined the effect of CO_2 emission controls on the Australian economy using the ORANI general equilibrium model. Richard Kosobud has developed a series of models, sometimes alone or sometimes in conjunction with others, to examine specific greenhouse gas issues (Kosobud, 1989; 1990).

3. A Stochastic Model with Learning

In this section, we present a general model of the dynamic evolution of an economy, incorporating emission control, pollution accumulation, and pollution damage. To a large extent it is a standard optimal growth model, although some aspects having to do with the climate are nonstandard. It is based on the climate-economy model of Prof. William Nordhaus (Nordhaus, 1992). His model is deterministic however, and our model is stochastic.

The model is not regionally differentiated and involves the maximization of the net present value of expected utility. Utility is enhanced by consumption and depressed by pollution damage. Output can be channeled to consumption, emission control, or investment. Uncertainty enters in that several states of the world (s) are possible and one wishes to maximize expected utility. The following represents such a model. The parameter h_t can be ignored (assumed constant) for the time being; it will be used later when we consider learning.

$$\max_{I,E} \sum_t \rho^{-t} \sum_{h_t} \sum_s \pi_s (h_t, t)\, u[c(h_t, t),\ d(h_t, t), s] L(t) \tag{2}$$

$$s.t.\ I(t, h_t),\ E(t, h_t)\ \geq 0 \tag{2a}$$

$$Y(t, h_t)\ =\ f[K(t, h_t),\ L(t),\ E,\ (t, h_t),\ t] \tag{3}$$

$$c\,(t, h_t)\ =\ [Y(t, h_t)\ -\ I(t, h_t)]/L(t) \tag{3a}$$

$$d\,(t, h_t)\ =\ g[T(t, h_t),\ Y(t, h_t)]/L(t) \tag{3b}$$

$$\frac{E(t+1, h_{t+1})}{Y(t+1, h_{t+1})} \leq \frac{E(t, h_t)}{Y(t, h_t)} \tag{3c}$$

$$K(t+1,\ h_{t+1})\ =\ (1-\delta_K)K(t, h_t)\ +\ I(t, h_t) \tag{3d}$$

$$M(t+1,\ h_{t+1})\ =\ (1-\delta_M)M(t, h_t)\ +\ \beta E(t, h_t) \tag{4}$$

$$T(t+1,\ h_{t+1})\ =\ s[T(t, h_t),\ M(t,\ h_t),\ O(t,\ h_t)] \tag{4a}$$

$$O(t\ +\ 1,\ h_{t+1})\ =\ r[T(t, h_t),\ O(t,\ h_t)] \tag{4b}$$

where

I = investment (control)
E = emissions of greenhouse gases (control)
K = capital stock (state)
M = stock of greenhouse gases (state)
T = mean atmospheric temperature (state)
O = mean deep ocean temperature (state)
c = per-capita consumption
d = per-capita climate damage
Y = gross output of goods and services

ρ = discount factor
δ_K = capital depreciation rate
δ_M = greenhouse gas decay rate
L = Population/labor supply
t = time/technology
s = state-of-the world
β = Greenhouse gas emission factor
π_s = Probability of state s: $\sum \pi_s = 1$

Equations (2-3) constitute the basic economic model and equations (4) describe the evolution of the climate. Equation (3c) indicates that the emission rate of greenhouse gases is nondecreasing; i.e. investment in emission control is irreversible. The links between the economic model and the climate are E and T. Emissions (E) increase CO_2 levels (M) which increase temperature (T) which causes damage (d) which yields disutility. The goal is to choose the investment path and emission path that maximize expected utility.

Learning

Introducing learning into this model involves introducing a second set of states corresponding to different messages that might be received (see discussion of equation 1). Each message yields a different outcome of the learning process where an outcome is a new probability on states of nature, $\pi_s(t)$. Let Y_t be the set of possible single period outcomes of the learning process at time t. One can think of these as messages as was previously discussed (see also Laffont, 1989). For instance, Y_t could contain three elements, $Y_t = \{y_1, y_2, y_3\}$ where y_1 = learning which increases the likelihood that global warming is serious, y_2 = learning which indicates global warming is a modest problem. y_3 = learning which indicates that global warming is not serious. Before learning occurs we do not know whether y_1, y_2 or y_3 will be realized although we do know the probabilities of elements of Y_t occurring.

While Y_t indicates the possible outcomes of the learning process at t, to know the current state of knowledge, it is also important to know the learning that has preceded t. We call this the history of learning, $H_t = \{(y_o, \ldots, y_t) \mid y_i \in Y_i \forall 0 \leq i \leq t\}$. Notationally, H_t contains the learning that occurred in time period t. An element of H_t is a particular history.

For instance, consider a ten period world in which learning can proceed in three directions {-1, 0, 1} at any point in time. Figure 2 illustrates the history (0, 1, -1, -1, -1, 1, 0, 1, 1, 0). If we partition any h_t as (h_{t-1}, y_t),

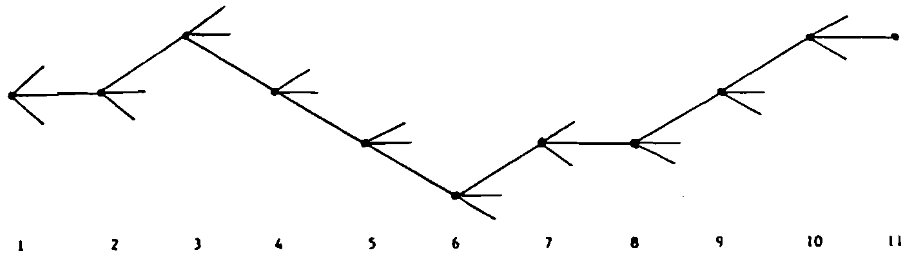

Figure 2. The learning history: (0,1,-1,-1,-1,1,0,1,1,0).

then we define the "predecessor" and "most recent" functions, φ: $H_t \to H_{t-1}$ and ψ: $H_t \to Y_t$ as $\varphi(h_t) = h_{t-1}, \varphi(h_t) = y_t$. The function ψ indicates the most recent learning whereas φ indicates learning that occurred earlier. This allows one to functionally represent the learning path and to compute the probability vector on states of the world, $\pi(h_t, t)$. Define the transition matrix $\Pi_t(h_t)$ such that each column is a posterior probability vector corresponding to a different element of Y_{t+1}. Thus $\pi(h_t, t)$ is the column of $\Pi_{t-1}(\varphi(h_t))$ corresponding to $\psi(h_t)$. Furthermore if $q_t(h_t)$ is the probability vector associated with different elements of Y_{t+1}, then

$$\pi(h_t, t) = \Pi_t(h_t) q_t(h_t). \tag{5}$$

$(\Pi_t(h_t), q_t(h_t))$ is a learning structure as described earlier.

It is "easy" to modify model (2-4) to incorporate this learning. All of the variables in the model are already indexed by h_t, we only need to define how h_t evolves.

$$\pi(h_{t+1}, t+1) = \begin{cases} (1-\lambda)\pi(h_t, t) + \lambda e_s & \text{if } \psi(h_{t+1}) \text{ indicates s} \\ (1-\lambda)\pi(h_t, t) & \text{otherwise} \end{cases} \tag{6a}$$

where

$$h_t = \varphi(h_{t+1}) \tag{6b}$$

where e_s is a vector of 0's and 1's with a 1 in the s^{th} position, 0's in the rest of the positions, and λ is the rate of learning. We assume the message space is the same as the space of possible states of the world. Thus messages are noisy indications of the true state of the world.

There are many ways uncertainty can enter a model such as this. We assume uncertainty in the damage from global warming. Specifically, we write utility as

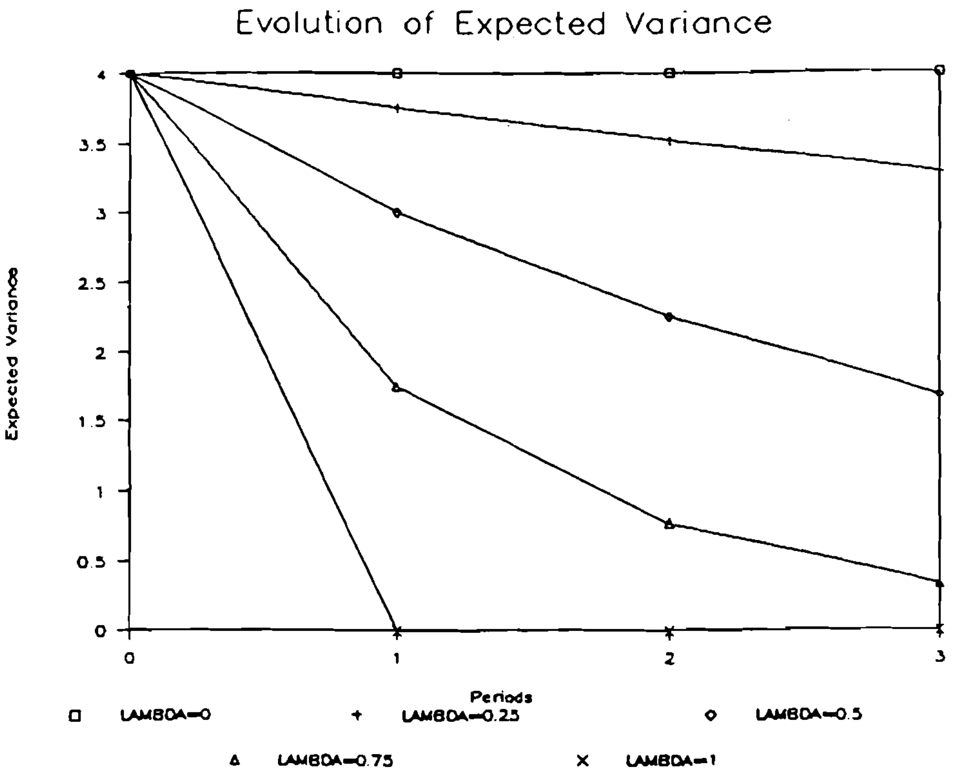

Figure 3. Evolution of expected variance of $\Delta[\pi_o(\Delta = 5) = .2; \pi_o(\Delta = 0) = .8]$.

$$u[c(t), d(t), s] = \log\left[c(t) - \Delta_s d(t)\right]. \tag{7}$$

We further assume there are two states of the world, B and L, corresponding to global warming being a big problem (B) vs. global warming being a little problem (L). We assume $\pi_{\mathrm{B}}(\mathrm{t}=0) = .2$ and $\pi_{\mathrm{L}}(\mathrm{t}=0) = .8$ with $\Delta_B = 5$ and $\Delta_L = 0$. This is somewhat arbitrary but yields an expected value of Δ of 1 and reflects the fact that damage could be serious. The variance of Δ is 4. Figure 3 shows how the expected variance of Δ changes with learning at various learning rates.

4. Results

The model described by equations (2-7) has been implemented using time points at 10-year intervals beginning in 1965. See the appendix for details on

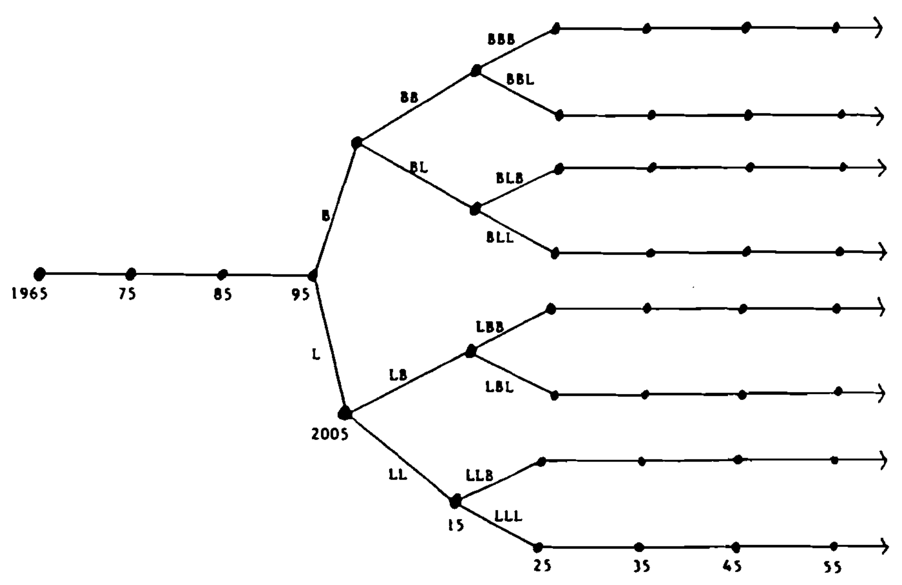

Figure 4. Three-period learning.

the implementation. The first three points (1965–1985) are used as calibration and control of emissions is fixed at zero. Optimal emission control levels are computed beginning in 1995. Learning occurs in 1995–2005, 2005–2015, and 2015–2025. No learning occurs thereafter. Learning can be of two types, B or L, corresponding to suggesting global warming is a big problem (B) vs. suggesting global warming is a little problem (L). Figure 4 illustrates the possible paths learning can take. If the probability of B in 1965 is $\pi(0)$, it will stay at that value through 1995. At that point the probability change depends on how learning progresses. In 2025 and thereafter there will be eight possible values of this probability, depending on the learning history. All of the variables in the model must be indexed on the path learning takes.

The model described in the previous section was an infinite horizon model. Such a model takes a fair amount of computer time to solve so we have chosen to approximate this with a 20 period/200 year finite horizon model. Figure 5 shows, for the case of the deterministic model (2-4), the effect of the horizon on optimal emission control rates.[3] Clearly the control level in 1995 is largely unaffected for horizons in excess of 20 periods.

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[3] The figure shows the solution to the deterministic model using equation (7) as an objective with $\Delta_s = 1$ for S = B,L. This is the expected value (equation 3c removed) of Δ, and no learning occurs.

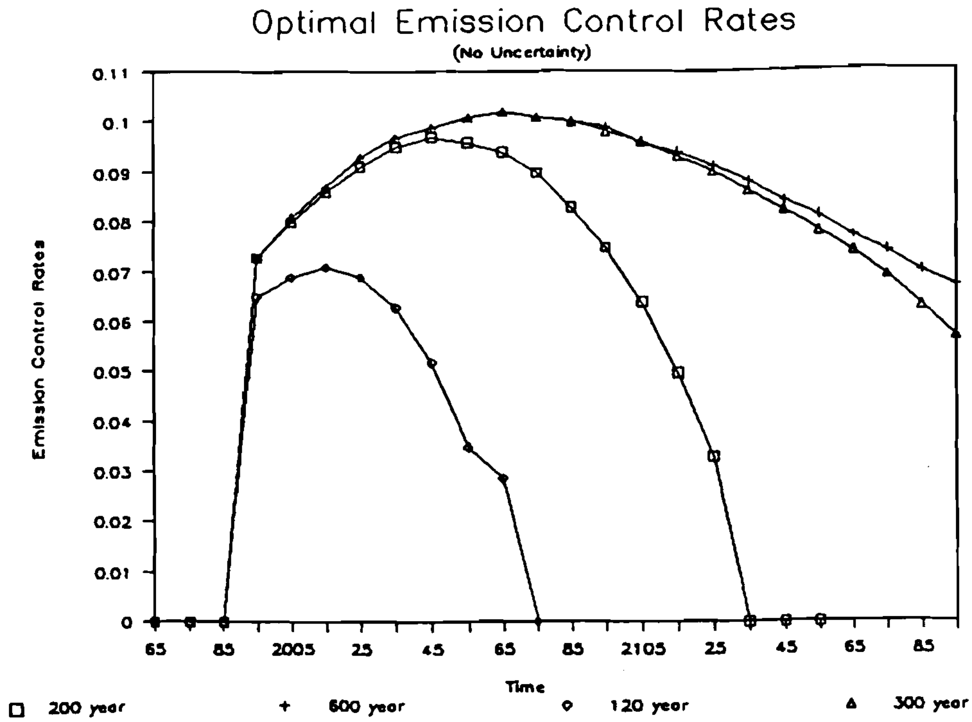

Figure 5. Optimal emission control rates.

Model (2-7) was solved under two conditions. In one, emissions were allowed to take any positive value. In the other, the emission control rate was restricted to be monotonically non-decreasing (equation 3c included), reflecting the fact that emission control investments tend to involve sunk costs: once a control level is implemented, it is unlikely to be decreased at a later date.

Focusing on the year 1995, with reversible emission control rates (i.e., equation 3c is omitted), we find that optimal control levels for greenhouse gases are virtually unaffected by the rate of learning. If one overcontrols today, then that error can be corrected in the future. Thus the fact that learning is taking place does not impact current decisions to control emission.

It is for this reason that we focus on emission control rates that are monotonically non-decreasing. In this case, once an emission control level is implemented it cannot later be reduced, even if climate change turns out to be less significant. Figure 6 shows how the level of emission control in 1995 is affected by the rate of learning, λ. Recall that $\lambda = 0$ corresponds

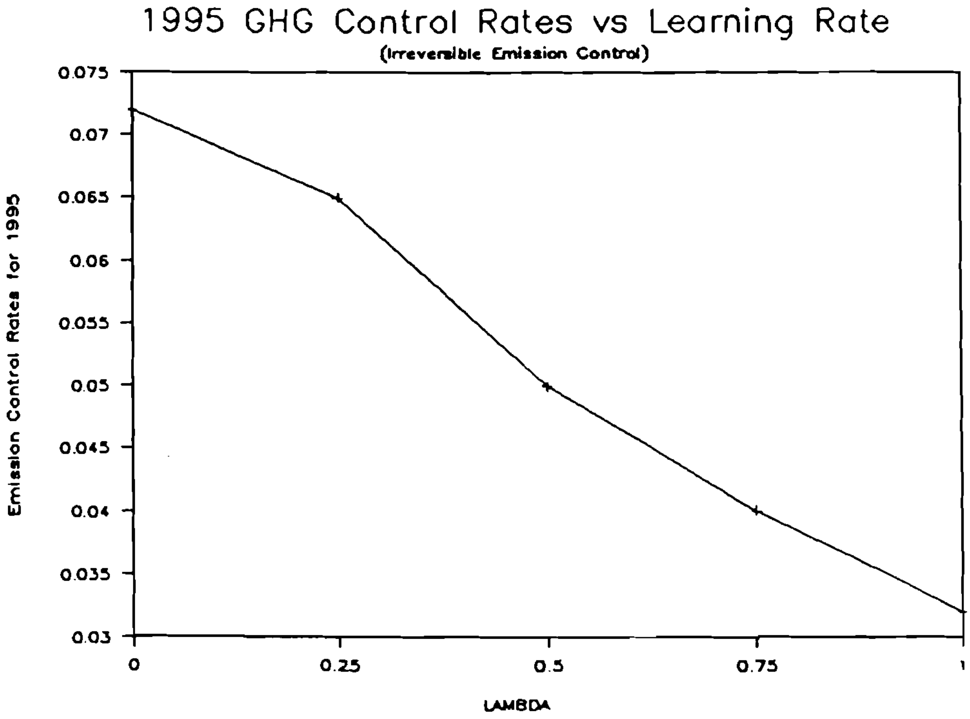

Figure 6. 1995 GHG control rates vs. learning rate.

to no learning whereas $\lambda = 1$ corresponds to resolution of all uncertainty in one period. Thus when learning is occurring rapidly, it pays to reduce greenhouse gas control rates from approximately 7% to as low as 3%. More modest learning rates involve more modest reductions in control rates, but reductions nevertheless.

The reason for lower emission control levels with more rapid learning is that it is better to defer irreversible control decisions until more is known. It is interesting that the irreversibility in control capital dominates the climate irreversibility. This is no doubt because of the long lags involved in climate change. Figure 7 shows, for $\lambda = 0.5$, how atmospheric temperature increases vary with learning histories.[4] Atmospheric temperature changes come long after the emissions occur. This suggests the potential payoff from control measures that are reversible.

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[4] The learning histories are shown in the figure. The path BBL, for instance, corresponds to learning in the direction B in the first two periods, followed by learning in the direction L.

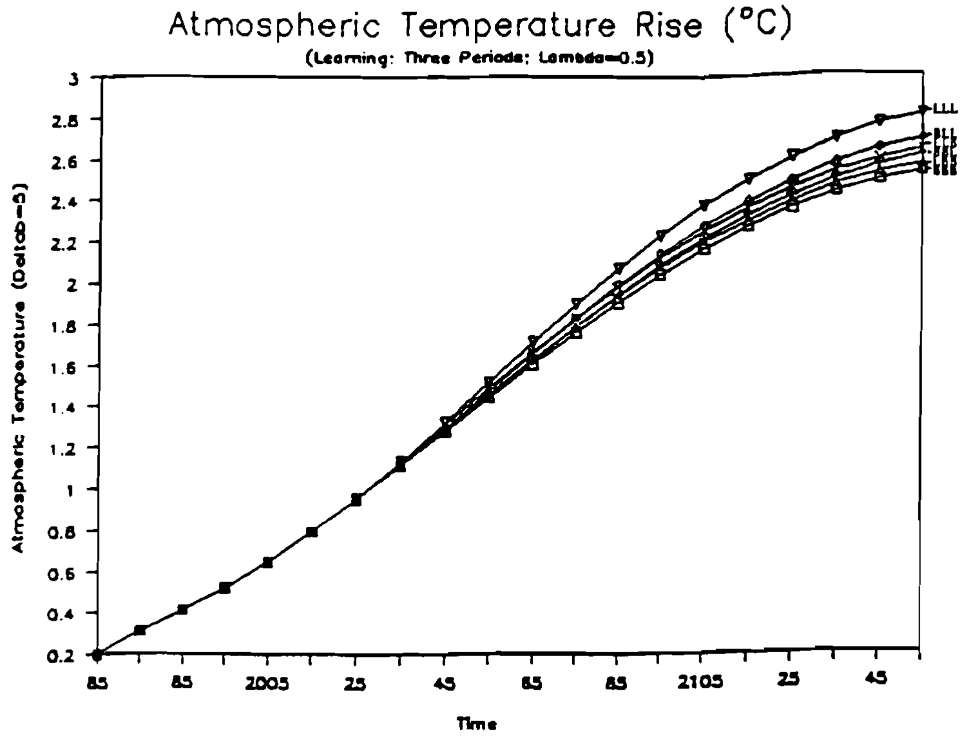

Figure 7. The evolution of atmospheric temperature.

It is interesting to compare this result to that of Manne and Richels (1992). While their model is substantially different than ours, they show that immediate resolution of uncertainty (very rapid learning) results in lower emission control rates (higher emissions) than when uncertainty is not resolved. This is qualitatively the same as our result.

Figure 8 shows how emission control evolves with learning over time for $\lambda = 0.5$. In 1995, control goes to 5%, before learning occurs. In 2005 one period of learning occurs. If that learning is B, control goes to 11%; otherwise it stays at 5%. After another period of learning, the range of control levels grows even further.

Figure 9 shows the value of information as a function of λ. The expected value of perfect information is the difference between the net present value of expected consumption less damage if emission control can be made completely contingent on the state of nature and the same figure with uncertainty and non-state-dependent controls. The expected value of perfect information (EVPI) shows what it could be worth to resolve all uncertainty instantaneously. Even modest learning rates substantially reduce the EVPI.

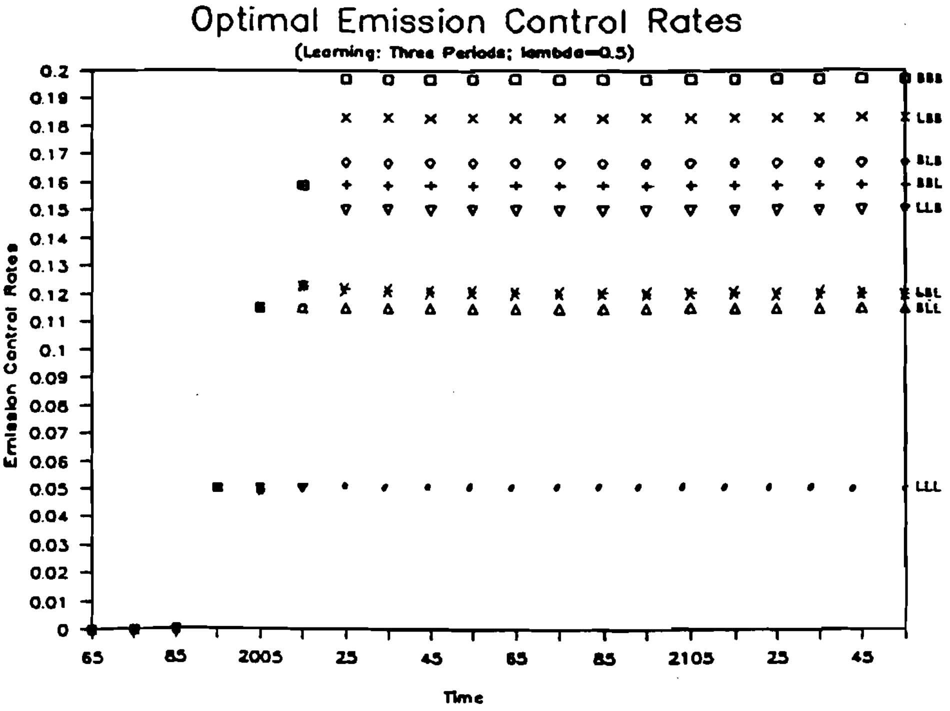

Figure 8. Emission control paths.

This is somewhat consistent with Peck and Teisberg (1992) who show only modest value to resolving uncertainty.

5. Policy Implications

The results of this simple model do suggest that rapid learning biases current period CO_2 control levels downward. Thus these results tend to support those who argue that policy-makers should take a wait-and-see approach to CO_2 mitigation. There are two important qualifiers to this result, however. One is that learning only biases control downward and does not eliminate the desirability of some control. Secondly, the assumption of complete irreversibility of emission control investment may be extreme and certainty suggests the development of control strategies which are reversible; this is related to but not quite the same as a no-regrets strategy.

The most important caveat of all, of course, is that the model presented here is highly stylistic and is really only intended as an illustration or research tool; it is certainty not intended to be used to develop policy.

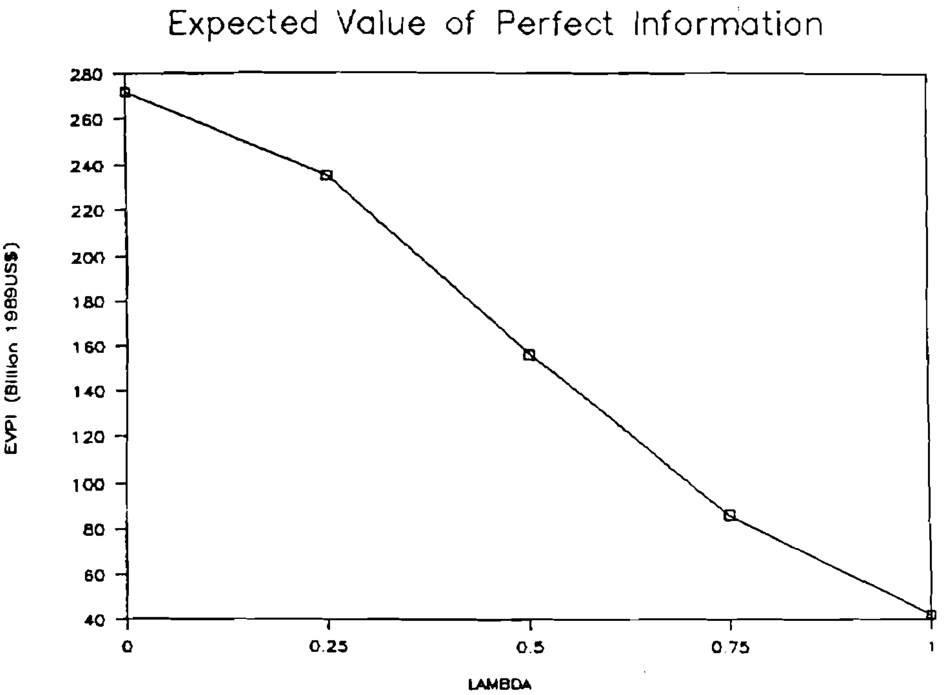

Figure 9. Expected value of perfect information.

6. Conclusions

In this paper we have presented an empirical model of learning with uncertainty in the context of the control of greenhouse gases. We have demonstrated that when irreversibilities exist in both climate change and emission control, emission control dominates. Thus accelerated learning tends to reduce current period optimal emissions.

Appendix: Model Implementation

In implementing the model (2-7), we have followed closely the deterministic DICE model (Nordhaus, 1992). Thus, suppressing h_t for the moment, the functions f, g, s and r in equations (3) and (4) are defined as

$$\text{f:} \qquad Y(t) = \left[1 - b_1 \mu(t)^{b_2}\right] A(t) K(t)^{\gamma} L(t)^{1-\gamma} \qquad \text{(A-1)}$$

$$\text{where} \qquad \mu(t) = 1 - \frac{E(t)}{\sigma(t) Y(t)} \quad (0 \le \mu \le 1) \qquad \text{(A-2)}$$

g: $$d(t) = \frac{Y(t)\Theta_1 T(t)^{\Theta_2}}{L(t)\left[1+\Theta_1 T(t)^{\Theta_2}\right]} \qquad \text{(A-3)}$$

s: $$T(t+1) = T(t) + \frac{1}{R_1}\left\{F(t) - \wedge T(t) - \frac{R_2}{\tau_{12}}[T(t) - O(t)]\right\} \qquad \text{(A-4)}$$

where $$F(t) = 4.1 \log[M(t)/590]/\log(2) \qquad \text{(A-5)}$$

r: $$O(t+1) = O(t) + \frac{1}{R_2}\left\{\frac{R_2}{\tau_{12}}[T(t) - O(t)]\right\} \qquad \text{(A-6)}$$

where A(t) and σ(t) are exogenous technology change parameters. Parameter and starting values are documented in Nordhaus (1992).

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Part 2
Impacts and Damages

The Economic Costs of Global Warming: Some Monetary Estimates

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Abstract

The paper outlines order of magnitude estimates of the damage caused by a doubling of atmospheric CO_2 concentration. Results are presented for five regions and the world as a whole. The estimates for industrialized countries confirm the Nordhaus damage range of 0.25 to 2% of GNP, although they tend towards the upper bound. The estimates for developing countries are about twice as high, confirming the view that the poorest countries will suffer most, even if adequate protection measures are taken. Regional differences may, however, be considerable, as is exemplified by the estimates for the former Soviet Union and China.

1. Introduction

It has repeatedly been argued that an efficient policy response to global warming will have to consider both the costs and benefits of greenhouse gas abatement. Evidently, the precondition for such an approach is at least a vague knowledge of the costs as well as the benefits of policy action. Several studies already exist on the costs of greenhouse gas control and the number is growing steadily (for a survey see e.g. Boero *et al.*, 1991). This paper thus concentrates on the benefits – or, more correctly, the avoided damage – of abatement policies, an aspect which has gained less attention so far.

Given the large amount of uncertainty which still dominates the impacts discussion, any attempt towards a monetary damage estimate can hardly

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be more than a rough assessment of the order of magnitude. In addition, several simplifying assumptions had to be introduced to pursue the task. Most importantly, we do not aim to estimate a whole damage function, but only provide an estimate for *one point in time*. Specifically, we try to estimate the damage occurring with an atmospheric CO_2-concentration of twice the preindustrial level ($2 \times CO_2$). Based on IPCC (1990a), $2 \times CO_2$ is assumed to lead to an (equilibrium) increase in global mean temperature of 2.5 °C. In a recent paper, Wigley and Raper (1992) estimate that this will be accompanied by a sea level rise of about 50 cm by the year 2100, considerably lower than IPCC's initial prediction of 66 cm. The following results will be based on this more optimistic estimate. In order to avoid predictions of growth and future development, we choose the year 1988 as base period, i.e. we estimate the damage which $2 \times CO_2$ would cause to a world with the economic structure of 1988. Six different (partly overlapping) "regions" are considered: EC, USA, the countries of the former USSR, CHINA, the OECD nations (including EC and US), and the WORLD as a whole. In this respect the paper goes beyond the studies by Cline (1992), Nordhaus (1991a, 1991b), and Ayres and Walter (1991) which pursue a similar task, but are basically restricted to the United States. Like these studies, the paper neglects multiplier effects. That is, we will only estimate, for example, the impacts on forests and forestry (including price effects), but will ignore the effects this may have, say, on the furniture industry.[2]

Climate change will affect a wide range of activities and sectors. An attempt at a classification is made in Figure 1. The paper follows this categorization and deals with each aspect in turn. Total damage is the sum of the costs in each sector. It is evaluated and discussed in the final section. The figures presented are based on Fankhauser (1992) of which the present paper is an extended summary.[3]

2. Capital Loss

The rise in sea level triggered by global warming threatens to inundate vast land areas along low lying coastlines. Not all threatened areas will necessarily be abandoned, however. It is quite likely that at least the more valuable areas will be protected. Like Titus *et al.* (1991) and IPCC (1990c), we assume

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[2] For an assessment of this method compared to the "true" general equilibrium welfare costs, see Kokoski and Smith (1987). While the measure is inexact, the sign of the deviation is unclear.

[3] The detailed paper Fankhauser (1992) is available from the author on request.

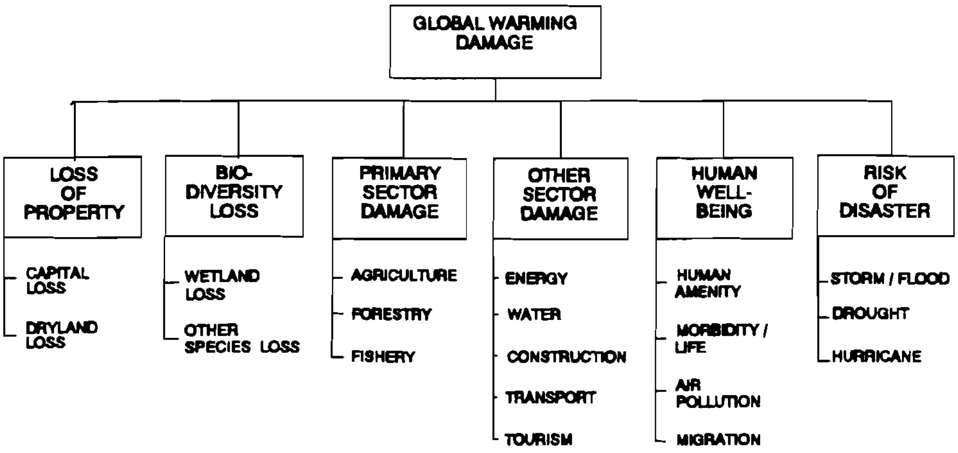

Figure 1. Overview on global warming impacts.

that it will be cost efficient to protect highly developed areas such as cities or tourist beaches, while undeveloped or sparsely populated regions will be abandoned (partial retreat scenario).[4] This assumption, although certainly a reasonable one, is made not least for data reasons. Instead of calculating the potential capital loss, we evaluate the costs of *capital protection.* The value of the unprotected areas lost will be considered in the following section.

The estimates are based on a study by Delft Hydraulics, which calculates the worldwide costs of protecting beaches, cities, harbors, and densely populated coastlines against a sea level rise of one meter within 100 years (see IPCC, 1990c). The measures considered include the building of seawalls, levees and dikes, beach nourishment, and the elevation of islands. They include protection as well as maintenance costs.

The Delft figures are adjusted to our assumption of a 50 cm rise assuming an exponential relationship between protection costs and sea level rise (Titus *et al.*, 1991). The Titus *et al.* estimates imply a power factor of 1.28. For a 50 cm rise, the Delft figures thus had to be multiplied by a factor of $(\frac{1}{2})^{1.28} = 0.41$. In addition, as they are estimates of the undiscounted total costs of protection, the Delft estimates had to be translated into an annual expenditure stream (see Cline, 1992). The resulting estimates are shown in the first row of Table 1.

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[4] This assumption is probably too optimistic for poorer countries which will lack the funds to protect their coasts sufficiently. Initiatives for insurance funds or technical aid are therefore not only desirable on equity grounds, but necessary conditions for the cost efficient response to become feasible.

Table 1. Damage due to 2 × CO_2 (bn$).

	EC	USA	Former USSR	CHINA	OECD	World
Coastal defense	0.1	0.2	0.0	0.0	0.5	1.1
Dryland loss	0.3	2.1	1.2	0.0	8.1	14.0
Wetland loss	4.9	5.6	1.2	0.6	15.9	31.6
Special loss	7.1	6.4	2.6	1.5	17.3	28.2
Agriculture	9.7	7.4	6.2	7.8	23.1	39.1
Forestry	-4.1	-1.8	-2.9	1.1	-10.0	-10.8
Fishery[a]	–	–	–	–	–	–
Energy	–	–	–	–	–	–
Water	14.1	13.7	3.0	1.6	34.8	46.7
Other sectors	?	?	?	?	?	?
Amenity	7.0	6.8	-0.7	0.7	20.1	23.1
Life/morbidity[b]	22.0	16.6	3.9	7.3	57.3	89.3
Air pollution	3.5	6.4	2.1	0.2	11.9	15.4
Migration	1.0	0.5	0.2	0.6	2.0	4.3
Natural hazards[c]	0.0	0.2	0.0	0.2	1.1	3.2
Total (bn$)	65.6	64.1	16.8	21.6	182.1	285.2
(% GNP, 1988)	(1.5)	(1.3)	(0.7)	(6.1)	(1.4)	(1.5)

Note: Negative numbers denote benefits ("negative damage").
[a] Fishery loss is included in wetland loss.
[b] Mortality only.
[c] Hurricane damage only.

3. Dryland Loss

As argued above, we presume that densely populated areas will be protected against the rising sea. The loss of dryland due to climate change will therefore be restricted to undeveloped and sparsely populated areas.

The area affected was estimated using Rijsberman's (1991) estimates of sparsely populated, low lying coastlines, which was completed by our own calculations. To get an area estimate we assumed a loss of 0.46 km^2 per kilometer of undeveloped coastline (based on the calculations of Titus *et al.*, 1991). The figures are shown in Table 2.

Valuing coastal lands is rather difficult and figures differ by several orders of magnitude depending on use and location of the piece of land in question. For the OECD regions, we adopted the average value of 2 m$/$km^2$ used in Titus *et al.* (1991) and Rijsberman (1991). For the former USSR, where the main area under threat is the almost uninhabited north coast, we used an arbitrarily chosen price of 0.5 m$/$km^2$. For the world as a whole we assumed

Table 2. Dry- and wetland loss due to 2 × CO_2 (partial adjustment scenario).

	EC	USA	Former USSR	China	OECD	World
Wetland loss[a] (km^2)	9,887	11,121	9,788	11,918	33,862	252,985
Dryland loss (km^2)	1,596	10,695	23,920	0	40,420	139,923

Source: Compiled from Rijsberman (1991) and Titus *et al.* (1991). See Sections 3 and 4.
[a]OECD excluding Australia, Canada and New Zealand. World excluding some 60 countries.

1 m\$/km^2 as an average between the high price in the industrialized world and the lower prices in less developed countries.[5]

Following Cline (1992) in assuming a 10% return on land per year, we can derive the annual revenue losses reported in Table 1.

4. Coastal Wetland Loss

The amount of wetlands likely to be lost through 2 × CO_2 depends mainly on the possibility for the systems to migrate inland, and therefore on the amount of coastal protection measures taken. The more comprehensive the defense measures, the more difficult backward migration becomes and the more coastal wetlands will be lost. Titus *et al.* (1991) estimate that for the United States about one third of all remaining wetlands would be lost under a partial protection scenario. We assumed this value to hold worldwide. The resulting area estimates are shown in Table 2.

To achieve a monetary estimate, wetlands were valued at between 0.5 m\$/km^2 (China) and 5 m\$/km^2 (OECD regions).[6] Again we assumed a return on land of 10%.

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[5] As an example for the land price in the less developed world, Ayres and Walter (1991) report a value of 0.3 m\$/km^2 for arable land in Bangladesh. However, also note their objection on using lower land values for poorer countries, a line which we do not follow in this study.

[6] The figures denote the total value of wetlands, i.e., they also include the benefits to coastal fisheries. This fact will be of importance when discussing the impacts of fisheries in Section 7.

5. Species and Ecosystems Loss

Most studies on the impacts of global warming predict a decrease in biological diversity. Specially threatened are, according to IPCC (1990b), geographically localized and slowly reproducing species as well as poor dispersers and species "at the edge of (or beyond) their optimal range" (p.10).

In measuring the total value of a species or a sight, economists distinguish between use, option and existence value. This latter has been estimated for various species and Pearce (1991) reports results from US-studies which yield a willingness to pay of 5–15 \$(mid 1980's) per person and year for the preservation of animals ranging from the emerald shiner to the grizzly bear. Based on this, we assumed a willingness to pay in OECD countries of 10 \$(1988) per person and year for the wider, although as yet unspecified, threats from global warming. Use values generally tend to be lower than the corresponding existence value, and as an average we worked with a figure of half the existence value. Again, we assumed lower values for non-industrialized countries.

Existence values are more or less independent of geographical locations and were therefore distributed simply in proportion to population. Use and option values on the other hand depend on the geographical distribution of the losses. As an approximation, we used the number of threatened species in each region. This seems to be a reasonable index, given that already endangered species are particularly at risk (see above).

6. Agriculture

Together with the costs of sea level rise, the effects on agriculture are probably the most studied aspect of global warming damage (see e.g. Parry, 1991 and Parry *et al.*, 1988). Most of this research concentrates on productivity or output aspects, however, and does not include the impact of changing prices. Price effects are crucial, though, for the economic valuation of agricultural damage. Most studies also neglect the – admittedly difficult to estimate – benefits from an adaptive adjustment of the production technology (e.g. by using different crops etc.) and are mere *ceteris paribus* exercises.

Our estimates are based on a study by Kane *et al.* (1992) which includes price effects, but neglects managerial responses as well as the effect of CO_2-fertilization. Kane *et al.* work with two scenarios: An optimistic scenario A which assumes positive yield effects in most regions, and a more pessimistic scenario B which is roughly within the same range as Cline (1992). It assumes negative yield effects even for northern regions such as Canada and the former USSR. For the estimates in Table 1, we took the average between the two.

7. Forestry

The extent to which the forestry sector will be affected by climate change depends on various factors like, for example, the species and age of trees, possibilities for forests to migrate, and the quality of forest management. The impact of global warming on wood production is therefore ambiguous. IPCC (1990b) assumes that, although stand growth rates may increase in some areas, the overall net increment (including mortality) will be negative. Regional impacts will be strongly influenced by the extent to which forest zones can shift northwards. An analysis of the economic effects would also have to include price changes, and one of the few studies doing that is Binkley (1988).

The study is restricted to boreal forests, the species probably most affected by global warming. Binkley is less pessimistic than IPCC and assumes that climate change will be favorable for wood production in northern countries. Consequently, income from timber sales will increase in these regions, while the induced fall in timber prices will lead to lower revenues in other countries. His estimates translate into an annual welfare gain of 10.8 bn$.

The figure includes changes in both producer and consumer surplus, and it is reasonable to assume that the two categories are distributed differently between countries. We approximated the producer losses for each region by the change in income from timber sales, which has been estimated by Binkley. The annual loss in producer surplus amounts to 10.1 bn$ worldwide, and gains in consumer surplus are thus 20.9 bn$ per annum. They were distributed in proportion to GNP.

8. Fisheries

As one of a few sectors, the fishing industry will be affected by both the rise in sea level and the changing climate itself. A large proportion of the coastal infrastructure threatened by sea level rise (see Section 2) can be associated to fisheries. Changing climate patterns will affect the location and quality of fish grounds, as species move to new grounds or, in the worst case, simply disappear. Of particular importance for the fishing industry

Table 3. Reduction in fish harvests.

	Nominal catches (1988, 1000 t)	Reduction (8%, 1000 t)
EC	6,977	558
USA	5,656	452
Former USSR	10,171	814
China	5,806	464
OECD	31,288	2,503
World	85,358	6,829

Source: See Section 8; nominal catches from FAO (1991).

could be the loss of coastal wetlands. Wetlands serve as habitat or breeding ground for various species, and changes in this area could easily spread through the food chain. Bigford (1991) estimates that a 50% reduction in marsh productivity (for whatever reason) would lead to a 15–20% loss in estuarine dependent fish harvests. Given an expected loss of about 33% of all coastal wetlands (see Section 3), we can expect a loss of 10–13% in estuarine dependent fish harvests. Bigford also estimates that about 68% (by weight) of all commercially harvested species in the US are in some way estuarine dependent. This would imply a reduction in total catches of 7 to 9% in the US. Assuming that this average holds worldwide we derived the reductions in annual catches shown in Table 3.

Remember, however, that the estimates for wetland loss in Section 3 already include the damage to commercial fisheries (see footnote 6). The figures of Table 3 are thus only for illustration. Including them in the total damage costs would lead to double counting.

9. Energy

Both Cline (1992) and Nordhaus (1991a,b) have identified the energy sector as one of the most strongly affected by climate change. They argue that, in addition to being the target of most global warming prevention policies, the energy sector will face a significant shift in the demand for space heating and cooling.[7] The US Environmental Protection Agency (EPA), for example,

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[7] There will also be effects on the energy supply, particularly through changes in the availability of fuelwood and water for hydropower generation. Unfortunately, an estimation of the former effect is not possible with the present data. The latter will be assessed in the broader context of Section 10 on water.

estimates that the US-demand for electricity could increase by 1–1.5% per °C of warming (Smith and Tirpak, 1990; Cline, 1992).

However, although we do not deny that such a shift will have an enormous impact on the energy sector, we are reluctant to subsume this under "damage to the energy sector". Rather, we see it as a second round effect, with the first round damage occurring to the public.

To see this, remember that electricity consumption as such does not create utility. What enters the utility function is temperature (or climate), and heating or cooling expenditures are only made to adjust (inside) temperature to a more favorable level. The situation is visualized in Figure 2. An increase in temperature, i.e., a shift in the endowment from E to E', makes people move from equilibrium O to O'. In the new optimum O', an additional amount of AB is spent on cooling and utility has decreased from U_2 to U_3. It is this change in utility which has to be added to global warming damage, and it will be considered in Section 12 on human amenity. The move from A to B – which is what EPA has estimated – merely reflects a change in individuals' spending plans. Such second round effects, however, are by assumption not taken into account (see Section 1).

10. Water

Global warming will affect both the supply of and demand for freshwater. Higher temperatures are likely to cause an increase in water demand. At the same time, the supply of water will be affected mainly through the change in precipitation patterns and, in coastal areas, through the intrusion of saline water into freshwater reservoirs.

The damage from salt water intrusion is largely unknown. A Dutch study quoted by Rijsberman (1991) estimates salinity damage for Holland at 6 m$ a year, but wider studies are not available.

Abstracting from groundwater and other reservoirs, the amount of water available in a certain period of time is, roughly, the difference between precipitation and evapotranspiration in that period. Both factors will be influenced by global warming. Higher temperatures will lead to faster evaporation, which in turn will cause more precipitation, as the capacity of the atmosphere to store water is only modest. Global estimates predict an increase in precipitation of 7–15% and one in evapotranspiration of 5–10%. The annual runoff would thus increase on average (see Schneider *et al.*, 1990). The confidence in these estimates is, however, low. Further, seasonal and regional differences will be considerable and many regions will face a lower

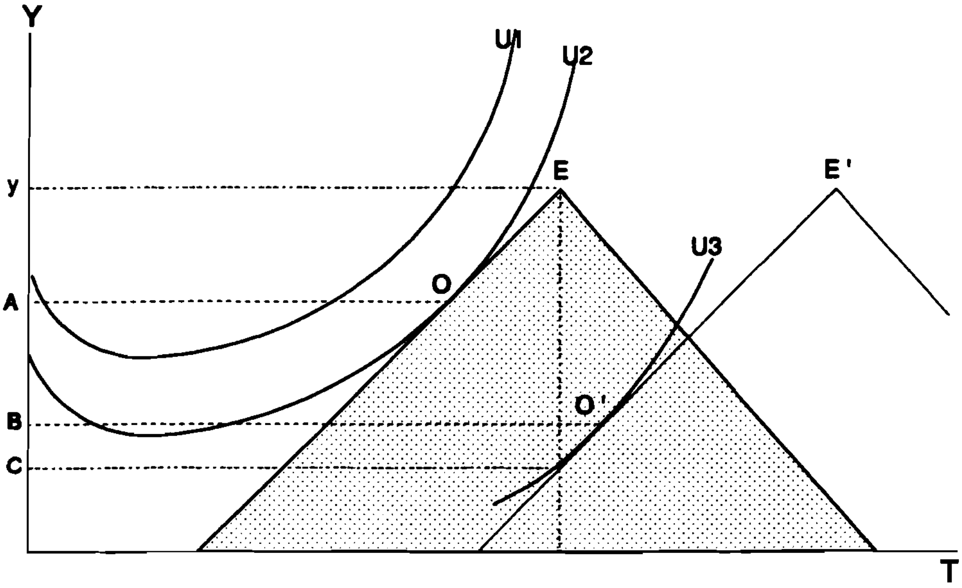

Figure 2. Global warming, energy demand and welfare.

Note: Suppose individuals gain utility from two goods, income Y and (inside) temperature T. The indifference curves are U-shaped, reflecting the fact that there is an optimal temperature level, after which further temperature increases become a bad. Individuals are endowed with an initial income and temperature bundle E. Income can either be consumed or spent on heating and/or cooling. Heating corresponds to a move downwards-right (a warmer temperature is substituted for income) and cooling to one downwards-left. The shaded triangle thus represents the feasible set or budget constraint, with the slopes of the right and left leg determined by the price of heating and cooling, respectively. The graph shows the case of a temperature beyond the optimal level, and the individual thus spends yA on cooling (optimal point O, with utility level U_2). Global warming leads to an increase in temperature, i.e. to a rightwards shift of E to the new endowment E'. In the new optimum O' more money is spend on cooling and utility is at the lower level U_3. Global warming has lead to a welfare loss of U_2–U_3, and an increase in cooling expenditure (energy demand) of AB.

runoff during at least some parts of the year. According to Schneider *et al.* these include the American Midwest, Mid Europe, South Canada, and probably also parts of Siberia and South China.

Following Cline (1992), the welfare loss from a reduced water supply is approximated by the monetary value of the quantity decline. Based on an EPA study on Southern California, which predicts a 7–16% reduction in annual water resources, Cline assumes a 10% reduction in water availability for the United States as a whole. Bearing in mind that South California is part of a zone which will probably be hit above average, we prefer to work with the lower bound value of 7% loss in each region. On the other hand, Cline's assumption of a water price of 8–20 cents/m^3 seems to be far too modest compared to the figures from The Economist (1991). Based on this latter source, we used water prices of 42 cents/m^3 (US) to 92 cents/m^3 (EC) for the OECD regions. For middle and low income countries we assumed 12 cents/m^3 and 5 cents/m^3, respectively.

It should be emphasised, however, that the figures estimated in this manner are averages. For areas in which runoff will increase and for those with an abundant supply of water, the figures may be too high. For many arid and semi-arid zones, however, a further decrease in the supply of an already scarce commodity could be disastrous. In poor countries in particular, a lack of safe drinking water could have devastating health impacts (see, e.g., WHO, 1990). The fact that areas of both types can be found in each of the regions considered gives some credibility to our average values shown in Table 1. Note also, that services are not only taken from water withdrawals. Instream uses, e.g., from recreation or fishery, may also be significant, albeit difficult to assess.

11. Other Sectors

Generally, every sector which in some way depends on climate will be affected by global warming. Abstracting from impacts through second round effects (see Section 1), the areas usually highlighted in addition to those already dealt with are construction, transport, and tourism. Unfortunately, data for a monetary valuation are not available for either sector.

12. Human Amenity

It is hardly disputed that climate constitutes an important factor in the quality of life. Global warming will therefore also affect human amenity. It has been claimed that this effect could be beneficial, given that warmer weather is in general preferred to cooler. However, warmer is not better throughout. Rather, there is an optimal temperature level beyond which further increases are detrimental. The overall effect of global warming on human amenity is thus ambiguous, the impact being positive in colder and negative in warmer regions. The case of a warmer area is depicted in Figure 2.

To estimate the monetary value of a certain climate we are interested in people's willingness to accept a change. In terms of Figure 2, we are interested in the distance yC, the income change required to make individuals the same off as without the change. Unfortunately, the monetary value of a benign climate is still largely unknown and hardly any studies exist. As a first approximation, we can work with the expected change in defense expenditures, i.e. with the change in money spent on space heating or cooling. This corresponds to the area AB in Figure 2.[8]

Estimates of this value exist for the United States. Adjusted to our assumption of 2.5 °C warming, they imply an increase in demand of about 3.2% for 2 × CO_2. The regional differences are, however, considerable and transferring the US average to other regions is therefore dangerous. Nevertheless, on a rough and ready basis, it can be argued that the US climate mix may be roughly representative for at least the OECD, the EC, and to a lesser extent also for China and the world as a whole. It is clearly not applicable for the former USSR, though. For this region, we assume a value of -1% (i.e., a reduction in electricity demand), based on EPA's regional estimates for the US north and north east.

The corresponding monetary values are shown in Table 1. The approach simplifies in at least three ways, though. First, as can be seen from Figure 2, the defense expenditures (AB) underestimate the true value (yC). Secondly, the EPA study is restricted to electricity demand and neglects other forms of energy such as fossil fuels. For the US, it is assumed that the demand for non-electricity energy could fall (Nordhaus, 1991a, 1991b; Cline, 1992). The limitation to electricity demand may thus lead to an overestimation of the total expenditure increase. Thirdly, we assume constant prices. Thus, we neglect the capital costs and possible price rises which could occur if

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[8] Note that our estimate of the amenity impact is therefore calculated in the same way as Cline's (1992) and Nordhaus' (1991a,b) energy damage. We have argued earlier (see Section 9) that energy damage is mainly a second round effect and should not enter the analysis. However, as Cline and Nordhaus do not estimate the damage on human amenity, there is no double counting. The difference between their studies and the present one is merely labeling. What is called amenity damage here is called energy damage there.

a capacity expansion becomes necessary. For the US, for example, Cline (1992) has estimated capital costs on the order of 500 m$ annually.

13. Morbidity and Mortality

Human beings are very capable of adjusting to climatic variations, and, as opposed to most other species, can live in more or less every climate on earth. Nevertheless, climate change will have its impacts on human morbidity and mortality. The literature on the health effects of global warming (e.g., Haines and Fuchs, 1991; IPCC, 1990b; Weihe and Mertens, 1991; WHO, 1990) predicts an increase in climate related illnesses such as cardiovascular, cerebrovascular, and respiratory diseases. Summer mortality from coronary heart disease and strokes may increase and is likely to offset the reduction in winter mortality. In addition to these direct effects, there may be changes in the occurrence of communicable diseases and an aggravation of air pollution (see Section 14). The risk areas of communicable diseases like malaria or yellow fever may shift as their vectors adjust to new climate conditions. Despite this qualitative knowledge, the available data is still not sufficient for a monetary assessment.

Some, albeit controversial, estimates exist on the warming induced change in mortality. In a case study carried out for EPA, Kalkstein estimated the change in mortality in 15 American cities (see Smith and Tirpak, 1990; Kalkstein, 1989). The figures strongly depend on the assumed degree of acclimatization, showing that cities already accustomed to a warmer climate are far less affected by a further warming than cities with a moderate climate. Under full acclimatization, Kalkstein reports an increase in net mortality corresponding to 45 death/million people. This figure – Kalkstein's most optimistic result - was used for our calculations, although it may still be rather on the high side (see Fankhauser, 1992).

Various methods and studies exist to estimate the value of a statistical life, see e.g., the survey tables in Pearce *et al.* (1991, 1992). The resulting values, all from studies for developed countries, range from about $ 200,000 up to over 10 m$, with an average of around 3 m$. The results suggest that a statistical life should plausibly be valued at at least 1.5 m$ (Pearce *et al.*, 1991). This still fairly conservative value was adopted for developed regions. A low value was preferred to counterbalance the rather high quantity estimate. Unfortunately, no study exists on the value of a statistical life outside the developed world. We thus use an arbitrary value of \$ 300,000 for middle income and \$ 150,000 for low income countries.[9]

14. Air Pollution

Given the wide concern about air quality and air pollution, it is surprising how little attention this aspect has gained in the context of climate change so far. Global warming will affect the quality of the air in two ways.

Firstly, as long as there exist no economical CO_2-removal technologies, attempts to limit CO_2 emissions will – via a reduction of energy use – also lead to a reduction in the emission of major pollutants such as SO_2, CO, and NO_x. Initial estimates suggest that this positive side effect – often termed the secondary benefits of greenhouse gas abatement – could be extremely large and may well exceed the primary benefits (Glomsrød *et al.*, 1992; Pearce, 1992). Clearly, a careful cost-benefit analysis would have to take such effects into account. In the present context, however, they are of no relevance as they are related to abatement activities only and do not depend on $2 \times CO_2$.

Many chemical reactions depend on temperature, and this is the second way in which global warming will affect air quality. Scientists predict a warming induced increase in the emissions of hydrocarbons (HC), nitrogen oxides (NO_x), and sulphur oxides (SO_x). In addition, the formation of acidic materials could increase. The effect on acid depositions is nevertheless unclear, because of changes in clouds, winds, and precipitation. More certain is an increase in the tropospheric ozone level, brought about through the increase in NO_x and HC emissions as well as through a higher reaction rate (see Smith and Tirpak, 1990). Based on two case studies carried out for EPA, we worked with an average increase of 5.5% in ozone concentration. For SO_2 we assumed a raise in emissions of 2%.

The monetary value of air pollution damage has been estimated by several authors, including the Norwegian Central Bureau of Statistics (1991), PACE (1990), and Pearce (1992) (based on Pearce *et al.*, 1992). In these studies the damage from an increased O_3 concentration is usually fully attributed to NO_x, and the estimates range from about 1.50 to 15 \$ of damage per kg emitted. The figure is exclusive the damage from acid rain, which was subtracted because its relationship to global warming is as yet unclear.[10]

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[9] This, of course, does *not* mean that the life of, say, a Chinese is worth less than that of an EC citizen. It merely reflects the fact that the *willingness to pay* for increased safety (a lower mortality risk) is higher in developed countries.

[10] A clear separation of acid rain and pure NO_x damage was not always possible, though. It should also be noted that the estimates are strongly site-dependent.

The divergence in the figures mainly stems from differences in the assessment of health impacts, which account for most of the damage in the high Norwegian estimate, but are assumed zero in the figure by Pearce. We use an average of 5 $/kg for developed countries, 1 $/kg for middle income countries, and 0.5 $/kg in LDCs. For SO_2 we used an average value of 2.5 $/kg in OECD countries, again excluding acid deposition. For middle and low income countries, we assumed 0.5 $/kg and 0.25 $/kg, respectively.

15. Migration

Global warming could trigger a large migration stream away from the worst affected regions. Ayres and Walter (1991), for example, talk about 100 million people going to be displaced worldwide. However, such figures are usually based on a scenario in which no coastal protection measures are taken at all. The view in this study is that, as a cost efficient response to sea level rise, densely populated coastlines will be protected (see Section 2). Under this assumption the number of people displaced will be considerably lower. Climate-induced migration may nevertheless still occur, e.g., away from unprotected coasts or from regions where climate became unfavorable for agriculture. The type of migration will range from voluntary resettlements to the occurrence of actual climate refugees, where the former group will cause the least (if any) costs and the latter probably the highest, specially if non-economic disutilities (e.g., from stress and hardship) are included.

Our estimates were derived from Cline (1992). His predictions correspond to an increase in long-term immigration by 17%, and this average was assumed to hold worldwide.

The costs of increased migration are estimated in Cline (1992), and Ayres and Walter (1991). Despite using completely different methods, both studies come up with an estimate of roughly 4500 $/immigrant for the United States. Although neither method is fully convincing, this value was used to estimate the immigration costs in OECD countries. For poorer countries, Ayres and Walter assume costs of 1000 $ per person. This value is deduced from the foregone output a person would have produced, had he or she not migrated. It was used for all immigrants to non-OECD regions.

To these costs would have to be added the costs of hardship and stress suffered by migrants. As Cline puts it, "peoples have often fought wars to avoid being forced to leave their homelands" (1992, p.119), and it is therefore quite likely that these costs exceed the pure economic losses. Unfortunately, it seems almost impossible to assess them properly.

16. Natural Disasters

Under 2 × CO_2, extreme events like floods and droughts are likely to become more frequent. IPCC (1990a) also predicts, albeit with only a low confidence, an increase in local rainstorms at the expense of gentler but more persistent rainfalls. Tropical storms (hurricanes, typhoons) may become more frequent and wider spread and could occur with increased intensity. Mid latitude winter storms may diminish, while the Asian summer monsoon could intensify.

Due to lack of data, the analysis had to be limited to the damage from tropical cyclones. Our figures are thus likely to underestimate the true damage.[11]

Cyclones can only form over warm oceans with sea surface temperatures above 26 °C. Consequently, they only occur in certain areas, the most important being the South West Pacific, Eastern Asia and the Caribbean Sea. In an average year, about 70 to 80 tropical cyclones are recorded in these regions. Annual damages have been estimated at about 1.5 bn$, with a death toll of 15,000 to 23,000 lifes (Smith, 1992; Bryant, 1991). Using the natural hazard map of the German reinsurance company Münchener Rück (see Berz, 1990 and Smith, 1992) we estimated that the United States are affected by about 6.6% of all cyclones. Some 7.2% affect China, and roughly 28.9% occur in OECD nations (Australia, Japan, New Zealand and the US). 0.4% of all storms reach as far north as to affect the former Soviet Union. Neglecting overseas dominions, tropical storms are unknown in EC countries.

The impact of global warming on tropical storms has been analyzed by Emanuel (1987). He estimates that 2 × CO_2 could lead to an increase in the destructive power of tropical storms of 40 to 50 percent. Accepting the estimates by Smith and Bryant, this would imply an additional 700 m$ in damages and about 9000 more lives lost. In breaking down this estimate into regional impacts, we have to remember that damages and casualties are not distributed in equal proportions. We assumed that the death toll per

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[11] Note, however, that some of the damage from increased sea-flooding is included in the protection cost estimate of Section 2. (Not included is the flooding of unprotected zones.) Also, it is not entirely clear as to how far the EPA study on California, on which the water damage estimate is based, includes droughts (see Section 10).

event is ten times lower in OECD countries, which instead face a ten times higher destruction damage.

17. Total Damage and Conclusions

Results of the previous sections are summarized and added up in Table 1 to obtain the total damage for each region. With the exception of China and the former USSR, total damage is on the order of about 1.3% to 1.5% of GNP. Our estimates are thus slightly higher than those by Cline (1992, for the US) and Nordhaus (1991a,b; US extended to the world), which both come up with a best guess of about 1% GNP. The figures are, of course, neither exact nor complete and one should allow for a range of error of at least ± 50%. Even so, the results are still roughly within the Nordhaus range of 0.25 to 2% of GNP.

Despite the broad agreement in the overall result, the three studies considerably differ for the individual damage categories, as can be seen from the detailed comparison of the US results in Table 4. Agriculture and forestry, for example, which constitute the main damage in Cline (1992), are far less important in the present study – the impact on forestry even being positive. This discrepancy is primarily due to different predictions on the quantitative impacts of $2 \times CO_2$ (yield effects, see Section 6), and thus mainly mirrors the scientific uncertainty still inherent in all impact forecasts. For other categories the estimated impacts roughly correspond quantitatively, but differences occur in the valuation of these effects. This is the case, for example, with the wetland loss and water estimates, and the life/morbidity figures.

At first sight, the estimate of coastal defense costs and dryland loss is within the same order of magnitude as Cline's. It should be remembered, though, that with 50 cm we assume a lower rise than both Nordhaus and Cline. Under the one meter assumption adopted by Cline, for example, defense costs would rise by a factor of about 2.5 and the area of lost dry- and wetland would increase by about 50%. Worldwide damage would mount to 1.6% of Gross World Product. For the US, even a "worst case damage" – assuming a one meter rise in sea levels and taking for each category the most pessimistic prediction of Table 4 – is still below 2% of GNP. Albeit tending towards the upper bound, our results thus broadly support Nordhaus' range, at least for industrialized countries.

In the developing world, on the other hand, the impacts are likely to be far more severe. Leaving the special case of the former Soviet Union aside, our results predict a damage of about 86 bn$ in the non-OECD regions.

Table 4. US damage compared to Cline and Nordhaus (bn$ 1988).

	This Study	Cline (1992)[a]	Nordhaus (1991a,b)[b]
Coastal defense	0.2	1.0	7.5
Dryland loss	2.1	1.5	3.2[b]
Wetland loss	5.6	3.6	[e]
Species loss	6.4	3.5	[e]
Agriculture	7.4	15.2	1.0
Forestry	−1.8	2.9	small
Fishery	–	–	small
Energy[c]	–	9.0	1.0
Water	13.7	6.1	[e]
Other sectors	–	1.5[d]	[e]
Amenity[c]	6.8	–	[e]
Life/morbidity	16.6	>5.0	[e]
Air pollution	6.4	>3.0	[e]
Migration	0.5	0.4	[e]
Natural hazards	0.2	0.7	[e]
Total (bn$)	64.1	53.5	48.6
(% GNP, 1988)	(1.3)	(1.1)	(1.0)

[a] Transformed to 1988 values based on % GNP estimates.
[b] Total land loss (dry- and wetlands).
[c] See also footnote 8.
[d] Tourism.
[e] Not assessed categories, estimated at $\frac{3}{4}$% of GNP.

Although this is less than a third of total worldwide damage, it corresponds to about 2.8% of GNP in these regions, twice the OECD average. The main causes for this high estimate are health impacts and the high portion of wetlands found in developing countries. The situation could be further aggravated by a failure to implement the cost efficient precautionary responses (e.g. coastal protection), something which is quite likely to happen if the necessary funds are not made available. Although the data are weaker in the case of non-OECD countries, it seems fair to say that global warming will have its worst impacts in the developing world, with a damage of *at least* 2.5% of GNP for 2 × CO_2.

Regional differences can, however, be substantial, as is exemplified by the estimates for the former USSR and China. For the former Soviet Union, damage could be as low as 0.7% of GNP, about halve the world average. Even this low level may come as a surprise to some people, however, as it has often been suggested that northern regions may benefit from global warming. Clearly, such a hope is fallacious. In the case of the former Soviet

Union, the positive impacts on forestry and human amenity are more than offset by the costs of sea level rise and the particularly high health costs. Similarly surprising may be the high agricultural damage, but even under the more favorable agriculture scenario A, which implies positive impacts on Soviet agriculture (see Section 6), 2 × CO_2 will still be clearly harmful.

The extremely high estimate for China is caused by two factors, agricultural loss and life/morbidity impacts. Especially the former is very volatile in the case of China, and the probability range of total damage is therefore particularly wide for this country. For an agricultural damage based on the optimistic scenario A, for example, overall damage would fall to 2.6% of GNP, compared to 9.6% if scenario B was used. The example clearly underlines the sensitivity of the results.

The emphasis in the damage discussion has so far been mainly on agriculture and sea level rise. In the light of the present analysis it seems that, although both are indeed main sources of damage, this view tends to overlook aspects which could be as important, particularly the effects on the supply of water, on health and on human wellbeing in general. This bias, which has already been deplored by Ausubel (1991) may partly be explained by the fact that these latter aspects are far more difficult to predict. However, while this is an explanation, it cannot be a justification and further research is thus needed, especially in these areas.

A word of caution is needed with respect to the policy implications of our results. Although the figures indicate a rather low damage with which at least the industrialized world should be able to cope, they do not necessarily imply that global warming is harmless. The figures analyze solely one point in time, i.e., shed light on the impacts of 2 × CO_2 only. However, global warming will not stop there, and what happens afterwards is as yet unclear. Cline's work suggests that damage will increase exponentially with concentration (Cline, 1992). Scientists speculate about the existence of discontinuities (see Nordhaus, 1991c) and crossing certain ecological thresholds may well lead to nasty surprises. Not least for these reasons global warming still deserves our attention.

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Macroeconomic Modeling and the Assessment of Climate Change Impacts

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1. Introduction

An historic Framework Convention on Climate Change was signed by 154 countries at the United Nations Conference on Environment and Development (UNCED) in Brazil in June 1992. This Convention commits the signatory countries, upon ratification, to take measures to reduce the adverse effects of climate change by mitigating its causes and adapting to its anticipated effects.

Considerable work has already been done to estimate the costs associated with alternative mitigation strategies. Strategies to reduce emissions of carbon dioxide (CO_2) from the burning of fossil fuels have received particular attention (see for example, Congressional Budget Office, 1990; Manne and Richels, 1990; Jorgenson and Wilcoxen, 1992; Nordhaus, 1992; and Gaskins and Weyant, forthcoming). Significant work has also been done to evaluate the potential *physical* effects associated with global climate change (US EPA, 1989; IPCC, 1990 and 1992). However, fewer efforts have been made to asses the *economic* impacts of the potential physical effects of climate change (Adams, 1989; Linder and Inglis, 1989; Nordhaus, 1991a and 1991b; Peck and Teisberg, 1992; and Cline, 1992). Consequently, policy makers have a much more limited set of information on the potential economic benefits of avoiding or slowing climate change. This is especially troublesome given the requirement that countries identify specific policy measures to reduce

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greenhouse gas emissions and adapt to climate change in fulfillment of their obligations under the UNCED climate convention.

One goal of our effort is to gain additional insights about the sensitivity of US economic activity to climate change. We diverge from previous work by employing a general equilibrium framework to analyze selected impacts. The limited research that has been conducted on the economic impacts and valuation of the effects of climate change has employed partial equilibrium frameworks. Partial equilibrium frameworks neglect potentially important interdependencies among the many choices made by households and firms. We employ a general equilibrium framework to explore the importance of these interdependencies. The general equilibrium framework allows us to examine, for example, how the direct impacts of climate change on agricultural production costs affect agricultural prices, prices of goods and services that use agricultural commodities in their production, and how these price changes feed back to the agricultural sector and agricultural prices. We can examine the substitutions made by firms in production processes, including changes in sectoral employment, and the substitutions made by households in consumption in response to the price changes. We can also examine how these substitutions influence the composition of output, savings and investment, labor supply, households' lifetime earnings, aggregate output, and economic welfare.

We present in this paper some preliminary results of our explorations on this topic. The results do not represent a comprehensive assessment of the potential impacts of climate change on economic activity. We have examined only three selected climate impacts: (i) a rise in agricultural production costs, (ii) a rise in electricity service costs, and (iii) a rise in expenditures to protect coastal lands from sea level rise. We also examine the combined effect of all three impacts. These scenarios are developed from research conducted by others on these impact categories. The scenarios assume a relatively severe projection of global warming in which mean annual temperature is assumed to increase through time, rising 4.0°C globally and 5.1°C in the USA by the year 2060.[2]

This exercise is not intended to forecast the future. Credible forecasts will not be possible until advances are made in the research community's understanding of the linkages between anthropogenic emissions of greenhouse gases, changes in atmospheric concentrations of the gases, global and regional

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[2] The IPCC estimates mean global warming will fall roughly in the range 1.0 to 2.5°C by the year 2060.

changes in climatic conditions (e.g., temperature, precipitation, evapotranspiration), physical impacts, economic valuation of those impacts, and feedbacks from changes in environmental conditions to economic activity. Thus, we are trying instead to bound the problem and gain a better sense of how important climate change may be in terms of macroeconomic impacts and changes in economic welfare. Also, our focus is on the magnitude of climate impacts that have market manifestations. However, considerable work still needs to be done to investigate the potential non-market impacts of climate change. Until this is done, a complete picture of the benefits associated with avoiding anthropogenically-induced climate change will not be in hand.

This paper reports on work in progress. Our preliminary results suggest that the combined effects of the three climate-induced impacts examined here are not large as a percentage of GNP. But price increases are projected for all sectors, causing a reallocation of spending and changing the sectoral composition of output. Our results also suggest that there may exist significant distributional effects. However, additional research is needed to examine the welfare impacts by household type to explore the distributional impacts more fully.

We have also gained useful modeling insights. This work has increased our awareness that existing state-of-the-art general equilibrium macroeconomic models do not contain important inputs to production that are directly sensitive to climate change (e.g., water and land). These inputs may provide important linkages between sectors, result in significant indirect climate-induced effects on production and consumption, and influence economic welfare.

This paper is organized as follows: In Section 2, we discuss the macroeconomic modeling approach and the particular scenarios used to conduct the analysis. Key policy-relevant insights are presented in Section 3, and insights for modelers are discussed in Section 4. Finally, in Section 5, we suggest implications of our results for the climate change research agenda.

2. Macroeconomic Modeling Approach

The Jorgenson-Wilcoxen macroeconomic model of the United States was chosen for this initial effort.[3] The Jorgenson-Wilcoxen model is a dynamic,

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[3] The Adaptation Branch of the EPA is also conducting a parallel effort using the Data Resources Inc. macroeconomic model of the USA to gain additional insights into this problem.

general equilibrium model. There are two main reasons for choosing a dynamic general equilibrium approach. The first is to capture both the direct and indirect effects of climate change on the US economy. The second is to capture the long-run dynamics of the adjustment of the economy. The general equilibrium framework enabled us to assess fundamental shifts in economic activity between industries, including changes in distributions of labor, capital, and other production factors within the economy, and changes in the distribution of goods and services.

The model is divided into four major sectors: domestic producers, households, government, and the rest-of-the-world. The behavior of producers and households are derived from models of intertemporal optimization. The behavior of government and the rest-of-the-world are determined by exogenously specified constraints. The interactions among sectors determine, for each period, aggregate domestic output, capital accumulation, employment, the composition of output, the allocation of output across different household types, and other variables. The outcomes represent a general equilibrium in all markets in all time periods.

Production is subdivided into 35 separate commodities produced by one or more of 35 industries (Table 1). Output supply and factor demands of each sector are modeled as the results of choices made by market value maximizing, price taking firms which are subject to technological constraints. Firms have perfect foresight of all future prices and interest rates. Factor inputs include capital services, labor, and the outputs of the 35 producing sectors. The production technology of each producing sector is represented by an econometrically estimated cost function that fully captures factor substitution possibilities and industry-level biased technological change. These outputs serve as inputs to the production processes of the other industries, are used for investment, satisfy final demands by the household and government sectors, and are exported.

Household consumption is modeled as a three-stage optimization process. In the first stage, lifetime wealth, which includes financial wealth, discounted future labor income, and the imputed value of leisure, is allocated to full consumption in each time period to maximize intertemporal utility. Households have perfect foresight of future prices and interest rates. In the second stage, the full consumption allocated to each period in the first stage is allocated between goods and leisure to maximize intratemporal utility. This allocation determines the labor supply. In the third and final stage, goods expenditures of each period are allocated among capital, labor, and the outputs of the 35 production sectors to maximize a subutility function for goods consumption. Allocations at each stage are based upon

Table 1. Definitions of industries within the Jorgenson/Wilcoxen model.

No.	Description	No.	Description
1	Agriculture, forestry, and fisheries	19	Stone, clay, and glass products
2	Metal mining	20	Primary metals
3	Coal mining	21	Fabricated metal products
4	Crude petroleum and natural gas	22	Machinery, except electrical
5	Nonmetallic mineral mining	23	Electrical machinery
6	Construction	24	Motor vehicles
7	Food and kindred products	25	Other transportation equipment
8	Tobacco manufacturers	26	Instruments
9	Textile mill products	27	Miscellaneous manufacturing
10	Apparel and other textile products	28	Transportation and warehousing
11	Lumber and wood products	29	Communication
12	Furniture and fixtures	30	Electric utilities
13	Paper and allied products	31	Gas utilities
14	Printing and publishing	32	Trade
15	Chemicals and allied products	33	Finance, insurance, and real estate
16	Petroleum refining	34	Other services
17	Rubber and plastic products	35	Government enterprises
18	Leather and leather products		

an econometrically estimated system of individual, demographically defined household demand functions.

The behavior of government is constrained by exogenously specified tax rates and budget deficit. Government revenues are determined by the specified tax rates and endogenous levels of economic activity. Government expenditures adjust to satisfy the exogenous budget deficit constraint.

The current account is specified exogenously. Imports are treated as imperfect substitutes for similar domestic commodities and compete on price. Export demands are functions of foreign incomes and foreign prices of US exports. Import prices and foreign incomes are exogenously specified. Foreign prices of US exports are determined endogenously by domestic prices and the exchange rate. The exchange rate adjusts to satisfy the exogenous constraint on the current account.

2.1. The General Equilibrium

The JW framework contains intertemporal and intratemporal models (Jorgenson and Wilcoxen, 1990b). In any particular time period, all markets clear. This market clearing process occurs in response to any changes in the levels of variables that are specified exogenously to the model. The interactions among sectors determine, for each period, aggregate domestic output, capital accumulation, employment, the composition of output, the allocation of output across different household types, and other variables.

The model also produces an intertemporal equilibrium path from the initial conditions at the start of the simulation to the stationary state. (A stationary solution for the model is obtained by merging the intertemporal and intratemporal models.) The dynamics of the JW model have two elements. The model includes both an accumulation equation for capital, and a capital asset pricing equation. Changes in the levels of exogenous variables cause several adjustments to occur within the model. First, the single stock of capital is efficiently allocated among all sectors, including the household sector. Capital is assumed to be perfectly malleable and mobile among sectors, so that the price of capital services in each sector is proportional to a single capital service price for the economy as a whole. The value of capital services is equal to capital income. The supply of capital available in each period is the result of past investment. When a change in the level of an exogenous variable occurs, the capital stock is augmented by the amount of savings from the previous period (i.e., investment). Capital at the end of each period is a function of investment during the period and capital at the beginning of the period. This capital accumulation equation is backward-looking and captures the impact of investments in all past periods on the capital available in the current period.

The capital asset pricing equation specifies the price of capital services in terms of the price of investment goods at the beginning and end of each period, the rate of return to capital for the economy as a whole, the rate of depreciation, and variables describing the tax structure for income from capital. The current price of investment goods incorporates an assumption of perfect foresight or rational expectations. Under this assumption, the price of investment goods in every period is based on expectations of future capital service prices and discount rates that are fulfilled by the solution of the model. This equation for the investment goods price in each time period is forward-looking.[4]

One way to characterize the JW model – or any other neoclassical growth model – is that the short-run supply of capital is perfectly inelastic, since

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[4] The price of capital assets is also equal to the cost of production, so that changes in the rate of capital accumulation result in an increase in the cost of producing investment goods. This has to be equilibrated with the discounted value of future rentals in order to produce an intertemporal equilibrium. The rising cost of producing investment is a cost of adjusting to a new intertemporal equilibrium path.

it is completely determined by past investment. However, the supply of capital is perfectly elastic in the long run. The capital stock adjusts to the time endowment, while the rate of return depends only on the intertemporal preferences of the household sector.

A predetermined amount of technical progress also takes place in response to changes in the prices of factors of production (Jorgenson and Fraumeni, 1981). This serves to lower the cost of sectoral production and causes changes in productivity. Finally, the quality of labor is enhanced, giving rise to higher productivity and lower costs of production.

Given all of these changes, the model solves for a new price vector and attains a new general equilibrium. Across all time periods, the model solves for the time paths of the capital stock, household consumption, and prices. The outcomes represent a general equilibrium in all markets in all time periods.

We use the model to evaluate the general equilibrium effects of selected impacts of climate change. A baseline projection of economic activity in the absence of any change in climate is made for the period 1993 to 2050. The climate impacts are then introduced to the model as exogenous changes in the costs of producing goods or changes in government expenditures. In each case the shocks are anticipated with perfect foresight. The model solves for a new general equilibrium, reflecting the effects of the climate shocks on the economy over the 1993 to 2050 time horizon. The projections of economic activity for the climate change scenarios are compared to the baseline projection to identify the effects of the selected climate impacts.

2.2. The Scenarios

We examine the effects of three climate impact categories on the economy. The impacts are (i) changes in agricultural production costs, (ii) changes in electricity service costs, and (iii) changes in government expenditures to protect coastal areas from sea level rise. The scenarios are based upon a projection of climate change for the world and the USA for an equivalent doubling of carbon dioxide (CO_2) concentration in the atmosphere above the preindustrial level. The climate projection selected for this exercise is from the Geophysical Fluid Dynamics Laboratory's (GFDL) general circulation model. That model projects mean global warming of 4°C and mean warming for the USA of 5.1°C for a doubling of CO_2. We assume that these temperature changes occur by the year 2060 and that temperatures rise gradually between the present and 2060. The assumed time path of mean annual warming for the USA is presented in Table 2.

This is an extreme climate scenario in comparison to the range of warming projected by the IPCC (1992). We selected an extreme case because part of our purpose is to bound the range of plausible macroeconomic effects and impacts on economic growth that may result from the three climate-induced impacts considered here. We believe that out estimates represent reasonable upper bounds on the potential changes in macroeconomic activity that may result from the selected climate impacts over a time horizon extending to 2060. They do not, however, represent an upper bound on the total effect of potential climate change on economic activity. The selected climate impacts represent only a subset of the potential climate impacts. The results of this exercise should also not be taken to be central or best estimates of the effects of the selected climate impacts on economic activity.

The damage functions developed for inputs to the JW model were derived from static (single-period), partial equilibrium assessments of the effects of global warming on particular sectors of the US economy. The proportionality of the damages to the degree of temperature rise was an assumption prompted by the complete absence of intertemporal information on how damages evolve as temperature rises.

Estimates of the impacts of climate change on agricultural production costs are based upon the work of Adams (1989) and Adams *et al.* (1989). These studies incorporate the results of research on crop yield responses to changes in climate variables and CO_2 concentration into a mathematical programming model of the agricultural sector of the USA. US agricultural production is disaggregated into 63 regions and 48 primary and secondary agricultural commodities. Total supply for each commodity is the sum of domestic production from all regions of the USA plus imports. Total demand is the sum of domestic demands for consumption, stocks, government programs, livestock feeding, and processing plus export demand. Prices and quantities of agricultural commodities are simulated by the model for selected climate scenarios. The simulations reflect estimated changes in domestic crop yields by region and crop in response to projections of regional changes in temperature, precipitation, evapotranspiration, and water supply and demand. The simulations do not reflect any changes in foreign demand or supply due to climate effects. Adaptations to changes in climate are allowed for through substitutions among factor inputs to agricultural production and substitutions among crops.

Simulations conducted by Adams for the GFDL scenario for a doubling of CO_2 project aggregate price increases of 28% for field crops and 7% for livestock commodities. In our work, we further aggregate the price increases into a single price change for all agricultural output. We use the projected price change as an estimate of the impact of a doubled CO_2 climate on the unit cost of agricultural production in the year 2060. The assumed rise in unit cost in 2060 is 16%. This change reflects the combined effects of regional changes in temperature, precipitation, and evapotranspiration, and the direct effect of raised CO_2.

In addition to the estimate of the impacts of climate change on agricultural costs in 2060, we also need estimates for the years 1993 to 2059 for our analysis. To do this, we assume that the percentage change in unit cost is a linear function of the projected annual average temperature change in the USA. For each 1.0°C temperature rise, agricultural unit cost is assumed to rise approximately 3% relative to the base case. The assumption is crude. But it permits us to examine the general equilibrium impacts of changes in agricultural costs that are roughly consistent with the GFDL projection of equilibrium climate change for doubled CO_2 and Adams' analyses of the impacts of this climate scenario on agricultural production.[5] The unit cost changes are introduced to the Jorgenson-Wilcoxen model as exogenous shifts of the production technology for agriculture that increase the factor requirements for given output levels. The assumed time path of changes in agricultural unit costs as a percentage of baseline costs are presented in Table 2.

Estimates of the impacts of climate change on the costs of electricity services is based upon the work of Linder and Inglis (1989). A rise in outdoor temperatures during the summer will raise the quantity of electricity needed to produce a unit of indoor cooling service. During winter months, a rise in outdoor temperature will reduce the quantity of electricity needed to produce a unit of heating service. Linder and Inglis (1989) find that the net effect of the summer and winter impacts is to increase the quantity of

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[5] The assumption that percentage changes in unit costs for aggregate agriculture is a linear function of average annual temperature change across the USA is a substantial abstraction from reality. Crop yields and agricultural costs are complex functions of spatial and intertemporal variations of climate variables including, but not limited to, temperature. The crop yield models employed by Adams project substantial yield reductions in much of the USA for the regional changes in climate that are projected by the GFDL model for an equivalent doubling of CO_2. The direct effect of CO_2 on plant physiology, however, raises crop yields, offsetting much of the negative impacts of the projected changes in climate variables. It is unlikely that a linear function of temperature will provide a reasonable approximation of these processes. We, nevertheless, adopt the assumption for expediency. Because of this, the links between our analysis and the GFDL climate scenario and the work of Adams are tenuous. Our results should therefore not be interpreted as an analysis of the agricultural impacts of the GFDL climate scenario.

electricity demanded annually and peak electricity demand.[6] Drawing on estimates of the impacts of weather variations on electricity demands from a set of case studies, Linder and Inglis estimate the effects of warming on peak and annual electricity demand in the USA and the costs of generating electric power. Using transient projections of regional temperature changes from the Goddard Institute for Space Studies (GISS), they estimate that annual electricity demand would increase approximately 4% to 6% and peak demand would increase 13% to 20% in the year 2055 relative to their base case.

We adopt Linder and Inglis' high estimate and treat the increase in annual electricity demand as an increase in the quantity of electricity needed to produce a unit of electricity services. A rise in the electricity input per unit of service causes an equal percentage rise in the unit cost of electricity services. Assuming a linear relationship between the percent change in electricity input per unit of service and the average temperature change for the USA, a 1°C rise in temperature will raise the cost of producing a unit of electricity services 1.5%.[7] Thus, for a projection of 5.1°C warming in the USA for the year 2060, the unit cost of electricity services is raised 7.7%.

The unit cost of electricity services is also changed by changes in the unit cost of generating electricity. Changes in the patterns of peak demand are estimated by Linder and Inglis to increase generating costs. Unit generating costs increase by approximately 2% in 2010 and 5% in 2055 in their simulations. These estimates are used to generate a time path of percentage increases in unit generating costs. The combined effects of increases in electricity input requirements for producing electricity services and increases in generating costs are shown in Table 2. These cost increases for electrical services are introduced into the Jorgenson-Wilcoxen model as increases in the unit costs of output of the electric utility sector.

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[6] Although the net effect of climate change is to increase *electricity* demand, the net effect of warming on US *energy* use is ambiguous. For example, even though electricity demand is projected to rise by Linder and Inglis, there could be a decline in oil and natural gas use. We do not consider changes in energy demands other than electric energy.

[7] The mean annual temperature increase in the USA for the year 2055 in the GISS transient climate projection is approximately 4.3°C. Our assumption that the percentage change in the electricity input per unit service is a linear function of average annual temperature change in the USA is a substantial simplification. For example, changes in electricity demand will depend upon regional and seasonal changes in weather. There are some significant differences in the projection of regional and seasonal climate changes between the GISS model and the GFDL model. These differences are ignored in our extrapolation of Linder and Inglis' estimates of changes in electricity demand for a climate scenario projected by the GISS model to a GFDL-based temperature scenario.

Titus *et al.* (1991) estimated the costs of protecting developed coastal areas from sea level rise. For a 100 cm rise, they estimate the cost of coastal defenses to be $140 billion to $300 billion. We adopt the midpoint of this range as our estimate of the cost of coastal defenses and allocate the costs over the time horizon 1993 to 2060. In our allocation, annual costs increase roughly linearly. The cost allocation is shown in Table 2.[8]

The costs of coastal defenses are incorporated into the Jorgenson-Wilcoxen model as increases in government purchases from the construction sector. The purchases are financed by increases in the average tax on labor income, so that the government budget deficit is unchanged.

3. Policy-Relevant Insights

The long-term economic effects of the three selected climate impacts are presented in Tables 3 and 4. The physical impacts induced by climate change lead to higher prices and costs. In turn, these reduce overall economic performance leading to a decline in the level of consumption. Government and net foreign purchases also decline as a consequence of higher costs. But investment increases, financed by additional household savings. While more labor and capital are available for production, their impacts are more than offset by the declines in industry-level productivity that follow from higher prices. Structurally, the economy moves away from agricultural and consumption-related activities and toward investment and capital-related industries, including increased use of coal, oil, and gas.

Several key policy-relevant insights emerge from these results (see Table 5). First, the economic effects due to the rise in agriculture prices, the rise in electricity service costs, and the rise in expenditures to protect coastal lands from sea level rise, do not have a significant impact on aggregate economic growth. None of the effects is large. Indeed, they combine to yield a decline in economic growth that leaves GNP 0.8 percent lower in the year 2050 (Figure 1).[9] Of the three impacts examined, the rise in agricultural prices has the largest effect on GNP, accounting for 60 percent of the loss. The second largest impact is from changes in the cost of electricity services.

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[8] A rise in sea level of 100 cm by the year 2060 is much higher than most estimates of sea level rise. The IPCC (1992) estimates that sea level rise will be less than 30 cm by 2100.

[9] The term "combined" in Figure 1 refers to the fact that all three climate impacts were imposed *simultaneously* within the Jorgenson-Wilcoxen model. It does *not* represent a simple linear combination of the impact on GNP of all three scenarios imposed independently.

Table 2. Summary of exogenously specified climate impact scenarios.[a]

Year	Temperature rise (°C)	Agriculture (% change)	Coastal expend. ($ bill.)	Electr. services (% change)
1992	0	0	0	0
2000	0.8	2.5	1.2	1.8
2010	1.7	5.4	2.7	5.6
2020	2.5	8.0	4.1	7.9
2030	3.3	10.3	5.3	9.8
2040	4.0	12.4	6.2	11.3
2050	4.6	14.3	7.3	12.4
2060	5.1	16.1	8.1	13.1

[a] The impact on agriculture is measured as the percentage increase in unit costs of production associated with agricultural output under the assumed climate change conditions. The impact from rising sea levels is measured in billions of 1990 dollars. The impact on electricity services is measured as the percentage increase in the effective unit cost of these services.

Finally, expenditures to protect property from sea level rise has virtually no impact on overall economic growth. However, it does affect the structure of the economy slightly.

It is important to recognize that although the combined impacts of the three effects categories are not large as a *percentage* of GNP, the *absolute* dollar decline may be considered significant. As illustrated in Table 4, the present discounted value of the decline in real GNP from the combined impacts is $221 billion (in $1990). Further, it is also important to recognize that the estimated economic impacts are not insubstantial relative to the costs that have been estimated for all existing environmental regulations in the USA. Jorgenson and Wilcoxen (1990a) estimate that the long-run cost of all existing environmental regulations in the USA is 2.6 percent of GNP.[10]

A second important insight is that consumption declines in 2050, although real investment rises.[11] When agricultural yields decline as a result

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[10] Our "combined" climate scenario results in a slow decline in GNP until it falls to 0.8 percent below baseline levels in the distant year 2050. The JW estimate of a 2.6 percent decline in GNP from all existing environmental regulations is also a long-run effect. However, JW also show that the economy follows the transition path to the new steady state fairly rapidly in their assessment of the impacts of all existing environmental regulations. In particular, they show that the capital stock changes rapidly, driven by large changes in the price of investment goods. The quantity of full consumption changes at a similar rate, as does real GNP.

[11] It is also interesting that the fall in GNP is larger than the fall in consumption. This occurs because the trade balance is fixed in nominal terms and the exogenous shock due

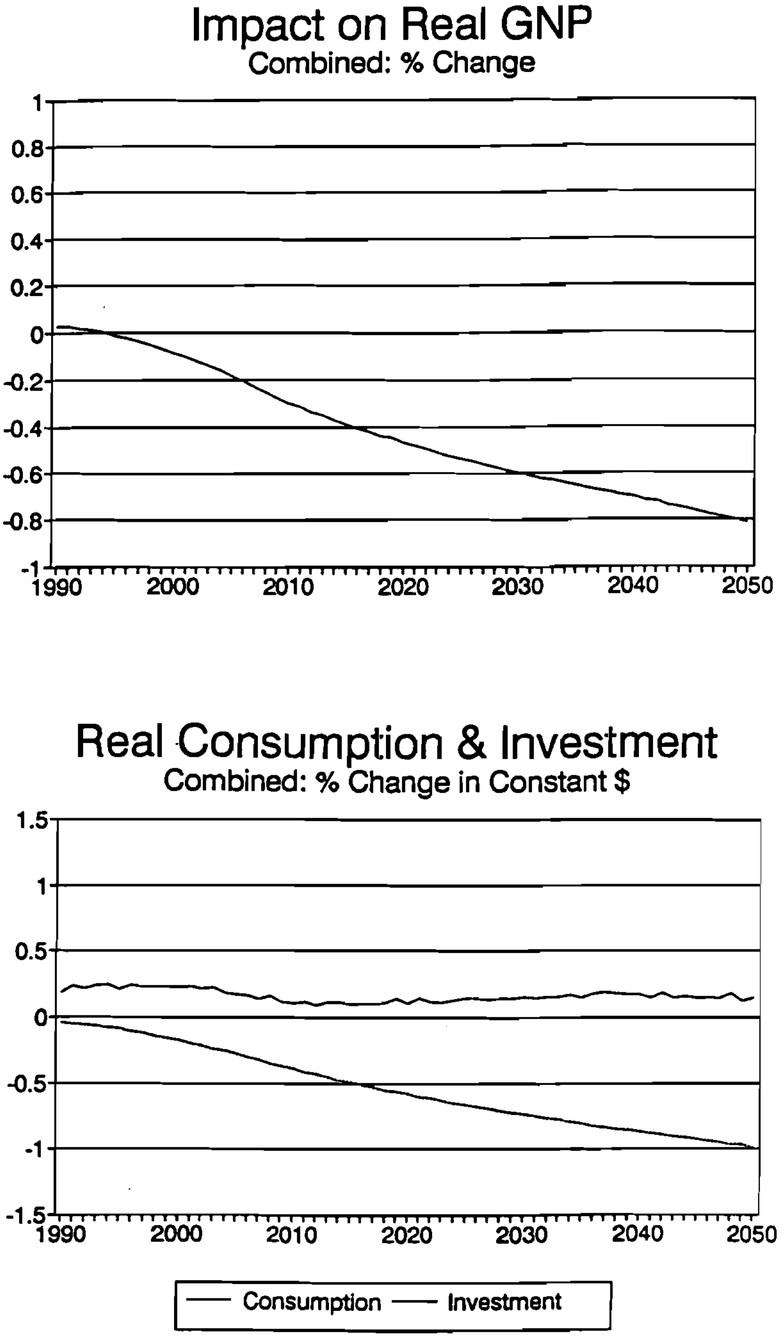
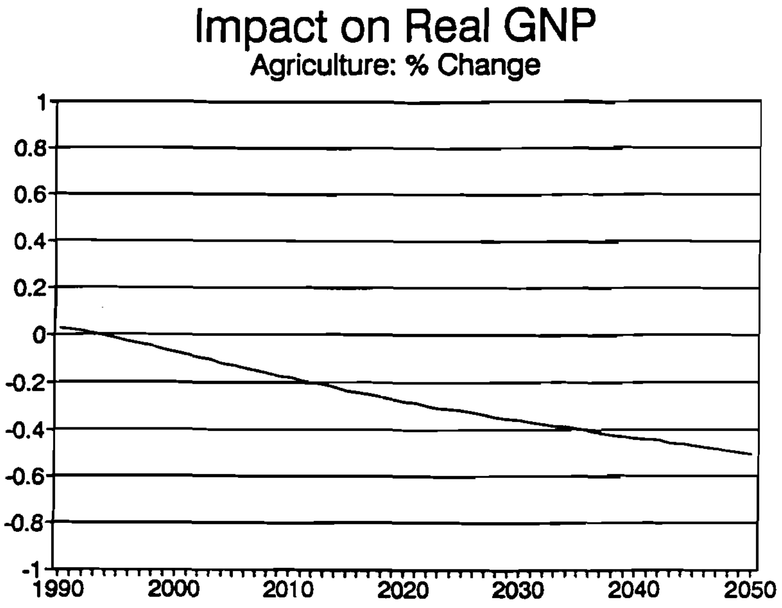


Figure 1. Impact on real GNP, consumption, and investment; combined case.



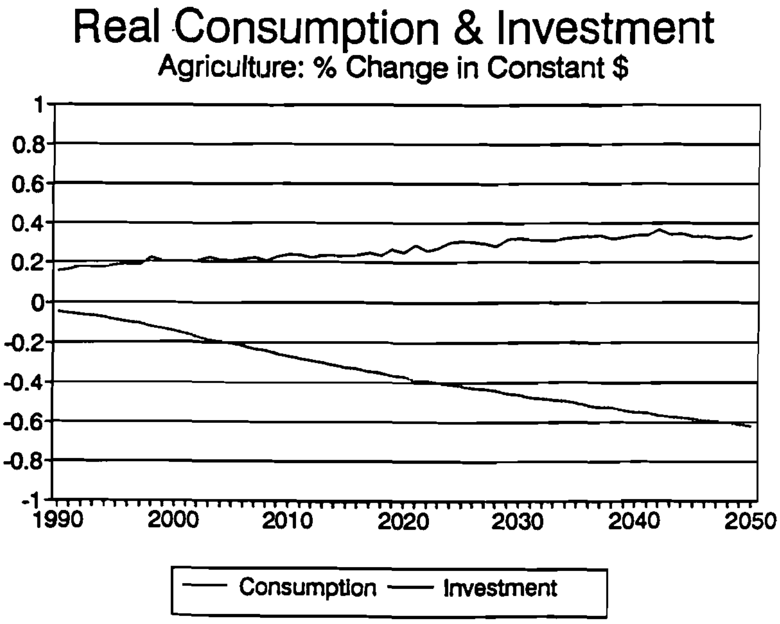


Figure 2. Impact on real GNP, consumption, and investment; the case of agricultural yield decline.

Table 3. Summary of long-term economic impacts (2050).

	Agriculture	Sea level	Electricity	Combined
	Percentage change in real magnitudes			
Real GNP	-0.5	0.2	-0.3	-0.8
Consumption	-0.6	0.0	-0.3	-1.0
Investment	0.3	0.0	-0.2	0.1
Government	-0.5	0.6	-0.3	-0.5
Net exports	-4.3	0.1	-2.0	-6.4
	Contribution to percentage change in real GNP			
Real GNP	-0.5	0.1	-0.3	-0.8
Consumption	-0.4	0.0	-0.2	-0.6
Investment	0.1	0.0	0.0	0.0
Government	-0.1	0.1	0.0	-0.1
Net exports	0.1	0.0	0.0	0.1

of climate change, consumption declines by 0.6 percent (Figure 2). This reduction in consumption is 80 percent of the overall reduction in income and spending. In the case of increasing costs for electricity services, all categories of final spending decline. The decline in consumption accounts for more than 60 percent of this reduction. In the case of sea level rise, the increased construction activities lead to a redirection of spending away from consumption toward public and private investment. However, this results in a trivial reduction in consumption.

In addition to analyzing the effects of selected climate impacts on aggregate measures of economic activity such as GNP, consumption, and investment, the methodology also allows us to examine changes in the sectoral composition of output. For example, in the input scenario of agricultural impacts, a projected decline in crop yields raises agricultural prices over 20 percent in 2050. This raises the costs of agricultural inputs to other sectors such as food processing, tobacco, and textiles, causing price increases in these and other sectors (Figure 3).

Price increases are projected for all sectors, though in the majority of instances the price rises are slight. Not surprisingly, the largest price increase is for food products. Modest price increases are also projected for tobacco, lumber, and textiles.[12] These price changes cause a reallocation of spending

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to climate change causes the exchange rate to devalue. This is more a consequence of the closure of the model than anything else.

[12] The rise in lumber prices is a result of the aggregation of agriculture, forestry, and fisheries into a single sector in the Jorgenson-Wilcoxen model. This sector is modeled as if it produces a homogeneous product that is used as an input to the lumber and wood

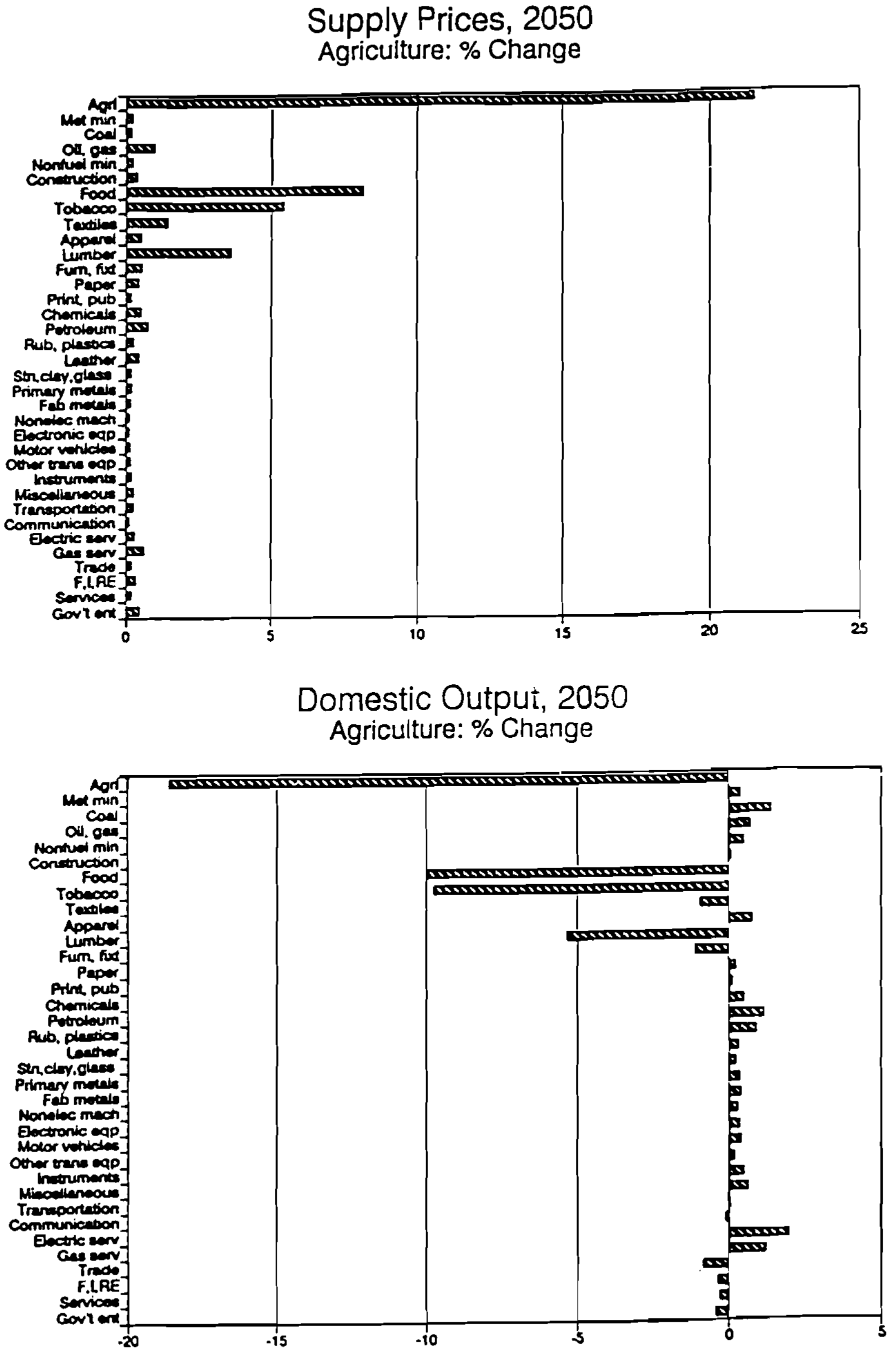

Figure 3. Impacts on supply prices and domestic outputs; the case of agricultural yield decline.

Table 4. Summary of cumulative economic impacts, in billions of 1990 dollars, 7% discount rate.

	Agriculture	Seal level	Electricity	Combined
Real GNP	-144	36	-92	-221
Real consumption				
Households	-143	-7	-57	-201
Households & government	-166	28	-69	-228

such that food and tobacco output decline 10 percent and a handful of other sectors experience modest declines.[13] Increased spending is spread out in small increments to a large number of sectors.

The projected rise in food prices as the primary impact suggests that the burden of climate change may be distributed regressively across households. Low income households spend a larger share of income on food and will be disproportionately impacted relative to wealthier households by a rise in food prices. In future research, we will examine the welfare impacts by household type to explore the distribution of burdens more fully.

Once again, these economic impacts are not large as a percentage of GNP. But our results help to illustrate that the economic vulnerabilities to climate change are not limited to those sectors that are directly affected. From a policy perspective, such indirect effects on other sectors may be important, especially if they are concentrated in particular geographic areas.

4. Modeling Insights

As we conducted this exercise, several key insights for modelers of economic and environmental processes were gained (see Table 6). In particular, our results demonstrated the potential importance of accounting for the labor-leisure choice by households, the need to ensure that appropriate measures of economic impacts are chosen, and increased our awareness that state-of-the-art general equilibrium models do not contain important factor inputs that are themselves sensitive to climate change.

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products sector. Therefore, a rise in agricultural prices, which raises the price of the aggregated sector, is treated as an increase in the price of material inputs to the lumber and wood products sector.

[13] Again, the change in the lumber and wood products sector is a spurious result of the model structure.

Table 5. Key policy-relevant insights.

- The economic effects due to the climate-induced rise in agricultural prices, rise in electricity service costs, and rise in expenditures to protect coastal lands from sea level rise, do not have a significant impact on aggregate economic growth.
- Although the combined impact is not large as a percentage of GNP, the impact is not insubstantial relative to the long-run costs of all existing environmental regulations in the USA.
- There may exist significant distributional effects.
- It is possible to identify sectors that are *economically* vulnerable to climate change. These effects may be direct or indirect.
- Structurally, the economy moves away from agricultural and consumption-related activities and toward investment and capital-related industries.

4.1. The labor-leisure choice

Our results suggest that the labor-leisure choice is a potentially important response to climate impacts. More research is needed to determine the magnitude of this effect, and whether modelers need to ensure that this choice is accounted for in their frameworks.

To illustrate this point, consider the changes in economic activity that occur as climate change leads to a reduction in crop yields in agriculture. Recall that the agricultural impacts reduce overall economic performance and lead to a 0.5 percent reduction in real GNP in 2050. Global climate change increases the relative costs of production in agriculture in the USA.[14] The higher costs result in higher prices for US food and food products that are faced by consumers, governments, and foreign purchasers. Households view this as a permanent loss in real future earnings and reduce their spending on all goods and services. They also reduce their demand for leisure and offer additional labor services. This arises because the income effects of the decline in real earnings dominate the substitution effects of higher goods prices. The quantity purchases of governments fall in real terms as expenditures are constrained by the combined effects of higher prices, available tax

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[14] The results of our analysis of agricultural impacts must be carefully interpreted. We have not modeled the impact of climate change on agricultural production in the rest of the world. Recent work sponsored by the EPA (Rosenzweig *et al.*, forthcoming; Fischer, 1992) suggests that the global agricultural impacts may have important trade implications, but also suggests that US agricultural production and net exports of the grain sector may still decline even when global agricultural impacts are considered.

revenues and limits on the overall deficit. Real exports fall and real imports rise as US production becomes less competitive. The drop in real consumption and the rise in income from the absorption of additional labor services by producers lead to a permanent boost in household saving. These funds flow to increase private investment by households and businesses. The capital stock increases, encouraged by the more favorable returns on saving and investment. As in the composite case, the economy structurally moves away from agricultural and consumption-related activities and toward investment and capital-related industries.

4.2. Important climate-sensitive factors of production

Today's state-of-the-art general equilibrium models do not contain important inputs that are directly sensitive to climate change. These inputs (e.g., water, land) may link sectors.

Partial equilibrium models, such as those that were used in this exercise to determine the exogenous inputs, may include such climate-sensitive inputs. For example, the Adams agricultural model includes water supply as a factor of production. Within the context of these partial equilibrium models, changes in these inputs often lead to small market impacts within the sector under consideration. However, because they are partial equilibrium models, they typically do not look at costs associated with intersectoral reallocations of the inputs.

Whether or not the intersectoral flows of climate-sensitive inputs are significant is an empirical question. It is a question that still remains unanswered. However, as these macroeconomic tools are used to evaluate climate change impacts and address other climate-related questions, they will have to be extended to account for these additional factor inputs and resource flows.[15]

4.3. Appropriate measures of economic impacts

Measuring changes in social welfare that result from climate change impacts is difficult. Economic modelers often rely on Gross National Product and Gross Domestic Product as proxies or "indicators" of welfare changes, even though they are not themselves welfare measures.

We suggest that in the assessment of climate change impacts, it is essential that measures other than GNP or GDP be used to evaluate welfare

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[15] Work is already underway to construct such frameworks. Of particular note is the "Second Generation Model" being developed by Jae Edmonds.

changes. In fact, focusing on changes in GNP may lead to misleading conclusions.

Consider the case of increased expenditures to protect coastal areas against sea level rise. As in the composite case, households bear a significant share of the burden of adjustment to the impacts of sea level rise (Figure 4). While the impacts are extremely small, the economy is affected nevertheless. The increase in government construction expenditures requires that resources be bid away from other production activities and redirected to construction and its supplying sectors. This bids up the prices of all goods and services, including those facing consumers. As with agriculture, households view this as a permanent reduction in real future earnings and reduce their consumption of goods, services, and leisure. The additional labor services offered by households are easily absorbed into the comparatively labor-intensive, construction-related industries. The drop in consumption and the rise in labor income lead to increases in household savings. In turn, these funds flow to investment in plant and equipment by households and businesses. In short, final demand is restructured away from consumer spending and toward public construction and private investment. The industrial mix of domestic output strongly reflects the consequences of this reconfiguration.

A result of our analysis is that GNP and consumption expenditures *move in opposite directions* over time. GNP increases until it is 0.1 percent higher in 2050. Consumption expenditures decline a small amount so that they are below baseline levels in 2050.

This result suggests that GNP is not a reliable indicator of changes in economic welfare that may arise from climate change. As a response to climate change, we can expect to see a reallocation of expenditures, both intratemporally and intertemporally, and these reallocations will influence GNP and GNP growth. Whether these reallocations result in greater or lower economic welfare, cannot be proxied by changes in GNP.

To evaluate economic welfare impacts of climate change, there are no good substitutes for equivalent and compensating variation measures of willingness to pay by households. One of the great advantages of a general equilibrium model that is grounded in consumer and producer theory is that it can provide estimates of changes in willingness-to-pay to evaluate welfare changes.[16] In future work, we will carry our analysis through to this last

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[16] An important contribution in this area is Hazilla and Kopp (1990). They constructed an econometric general equilibrium model of the USA that estimates dynamic social costs derived from modern applied welfare economics. They also demonstrate that general equilibrium impacts of environmental quality regulations mandated by the Clean Air and Water Acts are significant and pervasive.

Table 6. Modeling insights.

- The labor-leisure choice is a potentially important response to climate impacts.
- Today's state-of-the-art general equilibrium models do not contain important inputs that are directly sensitive to climate change. These inputs (e.g., water, land) may link sectors.
- Appropriate measures of economic impacts must be chosen. Alternatives include GNP, household consumption, and equivalent and compensating variation.
- If consumer surplus measures are desired, a general equilibrium modeling approach is appropriate.

stage to examine the welfare implications of the scenarios analyzed in this paper.[17]

5. Insights for the Research Agenda

Our results suggest that macroeconomic models provide a useful tool for gaining valuable insights about the economic effects of climate change. But macro models, like many other types of models, are limited in that they only capture those effects that manifest themselves in the market (Scheraga *et al.*, 1992). Conventional economic modeling lends itself to the assessment of costs and benefits that are manifested in the market. Macroeconomic modeling is particularly useful for programs that produce significant market interactions. Where conventional modeling fails us is in accounting for non-market costs and benefits (Table 7). These effects are important because they represent changes in social welfare which need to be considered by policy makers. Estimation of these effects should be a major focus of ongoing economic research.

A second focus for future research should be on the development of improved and more meaningful damage functions. Improved damage functions should be derived from a dynamic, general equilibrium assessment of the effects of global warming on the US economy, rather than on static, partial equilibrium assessments. Also, researchers should focus on deriving intertemporal information on how damages evolve as temperature (and other weather variables) change, so that the assumption about the proportionality of damages to the degree of temperature rise can be relaxed. Improved damage functions should also permit the identification and assessment of

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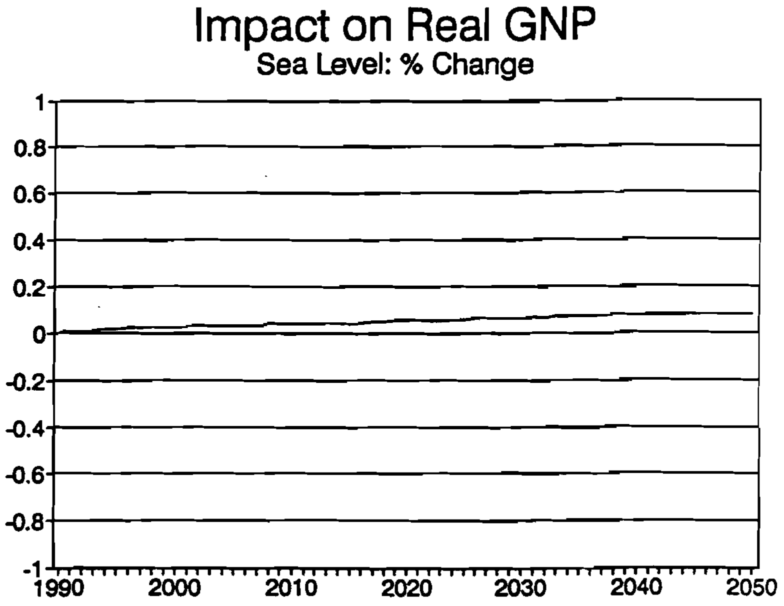
[17] For related work, see Jorgenson, Slesnick, and Wilcoxen (1992).



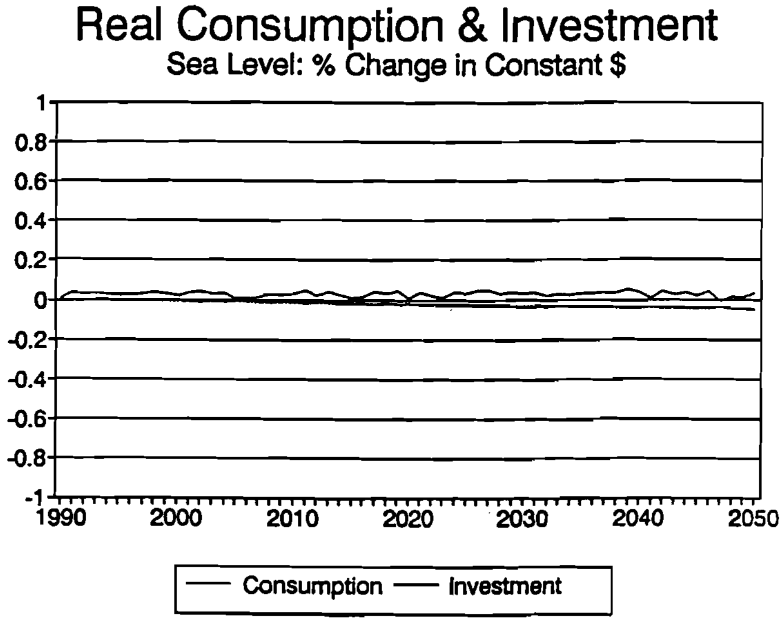


Figure 4. Impacts on real GNP, consumption, and investment; the case of sea level rise.

Table 7. Assessment taxonomy.

	Benefits	Costs
Market manifestation	• Medical expenditures • Agricultural yields • Worker productivity	• Compliance costs • General equilibrium effects
No market manifestation	• Visibility aesthetics • Pain & suffering • Existence value • Ecosystem damages	• Pain & suffering due to job loss, increased illness, and alcoholism resulting from environmental regulation (health-health effects)

regional climate impacts. Finally, damage functions should be derived that will permit the identification of marginal benefits associated with alternative policy actions. What we have done in our work is estimate credible upper bounds for the impacts from three climate-induced effects on economic growth. However, these estimates cannot be used to justify any policy package other than one which completely eliminates *all* of the relevant damages. In fact, for this type of analysis to be more useful to policy makers, marginal benefits estimates will need to be derived.

Finally, as we have already discussed, existing macroeconomic models do not include key climate-sensitive factors of production, such as water and land. There is a need to broaden the scope of macroeconomic models so that they include these inputs. One alternative is to develop a new generation of macroeconomic models that incorporate all key inputs, as well as potential feedbacks from the environment to economic activity. Another alternative is to explore linkages between narrower, more detailed sectoral models and existing macroeconomic models. For example, we expect to investigate how one might measure directly the influences of climate on production decisions on a sector-by-sector basis, and then use the JW model as a platform for looking at the general equilibrium effects. We also expect to examine how climate influences consumption decisions. Most economic analyses of climate change have focused on the impacts of climate on production. However, virtually no work has been done to examine the value of climate as a consumption good, in and of itself. Future work should address this issue.

6. Conclusions

The goal of this project has been to assess the sensitivity of US economic activity to three particular climate-induced effects: (i) changes in agricultural

Table 8. Insights for the research agenda.

There is a need to:

- Focus on non-market impacts.
- Measure directly the influences of climate on production and consumption decisions.
- Derive more meaningful damage functions that will permit:
  - ◇ Identification of the marginal benefits associated with any particular policy action
  - ◇ Assessment of regional damages due to climate change.
- Develop linkages between narrower sectoral models and macroeconomic models.

production costs, (ii) changes in electricity service costs, and (iii) changes in government expenditures to protect coastal areas from sea level rise. We have discovered that the economic impacts attributable to these climate change effects are not large as a percentage of GNP. There is a decline in consumption, although real investment rises. We have said nothing about the distribution of the consumption decline across household types, but some of our results suggest that low-income households may be differentially affected. However, further analysis is required before any statments can be conclusively made about the distributional effects of climate.

From a modeling perspective, we verified that climate change may lead to significant intersectoral flows of resources, which can only be adequately assessed with a general equilibrium framework. Yet, even state-of-the-art general equilibrium macroeconomic models are limited for climate change analyses because they do not contain important inputs that are directly sensitive to climate change.

Finally, our focus has been on the magnitude of climate impacts that have market manifestations (see Table 8). However, considerable work still needs to be done to investigate the potential non-market impacts of climate change. The non-market impacts of climate change may be significant, and are of considerable concern to decision makers concerned with the formulation of efficient and efficacious climate change policy.

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Climate Change and World Food Supply, Demand and Trade

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1. Background

Since the beginning of the 1980s, the threat of a global climate change has caused concern and attracted much attention. Many climatologists predict significant global warming in the coming decades due to increasing atmospheric concentration of carbon dioxide and other trace gases. As a consequence, major changes in hydrological regimes have also been forecast to occur.

In 1989 the US Environmental Protection Agency commissioned a three-year study on the effects of climate change on world food supply. The study has been jointly managed by the Goddard Institute for Space Studies (GISS) and the Environmental Change Unit (ECU), University of Oxford, in collaboration with the International Institute for Applied Systems Analysis (IIASA), and involved about fifty scientists worldwide.

2. Study Approach

Recent research has focused on regional and national assessment of the potential effects of climate change on agriculture. For the most part, this has treated each region or nation in isolation, without relation to changes in production in other places. The present study is a first attempt to arrive at an integrated global assessment of the potential effects of climate change on agriculture. The implementation of the study involved four elements:

1. Selection of climate change scenarios.
2. The estimation of site specific potential changes in crop yields.
3. Aggregation of crop modeling results to estimates of potential national/regional productivity changes.
4. Dynamic simulation of climate change yield impacts on the world food system.

2.1. Climate Change Scenarios

Scenarios of climate change were developed in order to estimate their effects on crop yields and food trade. A climate change scenario is defined as a consistent set of changes in meteorological variables, based on generally accepted projections of CO_2 (and other trace gases) levels. The range of scenarios used is intended to capture the range of possible effects and set limits on the associated uncertainty. The scenarios for this study were created by changing observed data on current climate (1951–1980) according to the results of doubled CO_2 simulations of three general circulation models (GCM). The GCMs used are those from:

GISS:	Goddard Institute for Space Studies (Hansen et al., 1988)
GFDL:	Geophysical Fluid Dynamics Laboratory (Manabe and Wetherald, 1987).
UKMO:	United Kingdom Meteorological Office (Wilson and Mitchell, 1987).

Mean monthly changes in climate variables from the appropriate gridbox were applied to observed daily climate records to create climate change scenarios for each site. Although GCMs currently provide the most advanced means of predicting the potential future climatic consequences of increasing radiatively active trace gases, their ability to reproduce current climate varies considerably from region to region (Houghton et al., 1990). They also cannot reliably project changes in climate variability, such as changes in the frequencies of droughts and storms.

Rates of future emissions of trace gases, as well as when the full magnitude of their effects will be realized, are not certain. Because other greenhouse gases besides CO_2, such as methane, nitrous oxide, and the chlorofluorocarbons, are also increasing, an "effective CO_2 doubling" has been defined as the combined radiative forcing of all greenhouse gases having the same forcing as doubled CO_2, usually defined as 600 ppm. For this study, CO_2 concentrations are estimated to be 555 ppm in 2060. If current emission trends continue, the effective CO_2 doubling will occur around year 2030. The climate change caused by an effective doubling of CO_2 may be delayed by 30 to 40 years or even longer, hence the projections to the year 2060 in this study.

2.2. Estimation of Site Specific Potential Changes in Crop Yields

Crop models and a decision support system developed by the U.S. Agency for International Development's International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1989) were used to estimate how climate change and increasing levels of carbon dioxide may alter yields of major crops at 112 sites in 18 countries, representing both major production areas and vulnerable regions at low, mid, and high latitudes. The IBSNAT models simulate crop growth and yield formation as influenced by genetics, climate, soils, and management practices. Models used were for wheat (Ritchie and Otter, 1985; Godwin et al., 1989), maize (Jones and Kiniry, 1986; Ritchie et al., 1989), rice (Godwin et al., 1992), and soybean (Jones et al., 1989).

The IBSNAT models were selected for use in this study because they have been validated over a wide range of environments and are not specific to any particular location or soil type. Furthermore, because management practices, such as the choice of crop varieties, planting date, fertilizer application, and irrigation, may be varied in the models, they permit experiments that simulate adjustments by farmers and agricultural systems to climate change.

The crop models used in this study account for the beneficial physiological effects of increased CO_2 concentrations on crop growth and water use (Peart et al., 1989). Most plants growing in experimental environments with increased levels of atmospheric CO_2 exhibit increased rates of net photosynthesis and reduced stomatal openings, thereby reducing transpiration per unit leaf area while enhancing photosynthesis. Simulation experiments were conducted for baseline climate (1951-80) and GCM doubled CO_2 climate change scenarios with and without the physiological effects of CO_2.

The study also tested the efficacy of two levels of adaptation: Level 1 implies little change to existing agricultural systems reflecting farmer response to a changing climate. Level 2 implies more substantial changes to agricultural systems possibly requiring resources beyond the farmer's means.

It must be noted that costs of adaptation and future water availability for irrigation under the climate change scenarios could not be considered.

2.3. Aggregation of Crop Modeling Results

Data on crop yield changes expected for different scenarios of climate change had to be compiled for all the crop sectors and all the geographical groupings represented in the IIASA/FAP world food model, the Basic Linked System (BLS). Crop model results for wheat, rice, maize, and soybean, from 112 sites in 18 countries, were aggregated by weighting regional yield changes, based on current production levels, to estimate changes in national yields. The regional yield estimates represent the current mix of rainfed and irrigated production, the current crop varieties, nitrogen management, and soils. Production data were gathered by scientists participating in the study and from the FAO, the USDA Crop Production Statistical Division, and the USDA International Service.

Changes in national yields of other crops and commodity groups and regions not simulated with crop models, were estimated based on similarities to modeled crops and growing conditions, and previous published and unpublished climate change impact studies. Estimates were made of yield changes for the three GCM scenarios with and without direct effects of CO_2. The yield changes with the direct effects of CO_2 were based on the mean responses to CO_2 for different crops in the crop model simulations.

2.4. Simulation of the World Food System

The working name of the global general equilibrium model system developed by the Food and Agriculture Program (FAP) at IIASA is: Basic Linked System of National Agricultural Policy Models (BLS). It currently consists of some thirty-five national and/or regional models: eighteen national models, two models for regions with close economic cooperation (EC and Eastern Europe and former USSR), fourteen aggregate models of country groupings, and a small component that accounts for statistical discrepancies and imbalances during the historical period. The individual models are linked together by means of a world market module. The system is of Walrasian general equilibrium type. There is no money illusion on the part of any economic agent. As a consequence of this, the outcome in terms of "real" variables is neutral with respect to monetary changes. The system is recursively dynamic, working in annual steps, the outcome of each step affected by the outcomes of earlier ones. Each model covers the whole economy, for the purpose of international linkage aggregated to nine agricultural sectors and one non-agricultural sector. All accounts are closed and mutually consistent: the production, consumption and financial ones at the national level, and the trade and financial flows at the global level.

The concept of an economic agent who decides on production and disappearance is the basis on which the BLS is built. Producers maximize returns to primary factors they are endowed with in their production activities. Consumers are assumed to maximize utility. Governments follow prescribed objectives in their policy setting within the constraints of balancing expenditures with the revenues generated through taxes, tariffs or other means and international transfers. A detailed description of the entire system is provided in Fischer et al. (1988).

The considerable length of the projection period, 1980 to 2060, makes it virtually impossible to avoid judgment and speculation concerning some of the exogenous variables in the system. The reference scenario presented here, therefore, is born out of a mixture of statistically estimated relationships, expert judgment on some of the exogenous variables, and, perhaps, wishful thinking regarding the effectiveness of future economic development and policies.

3. Dynamic Assessment of the World Food System under Alternative Climate Change Yield Impact Scenarios

The evaluation of dynamic impacts of climate change on production and trade of agricultural commodities, in particular on food staples, is carried out by comparing the results of a number of suggested climate change scenarios to a reference scenario. The primary role of such a reference scenario is to serve as a "neutral" point of departure, from which climate change scenarios with their altered assumptions on crop productivity, sometimes combined with changes in policy settings, take off as variants, with the impact of climate change being seen in the deviation of these simulation runs from the reference scenario.

We emphasize that the reference run itself is regarded a consistent projection of the world food system into the future to the year 2060, and not a forecast. This base scenario is essentially an extrapolation of the past into the future. Subject to data availability, the BLS was estimated using observations from 1961 to 1986, and has been calibrated to the more recent past. The system is simulated over the period from 1980 to 2060 to generate the reference scenario. Simulation is done in one year increments. Scenarios about climate change impact start in 1990 and end in 2060.

Yield variations caused by climate change were introduced into the yield response functions by means of a multiplicative factor impacting upon the relevant parameters in the mathematical representation. In particular, this implies that both average and marginal fertilizer productivity are affected by the imposed yield changes. Since no additional country and/or crop specific information was available to suggest explicit modifications of crop acreage due to impacts of climate change, the acreage allocation was only indirectly influenced through the implied changes in overall performance of the agricultural sector as well as changing comparative advantage of the competing crop production activities. It should be noted, however, that the BLS is equipped to handle explicit acreage constraints in the resource allocation module of the agricultural production component.

In the experiments presented here, climate change yield impacts have been phased in linearly, i.e., the yield change multiplier terms incorporated in the yield response functions are being built up gradually as a function of time so as to reach the full impact in year 2060. More complex, nonlinear schemes are conceivable and were used for sensitivity testing.

The climate change yield impact scenarios devised within this project involve a large number of experiments that relate to

1. different GCM double CO_2 simulations;
2. different assumptions with regard to the impacts of climate change on plant growth and yield levels, such as direct physiological effects of 555 ppm CO_2, or time pace of impact;
3. different assumptions regarding farm level adaptation to mitigate yield impacts; and
4. policy changes to affect both the reference run and climate change experiments, e.g. population growth, trade policies, economic growth, and GHG policies, such as limitation of arable land expansion, rice acreage or use of chemical fertilizers.

Altogether, well over fifty climate change and policy experiments were simulated. Results from twelve of these experiments are reported here. Estimates were made of yield changes for the three GCM scenarios, GISS, GFDL, and UKMO, with and without direct effects of CO_2, and for different assumptions regarding farm adaptation measures.

The four sets of estimates described in this paper are:

1. Simulations *without* the physiological effects of 555 ppm CO_2 on crop yields.

2. Simulations *with* the physiological effects of 555 ppm CO_2 on crop yields.
3. Simulations *with* the physiological effects of 555 ppm CO_2 on crop growth and yield, and adaptations at the farm level that would not involve any major changes in agricultural practices to mitigate negative yield impacts, *Adaptation Level 1.*
4. Simulations *with* the physiological effects of 555 ppm CO_2 on crop growth and yield, and adaptations at the farm level that, in addition to the former, would also involve major changes in agricultural practices, *Adaptation Level 2.*

In this way, data on crop yield changes estimated for twelve different scenarios of climate change were compiled for 34 countries or major regions of the world. The crop yield changes relate to an equilibrium $2 \times CO_2$ climate, with the equivalent doubling of CO_2 assumed to occur around 2030. The climate change caused by an effective doubling of CO_2 may be delayed by 30 to 40 years or even longer, hence the projections to year 2060 in this study.

The agricultural production components of the national models in the BLS were modified so as to accept the exogenously provided productivity changes in average national yields. In the scenarios reported here, no other additional constraints have been incorporated in comparison to the reference scenario. Exogenous variables, population growth and technical progress, are left at the levels specified in the BLS reference scenario. No specific adjustment policies to counteract altered performance of agriculture have been assumed beyond the farm adaptation specified above.

The adjustment processes taking place in the different scenarios are the outcome of the imposed yield changes triggering changes in national production levels and costs, leading to changes of agricultural prices in the international market. They, in turn, are affecting investment allocations and sectoral labor migration as well as reallocation of resources within agriculture. Time is an important element in this assessment as the yield modifications due to climate change are assumed to start occurring in 1990, reaching their full impact in 2060. Hence, this allows the economic actors in the national and international food systems to adjust their behavior over a 70-year period.

3.1. Static Climate Change Yield Impact

Before assessing the dynamic impacts of introducing a set of climate change induced yield modifications, we may ask what distortion such an exogenous change in agricultural productivity would imply in the world food system. This measure of distortion has been termed "static climate change yield impact", as it measures the hypothetical effect of yield changes, without adjustments of the economic system taking place over time. It refers to a state of the system that is not in equilibrium. As such, it is only of theoretical interest, but it helps to understand the nature and magnitude of adjustments taking place.

To obtain an estimate of the static climate change yield impact for any particular scenario, we apply the exogenously provided crop-wise percentage yield changes to the yield and production levels in the year 2060 observed in the BLS reference scenario. These impacts can be added up without weighting for cereals. To arrive at static impact estimates for other groups of crops, world market prices of the year 2060 as simulated in the reference scenario are used. Table 1 shows the static climate change yield impact estimated for the global and regional level.

The estimates of static climate change yield impacts without assuming direct physiological effects of increased (555 ppm) CO_2 concentrations on crop growth and yields represent a fairly pessimistic outlook, with decreases in crop productivity on the order of 20 to 30 percent. It may be noted that such an assumption is not regarded as very probable.

When direct physiological effects of CO_2 on yields are included, the magnitude and even direction of the aggregate static impact at world level varies with GCM and assumptions regarding farm level adaptation. In all cases the most negative effects are obtained in scenarios using the UKMO GCM climate change estimates. Scenarios derived from GISS GCM estimates show little negative effects or even gains at the global level. The static impacts are, however, quite unevenly distributed. Developed countries experience in all but the UKMO scenarios an increase in productivity, even to the tune of more than ten percent in the GISS estimates. In contrast, developing regions suffer a loss in productivity in all estimates presented here.

3.2. Dynamic Climate Change Yield Impact

The calculations above paint an effect that would result if climate induced yield changes were to occur without adjustment, overnight so to say. In the BLS scenario assumptions, however, yield productivity changes are introduced gradually to reach their full impact only after a 70 year period, 1990 to 2060. In scenarios with shortfalls in food production caused by climate change yield impacts, market imbalances cause international prices to change upwards and provide incentives to reallocation of capital and human

Table 1. Static climate change yield impact, in year 2060.

	GISS			GFDL			UKMO		
	Cereals	Other crops	All crops	Cereals	Other crops	All crops	Cereals	Other crops	All crops
WORLD									
Without physiological effect	-22.1	-21.8	-22.0	-25.4	-24.3	-25.0	-33.6	-33.4	-33.5
With physiological effect of CO_2	-5.1	3.1	-0.1	-9.0	0.5	-2.8	-18.2	-9.0	-12.2
Adaptation level 1	-1.7	3.1	0.9	-5.5	0.6	-1.7	-12.9	-8.3	-10.1
Adaptation level 2	1.4	4.8	3.2	-1.1	2.5	1.0	-6.1	-3.2	-4.4
DEVELOPED									
Without physiological effect	-13.9	-6.6	-10.3	-21.3	-16.0	-18.6	-30.4	-28.9	-28.9
With physiological effect of CO_2	2.6	18.4	10.6	-5.2	9.2	2.1	-15.8	-5.2	-9.8
Adaptation level 1	7.8	18.4	13.1	0.1	9.5	5.0	-6.7	-1.2	-3.6
Adaptation level 2	7.8	18.4	13.1	3.3	9.5	6.4	-2.8	0.8	-0.8
DEVELOPING									
Without physiological effect	-28.5	-25.3	-26.5	-28.6	-26.3	-27.1	-36.2	-34.4	-35.1
With physiological effect of CO_2	-11.2	-0.5	-3.7	-12.0	-1.5	-4.5	-20.1	-9.9	-13.0
Adaptation level 1	-9.2	-0.5	-3.2	-10.0	-1.5	-3.9	-17.8	-9.9	-12.3
Adaptation level 2	-3.6	1.7	-0.1	-4.5	0.9	-0.8	-8.7	-4.2	-5.6

resources. At the same time, consumers react to price changes and adjust their patterns of consumption.

Table 2 contains changes in world market prices, for cereals and overall crop prices, as observed in the respective climate change yield impact scenarios relative to the BLS standard reference scenario. When direct physiological effects of CO_2 on plant growth and yields are not included, then major increases in world market prices – four to nine fold increases of cereal prices depending on GCM scenario – would result. Note that such increases would call for strong public reactions and policy measures to mitigate the negative yield impacts. Hence, the outcome for scenarios without the physiological effects of CO_2 on yields, as shown in Tables 3 and 4, should be interpreted with care, both for their agronomic as well as economic assumptions.

When physiological effects of 555 ppm CO_2 on crop growth and yields are included in the assessment, then cereal prices increase on the order of

Table 2. Percent change in world market prices, year 2060.

	Cereals			All crops		
Scenario	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Without phys. effect of CO_2	306	356	818	234	270	592
With phys. effect of CO_2	24	33	145	8	17	90
Adaptation level 1	13	22	98	2	10	67
Adaptation level 2	-4	2	36	-8	-3	25

24 to 145 percent relative to the BLS standard reference scenario. Overall, crop prices increase by 8 to 90 percent, depending on the GCM climate change scenario. Price increases are further reduced when farm level adaptation is considered in addition. With adaptation measures involving major changes in agricultural practices, adaptation level 2, prices would even fall below reference run levels in the GISS and GFDL scenarios. Note that the assumptions underlying adaptation level 2 are hardly consistent with such an economic development, so that the stipulated adaptations would often not be viable.

Table 3 highlights the dynamic impacts of climate change on agriculture resulting after 70 years of simulations with the IIASA general equilibrium world model. According to these calculations, and with direct physiological effects of 555 ppm CO_2 on crop yields, the impact on global agriculture GDP would be less than 2 percent in all but the UKMO scenarios where decreases range between -2 and -5 percent. Developed countries are even likely to experience a fair increase in output. In contrast, developing countries are projected to suffer a production loss in all the analyzed scenarios. It is also important to note that these changes in comparative advantages between developed and developing regions are likely to amplify the size of the impacts suggested by the static analysis. Figures 1, 2 and 3 illustrate this observation, showing the estimated static climate change yield impact on agriculture vis-a-vis the simulated dynamic changes in GDP agriculture. Figure 4 shows the spatial distribution of changes in GDP of agriculture obtained for different GCMs assuming some adaptations at farm level (adaptation level 1).

With less agricultural production in developing countries and higher prices on international markets, it does not come as a surprise that the estimated number of people at risk of hunger[1] is likely to increase. Table 4 summarizes the simulated impacts.

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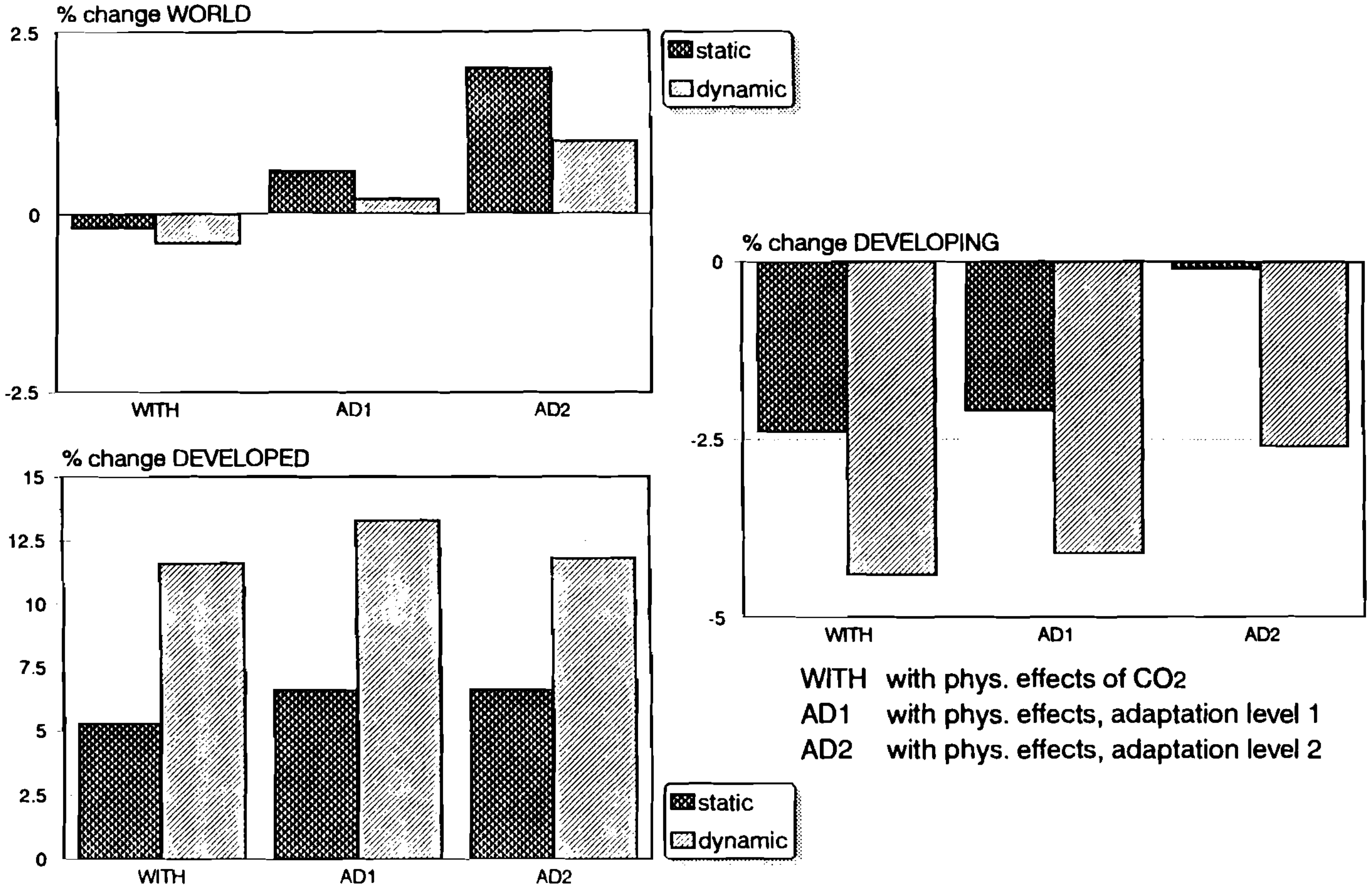
[1] In the BLS the number of people at risk of hunger in the developing world (excluding China) is estimated based on data and the methodology developed by FAO (FAO, 1984 and 1987).



WITH	with phys. effects of CO2
AD1	with phys. effects, adaptation level 1
AD2	with phys. effects, adaptation level 2

Figure 1. GISS climate change, static and dynamic impact on GDPA.

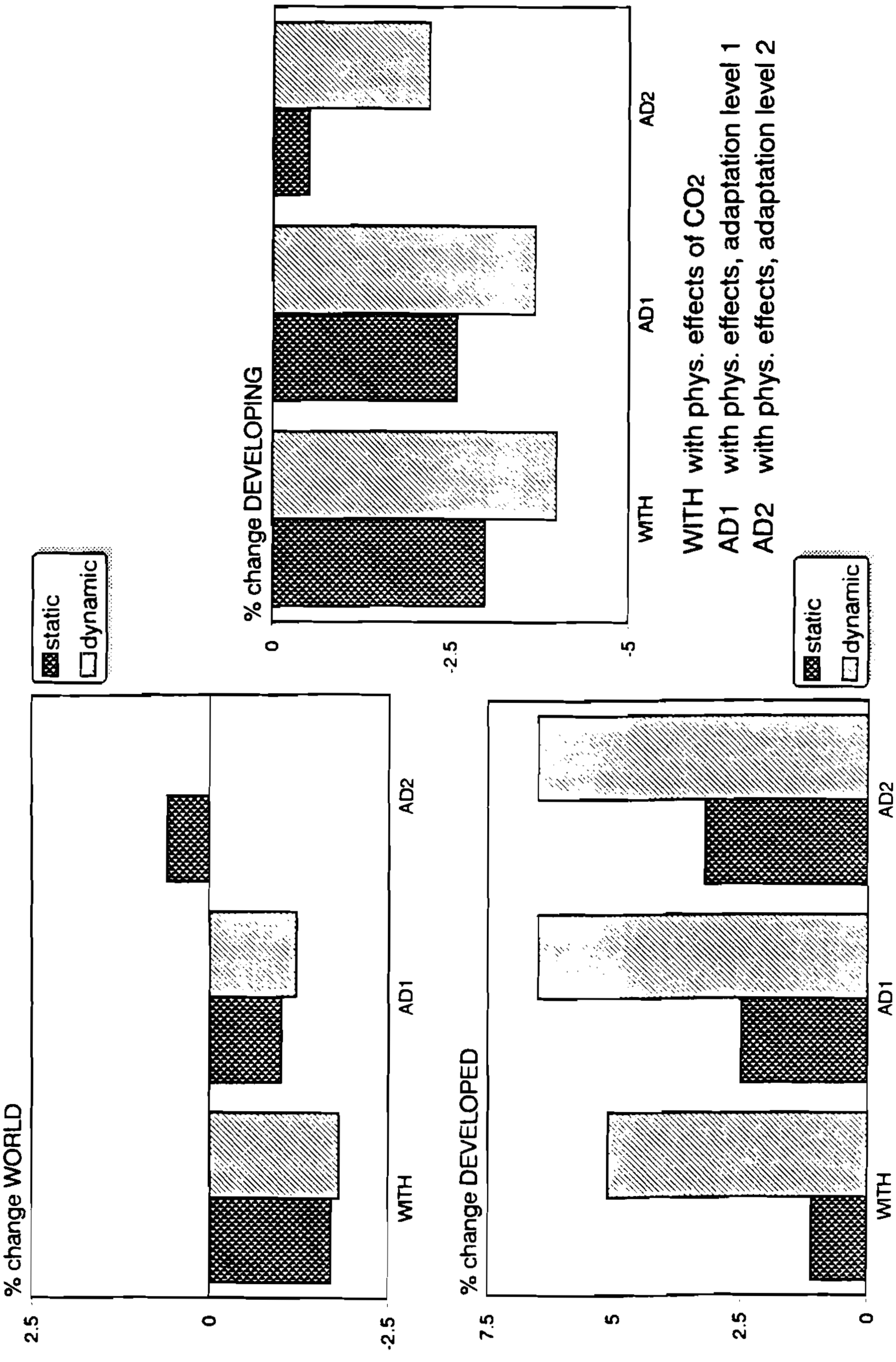


Figure 2. GFDL climate change, static and dynamic impact on GDPA.

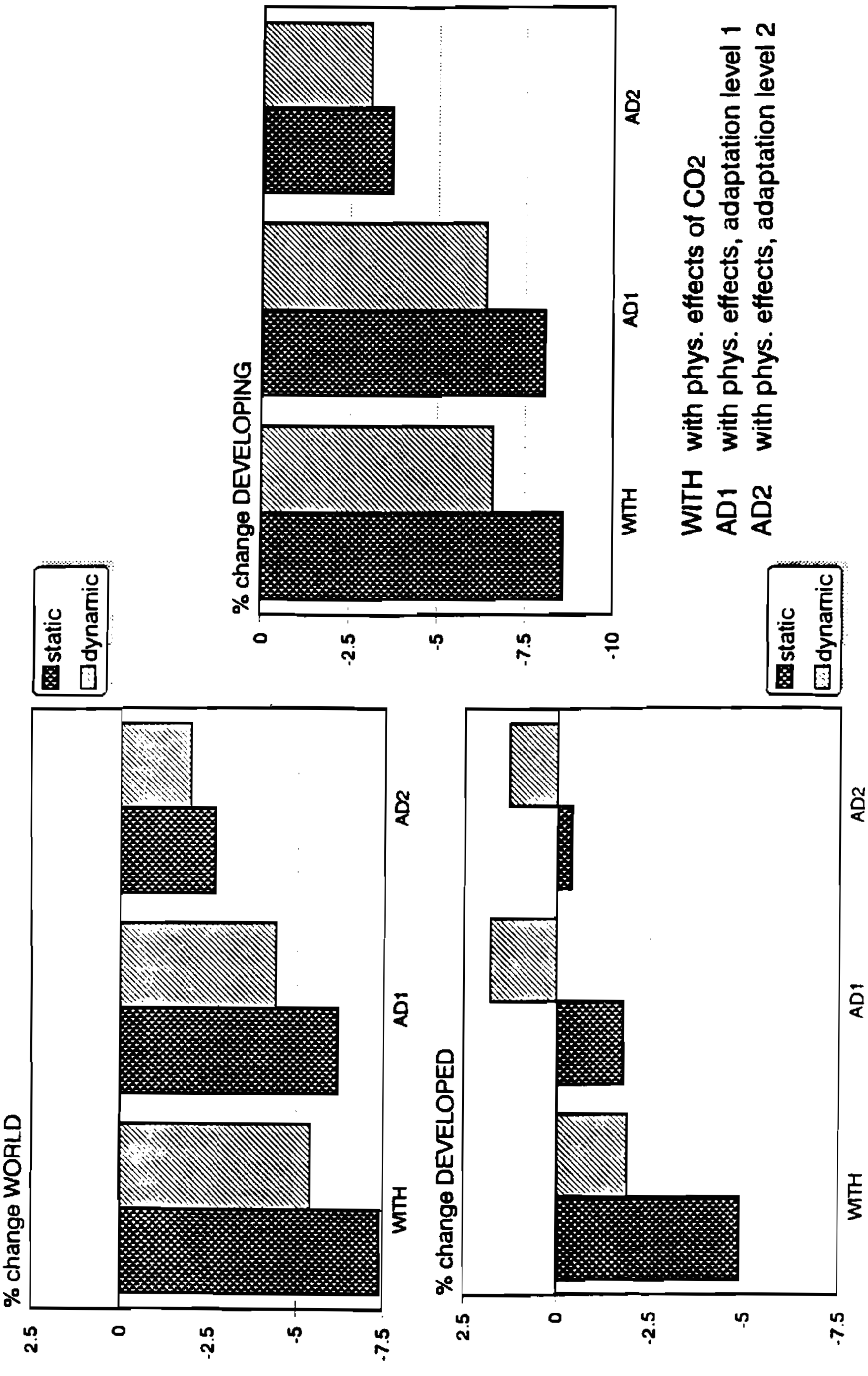


Figure 3. UKMO climate change, static and dynamic impact on GDPA.

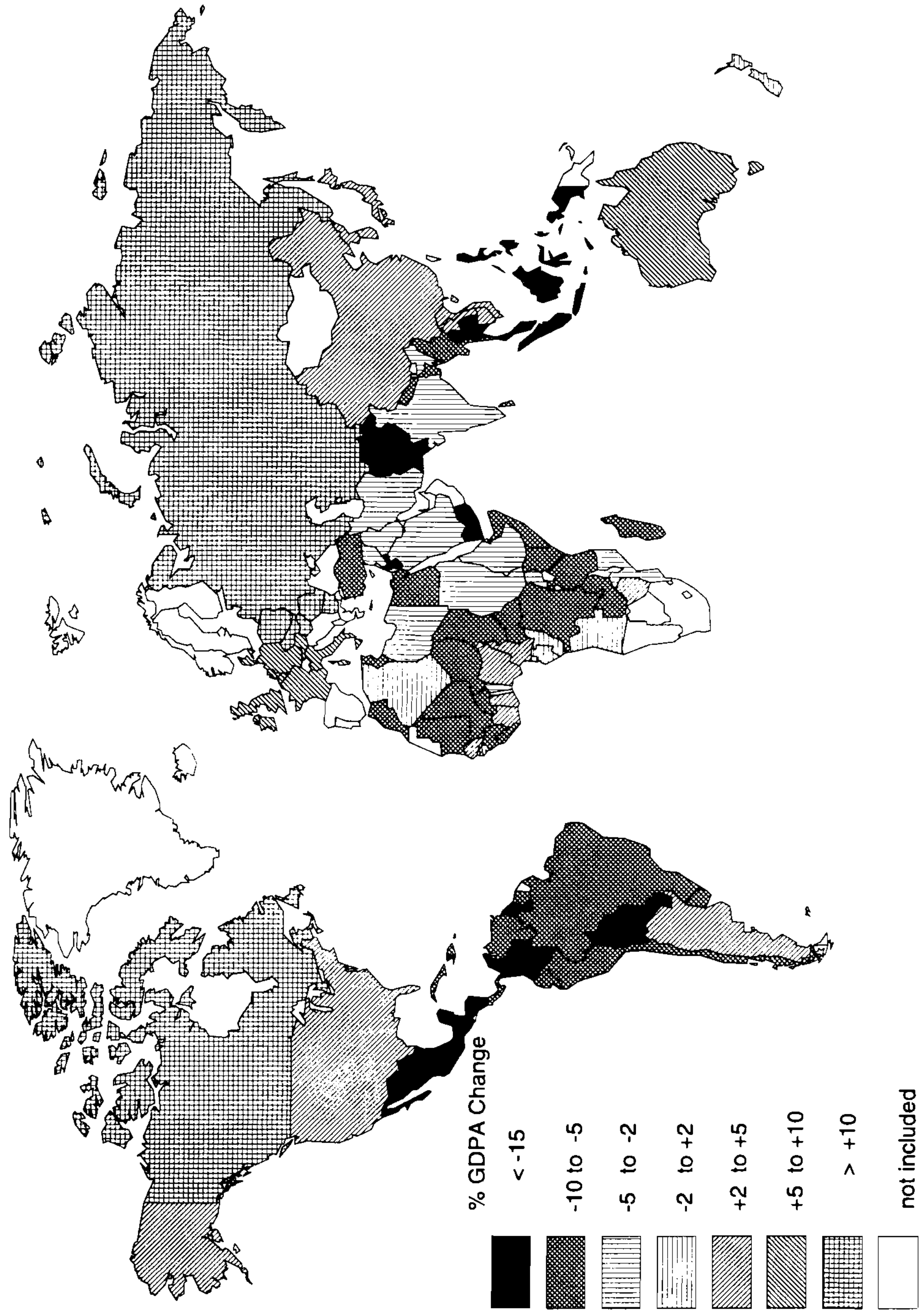


Figure 4a. Dynamic impact on GDPA-GISS GCM (Adaptation Level 1).

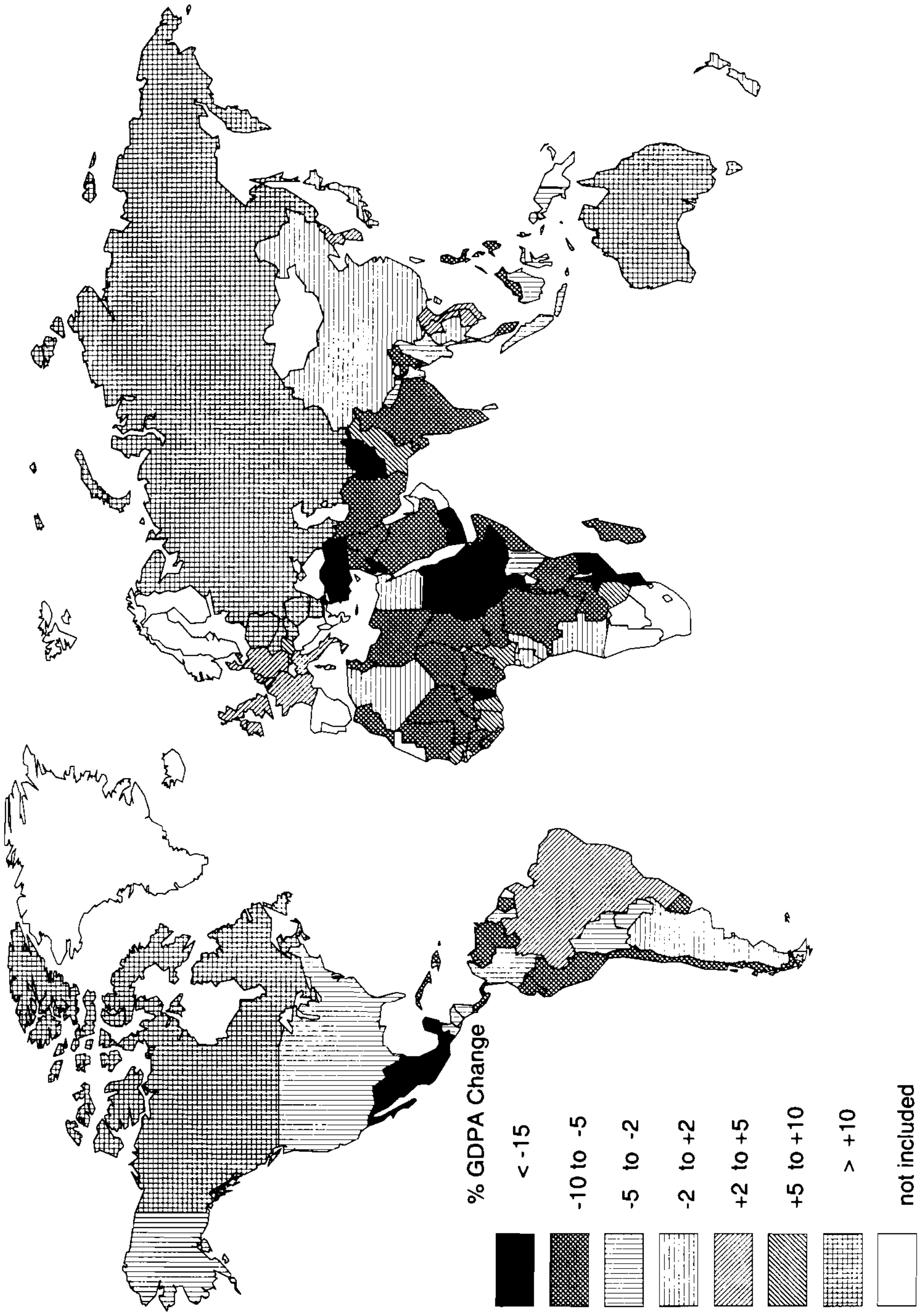


Figure 4b. Dynamic impact on GDPA-GFDL GCM (Adaptation Level 1).

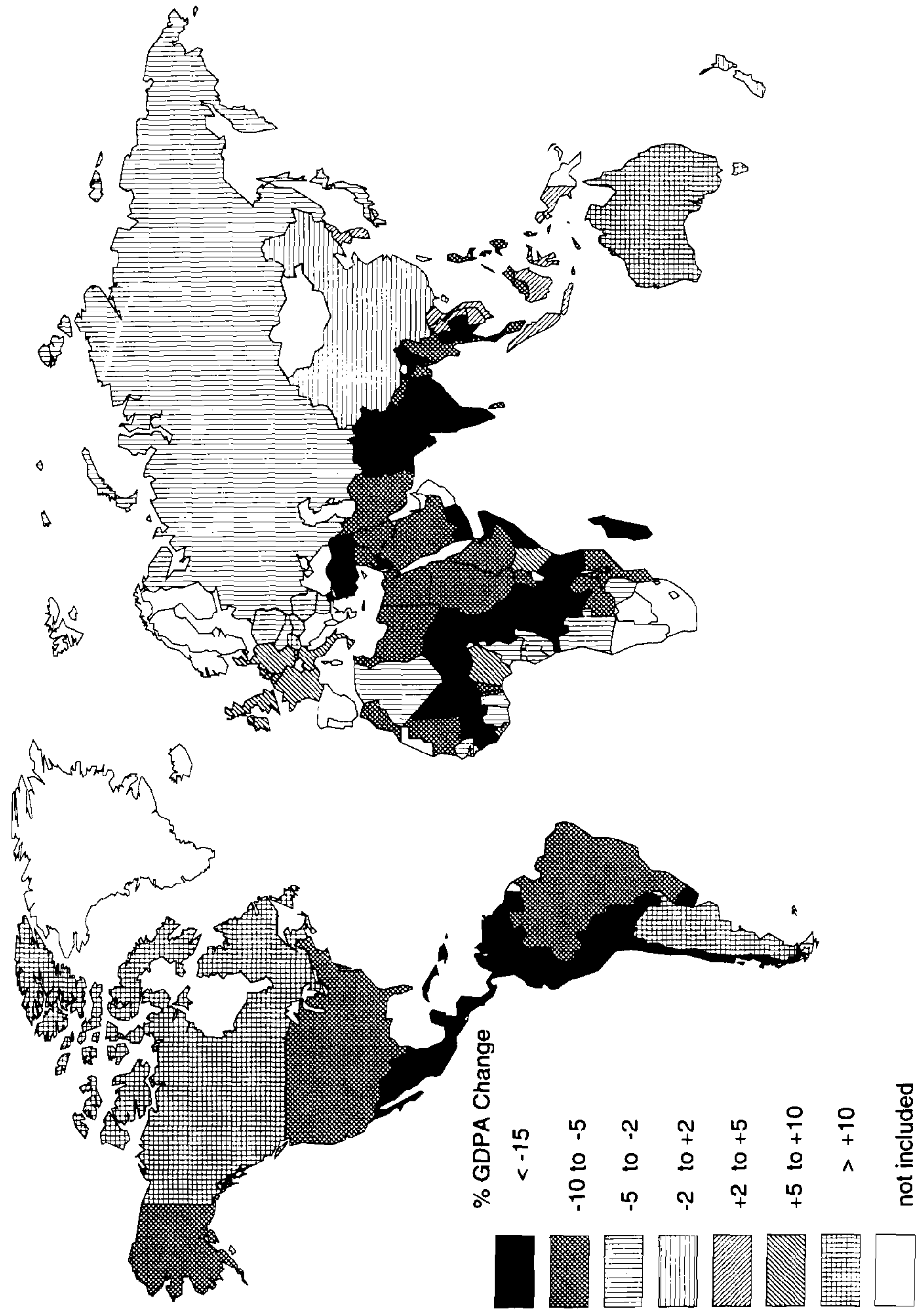


Figure 4c. Dynamic impact on GDPA-UKMO GCM (Adaptation Level 1).

Table 3. Dynamic impact of climate change, year 2060.

	Cereals production (% change)			GDP agriculture (% change)		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
WORLD TOTAL						
Without phys. effect of CO_2	-10.9	-12.1	-19.6	-10.2	-11.7	-16.4
With phys. effect of CO_2	-1.2	-2.8	-7.6	-0.4	-1.8	-5.4
Adaptation level 1	0.0	-1.6	-5.2	0.2	-1.2	-4.4
Adaptation level 2	1.1	-0.1	-2.4	1.0	0.0	-2.0
DEVELOPED						
Without phys. effect of CO_2	-3.9	-10.1	-23.9	1.1	-6.2	-12.5
With phys. effect of CO_2	11.3	5.2	-3.6	11.6	5.1	-1.9
Adaptation level 1	14.2	7.9	-3.8	13.3	6.5	1.8
Adaptation level 2	11.0	3.0	1.8	11.8	6.5	1.3
WORLD TOTAL						
Without phys. effect of CO_2	-16.2	-13.7	-16.3	-13.9	-13.5	-17.7
With phys. effect of CO_2	-11.0	-9.2	-10.9	-4.4	-4.0	-6.6
Adaptation level 1	-11.2	-9.2	-12.5	-4.1	-3.7	-6.4
Adaptation level 2	-6.6	-5.6	-5.8	-2.6	-2.2	-3.1

Table 4. Impact of climate change on people at risk of hunger, year 2060.

	Additional million people			% change		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
DEVELOPING (excl. China)						
Without phys. effect of CO_2	721	801	1446	112	125	225
With phys. effect of CO_2	63	108	369	10	17	58
Adaptation level 1	38	87	300	6	14	47
Adaptation level 2	-12	18	119	-2	3	19

Net imports of cereals to developing countries increase under all scenarios. The change in cereal imports, relative to the standard reference scenario, is largely determined by the size of the estimated static yield change, the change in relative productivity in developing and developed regions, the change in world market prices, and changes in incomes of developing countries.

4. Conclusions

The impact of climate change on agriculture and global food supply has been evaluated with a system of linked national models, called the Basic Linked System. Several scenarios of climate induced yield changes have been derived, based on a large number of site specific yield simulations with IBSNAT crop models. Considerable uncertainty still surrounds the magnitude and spatial pattern of expected climate change and the resulting impact on crop yields. The effects of changes in climate on crop yields are likely to vary greatly from region to region across the globe. Under the climatic scenarios adopted in this study, the effects on crop yields in mid and high latitude regions appear to be positive or less adverse than those in low latitude regions, provided the potentially beneficial direct physiological effects of increased CO_2 concentrations on crop growth can be fully realized.

Results of each simulated climate change yield impact scenario are compared to a reference scenario. The latter is a projection of the world food and agriculture system till the year 2060. Under the assumptions of the BLS standard reference scenario, agriculture can satisfy effective demand for food at prices even lower than observed at present. However, this scenario also clearly shows that, unless the poor receive a higher income share, there will still be a substantial number of people at risk of hunger, increasing from an estimated 500 million people in 1980 to some 600 million in year 2000 and reaching about 640 million in year 2060.

The ability of the world food system to dynamically absorb negative yield impacts decreases with the magnitude of the impact. Adaptation can largely compensate for moderate impacts of climate change such as under the GISS and GFDL scenarios but not greater ones like under the UKMO scenario.

Relative productivity of agriculture in all climate change yield impact scenarios changes in favor of developed countries. Economic feedback mechanisms are likely to emphasize and accentuate the uneven distribution of climate change impacts across the world, resulting in a net gain for developed countries in all but the UKMO scenarios and a noticeable loss to developing countries. This loss of production in developing countries, together with rising agricultural prices, is likely to increase the number of people at risk of hunger, on the order of 5 to 50 percent depending on the GCM scenario.

It must be realized that the ability to estimate climate change yield impacts on world food supply, demand, and trade is severely limited by large uncertainties regarding important elements, such as the magnitude and spatial characteristics of climate change, the range and efficiency of adaptation possibilities, the long term aspects of technological change and agricultural productivity, and even future demographic trends.

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The Costs of Climate Change: Critical Elements

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Abstract

The most widely quoted attempts to quantify the impacts of climate change suggest that the costs may be rather modest and insufficient to justify much abatement effort at present. However, these estimates suffer from five important limitations because they: do not reflect the probable dynamics of climate change; make invalid extrapolations from industrialized to developing countries; require largely subjective valuations of non-market impacts; neglect important issues raised by long-term and extreme atmospheric changes; and ignore the possibility of major and costly surprises arising from the sheer complexity of the global system.

To provide an estimate of impact costs which is directly relevant to policy formation, these components of the problem need either to be roughly quantified, or plausibly argued to involve negligible costs relative to the quantified components. Until this is done, cost analyses need to acknowledge far wider uncertainties than is presently admitted, potentially with much higher costs, if they are to be relevant as a guide to policy.

1. Introduction

Proposals to limit the buildup of greenhouse gases reflect concerns about the potential costs associated with climatic change. Most of the proposed emission targets reflect implicit individual or collective judgments about the dangers and costs involved. Recently, a number of studies have used explicit estimates of the costs of climate change as a basis for calculating optimal policy responses.

The first tentative numbers were those produced by Nordhaus (1991). Based on a detailed estimate of the possible impacts of climate change on the US economy, he suggested that a doubling of atmospheric CO_2 levels might impose total annual costs of around one percent of GDP as a best guess, with 2 percent as an upper estimate. Applying these estimates first in a steady-state analysis and later in a dynamic framework (Nordhaus, 1992) he concluded that relatively little abatement action is justified now. Peck and Teisberg (1992) have produced a number of cost-benefit studies which draw on Nordhaus' estimates of climatic damage, and point also towards very modest abatement efforts. Barrett (1992) has likewise used these numbers, and Schlesinger (1992) has drawn upon them to support his earlier conclusions that the costs of delaying abatement action may be very small. Many cost/benefit discussions now seem to start from the proposition that the costs of adapting to climate change will be modest.

Given the increasing attention being devoted to such studies, we would be well advised to ponder the numbers being used very carefully. This paper seeks to examine critically the extent to which current estimates really capture the potentially important costs, and suggests a need to think more carefully before we count.

2. ...But What was the Question?

The scenarios painted by commentators on climate change, without monetary quantification, span an immense range. At one end there are qualitative warnings of possible climatic disasters, with flooding, starvation and mass migration caused by sea level rises and changes in rainfall and storm patterns, extended further by warnings about possible global catastrophes (Leggett, 1990). At the opposite end, Idso (1991) and others have argued that CO_2-induced climatic change would be beneficial, with reduced frost damage, longer growing seasons, and CO_2-induced fertilization of plants – a veritable "green paradise".

The Impacts report of the IPCC 1990 assessment (IPCC, 1990) falls centrally between these two views, noting that agricultural impacts could be considerable at the regional level, but "studies have not yet conclusively determined whether, on average, the global agricultural potential will increase or decrease", and that water resources could be a particular concern because "relatively small climate changes can cause large water resource problems in many areas ...changes in drought risk represent potentially the most serious impact of climate change on agriculture". Such factors, combined with changes in disease patterns and the impact of sea level rise combined with storm surges, "could initiate large migrations of people".

There have been a few attempts to put economic costs on potential climate impacts and adaptation to them. The US EPA estimated the costs of

CO_2-doubling on US agriculture as about \$0.5±10bn (EPA, 1989), although Cline (1992, Chapter 2) has noted that this study made excessive allowance for CO_2 fertilization.[1] Nordhaus (1991) used these numbers as part of his broader study of potential impact costs in the US, extrapolated globally. His analysis also highlighted the fact that, outside agriculture, many sectors of the economy do not depend significantly on climatic conditions. His detailed estimates concluded that the impact on the formal economy of climatic changes predicted for a doubling of atmospheric CO_2 might be just a quarter of one percent of the US GDP, and suggested an overall figure for global impacts of one percent of global GDP to allow for various factors not included in the analysis.

Cline (1992, Chapter 3) has presented a more extensive critical analysis of the numbers involved, and suggested that many of the specific numbers may be significantly larger than the Nordhaus estimates. Nevertheless, his own quantification suggests that a doubling of CO_2-equivalent may cost one to two percent of GDP, plus certain elements (such as human amenity and morbidity impacts) added separately as as-yet-unquantified elements. Ayres and Walter (1991) have suggested rather higher numbers, but their analysis has received less attention; the underlying argument that much of the economy is not vulnerable to climatic change, and that therefore costs cannot be very high, is powerful and apparently backed by a number of studies to date.

In short, these studies suggest that we know the answer: it is on the order of one percent of GDP. But concerning such numbers, the critical issue is: what was the question?

The question for which we have an approximate answer is: what are the likely economic impacts on developed economies of a relatively smooth transition to a state with doubled atmospheric CO_2 concentrations, as estimated by mid-range, equilibrium GCM (General Circulation Model) modeling studies.

The question to which we are seeking answers is: what may be the impact of increasing greenhouse gas concentrations on the overall welfare of future generations globally, expressed in terms of present-day monetary equivalence.

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[1] The EPA study analyzed climatic change and CO_2 fertilization associated with a pure CO_2 doubling. In practice, the contribution of other trace gases means that this degree of climatic change may be reached at considerably lower CO_2 concentrations. Cline (1992, p. 94) estimates a corrected central figure for the US to be \$13bn/yr, though this itself depends significantly upon the very uncertain CFC contribution (and other uncertainties).

These are not the same questions. This paper highlights five issues which need to be addressed before we can claim to have attempted a complete quantification. These underline the partial nature of most current estimates, and suggest that the potential welfare impacts associated with rising greenhouse gas levels are much more uncertain – and potentially much higher – than suggested by most current cost/benefit studies.

3. Dynamic and Marginal Patterns of Change

Most impact costing studies focus on the costs of being in a warmer world (typically, a "doubled CO_2-equivalent" as analyzed in most climate modeling studies). This is not the same as the costs of adapting to climate as it changes, which is more difficult to assess. Ausubel (1991) and Cooper (1991) argue that modern societies tend to be increasingly insulated from climatic variations, and that the strength of market economies is their ability to adapt to changes so that steady climatic change will be lost in the noise of other societal changes.

However, it seems improbable that climatic changes will be smooth, or that average conditions are an adequate indicator. The most important change may be the increased probability of extreme events, such as the US drought of 1988, the current Sahelian and Southern African droughts, and the flooding in Bangladesh and elsewhere. These have all imposed considerable human and financial costs which would be greatly amplified if such events occurred in groups.

Furthermore, the extent to which models predict more extreme weather in a warmer world is not the only relevant factor. Local weather patterns reflect chaotic variations within the bounds set by the large-scale regional conditions, and chaos theory suggests that the transition from one state to another may involve more extreme local variations than would occur in either stable state (Markowski, 1991).[2]

Assessment is further complicated by the possible human reactions to such changes. Even when changes can be predicted in outline, adaptation may be severely constrained: for example, those in occupations or areas of greatest risk may be well advised to move, but in practice people may not want to, or may not be able to (due to migration or other restrictions) until

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[2] Weather patterns reflect an essentially chaotic variation of sub-systems within ranges set by the general forcing conditions. Chaos theory appears to indicate that, in general, chaotic variations of sub-components become more extreme if the driving force is itself changing, i.e., that the transition between two average forcing conditions may be expected to involve greater local variability than in either equilibrium condition.

the extremes strike – upon which even costly national or international relief efforts could not negate the suffering caused. To compound this, our ability to predict the occurrence of more extreme events, such as the duration of drought patterns, may be very limited.

Thus, the real-world costs may be much higher than suggested by models which assume relatively smooth climatic changes, optimal adaptation, and/or adequate foresight.

4. Extrapolation to Developing Countries

Reference to Bangladesh and migration highlights the second critical issue. Nearly all the impact costing studies to date have focused on the industrialized world or made extrapolations globally from the US analyses. But there is no way of extrapolating validly from a relatively robust and large industrialized society to one with very limited infrastructure in which many citizens may already be on the margins of existence. For example, the costing studies cited above all equate the welfare losses associated with agricultural changes as equivalent to GNP impacts. Since agriculture only accounts for a few per cent of GNP, it follows that the costs cannot be very high. Noting that agriculture is a higher percentage of GNP in developing countries, the impact costs have been scaled proportionately.

Unfortunately, this reasoning requires that money and food are globally interchangeable: that if climate change damages agriculture anywhere, that additional resources can and would be put into agriculture to produce more food irrespective of geography. Reality appears different. At a time when many industrialized countries are seeking to cut back agriculture, in the developing world hundreds of millions of people are suffering from malnutrition, and hundreds of thousands are dying from starvation or directly related causes. Many climate models suggest that central Africa will get drier with increasing CO_2 concentrations; the increases that have already occurred could have contributed to the undisputed drying trend of the past twenty-five years which has claimed many millions of lives. Similar remarks apply to the Bangladesh floods.

The real impact of climate change on the welfare of people may thus be a far cry from that reflected in extrapolations of GNP impacts on industrialized countries. Nor is it valid to assume that such impacts can simply be avoided by migration; quite apart from the fact that migration itself involves a hefty human cost on the people involved, in practice it is increasingly restricted by most countries, because of the various costs and stresses imposed on the receiving country.

5. Valuation of Non-market Impacts

Both the above issues and many others come into sharp economic focus when attempts are made to value the non-market impacts of climate change. Despite attempts to inject objectivity through criteria such as Willingness to Pay, Willingness to Accept, and various measures of revealed preference (for an overview see Pearce and Markandya, 1989) there remain large subjective elements in attempts to monetize many of the possible impacts of climate change. This applies equally to human and non-human impacts.

For example, whilst it may well be possible to keep managed ecosystems viable, ecologists express strong concerns about the possible impacts of climate change on unmanaged ecosystems, and (by implication) biodiversity. The literature on valuation indicates a wide range of possible values placed on species and habitats, varying with both the individuals making the assessment, and the subject, as indicated for example by the apparent willingness to sacrifice up to $160m annually to preserve the spotted owl and its habitat in the US (Cline, 1992, p. 106).

The contrast with the Dodo, almost unnoticed at the time of extinction, further serves to remind us how valuations can vary with time: we have little way of knowing how much future generations will value ecosystems and species such as those found in coral reefs, mangroves and boreal forests, which are amongst the ecosystems most likely to be diminished or lost to climatic change. This not only adds another layer of uncertainty; the value placed on such resources has tended to increase over time and with growing wealth, suggesting that our current valuations may be an underestimate of how future generations will value species and habitat losses.

The other major aspect of valuation concerns more direct human impacts. At the more trivial level, there is the question of how people will value (for good or bad) hotter weather. More serious issues are raised by migration, health and survival impacts. One discussion asks, "how much does a refugee cost", and attempts an estimate based on one person-year of lost production (Ayres and Walter, 1991). People driven from their homes or countries by famine or flood might suggest a rather different value scale. Concerning health and possible loss of lives noted above, much depends upon how economics values this. Scaling impact costs according to relative GDP implies valuation of human impacts based upon average earning power. In welfare economics this approach is contentious, in part because in fact many societies, directly or by implication, are clearly prepared to spend much more to prevent death than the "foregone earnings" measure implies. Pearce and Markandya (1989) suggest a figure of about £2m per life.

If estimates of possible greenhouse impacts are made with this figure applied equally to all human beings irrespective of their location, this might radically alter cost-benefit results. Lockwood (1992) cites an illustration that if climatic change causes one to ten million additional deaths annually, and a "cost of life" of between £1m and £10m is then applied, the potential monetized equivalent cost ranges from 5 percent to five times the projected global GNP – a rather different result from those cited above, and one which could justify quite drastic abatement action.

There is of course a major problem with such an approach because the blunt fact is that societies clearly do not value human beings in other countries equally. But if the above illustration is shaky in terms of consistent economics, the alternative assumption – that the human impacts of industrialized country pollution are far less significant if it is poor people who suffer – itself involves highly contentious ethical assumptions. It is not something that can be passed off simply as inevitable economic logic. It should be recognized that global impact costing studies inherently involve contentious value judgments, concerning which differing assumptions may completely reverse the conclusions.

6. Marginal and Very Long-term Changes

A fourth major issue in assessing impact costs concerns the implicit or explicit time horizon employed, and by implication, the assumed discount rate. Most published studies analyze the consequences of a doubling of CO_2-equivalent concentrations, or cut off around the middle of the next century (which is roughly equivalent).

Even if we could plot out the possible pattern of regional climatic change on the way to a doubling of CO_2, and estimate the associated costs, this would be of limited value. The pressures upon global energy consumption, and the inertia in global energy systems, are such that even if moderately strong measures were initiated now it appears most improbable that we could prevent atmospheric changes equivalent to doubling atmospheric CO_2 concentrations (Grubb, 1990). What we may be able to do is to slow the rate of change, and prevent concentrations rising much above that level. What is relevant to economic analysis is not the cost of a slow CO_2 doubling, but the incremental costs of getting there faster, and potentially going much further.

Nordhaus (1992) adopts a marginal cost approach and extends his analysis further, but this is on the basis of a simple quadratic extrapolation of cost vs. concentration which involved no analysis of what the greater atmospheric changes would actually mean. Cline (1992) has emphasized the immense long-term changes that would accrue from uncontrolled releases of fossil fuels – not a doubling of CO_2 concentrations but increases of four, six or even eight times pre-industrial levels, with potential global average temperature changes of perhaps 10°C.

It follows from the discussion above that knowledge concerning the way in which costs may vary with the rate of change is rudimentary. Knowledge of potential very long-term impacts is still more sketchy, but a potential global average temperature increase of more than twice that since the last ice age can hardly be regarded with equanimity.

Such changes are far away – 150 years or more. Most economic studies to date have consequently ignored the issue on the assumption that discounting would render any such impacts irrelevant, if the discount rates applied are remotely related to market rates. The potential contradictions in using much lower rates for public decisions than apply in existing private markets are well known. However, literature on discounting for public policy has for some time argued that the appropriate procedure is to discount using the social rate of time preference (which is generally much lower than the market interest or discount rate), and use a "shadow cost of capital" which reflects directly the impact on private sector investments (Arrow, 1966; Feldstein, 1972; Lind *et al.*, 1982). This places a far greater weight upon longer term costs than traditional discounting procedures.[3]

Howarth (1990) has also recently extended the debate about the ethical basis of market-related discounting between generations. Pearce and Markandya (1989) assume market-related rates, but in the environmental context note the potential for unsustainable outcomes, and thus suggest a separate "sustainability constraint" – a caveat which itself can destroy the validity of a discounted cost-benefit analysis if the policy implications of that analysis leads ultimately to unsustainability.

In short, focusing on a doubling of CO_2 is wholly inadequate. What matters is the marginal cost going faster and further, and there can be no prior assumption that very long term extreme impacts are not relevant to a

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[3] Cline (1992, Chapter 6) has invoked this literature, discussed briefly in Grubb (1990, Chapter 3). Many economists have questioned the utility of using a simple, market-related discount rate over such long time periods.

cost/benefit analysis; as Cline has stressed, it is an issue of potentially great importance, which to date has received far from adequate attention.

7. Climatic Surprise, Risk-aversion, and the Planetary System

A final issue is that of possible climatic surprises, and of associated risk aversion. The impact studies to date have tended to assume not only that climatic change is relatively smooth, but also that there are no surprises. But as noted above, there could be. Given current knowledge, perhaps the most credible "surprise" is that ocean current patterns will change, maybe rather suddenly. This could result in rapid regional temperature changes of well over 5°C (Dansgaard *et al.*, 1989; Calvin, 1991); Europe for example could become largely icebound if the Gulf stream were to switch, and icy regions elsewhere could melt with catastrophic subsidence and/or flooding. This could impose great costs, perhaps including starvation even in parts of the industrialized world as agriculture and infrastructure struggle to adjust.

Concerning other possible "surprises", disintegration of the West Antarctic Ice Sheet – raising sea levels by many meters – is almost certainly a slow phenomena taking many centuries . In principle the northern polar ice cap could change much faster, with little impact on sea levels but unknown implications for climatic patterns (Weiner, 1990). Another issue is how natural greenhouse gas sources and sinks may respond; current evidence suggests that these will respond to warming by amplifying the human-induced increase in greenhouse gas concentrations (Hoffert, 1992), and some have painted scenarios of runaway feedbacks (Leggett, 1991). Overall, the nagging fear is that there might be surprises in store which have simply not yet been thought of.

The underlying issue in all this is that humanity is interfering with immensely complex and interactive global systems that are far from adequately understood. Scientists and economists have sought to take a reductionist approach to climate change, modeling the components and trying to estimate the impact of changes on each. However, as highlighted eloquently by Weiner (1990), the Earth is a fantastically complex system, with major and ill-understood interactions between the atmosphere, the aquasphere (oceans), the cryosphere (ice), the lithosphere (physical and chemical structure of the surface), and the biosphere (life). Not only do these interact, but all are also affected directly by human activities, to varying degrees, and most are affected one way or another by the changing heat balance and chemical composition of the atmosphere. There is no way of tracing all the possible consequences.

Whether or not one accepts Lovelock's full "Gaia hypothesis" analogy of the Earth itself as a living organism, it is obvious that such a system has the potential for major surprises and highly non-linear responses to planetary-scale perturbations. The fluctuations of the last twenty thousand years alone suggest a far from constant and stable system. Lovelock (1988) suggests salt in the human system as an analogy for CO_2 in the planetary system, and considers that "the carbon dioxide regulation system is nearing the end of its capacity."[4] Given its role in fertilizing C_3 plant growth, and generally speeding up both the carbon and water cycles, steroids might be an equally appropriate analogy. It still does not follow that ever more is benign.

This seems an important complement to the reductionist approach because it serves as a reminder that the problem may not be just a matter of calculating the costs of raising sea walls and changing crops. In the famous words of Revelle and Suess (1957), humanity is conducting a "grand geophysical experiment".

Decision theory has of course long considered issues of decision-making under uncertainty, even very large uncertainties, generally within the framework of "subjective expected utility" (SEU) theory. One of the most basic outcomes is that unlikely outcomes are not necessarily irrelevant; as Collard (1987) puts it, "while it may or may not be possible to neglect tiny probabilities, it is not permissible to assume that they may be safely ignored". What matters is the relationship between the probability and cost of more extreme events. If the cost of successively more extreme outcomes rises more rapidly than the probability declines, the "cost benefit" analysis becomes dominated by the high cost, low-probability events. At present there is simply no way

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[4] Lovelock has been attacked by environmentalists for his suggestion that ozone depletion is a minor problem in Gaian terms, and has been misinterpreted by others as arguing that the earth has an immense natural capacity for automatically "healing" biotic damage. But concerning the CO_2 problem, and observing the oscillations of the Ice Age, Lovelock (1989) writes that:

> "biota everywhere on the land and sea are acting to pump carbon dioxide from the air so that the carbon dioxide which leaks into the atmosphere from volcanoes does not smother us ... we cannot live without it (CO_2), but too much is a poison ... Humans may have chosen a very inconvenient moment to add carbon dioxide to the air. I believe that the carbon dioxide regulation system is nearing the end of its capacity."

of knowing whether this is the case with climate change, but it certainly cannot be excluded.[5]

The importance of ignorance and possible surprises is amplified by the inertia and irreversibility of many climate change impacts. Over and above SEU-based results, such circumstances call for a strong measure of risk-aversion. Meade (1973) noted with some irony that "my own hunch would be that the disutility of Doom to future generations would be so great that, even if we give it a low probability and even if we discount future utilities at a high rate ... we would be wise to be very prudent indeed in our present actions".

8. Conclusions

Estimating the potential costs associated with rising greenhouse gas levels is an important, but very ambitious and at present speculative task. If such estimates are to be more objective and useful than the collective judgments expressed in terms of (for example) negotiated emission targets, they will need to convince observers that the major issues have been taken into account. Current estimates do not achieve this, and this paper has suggested five areas which require particular attention.

(i) The potential local and regional dynamics of climate change, and its predictability, appear poorly understood. Do we expect climate change to proceed relatively smoothly towards a new state, or is greater and unpredictable variability likely during the transition? How robust are agricultural systems especially to such variability, and what costs may it impose? This issue appears to have received very little attention, in part because of the focus of most GCM modeling upon aggregate statistics, and equilibrium changes.

(ii) The likely impacts on some developing countries appear much more severe than upon more robust developed economies. Some discussions paint scenarios of severe drought or flooding, with starvation, homelessness and forced migration. How likely are such outcomes? How should

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[5] It appears implausible that the (dis)utility of possible climate damages can be offset to zero by the possibility of beneficial outcomes. Even on an optimistic view of CO_2 fertilization, etc., the probability seems low that adapting to *changing* conditions at the rate and degree implied by most forecasts would result in net benefits. Even on such an extremely optimistic view the possible scale of gains seems clearly limited (e.g., set by the limited scope for further reductions in agricultural costs) – limits which do not necessarily apply to possible damages. The distribution of possible costs thus appears to be highly asymmetric.

they be valued? What could be done to reduce such impacts, and insofar as this requires international transfers, how likely is it that such assistance will be forthcoming in an effective and timely way? Such questions have received some popular attention, but relatively little analysis, although this is beginning to change with the country studies of UNEP for the IPCC, and the national studies required for the climate convention.

(iii) What might be the extent of non-market impacts, both in terms of direct human welfare (e.g., health and welfare losses and benefits associated with warmer climates and precipitation change), and other impacts (e.g., on ecosystems and species loss)? This issue has been more widely recognized among economic studies, but is still far from being resolved, and obviously depends heavily upon resolution of the first two issues raised.

(iv) What climatic and other changes might be implied by the very high CO_2 concentrations projected for the very long term? What impacts might these have: to what extent could they be mitigated over the long timespan available, or might they threaten more fundamental losses (e.g., from extensive sea-level rise)? How should such very long-term impacts be valued? These issues have received very little attention, with the exception of the recent work by Cline (1992), and it is to be hoped that the challenge issued by his analysis will provoke more serious work in this area; as yet, hardly anything seems resolved.

(v) What are the possible surprises in the system? Currently, a rapid change in ocean circulation patterns seems the most widely touted, despite which we have neither estimates of its probability, nor of the possible impacts if it should occur. Natural emission feedbacks and changing carbon fixation rates may amplify the growth in concentrations, and eventual disintegration of polar ice sheets seems likely, but the potential for more rapid-than-expected change in either seems uncertain. Is our understanding sufficient to be relatively confident that we have not missed something important? What costs would be involved? And how should we weight issues which are judged to be very low probability, but high cost? These issues are now beginning to receive more attention, but as yet we do not seem remotely close to answers.

Given all these factors, the task facing those who seek to quantify the costs of climate change is either to make and justify rough estimates concerning each of these (as Cline has attempted for some non-market, and for long-term impacts), or to argue plausibly that each of the five factors is negligible compared with factors already quantified.

This has not yet been done. Until this has been achieved, cost/benefit studies which focus upon quantifiable elements present a false sense of confidence and complacency. In such studies, it would be better to conduct analyses which recognize explicitly the wide range of uncertainties explicitly. For example, studies could examine the implications of:

- welfare losses of both one percent and 10 percent of global GDP associated with the 50-year transition to a doubled CO_2 equivalent;
- both high and low rates of time preference;
- both weak (e.g., linear) and strong (e.g., cubic) functions relating the degree of damage to the rate and/or degree of climatic change.

More disaggregated studies could seek to delineate the potential importance of developing country impacts, non-market impacts, and/or climatic surprises.

Such analyses would not provide simple policy answers, because none exist. But they would improve our understanding of the relationship between different impact uncertainties and optimal policies, and highlight the important uncertainties, and thus help to focus the policy and research agendas associated with climate change.

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Are we Underestimating, When Valuing the Benefits of Greenhouse Gas Reduction?

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The environment has no price but it certainly has a value. Restoring the environment or preventing environmental damage does have a price, but is it worth the value? The question on the benefits of GHG reduction is a political question with respect to the trade-off between costs and benefits. However, the present state of the art of monetary valuation of environmental damage of climatic change is such, that either the range of the monetary estimation is extremely large, or the estimation is severely biased downward (or both), which prevents such a trade-off in most cases. A good survey of estimates of damage is given in, e.g., Cline (1992), and an attempt to trade-off can be found in, e.g., Ayres and Walter (1991). Both are essentially speculations.

At the present state of the art, estimates of benefits of GHG reductions are, at most, wild guesses of the order of magnitude, that do not allow a fine-tuned trade-off of policy alternatives. They can, perhaps, be used as circumstantial evidence to justify political choices, not more. In this paper some reasons are given why this is the case.

The common use of the word "benefits" is somewhat euphemistic. Benefits of GHG reduction are prevented damages. As long as no reductions are being realized, it is more precise to speak of damages. The two words will be used interchangeably in this paper.

1. Substitutability

In economics, scarcity is measured in terms of utility, and the measuring unit is most often money. The aim of economics is to maximize utility. A basic, but not always evident, assumption behind the maximization of utility is that various types of utility are substitutable. This substitutability is indeed guaranteed if markets exist where goods and services can be freely traded, and money is a good expedient to facilitate this trade. Climatic change and its effects cannot be traded in a market. When climatic change occurs there is no possibility to undo it at the expense of other goods or services, money included.

Although climatic conditions certainly have a utility, we cannot exchange it for other types of utility. This is not too bad, if at least we can compensate with other types of utility, so as to feel equally well off. Even in the absence of an apple market, it is conceivable that a person feels equally well off with an ECU or a certain amount of apples. But the possession of an apple is not essential to well-being. Climatic change might well be. It is therefore questionable if we can measure the utility of climatic condition in the same terms as utility derived from apples, TV sets, cars, or other goods and services.

The case is comparable to the valuation of human life. In various sectors (traffic, medicine, food, environment) a trade-off must be made between costs of measures and the resulting reduction of risk, and valuation of human life is helpful to ensure efficiency within and between these various sectors. But for any individual, the question of value of his life is meaningless, as substitution is not possible.

The discipline of economics is concerned with small changes in prices, quantities, and utility. When such small changes occur, it is indeed probable that compensation or substitution is possible. But this basic assumption is not guaranteed when essential, irrevocable changes are involved. This makes monetary valuation questionable.

2. Time Scale

When choices are made with effects in time, a trade-off must be made between present and future costs and benefits. A discount rate is used to compare future effects with present effects. For individuals and firms the discount rate can be related to the interest rate of banks, which indeed provide the substitutability between present expenditures or gains and future ones. But a person's or a firm's time preference can also be higher than the interest rate.

Time preference of governments is generally lower than that of individuals; the official discount rate of the Dutch government is 5%, which means that the utility derived from Dfl 1 now is valued equal to the utility next year derived from Dfl 0.95, or the utility after 10 years of Dfl 0.60 (in constant prices, so under the assumption of zero inflation). This implies that the value of Dfl 1 shrinks in a period of 50 years, roughly two generations, to less than Dfl 0.08, in the present valuation. One can indeed argue that, if a small amount of money is invested in the bank or in a good enterprise, it will make a much larger amount after 50 years. But environment and climatic conditions cannot be banked, neither can they be bought back after 50 years with money invested now. The substitutability between the present and the future is not guaranteed with goods and services that cannot be traded in a market.

This is not to say that the concept of time preference is useless for environment. A trade-off has to be made in any case between present and future use of the environment.

The Brundtland Commission (WCED, 1987) introduced the concept of sustainable development, which is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This concept was officially accepted by many governments. The needs of present and future generations are put at the same level in the view of the Brundtland Commission. Discounting, when applied to essential living conditions that cannot be bought back with money, is therefore not in line with sustainability.

Although discounting is perfectly logical if applied to values that can be bought back, there is certainly a tension between discounting and sustainability when irreversible effects are concerned that are vital to meet the needs of future generations. And climatic change indeed bears the risk of compromising the ability of future generations to meet their needs, at least in some parts of the world. Thus, discounting and sustainability, both officially accepted concepts, are inconsistent.

In practice, discounting is being applied in the comparison between costs and benefits of GHG reduction; otherwise both costs and benefits are infinite. If sustainable development is the point of view, discounting leads to underestimation of the benefits of GHG reduction.

3. Cost-Benefit Approach

Typically, a cost-benefit analysis (CBA) approach is adopted when comparing the pros and cons of GHG reductions (Jansen *et al.*, 1991). It is well-known from theory that CBA is only applicable for marginal changes. If changes are more substantial, all kinds of adaptation and secondary effects will occur and CBA is no longer sufficient. But no models are available to reliably estimate the secondary effects of GHG reduction, in particular because climatic change has very long-term effects. Thus, the CBA approach is used for lack of alternatives.

Adaptation and secondary effects will generally diminish the primary effects of environmental changes, and thus the CBA approach tends to overestimate, not underestimate, the benefits of GHG reduction. But this goes for the costs as well.

In the comparison of costs and benefits of GHG reduction, which one of the two is more overestimated? We do not know, but one could guess that the possibilities for adaptation are larger on the cost side. Costs are financial and can therefore be compensated by other financial effects, such as economic growth. It was estimated (Steering Group, 1992) that a 100% energy charge in the Netherlands would lower the GNP with 6 to 7%. That is the economic growth of a few years only. Benefits of GHG reduction, or damage of no reduction, may be measured in money terms, but are not financial, for most part. This may limit the possibilities of adaptation. It is questionable if the adaptation mechanisms of the economic system are working equally well at the benefits side as at the cost side.

So although the CBA approach tends to overestimate both costs and benefits, it seems probable that the overestimation is larger on the cost side and, therefore, that the benefits are relatively underestimated.

4. Comprehensiveness and Completeness

Monetary estimates of benefits lack completeness and comprehensiveness (Kuik *et al.*, 1991, 1992). An estimate of benefits is complete if it contains all types of benefits. And it is comprehensive if all value categories are included, i.e., also consumers' surplus, option value, existence value, and bequest value. Some types of benefits (or damages) are easy to estimate in monetary terms. For instance, sea level rise will lead to costs of construction of higher dikes in the Netherlands. This is a purely financial effect. But many other effects of climatic change are much more difficult to estimate in monetary terms, for instance loss of ecologically valuable wetlands, loss of human life, loss of quality of life of ecological refugees. If such intangible effects are to be included in the monetary estimation, one has to resort to valuation methods that give results with very broad ranges of confidence, and even an indication of the order of magnitude may be unattainable. Value components such as consumers' surplus, option value, existence value, and bequest value are difficult to estimate reliably; yet they may well be of great importance in the case of climatic change.

To give an example: Ayres and Walter (1991) estimate the damage to one ecological refugee at $1,000. Perhaps this may be a sound estimate of the costs to society of resettling, but clearly the suffering of the refugees is not included.

An economist finds himself between Scylla and Charybdis: either he makes an accurate estimate by deleting types of damage and value components, or he makes a more complete and comprehensive estimate with such broad ranges that it is not useful for making a comparison with the more accurately measured costs. In practice, no estimate is fully complete and comprehensive, so each estimation is biased downward. Benefits are more underestimated to the extent that they are more accurate.

5. Risk and Uncertainty

Although often mentioned in one breath, risk and uncertainty are not the same. They may go together, but are different.

Uncertainty is simply not knowing. The occurrence of climatic change, its extent, and its long-term effects are for a large part uncertain. Policy makers can take different attitudes to uncertainty. The attitude of the Dutch government – at least in words, not so much yet in policy actions – seems to be that uncertainty with respect to irreversible effects urges to more caution. But the United States, a more important CO_2 emitter, hold the view that as long as no more certainty is reached, no costly policy actions should be taken; clearly an attitude of underestimation of potential damages.

Risk has to do with probability distributions. The risk of flooding and hurricanes may well increase as a result of climatic change. Most often, the valuation of risk events is made with the expected value, i.e., probability × monetary value of the event. In particular with low probability–high effect risk events, the expected value approach leads to underestimation. People in general are risk-averse for such extreme events with negative effects, and a risk aversion premium should be added. It is, however, difficult to estimate that premium accurately.

6. Climatic Change Compared to Other Environmental Problems

None of the mentioned problems in benefit estimation is unique for climatic change. Benefit estimation of, for instance, SO_2 reduction also suffers from the same problems. But in the estimation of benefits of GHG reduction, all problems come together, and each of them seems to be stronger than in the valuation of other types of pollution. As most of the mentioned problems give a tendency of underestimation of damage, it appears that in total there is a very strong tendency to underestimate.

Are benefits of GHG reduction high? This question is meaningful only in relation to the costs of reduction. Compared to other environmental problems, climatic change is a young field of environmental policy. So far, almost no policy action aimed at GHG reduction have been introduced. This implies that nations are still at the lower end of the cost curve of reduction. Engineering studies indicate that significant CO_2 reductions can be attained at zero costs (van der Burg *et al.*, 1992). Macroeconomic studies indicate that major policy measures, such as unilaterally doubling energy prices overnight, lead to a fall in GNP of only a couple of years of economic growth (Steering Group, 1992). In this light, benefits are high indeed, if compared to the costs of the first, initial GHG reduction steps.

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The Impact of Climate on Agriculture: A Ricardian Approach

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Abstract

Because of the potential for global warming, there are widespread concerns about the impact of changing climate upon the productivity of land in farming and other sectors. This paper develops a new approach for measuring the economic impact of environmental factors such as climate on production by examining the direct impact of the environmental factor on land productivity as measured by land prices. This new method is applied to examine the effect of climate on agriculture using cross sectional farm data for almost 3000 counties in the United States. It finds substantial impacts of climatic variation on both land values and farm revenues. Among the central findings are that higher temperatures in all seasons except autumn reduce average farm values in the United States. More precipitation in all seasons except autumn increases farm values. The relationships are, however, nonlinear and complex.

1. Introduction

Over the last decade, scientists have studied extensively the greenhouse effect, which holds that the accumulation of carbon dioxide (CO_2) and other greenhouse gases (GHGs) is expected to produce global warming and other significant climatic changes over the next century. Numerous studies indicate that there is the potential for major impacts on agriculture, especially if there is significant midcontinental drying and warming in the U.S. heartland.[1] The greenhouse effect is but one of a number of major environmental consequences of human activities.

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[1] See particularly the reports of the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1990) and the National Academy of Sciences Panel on Greenhouse Warming (NAS, 1991).

There are two approaches to valuing the impacts of environmental change. The traditional approach in the environmental valuation literature focuses upon measuring direct impacts on consumers. An alternative approach reflects the likelihood that a significant part of the damages from environmental changes come through impacts on production. For example, particulate emissions may increase the cost of operating processes which require especially clean settings. Changes in climate will affect agriculture, outdoor construction, electricity generation, ski resorts, and other sectors which involve natural systems or outdoor activities.

One issue addressed here is the development of a general theoretical approach that can be used directly to measure the impacts of environmental changes on production through their impact on land markets. This methodology, which is developed in Section 2 of this paper, takes into account adjustments that firms make in response to the environment.

We then develop in Section 3 an application of this model to the specific question of climatic effects on agriculture. This issue is not new. Studies of the impact of climate on farming include scholarly studies such as Adams *et al.* (1988), Adams (1989), Adams *et al.* (1990), Callaway *et al.* (1982), Decker *et al.* (1986), and Rosenzweig (1986) as well as surveys in NRC (1983), EPA (1989), and NAS (1991).

1.1. Ricardian vs. Production–Function Approaches

The approach contained in the current literature on climate effects we label the *production-function approach*, to distinguish it from the approach developed here. Under the production-function approach, changes in yield are estimated directly from a production function. Frequently, all other inputs are frozen and only the variable of interest is permitted to change. Studies using the production-function approach all find that climate change can affect agriculture through the impact of precipitation, temperature, carbon dioxide levels, changes in pests, as well as by changing the costs of irrigation. Quantitative estimates have been generated (for example, see Adams *et al.*, 1988; Adams, 1989; and Adams *et al.*, 1990) from experimental or agronomical production models. Depending upon the atmospheric scenario and the model utilized, crop-yield models (CERES and SOYGRO) predict a 10% increase or a 20% decrease in harvests, although some authors estimate a more substantial decline in yields (see Rind *et al.*, 1990).

While these studies provide a useful baseline for estimating the impacts of climate change on farming, they have an inherent bias that will tend to overestimate the impact. This bias arises because the production-function approach will omit many of the possible substitutions and adaptations that society can make to changing environmental conditions. Most studies assume that there is no adaptation at all and simply calculate the impact of changing temperature on farm yields. Others allow some changes in fertilizer application or irrigation or limited changes in the cultivars. None permit a detailed adjustment to changing environmental conditions by the farmer. Further, the literature does not consider the introduction of completely new crops (such as tropical crops in the south); technological change; changes in land use from farming to livestock, grassland, forestry; or conversion to cities, retirement homes, campsites, or the 1001 other productive uses of land in a modern post-industrial society.

By not permitting a complete range of adjustments, previous studies have overestimated damages from environmental changes. Figure 1 shows the hypothetical values of output in four different sectors as a function of a single environmental variable, temperature, in order to illustrate the general nature of bias. In each case, we assume that the production-function approach yields an accurate assessment of the economic value of the activity as a function of temperature. The four functions are a simplified example of how the value of wheat, corn, grazing, and retirement homes might look as a function of the temperature. For example, the curve to the far left is a hypothetical "wheat production function," showing how the value of wheat varies with temperature, rising from cold temperatures such as point A, then peaking at point B, finally falling as temperatures rise too high. A production-function approach would estimate the value of wheat production at different temperatures along this curve. For example, point F would describe the effect of being at a high temperature.

The production-function approach fails to take into account, however, that there will be economic substitution of alternative activities as the temperature changes. For example, when the temperature rises above point C, adaptive and profit-maximizing farmers will switch from wheat to corn. As temperature rises, the production-function approach would calculate that the yield has fallen to F in wheat, but wheat is in reality no longer produced; the realized value is actually much higher, at point D where corn is now produced. At a slightly higher temperature, the land is no longer optimally used for corn but switches to grazing, and production-function estimates that do not allow for this conversion will again overestimate the losses from climate change. Finally, at point E, even the best agricultural model will predict that the land is unsuitable for crops or even grazing and that the damage is severe. A more complete approach will find that the land

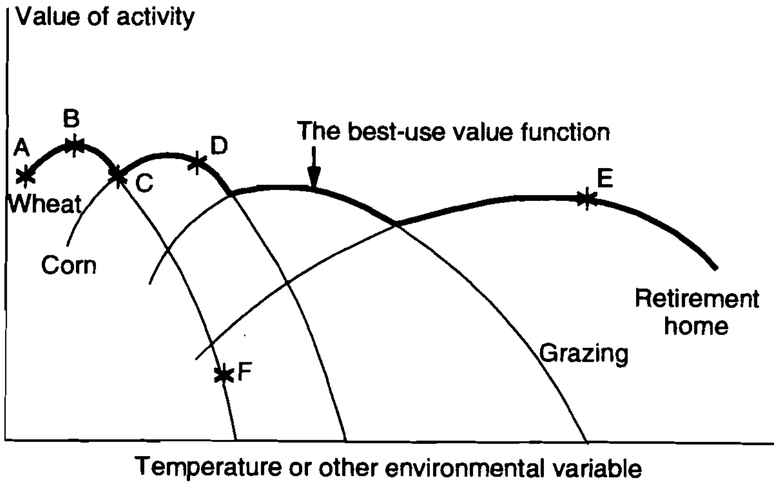

Figure 1. Bias in production function studies.

has been converted to retirement villages, to which old folks flock so they can putter around in the warm winters and dry climates.

All this is of course illustrative. But it makes the crucial point that the production-function approach will overestimate the damages from climate change because it does not, and probably cannot, take into account the infinite variety of substitutions, adaptations, and old and new activities that may displace no-longer-advantageous activities as climate changes. Of course, there is no guarantee that the picture will look anything like Figure 1. It might well be that the values of wheat are much greater than other activities. But the *direction* of the bias from the production function approach is unambiguous.

In this study, we develop a new technique that in principle can correct for the bias in the production-function technique by using economic data on the value of land. We call this the ***Ricardian approach***, after the great English economist who explored the economic determination of land rents. In the Ricardian approach, instead of studying yields of specific crops under different controlled settings, we examine how climate in different places affects the rent or revenue from farm land. By directly measuring rents, we take into account direct impacts of climate on yields of different crops as well as the potential for substitution of different inputs, introduction of different activities, and other potential adaptations to different climates. For example, by changing seed, irrigation, harvest length, or fertilizer, a farmer might adjust to changes in climate in ways that crop-yield models may fail to measure. If markets are functioning properly, the Ricardian approach will allow us to measure the economic value of different activities and therefore to verify whether the economic impacts implied by the crop yield experiments in the production-function approach are reproduced in the field.

The results of the Ricardian approach can be seen in Figure 1. We assume that the "value" measured along the vertical axis is the net yield per acre of land; more precisely, it is the value of output less the value of all inputs (excluding land rents). Under competitive markets, the land rent will be equal to the net yield of the highest and best use of the land. This rent will in fact be equal to the heavy solid line in Figure 1. We label the solid line in Figure 1 the "best-use value function."

In general, we do not observe market land rents, for most land is owner-occupied; moreover, the land rent is generally a small component of the total rent, which includes also the rent on capital items. We can, however, observe farm-land prices, which in competitive markets will be equal to the present value of the land rents. If the interest rate and rate of capital gains on the lands are equal for all parcels, then the land price will be proportional to the land rent. Therefore, by observing the relationship of land prices to climatic and other variables, we can infer the shape of the solid, best-use value function in Figure 1.

The Ricardian approach used here is closely related to hedonic property and wage studies which attempt to measure the non-monetary components of market decisions such as purchases of houses and cars or choices of jobs. In hedonic wage studies, the non-monetary components are due to working conditions, risk, the quality of the location, and similar factors. Hedonic studies have been conducted for a number of different purposes. Nordhaus and Tobin (1972) applied the hedonic model to wages to estimate urban disamenities in their construction of the Measure of Economic Welfare. Thaler and Rosen (1975) applied the model to valuation on human life, while Roback (1982) applied this technique to detect regional wage effects. Cropper and Arriaga-Salinas (1980) and Blomquist *et al.* (1988) have recently used the model to develop measures of the quality of life. The approach has also been used with land values to estimate the value of environmental goods, such as the implicit value of air pollution for households. For a general discussion, see Freeman (1979) and Pearce and Markandya (1989). Finally, Brown and Mendelsohn (1984) and Englin and Mendelsohn (1991) use the approach on recreation trips to value the characteristics of public lands.

This study measures the impact of environmental factors on production focusing upon the effect of climatic variables on agriculture. We examine both climatic data and a variety of fundamental geographical, geophysical, agricultural, economic, and demographic factors to determine the intrinsic value of climate on farming. The unit of observation is the U.S. county in the lower 48 states, and we are fortunate that there is a wealth of data at the county level in the U.S. We examine the effect of climatic variables as well as the non-climatic variables on both land values and on farm revenue, and the analysis includes a number of urban variables in order to measure the potential effect of development upon agriculture land values. The analysis suggests that climate has a systematic impact on agricultural rents through temperature and precipitation. These effects tend to be highly nonlinear and vary dramatically by season. The paper concludes with a discussion of optimal climates and the broader implications of the results.

2. Measuring the Effect of Environment on Production

This section develops the analytical apparatus that underlies the valuation of climate in this study. We postulate a set of consumers with well behaved utility functions and linear budget constraints. Assuming that consumers maximize their utility functions across available purchases and aggregating leads to a system of inverse demand functions for all goods and service:

$$\begin{aligned} P_1 &= D^{-1} \quad (Q_1,\ Q_2,\ \ldots\ ,Q_n,Y) \\ &\ \ \vdots \qquad\qquad\qquad \vdots \\ P_n &= D^{-1} \quad (Q_1,\ Q_2,\ \ldots\ ,Q_n,Y)\ , \end{aligned} \tag{1}$$

where P_i and Q_i are respectively the price and quantity of good $i, i = 1,..,n$, and Y is aggregate income. The Slutsky equation is assumed to apply, so that Equation (1) is integrable.

We also assume that a set of well-behaved production functions exist which link purchased inputs and environmental inputs into the production of outputs by a firm on a certain site:

$$Q_i = Q_i(\mathbf{K}_i, \mathbf{E}), i = 1,..,n \ . \tag{2}$$

In this equation, we use bold face to denote vectors or matrices. Q_i is the output of good i, $\mathbf{K}_i = (K_{i1},..,K_{ij},..,K_{iJ})$ where K_{ij} is the purchased input j (j = 1,...,J) in the production of good i, and $\mathbf{E} = (E_1,..,E_l,..,E_L)$ where E_l is the exogenous environmental input l (l = 1,...,L) into the production of goods, e.g., climate, soil quality, air quality and water quality, which would be the same for different goods' production on a certain production site.

Given a set of factor prices, R_j, for K_j , the exogenously determined level of environmental inputs, and the production function, cost minimization leads to a cost function:

$$C_i = C_i(Q_i, \mathbf{R}, \mathbf{E}) \quad . \tag{3}$$

Here, C_i is the cost of production of good i, $\mathbf{R} = (R_1,...,R_J)$, and $C_i(*)$ is the cost function. Firms are assumed to maximize profits given market prices:

$$\max_{Q_i} P_i Q_i - C_i(Q_i, \mathbf{R}, \mathbf{E}) \quad , \tag{4}$$

where P_i is the price of good *i*. This maximization leads firms to equate prices and marginal cost. Differentiating Equation (4) with respect to any purchased factor and setting the result to zero also reveals the first-order conditions pertaining to each factor used in production:

$$P_i \delta Q_i(\mathbf{K}_i, \mathbf{E})/\delta K_{ij} - R_j = O \quad . \tag{5}$$

Next consider the impact of changes in the exogenous environmental variables. Assume that the environmental change is from initial point $\mathbf{E}_A$ to new point $\mathbf{E}_B$. The change in value from changes in the environment are then given by:

$$V(\mathbf{E_A} - \mathbf{E_B}) = \int_0^{\mathbf{Q_B}} \sum D^{-1}(Q_i) dQ_i - \sum C_i(Q_i, \mathbf{R}, \mathbf{E_B}) - \tag{6}$$

$$[\int_0^{\mathbf{Q_A}} \sum D_{-1}(Q_i) dQ_i - \sum C_i(Q_i, \mathbf{R}, \mathbf{E_A})] \quad ,$$

where $\int \sum$ is the line integral evaluated between the initial vector of quantities and the zero vector, $\mathbf{Q_A} = [Q_1(\mathbf{K}_1, \mathbf{E}_A), .., Q_i\ (\mathbf{K}_i, \mathbf{E_A}), .., Q_n(\mathbf{K}_n, \mathbf{E_A})]$, $\mathbf{Q}_B = [Q_1\ (\mathbf{K}_1, \mathbf{E_B}), .., Q_i(\mathbf{K}_i, \mathbf{E_B}), .., Q_n(\mathbf{K}_n, \mathbf{E}_B)]$, $C_i(Q_i, \mathbf{R}, \mathbf{E}_A) = C_i(Q_i(\mathbf{K}_i, \mathbf{E}_A), \mathbf{R}, \mathbf{E}_A)$, and $C_i(Q_i, \mathbf{R}, \mathbf{E}_B) = C_i(Q_i(\mathbf{K}_i, \mathbf{E}_B), \mathbf{R}, \mathbf{E}_B)$. It is necessary to take this line integral as long as the environmental change affects more than one output. If only one output is affected, then Equation (6) simplifies to the integral of the equations for a single good. Note that as long as the Slutsky equation is satisfied, the solution to Equation (6) is path-independent and unique.

The damages in Equation (6) can be decomposed into two parts. On the one hand, costs have changed for the production of good i from $C_i(Q_i, \mathbf{E}_A)$

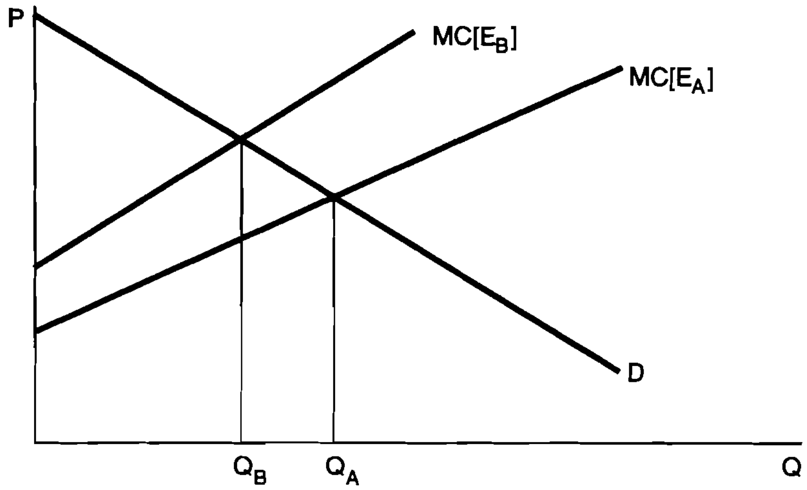

Figure 2. The effects of an environmental change.

to $C_i(Q_i, \mathbf{E}_B)$. Second, production has changed from $\mathbf{Q}_A$ to $\mathbf{Q}_B$. The value of the lost production is the difference between the consumer surplus under the demand function and the original cost of production (see Figure 2).

The present study investigates the impact of environmental changes through their impact upon a particular factor, land. We now explicitly separate land out from the firm's profit function in Equation (4):

$$\max_{Q_i} P_i Q_i - C_i(Q_i, \mathbf{R}, \mathbf{E}) - P_{LE} L_i \quad , \tag{7}$$

where L_i is the amount of land used to produce Q_i, and P_{LE} is the annual rent per unit of land given the environment **E**. We assume that there is perfect competition for land, which implies that entry and exit will drive pure profits to zero:

$$P_i Q_i - C_i(Q_i, \mathbf{R}, \mathbf{E}) - P_{LE} L_i = 0 \quad . \tag{8}$$

If use i is the best use for the land given the environment **E** and factor prices **R**, the observed market rent on the land will be equal to the annual net profits from production of good i.[2]

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[2] With imperfect competition, it is possible that a farmer could pay only as much as the next highest bidder for land and that this land payment would then be less than the productivity in the best use of the land. In addition, if the land is not put to the best use, the land payment may exceed the net productivity of the land.

Let us now reexamine the measure of environmental damages with this explicit land market. If we are examining changes in the environment which will leave market prices unchanged, then Equation (6) can be expressed:

$$V(\mathbf{E}_A - \mathbf{E}_B) = \mathbf{PQ}_B - \sum C_i(Q_i, \mathbf{R}, \mathbf{E}_B) - [\mathbf{PQ}_A - \sum C_i(Q_i, \mathbf{R}, \mathbf{E}_A)] \ , \quad (9)$$

where $\mathbf{P} = (P_1, .., P_i, .., P_n)$. Substituting Equation (8) into the above yields:

$$V(\mathbf{E}_A - \mathbf{E}_B) = \sum_i (P_{LEB} - P_{LEA}) L_i \quad , \qquad (10)$$

where P_{LEA} is P_{LE} at $\mathbf{E}_A$ and P_{LEB} is P_{LE} at $\mathbf{E}_B$. Equation (10) is the definition of the *Ricardian estimate of the value of environmental changes.* Under the assumptions used here, *the value of the change in the environmental value is captured exactly by the change in land rent.*

Note that all of the valuation expressions listed above implicitly assume that firms adjust their market inputs in order to adapt to the changing environment. It is important to recognize, however, that the measure of environmental damage incorporates this adaptive behavior. Rewriting Equation (9):

$$V(\mathbf{E}_A - \mathbf{E}_B) = \sum_i P_i Q_i(\mathbf{K}_{iB}, \mathbf{E}_B) - \sum_i \mathbf{RK}_{iB} -$$

$$[\sum_i P_i Q_i(\mathbf{K}_{iA}, \mathbf{E}_A) - \sum_i \mathbf{R} K_{iA}] \quad . \qquad (11)$$

As $\mathbf{E}$ deteriorates from $\mathbf{E}_A$ to $\mathbf{E}_B$, one would expect that farmers would adjust their purchases of $\mathbf{K}$ from $\mathbf{K}_{iA}$ to $\mathbf{K}_{iB}$ to reduce some of the losses, although the exact form of the adaptation will generally be extremely complex. If one fails to incorporate these adjustments by firms and instead assumes that $\mathbf{K}$ is fixed, then Equation (11) becomes:

$$V(\mathbf{E}_A - \mathbf{E}_B) = \sum_i P_i [Q_i(\mathbf{K}_{iA}, \mathbf{E}_B) - Q_i(\mathbf{K}_{iA}, \mathbf{E}_A)] \quad . \qquad (12)$$

This latter measure uses changes in gross revenues as a measure of environmental damage; it is closely related to the *production-function approach*, in which limited or no adaptation occurs. Scientific experiments where all factors are tightly controlled except for an environmental change use measure [Equation (12)].

The Ricardian measure in Equation (10), which includes all optimizing adaptations, is superior to the gross revenue or production-function estimate in Equation (12) because the former includes all adaptations. *An important result, however, is that the Ricardian measure in Equation (10) will always yield an estimate of environmental damage which is less than or equal to the estimate generated by the production-function approach in Equation (12).* This result is easily seen. The profits from adjusting all inputs and outputs optimally are clearly at least as great as the profits from not adjusting inputs or outputs at all or adjusting them incompletely. The former approach provides the estimate of the loss from the Ricardian approach while the later provides the loss from the production-function approach.

The impact of an environmental change on decisions is easily seen when there is only one input K and one environmental factor E in the production function of one good, Q = (K, E). Fully differentiating the first-order condition of profit maximization [Equation (5)] with respect to E and K and simplifying yields:

$$dK/dE = -Q_{KE}/Q_{KK} \quad .$$

The optimal response by the firm to improvements in E will be to increase K if $Q_{KE} > 0$ and $Q_{KK} < 0$. For example, if reduced concentrations of ozone make corn respond more positively to fertilizer $Q_{KE} > 0$, then farmers would increase fertilizer use with decreased ozone. If increased carbon dioxide decreases a plant's need for water and the marginal productivity of water $Q_{KE} < 0$, then with more CO_2 farmers will reduce irrigation. The profit function described by Equation (4) indicate adjustments of K with changes in E. If K is not permitted to adjust, the resulting profits for each level of production must be lower so that net societal benefits must be lower. Estimates that do not allow for adjustments in purchases of market inputs, for example by measuring just changes in revenue, underestimate the value of environmental improvements (or overestimate the value of environmental damages).

3. An Application of the Ricardian Technique to Agriculture

In this section, we apply the Ricardian technique by estimating the value of climate in U.S. agriculture. Agriculture is the most appealing application of the technique both because of the significant impact of climate on agricultural productivity and because of the extensive county-level data on farm inputs and outputs. As mentioned in the introduction, there is a vast literature on the impact of climate and weather on agriculture. All studies we have uncovered use the production-function approach, in which the physical impact of climate on crop yields is examined through statistical analysis or through experiments. Although this approach has great value for many purposes, it is unable to take account of the multitude of adaptations that individual farmers already make to different climates. As a complementary approach, we pursue the Ricardian approach outlined above as an independent way of investigating the impact of climate change.

3.1. Sources and Methods[3]

The basic hypothesis is that climate affects the production function for crops. Farmers on particular units of land must take environmental variables like climate as given and adjust their inputs and outputs accordingly. By examining the rents that land earns across different environments, we can measure the direct effect of climate on rents. This approach makes a number of simplifying assumptions. We assume that prices are fixed across the sample. Moreover, we assume perfect competition in both product and input markets, which is probably tenable here. Most important, we assume that the economy has completely adapted to the given climate; that is, we assume that the observed land prices have attained the long-run equilibrium that is associated with each county's climate. To the extent that there are short-run distortions, affecting either the discount rate on land rents or the relative prices within the agricultural sector or between agriculture and the rest of the economy, the observed rents and estimated climatic values may not accurately represent the longer-run values and impacts.

We rely on data from the 1982 U.S. Census of Agriculture to obtain much of the data on farm characteristics in each county. For the most part, the data are actual county averages, so that there are no major geographic issues involved in obtaining information on these variables. The *County and City Data Book*, and the computer tapes of that data, are the source for much of the agricultural data used here, including values of farm products sold per acre, farm land and building values,[4] and information on market inputs for farms in every county in the United States. In addition, in many of the equations, we include social, demographic, and economic data on each of the counties; these as well are drawn from the *County and City Data Book*.

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[3] Appendix A contains a complete description and definition of the variables used in this study.

[4] The definition and source of the farm value variable is critical to this study and its derivation is described in Appendix B.

The rest of the data required much more effort. Data about soils were extracted from the National Resource Inventory (NRI) with the kind assistance of Drs. Daniel Hellerstein and Noel Gollehon of the U.S. Department of Agriculture. The NRI is an extensive survey of land characteristics in the United States. For each county, NRI has collected several soil samples, each providing a measure of salinity, clay content, sand content, flood probability, soil erosion (K factor), rain erosion (R factor), slope length, wind erosion, whether or not the land is a wetland, and numerous other variables that are not used in this analysis. Each sample also contains an expansion factor, which is an estimate of the amount of land the sample represents in that county. Using these expansion factors, we average this data to yield an overall county estimate for each soil variable.

Climatic data is available by station rather than by county, so it was necessary to estimate county-average climates. To begin with, climate data was obtained from the National Climatic Data Center, which gathers data from 5511 meteorological stations throughout the United States. The data include information on precipitation and temperature for each month from 1951 through 1980. Since the purpose of this study is to predict the impacts of climate changes on agriculture, we focus on the long-run impacts of precipitation and temperature on agriculture, not year-to-year variations in weather. We consequently examine the climatological normal variables – the 30-year average of each climatic variable for every station. In this analysis, we collect data on normal daily mean temperatures and normal monthly precipitations for January, April, July, and October. We focus on these four months in order to capture seasonal effects of each variable. For example, cold January temperatures may be important as a control on insect pests, warm but not hot summers may be good for crop growth, and warm October temperatures may assist in crop harvesting.

In order to link the agricultural data which is organized by county and the climate data which is organized by station, we conducted a spatial statistical analysis which examines the determinants of the climate of each county. Although the specific climatic variables we analyze in this study have been measured frequently, there are some counties with no weather stations and others with several. Some of the weather stations are not in representative locations, such as the station on the top of Mt. Washington. Furthermore, some counties are large enough or contain sufficient topographical complexity that there is variation of climate within the county. We therefore proceeded by constructing an average climate for each county.

First, we assume that all the weather stations within 500 miles of the geographic center of the county provide some useful climate information.

The 500-mile circle invariably draws in many stations, so that our measure does not depend too heavily on any one station.

Second, we estimate a climate surface in the vicinity of the county by running a weighted regression across all weather stations within 500 miles. The weight is the inverse of the square root of a station's distance from the county center since we recognize that closer stations contain more information about the climate of the center. We must estimate a separate regression for each county since the set of stations within 500 miles and the weights (distances) are unique for each county. The dependent variables are the monthly normal temperatures and precipitations for January, April, July, and October. The independent variables include latitude, longitude, altitude, and distance from closest shoreline. The regression fits a second-order polynomial over these four basic variables, including interactive terms, so that there are 14 final variables in the regression, plus a constant term. Eight regressions (4 seasons times 2 measures) for each county given 3000 counties leads to over 24,000 estimated regressions.

Third, we calculate the predicted value of each climatic variable for the geographic center of the county. The predicted values of normal precipitation and temperature from the climate regressions are the independent variables for climate in the property value regressions. This complicated procedure is intended to provide accurate estimates of the climatic variables for each county.

3.2. Empirical Results

We now discuss the empirical results of this analysis. We begin with the results for the climate parameters. Figure 3 shows the temperature stations while Figure 4 shows the precipitation stations used to construct the individual climates of each county. As can be seen, these form a dense set of stations for most regions of the United States with the exception of some of the desert Southwest.

The estimates of the climate parameters for individual counties are too numerous to present, but we show two selected counties in Tables 1 and 2. These show the independent variables as well as the coefficients and summary regression statistics for Fresno, California and Des Moines, Iowa. Note that more coefficients are significant in the Fresno than the Des Moines regressions. There is more variation across the sample in Fresno because of the effects of the coast and nearby mountain ranges. Although there are more significant coefficients in the California regression, the Iowa regression has a better overall fit and smaller standard errors. In general, the fit east of

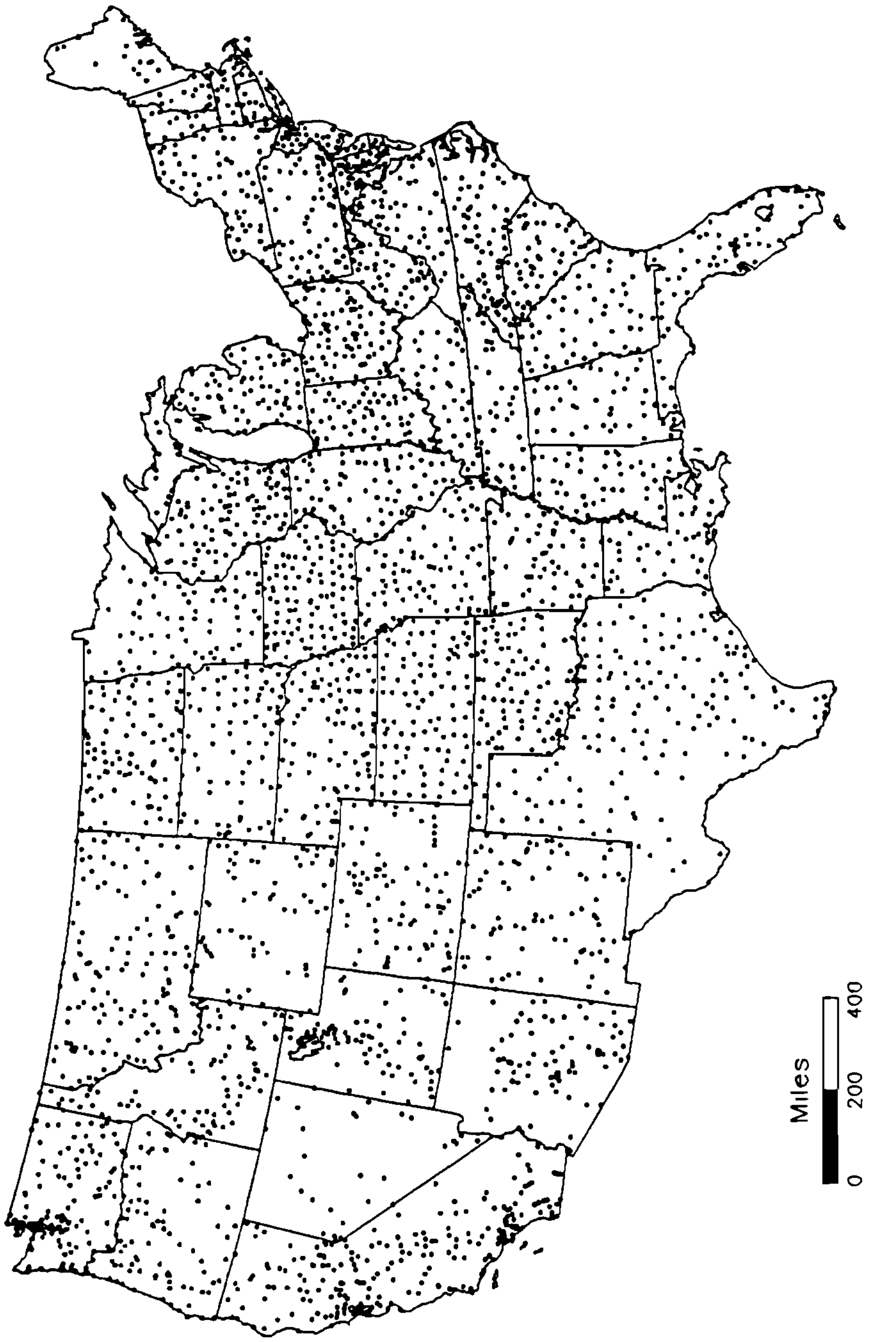

Figure 3. Temperature stations.

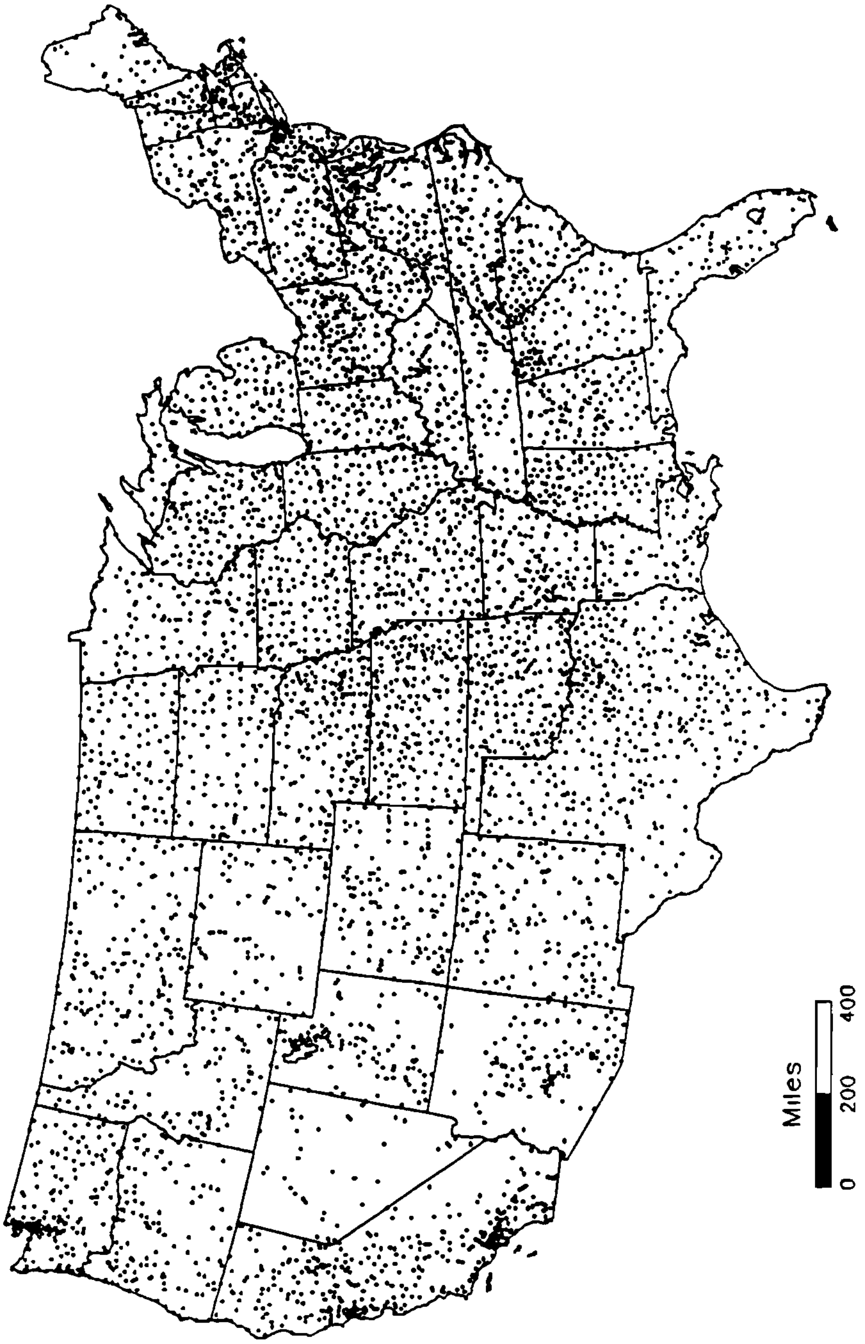

Figure 4. Precipitation stations.

Table 1. Interpolating county climate measures (Fresno, CA).

	Temperature			Precipitation		
	April	July	October	April	July	October
Constant	131535	231764	124970	-58846	-184063*	16551
Longitude	-32.8*	-59.6*	-29.2	26.7	45.2*	1.96
Latitude	-13.2	-18.2	-16.8	-19.6	21.7*	-16.33
Lat sq	1.9E-4	2.8E-4	4.1E-4	1.6E-3	-3.1E-4	1.6E-3*
Long sq	2.0E-3*	3.8E-3*	1.7E-3	-2.3E-3	-2.7E-3*	-3.9E-4
Long*lat	1.8E-3	2.8E-3	2.1E-3	1.5E-3	-2.9E-3*	1.1E-3
Altitude	-0.56*	-1.44*	-1.00*	0.525	1.28*	1.48*
Alt sq	-1.6E-6*	-3.0E-6*	-2.3E-6*	-3.7E-6*	-6.5E-7*	-2.4E-6*
Lat*alt	4.3E-5	8.8E-5	7.7E-5*	-4.8E-5	-1.1E-4*	-1.1E-4*
Long*alt	6.2E-5	1.8E-4*	1.1E-4*	-4.6E-5	-1.5E-4*	-1.7E-4*
Shore dist	-40.4*	-74.5*	-35.2	-5.47	59.4*	-26.6
Sdist sq	2.6E-3	4.2E-3	2.2E-3	2.9E-3	-4.9E-3*	4.8E-3*
Sdist*long	5.2E-3*	9.6E-3*	4.2E-3	-1.3E-3	-6.7E-3*	2.6E-3
Sdist*lat	2.0E-3	3.7E-3	2.3E-3	4.3E-3	-4.9E-3*	2.7E-3
Sdist*alt	6.7E-5	1.3E-4	9.7E-5*	-1.9E-4	-7.0E-5*	-2.3E-4*
Adj r^2	0.999	0.998	0.999	0.796	0.777	0.706
Std err	0.13	0.24	0.13	0.54	0.13	0.30
Observations	331	331	331	525	525	525

Notes: Variables marked with an asterisk are significant at the 5% level. Temperature is measured in Fahrenheit and precipitation in inches per month.

100 degrees longitude (the east slope of the Rocky Mountains) was tighter than in the West. By and large the equations do very well in predicting monthly temperature and vary from precise to somewhat less satisfactory for the noisy precipitation variable.

In order to gain some sense of the reliability of this geographic approximation method, we predicted the climate for each of the weather stations. Dropping the weather station itself, we predicted the climatic variables for the station from all stations within 500 miles in the manner explained above. Comparing these results with the actual measurements from each station reveals that the approximation method predicts between 87% and 97% of the variation in precipitation in the continental United States and between 97% and 99% of the variation in temperature. It should be noted that, even in a statistically stationary environment, the observations of "climate" themselves contain error because they contain only 30 observations. Depending upon the relative importance of idiosyncratic error in climate vs. misspecification error in our equation, it might well be that the predictions are actually

Table 2. Interpolating county climate measures (Des Moines, Iowa).

	Temperature			Precipitation		
	April	July	October	April	July	October
Constant	6425	5006	8967	-32243	77324*	41650
Longitude	-0.919	-1.12	-2.55	7.72	-15.8*	-9.61
Latitude	-2.48	-0.829	-1.55	10.0	-32.9*	-16.32
Lat sq	2.5E-4	2.0E-5	3.2E-5	-9.7E-4	3.2E-3*	1.6E-3
Long sq	3.7E-5	8.1E-5	2.0E-4	-4.9E-4	6.8E-4	5.9E-4
Long*lat	2.0E-4	1.0E-4	2.4E-4	-9.9E-4	3.8E-3*	1.8E-3
Altitude	-0.13	0.046	0.34*	0.353	3.02*	2.09*
Alt sq	-1.2E-6	-1.3E-6*	1.6E-6*	1.1E-5*	-1.5E-6	2.1E-5*
Lat*alt	2.1E-5	-1.6E-5	-6.9E-5*	-1.2E-4	-5.7E-4*	-2.8E-4*
Long*alt	1.1E-5	-9.7E-6	-4.9E-5*	-3.1E-5	-3.6E-4*	-3.2E-4*
Shore dist	1.14	-1.17	-0.564	-0.150	26.8	18.6
Sdist sq	1.8E-4	-3.1E-4	-1.9E-4	5.8E-4	-1.2E-3	1.4E-3
Sdist*long	-4.4E-5	1.9E-4	-1.2E-4	-4.1E-4	-2.7E-3	-1.9E-3
Sdist*lat	-3.6E-4	2.2E-4	9.0E-5	4.2E-4	-5.4E-3*	-3.8E-3
Sdist*alt	-2.2E-5	3.2E-5	9.9E-5*	-1.7E-4	6.9E-4*	3.6E-4*
Adj r^2	0.999	0.999	0.999	0.989	0.987	0.976
Std err	0.04	0.04	0.04	0.14	0.17	0.15
Observations	928	928	928	1477	1477	1477

Notes: Variables marked with an asterisk are significant at the 5% level. Temperature is measured in Fahrenheit and precipitation in inches per month.

a superior estimate of the local climate than are the recorded observations themselves.

Combining the agricultural and climatic data, we wish to predict agricultural land values. Land values are the present value of future expected rents. There is little reason for the riskless interest rate to vary across counties in the U.S., but the risk and capital-gains components of land value might vary considerably. For example, California agricultural land near growing cities might well have a larger capital-gains component than would rural land far from cities in an economically stagnant coal-mining region of Appalachia. Moreover, there are major potential errors in measurement of land values since values are estimated by farmers, and such estimates are often unreliable. However, there is no reason to believe that the errors of measurement are correlated with independent data such as temperature or precipitation. The major effect of measurement errors will be imprecision of the econometric estimates rather than bias in the estimation of the coefficients or an ultimate bias in the estimate of the economic value of climate on agriculture.

The next and crucial stage is to use the climate data in the estimates of economic value. The geographic distribution of farm value per acre is shown in Figure 5 and of farm revenues per acre in Figure 6. Both variables are measured in 1982. The unit of observation is the county. We use estimated climatic variables along with soil variables and socioeconomic data to estimate the best-value function across different counties. Table 3 shows the crucial regressions for the second stage. There are 2933 observations.

In order to give a sense of the importance of the non-farm variables in the model, we begin with a model which contains only climate variables. The first set of regressions in Table 3 is a quadratic model which includes the eight measures of climate (four months of precipitation and temperature). For each variable, a linear and quadratic term are included. This flexible functional form can reflect the nonlinearities that are apparent from field studies; the nonlinear terms introduce an appreciably better set of estimates.

In the second set of regressions, we add the balance of the urban, soil and other environmental variables to include other factors influencing land values and farm revenues. In these equations, we attempt to control for the influence that urban development and soils will have upon land values. As proxies for urban development, we include population density, net migration, and per capita income. Soil characteristics are measured using the percent of the land which is flood-prone, the percent of the land which is wetland, estimated potential for soil erosion, the salinity of the soils, whether soils are sandy or clay, and the slope length of the land. Other environmental factors included are solar energy, which is proxied by latitude, and altitude.

The full regression controls for urban development and soils with the additional included variables. The full specification is therefore more appropriate for estimating the impact of climate on farming, particularly if the omitted variables are spuriously correlated with land values. On the other hand, the more limited quadratic regression may be doing a better job of capturing the entire spectrum of the land rent function by endogenously incorporating non-farm land uses and allowing for the value of land in non-farm uses.

The results of this analysis are shown in Table 3. The squared terms for most of the climate variables are significant implying the observed relationships are nonlinear. However, the squared terms are not all negative as expected. Some of the squared terms are positive, especially for precipitation. The positive coefficient on the squared term implies that the function has a minimum value from which it increases in both directions. The expected negative coefficient implies that there is an optimal value from which the value function decreases in both directions.

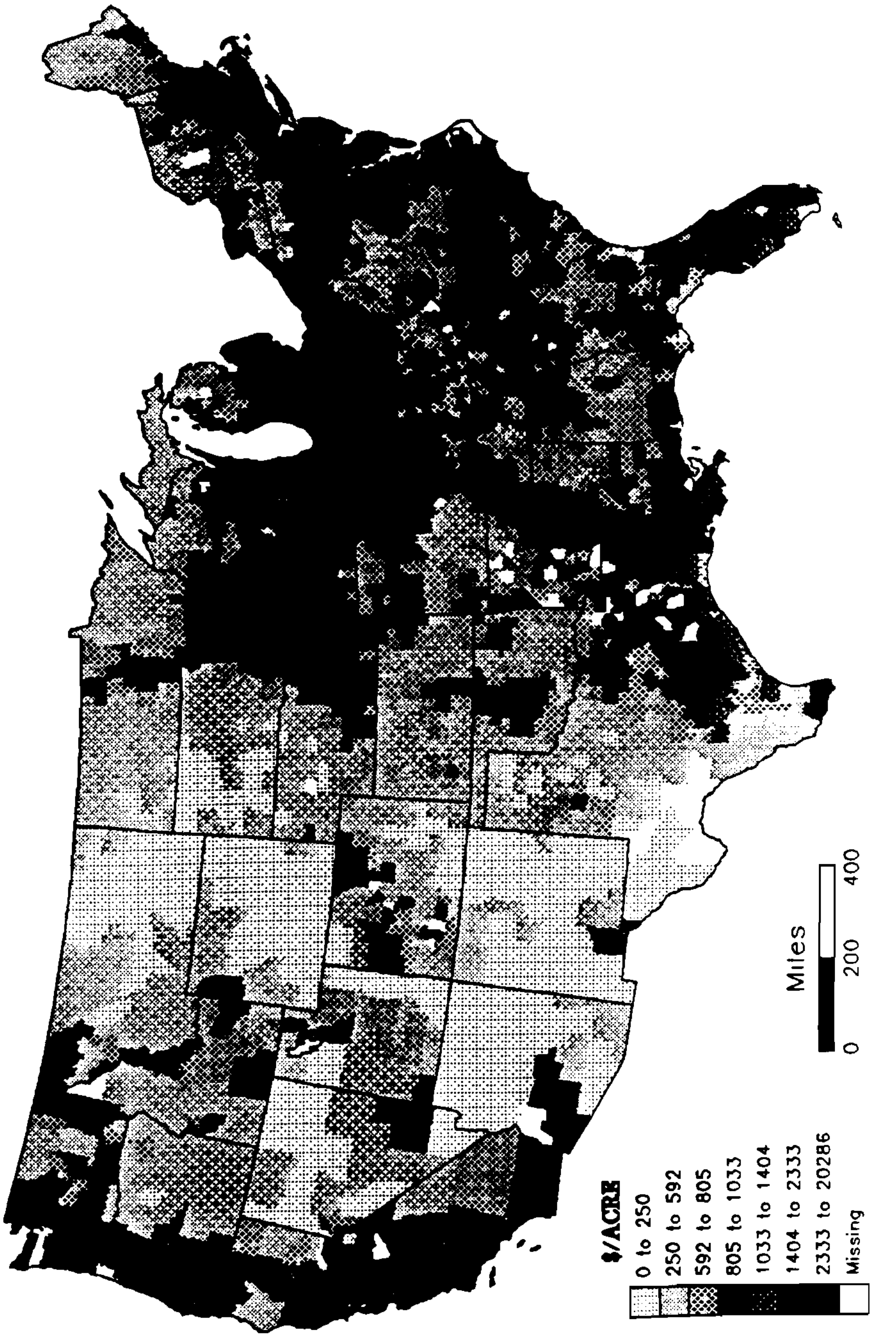

Figure 5. Total farm value in 1982.

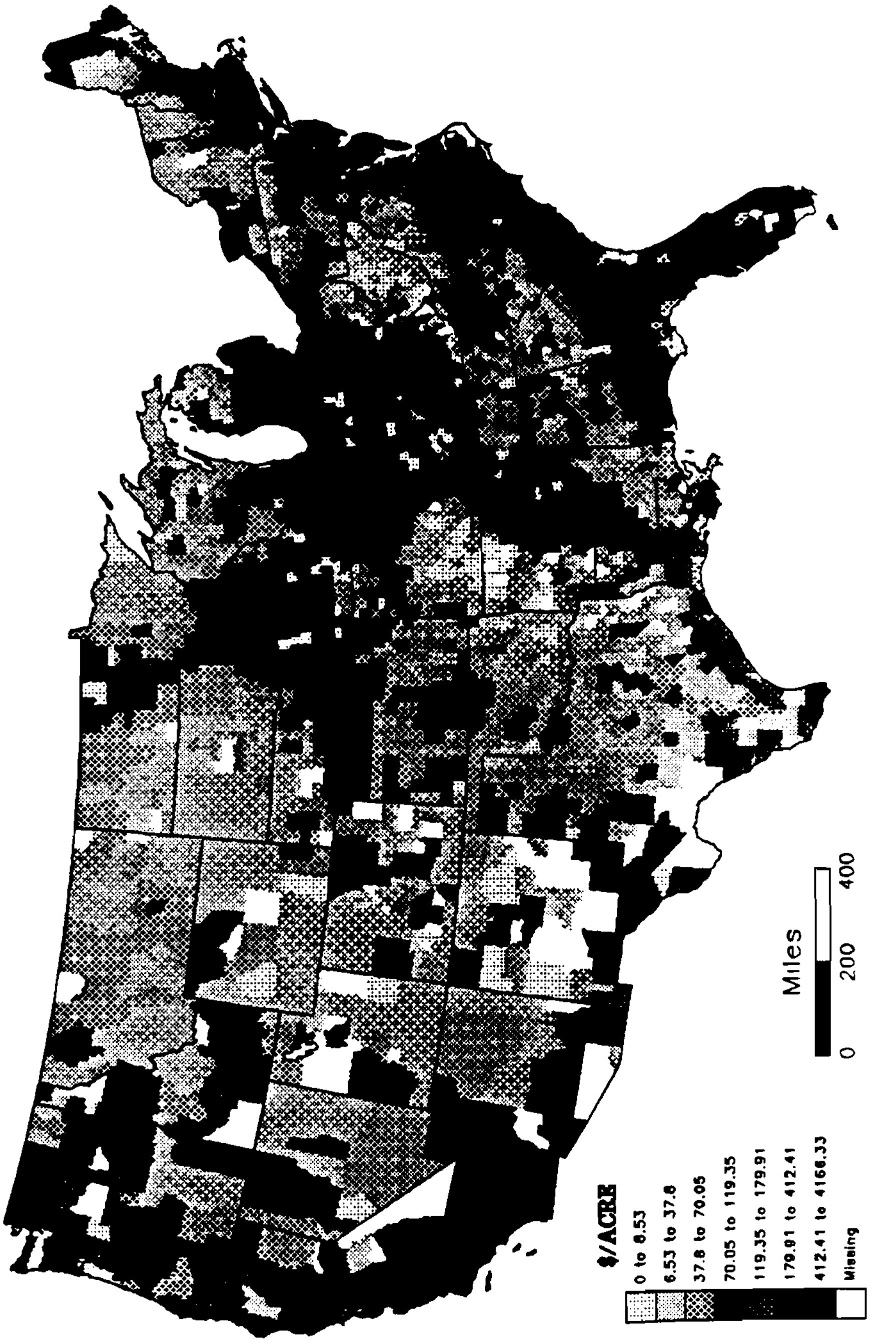

Figure 6. Farm revenue in 1982.

Table 3. Regression models explaining farm values and revenue.

	Farm Value ($/acre)			Farm Revenue ($/acre/year)	
Independent Variables	Quadratic 1982	Full 1982	Full 1978	Full 1982	Full 1978
Constant	-18417	-2604.9	-5358.7	377.2	-1221.2
	(4.98)	(0.79)	(1.26)	(0.46)	(1.30)
January temp	-36.9	-9.93	28.31	-6.19	-9.93
	(4.43)	(1.19)	(2.68)	(3.00)	(4.26)
Jan temp sq	-0.31	-1.20	-2.41	-0.064	0.071
	(1.36)	(5.72)	(9.03)	(1.23)	(1.21)
April temp	662	427.9	661.3	79.30	94.04
	(7.94)	(5.92)	(7.24)	(4.42)	(4.67)
Apr temp sq	-7.31	-3.83	-5.78	-0.86	-1.05
	(9.41)	(5.71)	(6.84)	(5.16)	(5.61)
July temp	393.9	169.4	432.70	-50.36	-16.58
	(3.43)	(1.76)	(3.50)	(2.11)	(0.61)
July temp sq	-3.71	-2.12	-4.36	0.18	-0.03
	(4.91)	(3.33)	(5.35)	(1.14)	(0.15)
October temp	-425.9	-405.82	-827.41	16.92	9.07
	(3.40)	(3.74)	(5.97)	(0.63)	(0.29)
Oct temp sq	6.82	5.02	9.18	0.21	0.28
	(6.28)	(5.30)	(7.61)	(0.90)	(1.05)
January rain	102.7	28.6	15.07	42.31	41.84
	(3.10)	(0.88)	(0.36)	(5.21)	(4.52)
Jan rain sq	-5.68	4.13	3.25	-3.56	-4.20
	(1.86)	(1.44)	(0.87)	(4.98)	(5.12)
April rain	181.6	168.8	146.92	-52.84	-43.01
	(2.44)	(2.59)	(1.77)	(3.26)	(2.35)
Apr rain sq	-10.7	-9.16	6.15	4.42	3.49
	(1.15)	(1.11)	(0.59)	(2.16)	(1.51)
July rain	-167.7	-330.2	-223.62	-46.42	-36.18
	(3.74)	(7.42)	(3.97)	(4.19)	(2.91)
July rain sq	19.5	45.6	34.57	7.39	6.01
	(3.43)	(8.29)	(4.98)	(5.41)	(3.92)
October rain	194.9	-51.1	-176.38	-153.31	-130.48
	(2.25)	(0.64)	(1.72)	(7.75)	(5.77)

Table 3. Continued.

Independent Variables	Farm Value ($/acre) Quadratic 1982	 Full 1982	 Full 1978	Farm Revenue ($/acre/year) Full 1982	 Full 1978
Oct rain sq	-39.6	-1.1	6.70	23.41	22.30
	(2.62)	(0.08)	(0.38)	(6.89)	(5.74)
Income per capita		0.081	0.14	2.21E-3	8.31E-3
		(17.70)	(20.45)	(1.95)	(5.38)
Density		1.22	1.21	0.14	0.156
		(15.89)	(12.30)	(7.42)	(7.19)
Density sq		-1.44E-4	-9.5E-5	1.32E-5	7.49E-6
		(4.36)	(2.34)	(1.60)	(0.84)
Latitude		-58.8	-101.3	-12.82	-9.50
		(3.99)	(5.35)	(3.50)	(2.28)
Altitude		-0.212	-0.277	-0.06	-0.061
		(7.76)	(7.87)	(8.92)	(7.90)
Migration		1.6E-3	...	1.05E-3	...
		(1.81)		(4.75)	
Salinity		-523.9	-482.8	-72.82	-102.64
		(2.55)	(1.84)	(1.43)	(1.77)
Flood prone		-284.2	-568.2	-13.65	0.32
		(5.90)	(9.21)	(1.14)	(0.02)
Irrigated		600.1	478.95	198.98	201.96
		(11.99)	(7.43)	(16.97)	(14.22)
Wetland		-246.2	-249.05	7.24	32.77
		(2.02)	(1.59)	(0.24)	(0.95)
Soil erosion		-797.2	-1293.9	-168.12	-123.75
		(4.24)	(5.38)	(3.60)	(2.33)
Slope length		15.7	26.79	-3.80	-2.69
		(2.64)	(3.47)	(2.56)	(1.59)
Sand		-209.4	-127.22	16.49	27.87
		(4.17)	(1.98)	(1.32)	(1.97)
Clay		114.5	97.87	11.23	8.20
		(5.60)	(3.72)	(2.21)	(1.41)
Adj r^2	0.671	0.782	0.779	0.539	0.504
Observations	2933	2933	2939	2933	2939

Notes: Observations weighted by percentage of county land covered by cropland. Values in parenthesis are t-statistics.

Table 4. Marginal effects of climate on agriculture.

	Farm Value			Farm Revenue	
	Quadratic	Full	Full	Full	Full
Month	1982	1982	1978	1982	1978
	Temperature ($/degree Fahrenheit)				
January	-56.8	-85.50	-123.57	-10.24	-5.44
	(-6.19)	(-9.64)	(-10.88)	(-4.64)	(-2.17)
April	-136.1	9.58	29.88	-14.76	-20.09
	(-10.75)	(0.83)	(2.04)	(-5.11)	(-6.22)
July	-168.2	-151.38	-228.75	-23.05	-20.79
	(-13.12)	(-14.19)	(-16.73)	(-8.69)	(-6.90)
October	350.6	165.42	217.82	41.12	40.77
	(19.32)	(9.46)	(9.68)	(9.46)	(8.22)
Annual	-10.43	-61.87	-104.62	-6.93	-5.56
	(-3.38)	(-2.46)	(-3.25)	(-1.11)	(0.78)
	Precipitation ($/monthly inch)				
January	72.9	50.25	32.11	23.63	19.80
	(3.17)	(2.30)	(1.15)	(4.34)	(3.21)
April	111.3	108.51	187.35	-23.74	-20.04
	(4.06)	(4.62)	(6.23)	(-4.07)	(-3.02)
July	-24.9	4.18	29.71	7.77	7.83
	(-1.81)	(0.32)	(1.76)	(2.37)	(2.11)
October	-2.9	-56.63	-142.92	-36.31	-19.03
	(-0.12)	(-2.54)	(-4.99)	(-6.56)	(-3.01)
Annual	39.10	26.58	26.56	-7.16	-2.86
	(3.42)	(2.58)	(2.01)	(-2.79)	(-0.98)

Notes: Marginal effects are calculated at the U.S. mean climate. The annual effect assumes uniform changes across all four seasons. The t-statistics are in parenthesis.

The marginal effect of changes in climate on agricultural values show the estimated impact on agricultural values of a one-degree or one-inch-per month increase in the climatic normals; those depend upon the season and the evaluating point. The marginal value for each variable evaluated at the national mean is presented in Table 4. For example, the full regression in Table 3 predicts that a one degree increase in monthly January temperature would reduce farm value by $86 per acre but a one degree increase in October temperature would increase farm values by $165 per acre.

In the quadratic model, warmer temperatures reduce farm values in all seasons except autumn. Wetter months increase farm values in winter and spring but not in summer and autumn. Adding the socioeconomic and environmental controls alters the seasonal patterns for farm values described above. Increasing temperatures in April are now beneficial and the benefits of warmer autumns are still present but reduced in half. Overall, annual increases in temperature are more harmful. The effect of precipitation on farm value changes so that summer rains are now unimportant and autumn rains are more harmful. The net effect of including controls is to reduce the benefits of an increase in annual precipitation.

Because marginal effects differ across seasons, overall annual effects will vary depending upon their seasonal distribution. One scenario is for a uniform change across all seasons. In this case, with the quadratic model, a one degree F increase in temperature results in a $10 decrease in farm value per acre. With the full model, a one degree F warming lowers average farm values by $62 per acre. An annual increase of one inch of precipitation spread uniformly across all seasons, according to the quadratic model, would increase property values by $39 per acre. Including control variables changes the net precipitation effect to an increase of only $27 per acre.

Without the full set of control variables, temperature changes have relatively little impact on farm value as compared to precipitation. When the non-farm controls are added, the losses from higher temperatures become from five to seven times as large, whereas the gain from increased precipitation is reduced by almost a third. One interpretation of these results is that the control variables eliminate both the potential for non-farm adaptation and the role of potentially spurious non-farm influences which are spatially correlated with climate. These non-farm influences place a higher value on warmer temperatures (the South) and wetter settings (the Coast), thus lowering the estimated damages from temperature but raising the gains from rains. By controlling these unwanted effects, the full model may more accurately describe the impacts on agriculture; at the same time, the equations without controls may capture non-agricultural adjustments of the kind illustrated in Figure 1.

The control variables in Table 3 provide a rich set of results in and of themselves. It is clear that economic variables play a role in determining both the value of farms and their current annual gross revenues. Farm values are higher in denser, growing, and wealthier counties presumably because of higher local demand for food and the potential for conversion of land to non-farm uses. Farm values also respond as expected to other environmental factors such as solar flux (latitude) and altitude. Salinity, likelihood of flooding, wetlands, and soil erosion all act negatively as expected. Irrigation increases the value of land by a substantial amount according to the model; this is not surprising given the importance of irrigation in many areas in the arid West. Slope length was slightly beneficial to land values but reduced farm revenues; long gradual slopes apparently have mixed effects.

Table 5 shows the estimated best and worst climate parameters according to the full model in Table 3. In these, we simply solve for the extremum of the quadratic function in temperature and precipitation. These results have relatively low reliability because of a variety of specification errors and the potential for dependence of some of the independent variables (such as salinity) on climatic variables. Nevertheless, they provide some interesting information especially concerning January and October. The optimal January temperature is *colder* than the average U.S. temperature by a significant margin, reflecting the value of cold weather in killing pests. Second, January rain is clearly beneficial, perhaps because it contributes to soil moisture without requiring clouds during the growing season. The farm value column of Table 5 also reveals the value of a warm dry October, shown by the optimal precipitation being zero and the minimum temperature being a cool 40 degrees.

One hypothesis suggested in the theory section is that the impacts of environmental effects would be exaggerated by a gross revenue model. We explore this hypothesis in Tables 3 and 4 by regressing the same climate and control variables on crop gross revenue. The marginal effects in Table 3 for the farm revenue model suggest similar seasonal patterns as the farm value equation except that April rain and warmth is clearly bad in the gross revenue equation. The net effect of either an additional degree F or an additional inch of rain using the full model is \$7/year of reduced revenue. Assuming a 5% real interest rate, these annual effects suggest a loss in present value of \$140/acre. In contrast, the property value study suggests only a \$62 loss for warmer temperatures and a \$27 gain for more precipitation.

One concern with the Ricardian approach to climate effects is that the results may not be robust over time but rather the result of a special condition of the year estimated. We consequently estimate the model again using data from 1978. These values have been converted to 1982 dollars using the GNP deflator obtained from the 1991 Economic Report of the President. The 1978 results are surprisingly similar to the findings using the 1982 data. The control variables have similar impacts in both years. The climate coefficients also have similar signs in both 1978 and 1982. Evaluating the marginal effects of climate in 1978 at the national mean and comparing the results with 1982 shows that the climate variables for each season are larger in 1978 than in 1982. For example, October rains are more damaging and other season rains are more beneficial in 1978. These differences cancel out so that the annual marginal precipitation effects are almost identical in 1978 and 1982. The marginal temperature effects in each season are also larger in 1978 than in 1982 but, in this case, annual impacts are also larger in

Table 5. Best and worst climates for agriculture.

	Best or (Worst) Temperature (Fahrenheit)				
	Farm Value		Farm Revenue		Actual
Month	1982	1978	1982	1978	Temperature
January	-4.1	5.86	-48.26	(69.52)	31.5
April	55.8	57.17	46.03	44.98	54.6
July	40.0	49.59	(139.78)	-298.0	75.8
October	(40.4)	(45.05)	(-39.80)	(-16.29)	56.9

	Best or (Worst) Precipitation (inches/month)				
	Farm Value		Farm Revenue		Actual
Month	1982	1978	1982	1978	Precipitation
January	(0)	(0)	5.94	4.98	2.6
April	9.21	(0)	(5.98)	(6.16)	3.3
July	(3.62)	(3.23)	(3.14)	(3.01)	3.7
October	0	(13.17)	(3.27)	(2.92)	2.5

The actual temperature and precipitation measure the U.S. average value. Values in parentheses report worst levels.

1978. The pattern of climate effects on agriculture is stable over time but apparently some factors can alter the magnitude of the effects from year to year.

The predicted overall effects from the existing climate across the United States are shown in Figures 7 through 10. Figures 7 and 8 are probably the most important summary of the results. These maps show the *Ricardian values of climate* by county in 1978 and 1982. To construct each map, we begin with the difference between the estimated climate for each county and the national average climate. We then multiply this climatic difference variable times the estimated coefficients for each climatic variables in Table 2. Figures 7 and 8 then show the estimated contribution of climate to the farm land value in each county. The results are both surprising and interesting.

Beginning with the economic "hot spots," we see that are areas of high value along the northwestern coastal region – basically due to the moist and temperate climates in these regions. In addition, the grain belt west of Chicago shows up as a hot spot of high Ricardian climate values. The other area that stands out is the area of low climatic values along the southwest border regions. (Note that these estimates use the national average irrigation rather than actual irrigation values.) For the most part these have little agriculture, although irrigation raises production and farm revenues considerably as can be seen in Figure 6. Figure 8 represents the identical map as

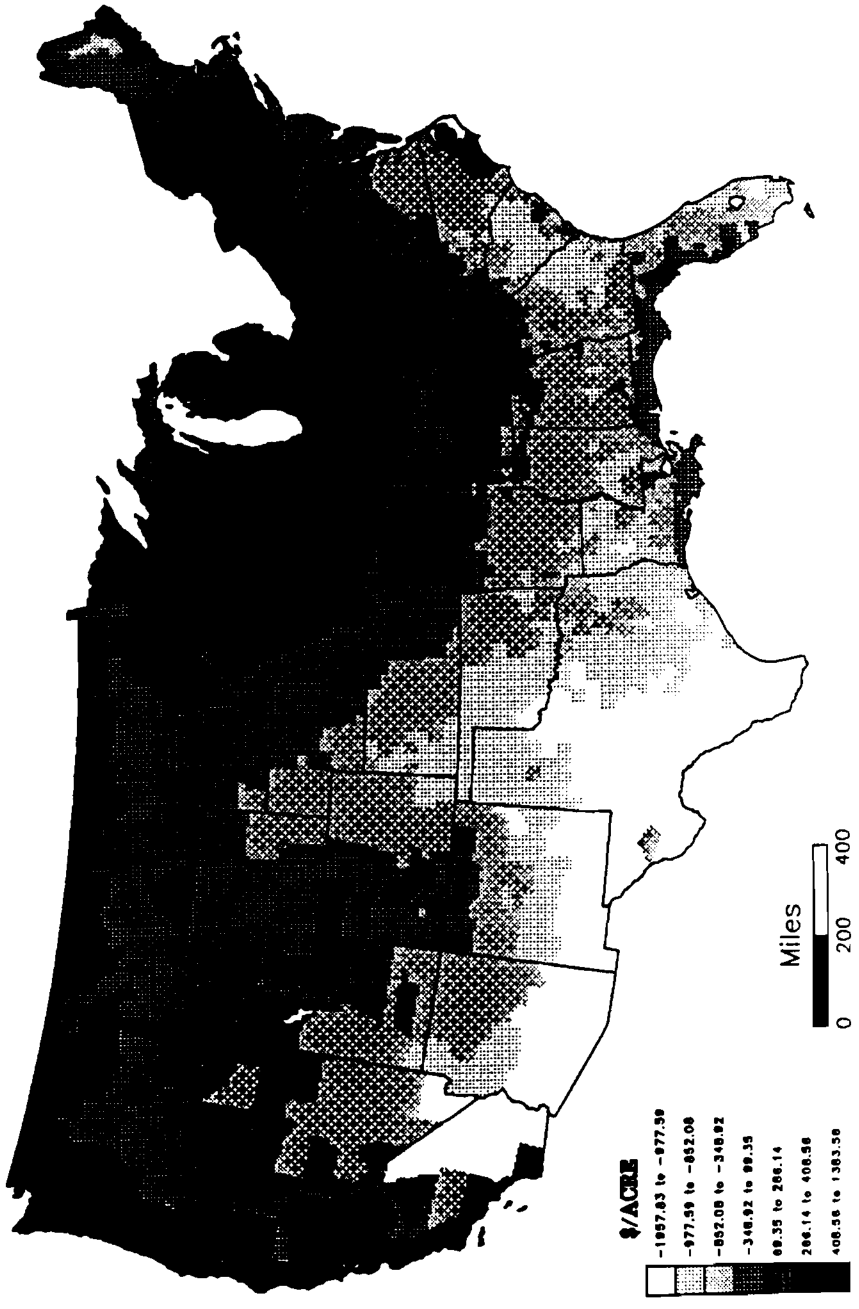

Figure 7. Climatic effects on farm value in 1982.

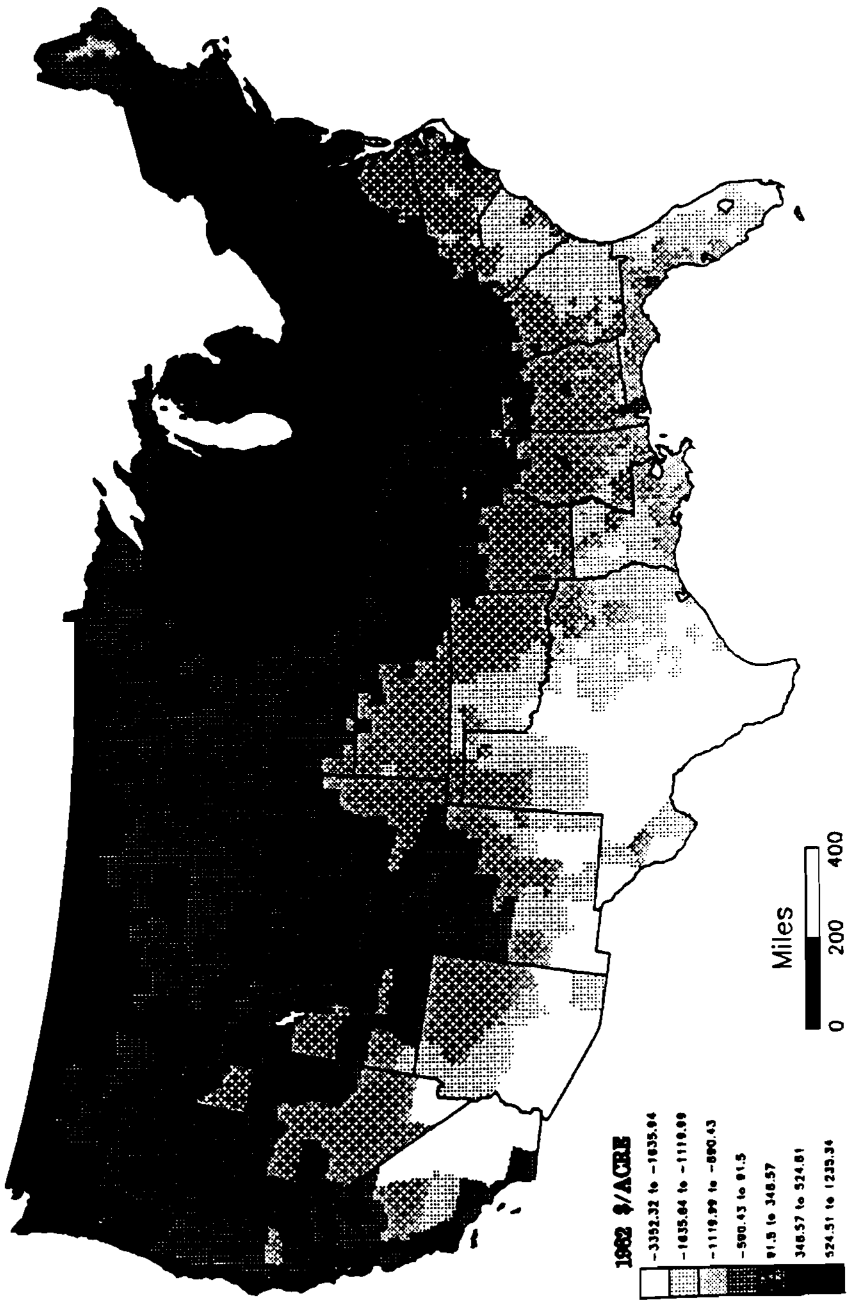

Figure 8. Climatic effects on farm value in 1978.

Figure 7 except that the analysis is based on 1978 data. Both models show almost identical geographic patterns. It would appear from this comparison that the results are quite stable.

Figures 9 and 10 separate out the Ricardian values of precipitation and temperature on farm values for 1982. The precipitation effect is quite revealing. There are significant positive effects of precipitation along the northwest coast and along the Gulf of Mexico coast. Negative effects are found roughly west of the 100th meridian and very strongly in the desert southwest.

The temperature effect is strongly positive in the midwest, with its combination of warm but not hot summers and cold winters. Negative effects of hot temperature are not surprisingly found along the southern border region, particularly in the southwest. Apparently, one must move significantly north into Canada before corresponding negative cold effects can be seen on the map.

4. Conclusion

In this study, we examine the impact of climate on economic activity focusing on the agricultural sector. According to economic theory, the economic value of site-specific characteristics will be reflected in the land rents and will be discounted in land values of the site. We denote the effects on land rents as being Ricardian to capture the mechanism by which land markets capture the economic value of climate and other variables. More generally, in the presence of a competitive land market, differences in rents or land value across space and time can serve as an accurate measure of environmental impacts.

The use of the Ricardian technique allows an entirely different approach to the evaluation of the impact of climate and climate change from conventional techniques. Relying on land rents and values has the important advantage of incorporating the effects of adaptation in the economy – changes in techniques of production or the output mix by firms. By contrast, conventional estimates that rely upon changes in yield or output – an approach we call the "production-function approach" – will tend to overestimate environmental damages.

This new methodology is applied to measure the effect of climate on agriculture. Examining counties across the United States, the effects of temperature, precipitation, and other factors on farm value and farm revenue are estimated. Climate and especially temperature clearly affect agriculture revenues and land values. Warming is generally harmful to farm values

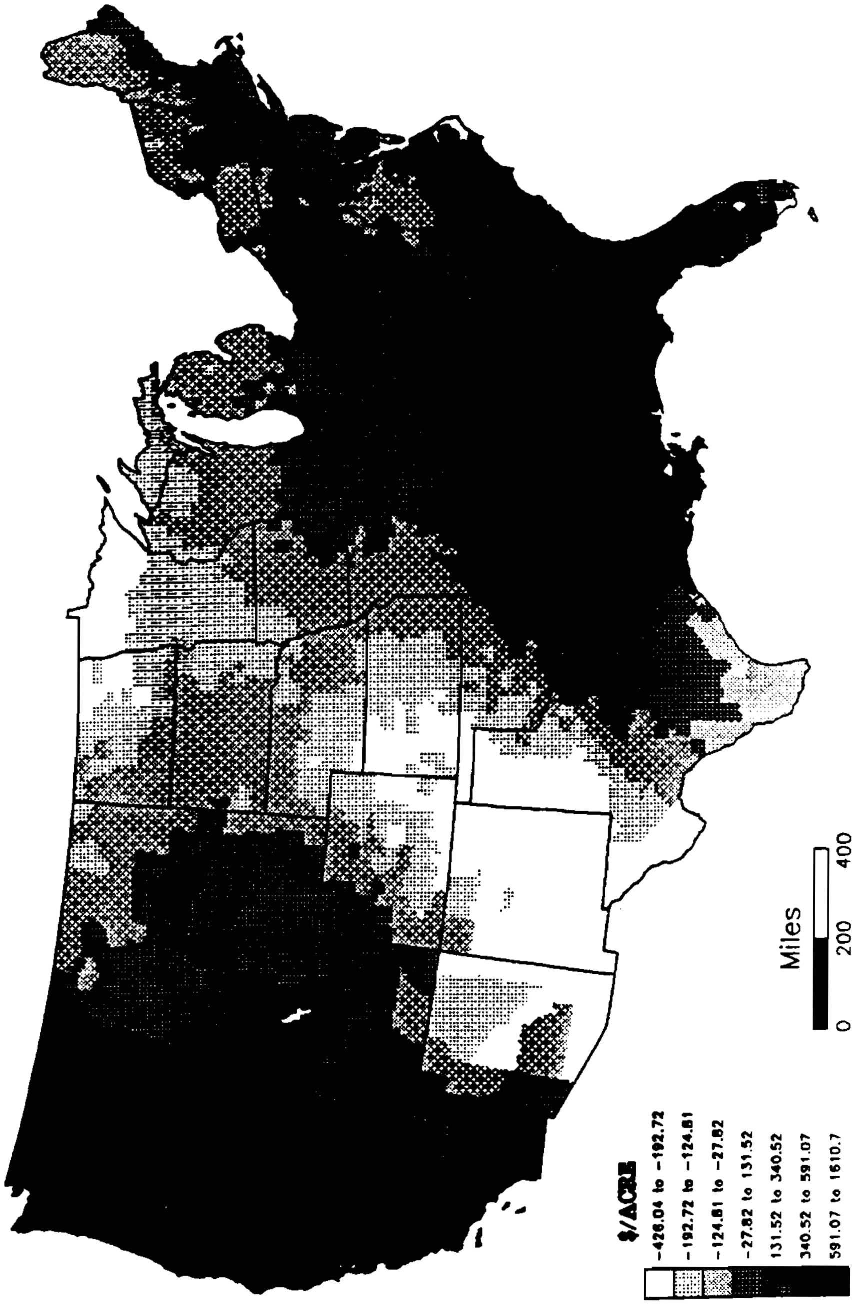

Figure 9. Precipication effects on farm value in 1982.

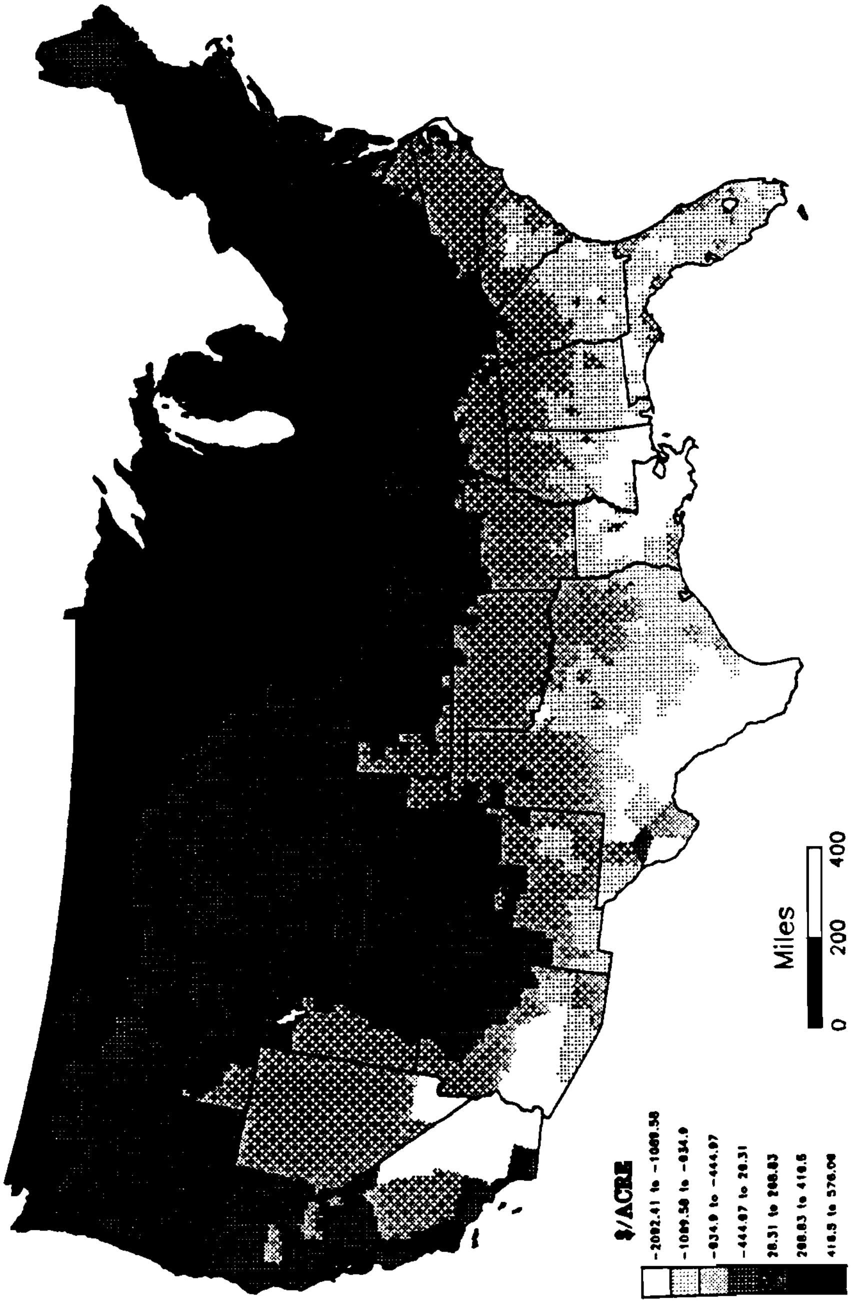

Figure 10. Temperature effects on farm value in 1982.

except in the fall where it helps with drying and harvesting crops. However, this fall effect is quantitatively extremely large, so it may actually offset the damaging effects of warming in other seasons. Additional precipitation is generally beneficial to farms, again except in the fall and possibly in summer where it may be associated with low levels of sunshine. Interestingly, we find that precipitation in winter is just as valuable as the legendary spring rains.

The study is of interest for understanding the impact of climate on agriculture as well as the extent to which different approaches can overstate the impacts of climate change or underestimate the force of adaptation. In addition, the analysis can provide alternative estimates of the impacts of global warming upon American agriculture. The precise impact of global warming on agriculture is a topic that will be pursued in detail in future research.

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Appendix A. Definition of Major Variables Used in this Study

Variable	Definition
Constant	A term equal to one
January temp	Normal daily mean temperature from 1951-1980 in the month of January, Fahrenheit
Jan temp sq	January temp squared
April temp	Normal daily mean temperature from 1951-1980 in the month of April, Fahrenheit
Apr temp sq	April temp squared
July temp	Normal daily mean temperature from 1951-1980 in the month of July, Fahrenheit
July temp sq	July temp squared
October temp	Normal daily mean temperature from 1951-1980 in the month of October, Fahrenheit
Oct temp sq	October temp squared
January rain	Normal precipitation from 1951-1980 in the month of January, inches
Jan rain sq	January rain squared
April rain	Normal precipitation from 1951-1980 in the month of April, inches
Apr rain sq	April rain squared
July rain	Normal precipitation from 1951-1980 in the month of July, inches
July rain sq	July rain squared
October rain	Normal precipitation from 1951-1980 in the month of October, inches
Oct rain sq	October rain squared
Income per capita	Annual personal income per person in the county, 1984
Density	Resident population per square mile, 1980
Density sq	Density squared
Latitude	Latitude measured in degrees from southern most point in U.S.
Altitude	Height from sea level in feet
Migration	Net of incoming people minus outgoing people from 1980 to 1986 for the county
Salinity	Percent of land which needs special treatment because of salt/alkaline in the soils
Flood prone	Percent of land which is prone to flooding
Irrigated	Percent of land where irrigation provides at least 50% of water needs
Wetland	Percent of land considered wetland
Soil erosion	K factor-soil erodibility factor in hundredths of inches
Slope length	Number of feet length of slope (not steepness)
Wind erosion	Measure of wind erosion in hundredths of inches
Farm value	Estimate of the current market value of farm land including buildings for the county expressed in dollars per acre, 1982
Farm revenue	Gross revenue from crops sold in 1982 for the county in dollars per acre

Appendix B. Data on farms and value of land and buildings[5]

The data on farms and on farm land values is central to this study. This appendix describes the definition and sources of the data. The current definition of a farm, first used for the 1974 Census of Agriculture final reports, is any place from which $1,000 or more of agricultural products were sold or normally would have been sold during the census year.

Land in farms is an operating-unit concept and includes land owned and operated as well as land rented from others. The acreage designated as "land in farms" consists primarily of agricultural land used for crops, pasture, or grazing. It also includes woodland and wasteland not actually under cultivation or used for pasture or grazing, provided it was part of the farm operator's total operation.

The land is defined to lie in the operator's principal county, that is, the county where the largest value of agricultural products was raised or produced. Irrigated land includes land watered by any artificial or controlled means, such as sprinklers, furrows or ditches, and spreader dikes. Cropland includes land from which crops were harvested or hay was cut, land in orchards, citrus groves, vineyards, nurseries, and greenhouses, land used only for pasture or grazing that could have been used for crops without additional improvement, and all land planted in crops that were grazed before the crops reached maturity. Also included were all cropland used for rotation pasture and land in government diversion programs that were pastured.

Respondents were asked to report their estimate of the current market value of land and buildings owned, rented, or leased from others, and rented or leased to others. Market value refers to the respondent's estimate of what the land and buildings would sell for under current market conditions. If the value of land and buildings was not reported, it was estimated during processing by using the average value of land and buildings from a similar farm in the same geographic area.

The value of products sold by farms represents the gross market value before taxes and production expenses of all agricultural products sold or removed from the place regardless of who received the payment. In addition, it includes the loan value received in 1982 for placing commodities in the Commodity Credit Corporation loan program.

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[5] This description is drawn from the *City and County Data Book*, and the underlying data is from U.S. Bureau of the Census, *1982 Census of Agriculture*.

The Implications of Non-linearities in Global Warming Damage Costs

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The possibility of global warming due to greenhouse gas emissions presents a difficult policy problem because of the tremendous uncertainties involved. Both the costs and benefits of controlling greenhouse gases are uncertain.

A model called Carbon Emissions Trajectory Assessment (CETA) has been constructed by Thomas Teisberg and Stephen Peck (Peck and Teisberg, 1992). CETA is a world growth model representing energy technologies and resources, the conversion of capital, labor and energy inputs into output, the emissions and accumulation of greenhouse gases (particularly carbon dioxide), the increase in global temperature and the consequent warming damage and, finally, the optimal split of output (after subtracting energy and warming damage costs) into consumption and investment.

The base case of CETA shows worldwide emissions of CO_2 (measured as carbon) rising relatively slowly from today's level of 6 billion tons per year to 12 billion tons annually in 2030, then declining somewhat as the oil and gas resource base is exhausted and as non-carbon based fuels replace carbon-based fuels in the electric sector. Between 2040 and 2100, carbon dioxide emissions accelerate as carbon intensive synthetic fuels replace oil and gas use in the non-electric sector. In 2100 carbon dioxide emissions are projected to be about 45 billion tons (as carbon) annually. Finally, emissions begin to decline after 2100 when the coal resource base starts to be exhausted. Extensive sensitivity testing has shown that optimal emissions of carbon dioxide are remarkably insensitive to changes in most parameter values up to 2030, but quite sensitive to a subset of parameter variations in 2100 and beyond.

One key uncertainty on the benefits side of CETA is the relationship between climate change and resulting damages (i.e., costs of impacts and of adaptations undertaken to reduce impacts). In particular we have found (Peck and Teisberg, 1993) that the optimal emissions policy is much more sensitive to the degree of non-linearity in damages than it is to the level of damages (at a specified temperature increase). We interpret the non-linearity of the damage function to be related to the notion of a threshold for damages.

We have made some simple value of information calculations designed to measure the benefits of accelerating the resolution of uncertainty by one hundred years. Given the sensitivity results reported above, it is not surprising that we found that the value of information about damage function non-linearity is about five times larger than the value of information about the damage function level.

Finally, we have explored the implications of damage function non-linearity for the value of information about a key climate response parameter – the equilibrium temperature increase per CO_2 doubling or "warming rate". We valued information about the warming rate for three alternative maintained assumptions about the warming damage function – that it is linear, quadratic, or cubic. We found that the value of information about warming rate is much higher if the damage function exhibits highly non-linear response to temperature change. Specifically, the value of information is about two orders of magnitude greater if the damage function is cubic than if it is linear. Thus the value of resolving other global warming uncertainties was shown to be importantly affected by the degree of non-linearity in the damage function.

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Part 3

Costs: Global Estimates

What Do Global Models Tell Us About the Carbon Taxes Required and the Economic Costs Entailed in Reducing CO_2 Emissions?

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1. Introduction

Ever since global warming came to the top of international agenda a few years ago, scientists have been intensively engaged in trying to establish the facts of climate change while economists have been trying to establish values for the damages that might be entailed and the costs for slowing climate change. The emphasis of the economic work has tended to be more on costs than on benefits (the damage avoided), perhaps because the costs of policies to slow climate change have always looked easier to gauge than the very uncertain costs to economic activity of changes in climate. In reality, both sides of the account are subject to enormous margins of uncertainty, as the scientists make clear, but the economist typically takes short cuts in moving toward quantification. Typically, the economist will not be concerned with scientific uncertainties but will start his research with assumptions or model estimates of future greenhouse gas emissions and then set out his calculations on the basis of some notional reduction in emissions. There may be uncertainties concerning the carbon taxes required to achieve these reductions, but these are easily identified in a modeling environment and can be examined by using sensitivity analysis. In general, the scientific uncertainties are ignored and the focus is put on modeling uncertainties.

Differences between models arise from many different sources – model structures, calibration (parameter estimates), time horizons, degree of sectoral disaggregation, key baseline assumptions, and types of reduction scenarios. Because of these differences, it was usually not possible to compare like with like across the different studies. Following some initial survey work

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[1] The views expressed are those of the author and should not be attributed to the OECD. The author is grateful to Peter Hoeller, Jackie Gardel and other colleagues at OECD for their help in preparing this paper. Fuller detail on the results of the OECD model comparisons project are referenced in Dean and Hoeller (1992); OECD (1993).

of the different estimates where such problems were immediately apparent,[2] two different projects were launched to get some standardization of assumptions and the type of reduction scenario in order to be able to make better comparisons of results. The first project was organized by the Energy Modelling Forum (EMF12) of Stanford University.[3] They specified assumptions on growth rates, population, the resource base and oil prices. These assumptions were also used in the second project that was organized by the Economics Department at the OECD and reported here. The OECD project proceeded in close cooperation with the more comprehensive EMF12 exercise. While EMF12 included many U.S. national models and much energy detail, the OECD work focused more on global models and macroeconomic costs. The remainder of this paper reviews these global models and its results.[4]

2. An Overview of the Participating Models

The major features of the six global models participating in the OECD project are given in Table 1. The differences in model type heavily influence the sort of comparisons that can be considered here and, in spite of the standardization of baseline inputs and scenario design, limit the degree to which results are comparable. The various dimensions in which the comparisons are constrained is explored below by referring to some of the salient features of the models.

Model type. There is one comparative-static general equilibrium model, the Whalley-Wigle model (WW) which is used to generate results for the period 1990–2100. It is in the nature of such models that they cannot give dynamic paths so that the results cannot therefore be presented alongside

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[2] Hoeller *et al.* (1991) which was first circulated in mid-1990, covered a wide range of both global and national models, comparing emission paths, taxes and costs. Since then, Barrett (1991), Boero *et al.* (1991), Cline (1991) and Nordhaus (1991) have provided surveys of the cost of reducing emissions. All these surveys are excellent overview papers which try to cover different topics: the paper by Cline (1991) explains five global models and results in detail; Boero *et al.* (1991) focus on differences in model outcomes and their causes; Barrett (1991) discusses the issues surrounding the potential use of economic instruments to respond to global warming; and Nordhaus (1991) reviews cost estimates for reducing CO_2 and CFC emissions as well as the cost of reforestation.

[3] See Energy Modelling Forum (1993) and also the paper by John Weyant presented at this meeting.

[4] More detail is given in Dean and Hoeller (1992), while the full set of project papers can be found in OECD (1993).

Table 1. Summary of participating models[a].

	Model type	Time horizon	Regions	Fuel sources	Comment
Rutherford (CRTM)	recursive dynamic general equilibrium model, calibrated on Global 2100	2100	five	seven including backstop technologies	focus on impact of restrictions on international trade; tradable permits
Edmonds-Reilly (ERM)	partial equilibrium model with detailed dynamic energy model	2095	nine	six primary and four secondary fuels	energy traded; includes other greenhouse gases; energy-economy links simple
GREEN	recursive dynamic general equilibrium model	2050	twelve	three primary and two secondary fuels plus three backstop technologies	full trade links plus tradable permits; oil price endogeneous
IEA	econometrically-estimated detailed energy model	2005	ten	five with many product breakdowns	much energy detail for OECD regions; no feedback from the energy sector to the rest of the economy
Manne-Richels (Global 2100) (MR)	dynamic intertemporal optimizing model with detailed energy model	2100	five	nine including backstop technologies	forward-looking intertemporal model; only oil trade is modeled; tradable permits
Whalley-Wigle (WW)	comparative static general equilibrium model	1990–2100	six	two	trade links; focus on international incidence of carbon taxes

[a] The table describes versions of the models as used for this project. A description of the models and their results is provided in the Working Papers written specifically for this project; see Barns *et al.* (1992), Manne (1992), Oliveira Martins *et al.* (1992), Rutherford (1992), Vouyoukas (1992), and Whalley and Wigle (1992).

the time-paths of the results for the five other models. The IEA model is an econometrically-estimated partial equilibrium model of the energy sector but it takes no account of economic feedbacks from the energy sectors to the aggregate economy; results can therefore only be given for carbon taxes and not for GDP effects. The remaining four models – Edmonds-Reilly (ERM), Global 2100 by Manne-Richels (MR), the Carbon Rights Trade Model by Rutherford (CRTM) and the OECD model (GREEN) – are all dynamic models of a partial or general equilibrium type with differing degrees of sectoral and energy detail.

Time horizon. Four of the models have a long-term horizon that extends to the end of the next century – CRTM, ERM, MR and WW – although results for the latter for the period 1990–2100 are given as 1990 discounted present values. The other models have shorter time horizons – 2050 for GREEN and 2005 for the IEA.

Regions. The regional breakdown of the different models does not always correspond to the breakdown specified for the project. The breakdown requested – United States, other OECD, China, the former Soviet Union and the Rest of the World (RoW) – is based on MR and is thus also available for CRTM. GREEN can also comply with the five-way breakdown. Regional comparisons are less valid for ERM and the IEA (which is also incomplete, excluding the non-OECD) and most problematic (in the context of this exercise) for WW.

Fuel sources. The GREEN and WW models have less energy detail than the other four models. However, WW is the most rudimentary, having only a composite fossil fuel and one non-fossil fuel. This means that inter-fossil fuel substitution – which is important in most models until well into the next century – is not feasible in WW, an important factor to bear in mind when considering the costs of reducing CO_2 emissions. For the other models, the substitution between fuels with different carbon intensities is an important part of both baseline emission paths and reduction scenarios.

Backstop technologies. There are no backstop technologies in WW and ERM, an omission which is critical to the results since there is no effective ceiling to the carbon tax. The IEA model also has much technological detail, but backstops are much less important over the short time horizon up to 2005. In contrast, MR, CRTM and GREEN have backstop technologies which limit the carbon tax and hence the cost of emission reductions.

Data sources. In addition to the above "structural" differences in the six models, there are also significant variations in base-year data. These arise from differences in data requirements for the different models, definitional differences, different starting points (involving different exchange rates, base-year prices and so on) and a significant amount of estimation to get a coherent 1990 starting point. The most important difference, because it influences the business-as-usual (BaU) emissions and the reduction scenario results, is the difference in baseline energy prices. Since substitution among fuels is largely price-induced, differences in relative energy prices can lead to considerable differences in fuel composition, and hence emissions, in the BaU scenario. In the reduction scenarios, with carbon taxes being based on absolute amounts of dollars per unit of carbon embodied in different fuels, the relative energy price differences both within and across the models are even more important in leading to differences in results. Baseline price differences are especially important for China and the former Soviet Union since the very large energy subsidies in these regions are not taken into account in all of the models.

3. The Specification of the OECD Model Comparisons Project

Standardization across models was carried out in two key ways; (i) specifying a few key economic assumptions for the baseline or BaU scenario of unconstrained CO_2 emissions growth, and (ii) specifying a set of common simulations for reducing CO_2 emissions.

Business-as-usual (BaU) emissions; key assumptions

Modelers were asked to assume the growth paths for real GDP and population agreed for the parallel project of the Energy Modelling Forum at Stanford University as well as a common resource base and oil price assumption. The key assumptions are:

(i) *population* rises from 5.3 billion in 1990 to 9.5 billion in 2050 and to 10.4 billion by 2100, by which time it is hardly growing at all (World Bank projections); nearly all of the growth is in China and other developing countries;

(ii) *output growth* slows down throughout the next century – from 2.5 percent per annum in the 1990s in OECD countries to only one percent by 2100, and from 4 percent to less than 3 percent in developing countries;

(iii) *oil prices* are set exogenously at \$26 per barrel in 1990 rising by \$6 per decade in real terms to reach \$50 in 2030, being unchanged thereafter.

Reduction scenarios

Three of the scenarios are specified in terms of reductions (from the BaU emission path) in the growth rate of emissions for each region – by 1, 2 and 3 percentage points per annum, respectively. In this way, the amount of the reduction, in percentage terms, will be similar across models, although the starting points (baseline) and destination will vary. Using this method implies that most of the differences between models can be ascribed to model structures rather than being a hybrid, representing both different model structures and different degrees of reduction – as in target level exercises. The fourth scenario is a stabilization of emissions at 1990 levels in each region. This would be most stringent for those regions, such as China and RoW, where BaU emission growth is most rapid, and least stringent for the OECD.

The emission reduction scenarios are applied to all regions, even though the baseline emission growth varies significantly. These reductions are in no way a recommendation or proposal. Uniform reductions in all regions have been suggested for purely expositional reasons and considerations of equity, and political feasibility have been ignored. Clearly, the 3 percent scenario would be regarded as extreme, although it is relatively close to the IPCC scenario for stabilizing concentrations by the middle of the next century. The one percent scenario would represent an approximate stabilization of OECD emissions and perhaps those in the former Soviet Union too – although this varies across the different baselines – while still permitting a relatively rapid growth of emissions elsewhere. The 2 percent scenario, on the other hand, would require absolute cuts in emissions in the OECD and the former Soviet Union and allow some continued, albeit very low growth elsewhere. The policy instrument used to achieve these emission curbs is a carbon tax, i.e., a tax levied on the carbon content of primary energy sources.

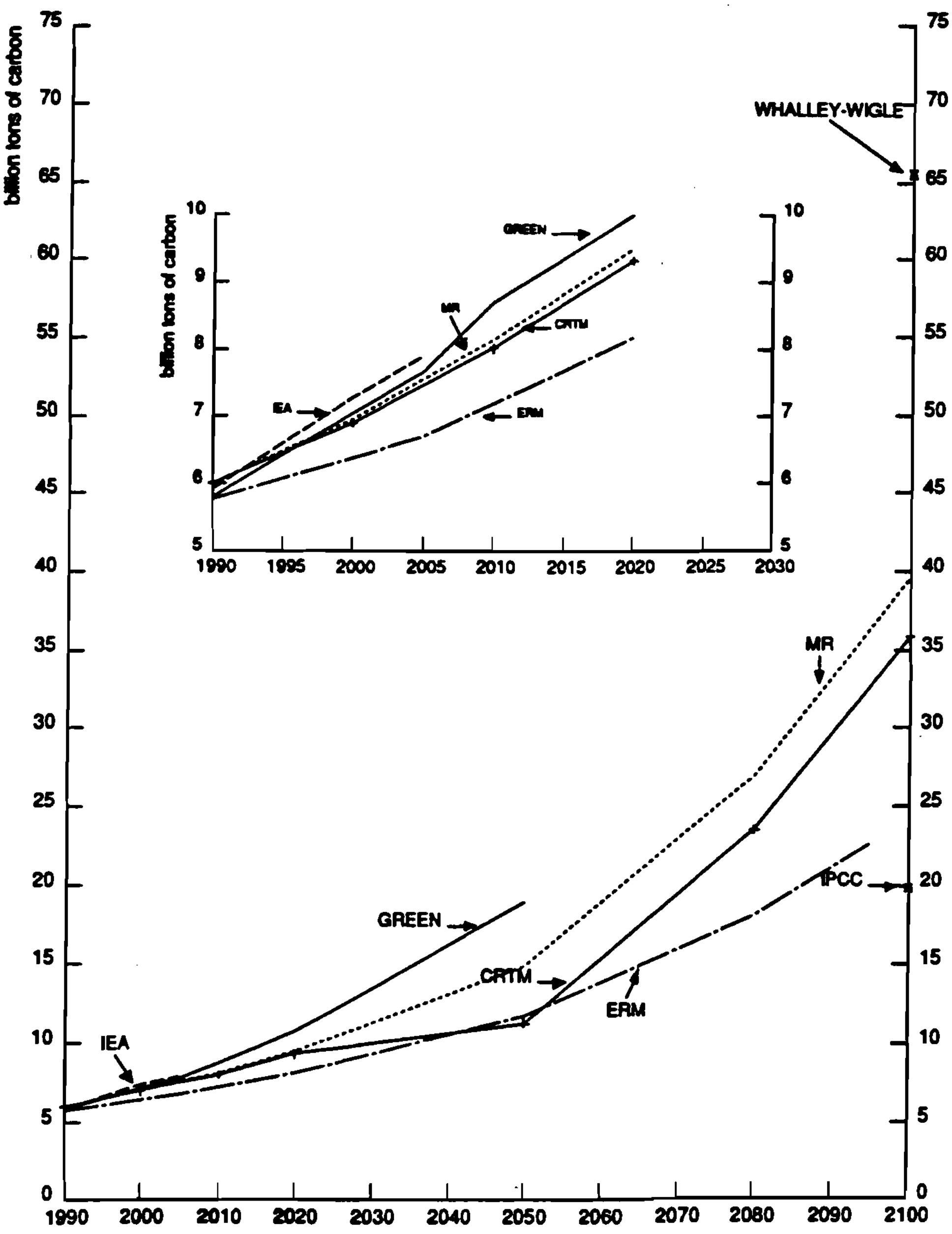
4. "Business-as-Usual" Emission Paths

Even with a standardization of assumptions on growth, population and resources, the BaU emission paths vary greatly across the models. World emissions grow more rapidly over the short to medium-term in GREEN and IEA than in the other models (Figure 1 and Table 2). ERM shows the slowest emission growth. The emissions in GREEN are growing by up to one-half percent per annum faster than in ERM, despite the assumption of the same autonomous energy efficiency improvement of one percent per annum. Hence, a gap of over 1.5 billion tons of carbon opens up by 2020 between the top and bottom of the range of models, the 10.8 billion tons of GREEN and the 8.2 billion tons of ERM (Table 2).

The divergent emission paths for the earlier period open up much farther in later years, so that world emission projections for the year 2100 are almost a magnitude of two different (Figure 1). Of course what may look to be relatively small differences in annual growth rates of CO_2 emissions compound over a century into significant differences in terms of levels (Table 2). The average growth rate of emissions over the entire period of 1990–2100 is 1.3 percent in ERM, 1.6 percent in CRTM and 1.7 percent in MR. But the spread between the lowest and highest emissions in 2100 – 22.5 billion tons of carbon in ERM and 39.5 billion tons in MR – is quite startling. WW has a point estimate for 2100 of 65.5 billion tons (and an average growth throughout the period of 2.3 percent), but this seems to reflect both an extremely pessimistic assessment of no autonomous energy efficiency improvements and the lack of substitution possibilities imposed by the two-fuel structure of the model. All of the model estimates are nevertheless above the new IPCC reference case (in the 1992 IPCC Supplement work) of 19.8 billion tons of carbon in 2100. However, five other scenarios are now given by the IPCC, ranging from 4.6 billion tons (a low population, lower growth, and low oil and gas availability scenario) to 34.9 billion tons (with more rapid improvement of GNP per capita, a nuclear phase-out and plentiful fossil resources).

The importance of the autonomous energy efficiency parameter (AEEI) in contributing to the large differences in emissions has been revealed by some sensitivity testing (as shown in Table 2). In an alternative BaU scenario, using ERM but reducing AEEI from one percent per annum to one-half per cent in all regions (roughly the MR assumption), world emissions rise from the previous 22.5 billion tons to around 42 billion tons by the end of the next century, much in line with the MR results (although there are some offsetting factors that lie behind these rather close results). A similar exercise with MR, this time increasing its AEEI to one percent per annum in all regions, leads to emissions in 2100 of 26 billion tons, much closer to the standard ERM result of 22.5 billion tons.

The wide range of estimates for BaU emissions through the end of the next century contrasts rather starkly with the precise numbers set out in the 1990 report by the Intergovernmental Panel on Climate Change (IPCC). However, the IPCC now presents a variety of scenarios with a very wide range of 2100 emissions (IPCC 1992 Supplement). Clearly, a high degree of



IPCC = the new (1992) IPCC reference case.

Figure 1. Worldwide BaU CO_2 emissions.

Table 2. World BaU CO_2 emissions.

	CRTM	ERM(1)	*ERM(2)*	GREEN(1)	*GREEN(2)*	IEA[a]	MR(1)	*MR(2)*	WW
1990	6.003	5.767	*5.767*	5.815	*5.815*	5.919	6.003	*6.003*	[av. 1990 to 2100 is 25.2]
2000	6.931	...	...	7.071	*7.418*	7.316	6.970	*6.748*	
2005	...	6.709	*7.856*	7.704	*8.250*	7.932	...	...	
2010	8.031	...	...	8.705	*9.452*	...	8.153	*7.581*	
2020	9.327	8.180	*10.505*	10.806	*11.938*	...	9.520	*8.681*	
2050	11.337	11.838	*17.606*	18.998	*21.769*	...	14.992	*11.356*	
2080	23.519	18.099	*32.185*	...	...	...	26.945	*18.701*	
2100	35.863	22.579[b]	*41.594*[b]	...	...	...	39.636	*26.039*	65.5

[a] The IEA model projections in this table have been adjusted to exclude non-fossil solid fuels, bunkers, non-energy use of fossil fuels and petrochemical feedstocks. These categories, included in the standard IEA model output, have not been excluded from the tables in the Appendix or from the results reported in the IEA paper and add around 900 million tons to the 1990 global figure of carbon emissions.

[b] 2095.

Note: In the three cases (ERM, MR, GREEN) where two emission paths are indicated, the first column denotes the standard model and the italicized second column shows the sensitivity to a different assumption on the autonomous energy efficiency improvement (AEEI). ERM(1), GREEN(1) and MR(2) have an AEEI of 1 percent per annum while ERM(2), GREEN(2) and MR(1) have an AEEI of one-half percent per annum.

CRTM = Carbon Rights Trade Model (see Rutherford, 1992).
ERM = Edmonds-Reilly Model (see Barns *et al.*, 1992).
GREEN = OECD Model (see Oliveira Martins *et al.*, 1992).
IEA = International Energy Agency Model (see Vouyoukas, 1992).
MR = Manne-Richels Global 2100 Model (see Manne, 1992).
WW = Whalley-Wigle Model (see Whalley and Wigle, 1992).

uncertainty attaches to all of these numbers and this of course complicates the task of looking at the cost of reaching specific targets set in terms of CO_2 emission levels. This is one reason why the current comparisons project has been focused mostly on reductions in the growth rates of emissions rather than on target levels.

5. Analysis of the Reduction Scenarios

What are the carbon taxes required?

The carbon taxes required to reduce world CO_2 emissions to certain levels in terms of billions of tons of carbon are set out in Figure 2 in a series of marginal tax curves for the years 2000, 2020, 2050 and 2100. Each curve plots out for each model the results of cutting the growth rate of CO_2 emissions in each region by 1, 2 and 3 percentage points plus the scenario for stabilization of emissions at 1990 levels (about 6 billion tons). These global tax curves are an emission-weighted average of regional tax curves. Note that the BaU starting points, i.e., the emissions at a zero carbon tax (along the horizontal axis), vary significantly by the later periods, as discussed in the previous section. The main conclusions stemming from the tax curves shown in Figure 2 are the following:

- The curvature indicates the need for increasing marginal tax increments per unit of reduction in carbon emitted. There are diminishing marginal returns to the tax as cheaper options to reduce emissions are taken first, but it becomes increasingly more difficult to substitute for or economize on fossil fuels. Furthermore, squeezing out the very last units of carbon would entail very high carbon taxes, the world average tax being more than $500 per ton (equivalent to $60 on a barrel of oil) in both 2050 and 2100.
- In the earlier periods (2000 and 2020) the model results for the world tax curves line up reasonably together, but this is no longer the case (noting also the change in scales in Figure 2) once deep cuts are being made in the later years (2050 and 2100). This is because there are no backstop technologies (unlimited supplies of new, but more expensive, carbon-free fuels) in ERM so that there is no limit to the rise in the tax. Hence, already by 2050, ERM has taxes which rise beyond $1,000 a ton, and these taxes rise to above $2,000 a ton by 2100. The backstops act

to limit the rise in the required tax in CRTM, MR and GREEN because switching to new technologies is induced by higher carbon taxes.[5]

What are the costs involved?

The average economic costs for reducing emissions are closely related to the level of carbon taxes required to ensure the reductions, although there is no simple one-to-one link as many factors come into play. The best cost measure to focus on would be some measure of economic welfare,[6] such as the Hicksian equivalent variation[7] that is computed by GREEN and WW. This is not, however, available for any other models which give results only for production-side measures such as GDP. Although GDP is a familiar measure of output, it is only a partial indicator of welfare, failing to take into account, *inter alia*, changes in the terms of trade (which can be especially important for oil-producing countries) and the consumption losses due to the tax. The GDP losses across models are shown in a series of abatement cost curves in Figure 3, with world losses being plotted against reductions in terms of billions of tons of carbon for four snapshot years, in the same way as with the corresponding tax curves in Figure 2.

The initial GDP costs in 2000 lie between one and 3 percent of GDP in the case of the fastest cut in emissions (3 percentage points per annum) while the costs in the 2 percent case are perhaps half or less. This reflects the upward curvature of the tax curves, indicating again that the speed of adjustment is itself important. By 2020 the range of GDP losses for the largest cuts (3 percent reduction case) is from 3 to 6 per cent of GDP and by 2100 the range is 4 to 8 percent. The greatest loss is shown by ERM,

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[5] In CRTM and MR, backstop technologies restrict the tax to just over $200 per ton in all regions except for the former Soviet Union, the latter exception means that the average world tax in these models is still rising steeply in 2100 for continuing emission cuts. In GREEN, the tax level at which the switch to backstop technologies occurs depends on the initial starting point for the prices of different fuels. This is particularly important for the non-OECD regions because initial energy prices are often far below world prices, so that much higher taxes than in the OECD regions are needed before the backstop technologies become competitive.

[6] In the context of this modeling project, which focuses on the costs of policies to slow climate change and ignores the benefits (the damage avoided), the welfare being measured refers only to the cost side; if, in addition, one took into account the benefits, then one would have an overall measure of the welfare effects of policy change and could then judge the optimal level of abatement.

[7] The Hicksian equivalent variation is the increase in income that a consumer would need before the imposition of a carbon tax to allow him to reach the welfare level actually attained after the change in policy.

Note: The scales on the different panels are not standardised.

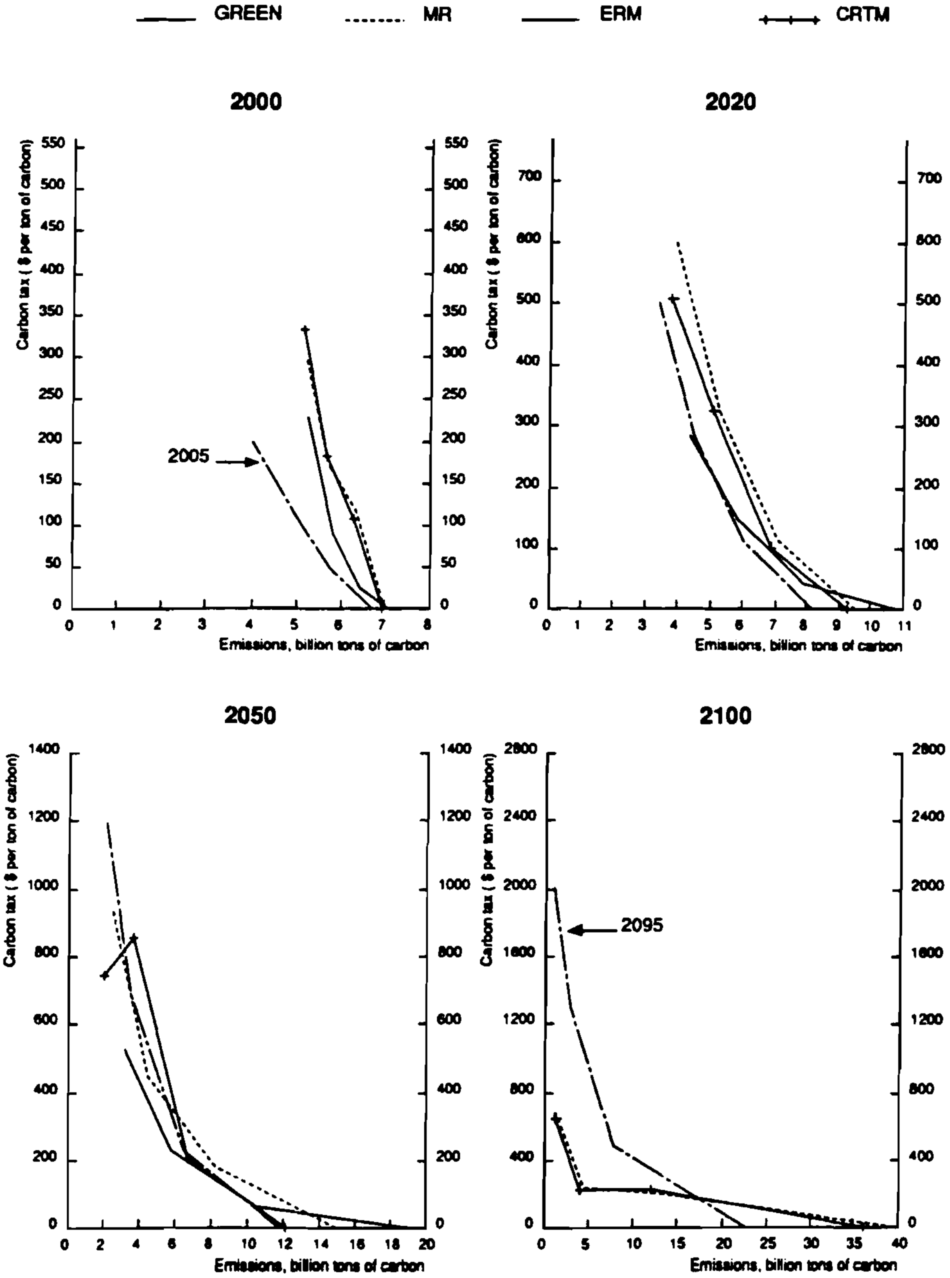


Figure 2. World emissions and carbon taxes.

Note: The scales on the different panels are not standardised.

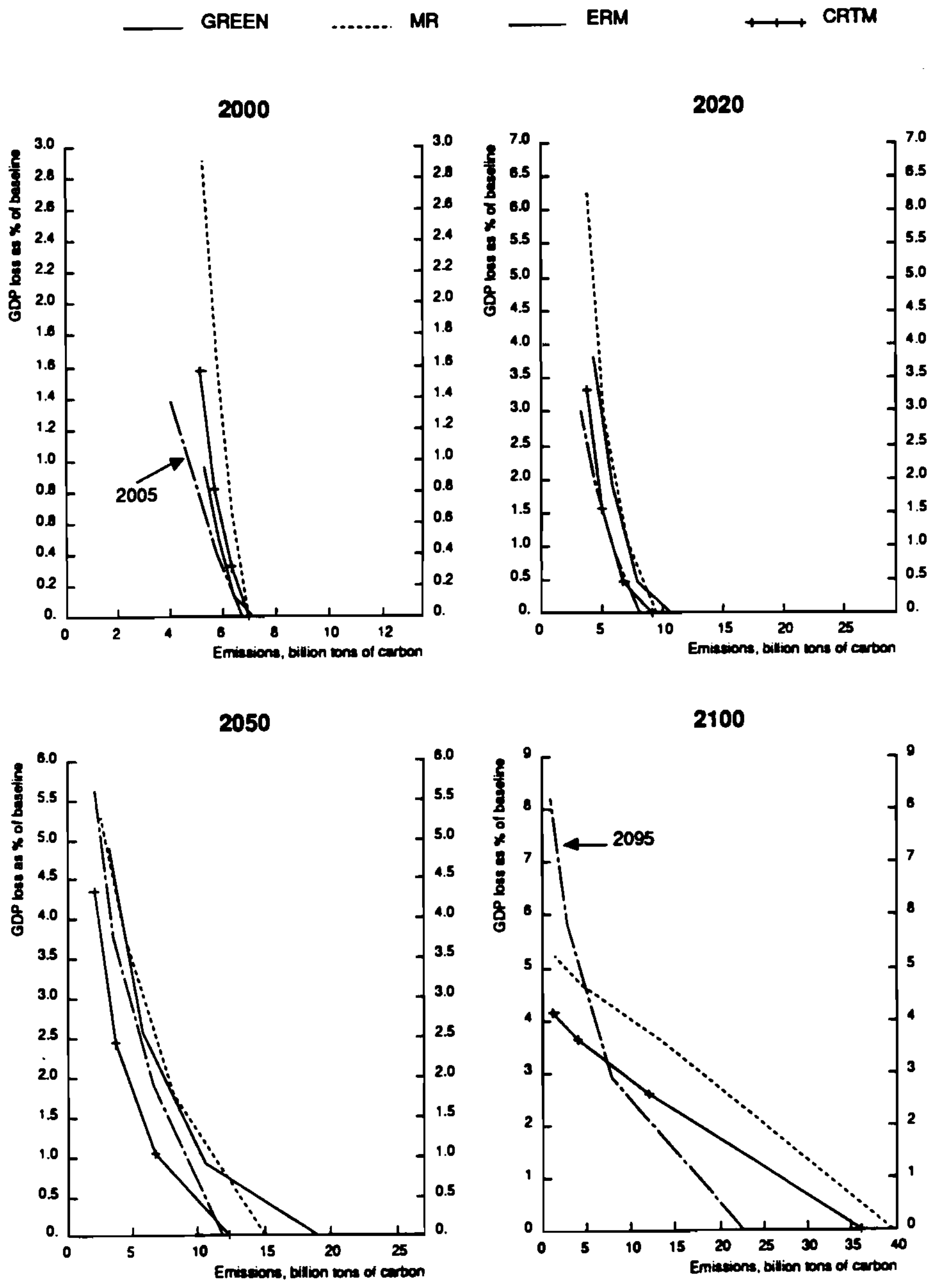


Figure 3. World emissions and GDP losses.

reflecting both the highest tax (Figure 2) and also a fairly rigid link between energy prices and GDP that even the authors tend to doubt (Barns *et al.*, 1992).

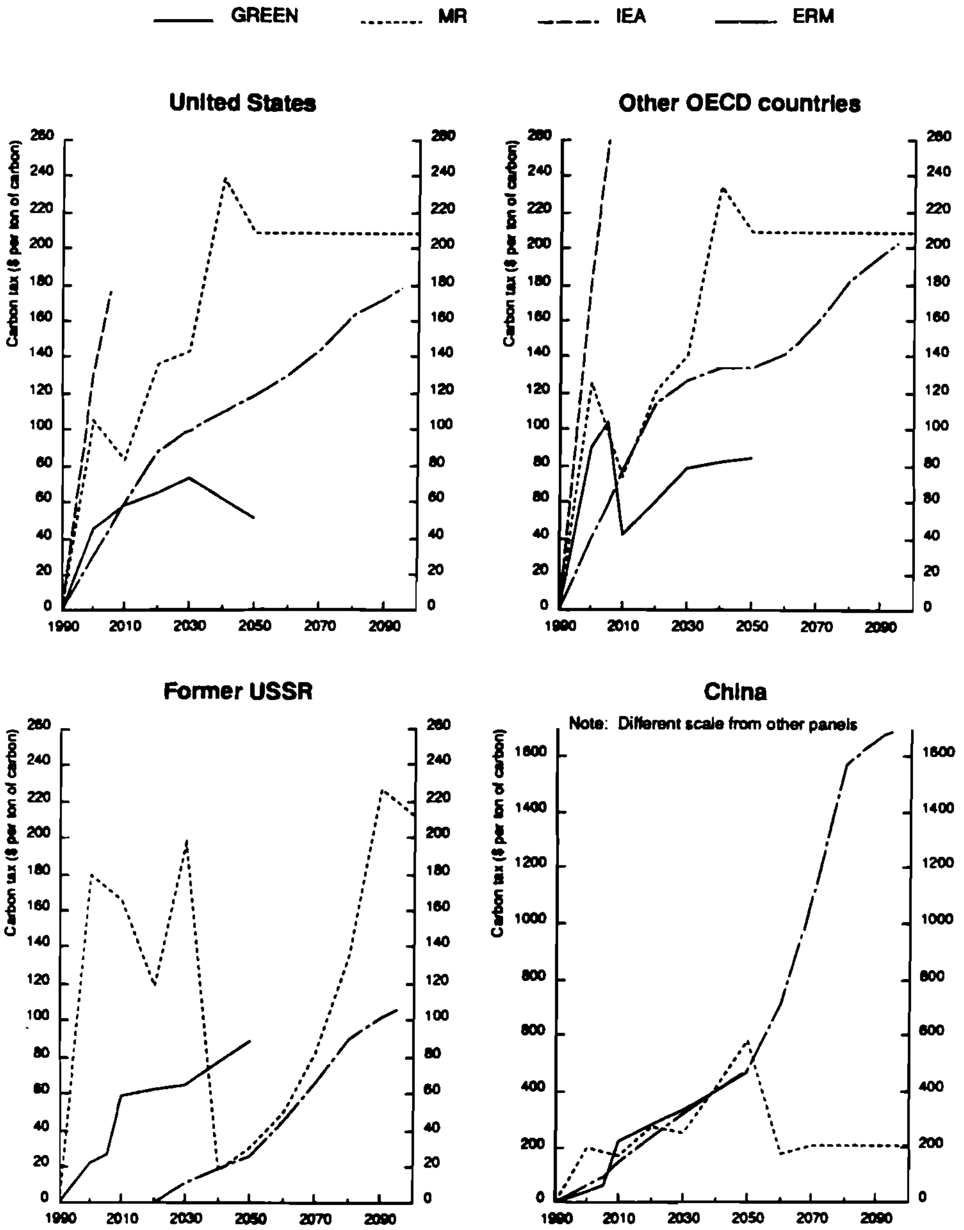
6. Stabilization of Emissions

The stabilization scenario has an entirely different character from the other reduction scenarios. Stabilization of emissions at 1990 levels is an absolute target and hence the required carbon taxes and its associated costs are strongly dependent on the BaU emissions. In principle the results could indeed be inferred from the analysis of the BaU scenarios in Section 4 and from the reduction scenarios given above, with large reductions (similar to the 2 or 3 percent case) being required in most models for China and RoW in order to stabilize emissions and smaller reductions (similar to the 1 percent case) being required for the OECD regions and the former Soviet Union. As can be seen from the BaU scenarios (Figure 1) the size of cuts to achieve stabilization will have to be greatest for WW and then for GREEN and the IEA while the smallest cuts will be for ERM. In comparing the models, it is necessary to consider the different BaU paths and hence the size of the cuts.

The interest of the stabilization scenario is that the climate change convention signed in Rio in June 1992 incorporated the goal for developed countries in stabilizing all greenhouse gas emissions at 1990 levels. This was not a firm undertaking, but much of the discussions in international negotiations preceding the signing revolved around a stabilization objective. It is not clear, however, that the degree of uncertainty over both the BaU emission paths themselves and the costs involved in reining CO_2 emissions to 1990 levels has been fully recognized.

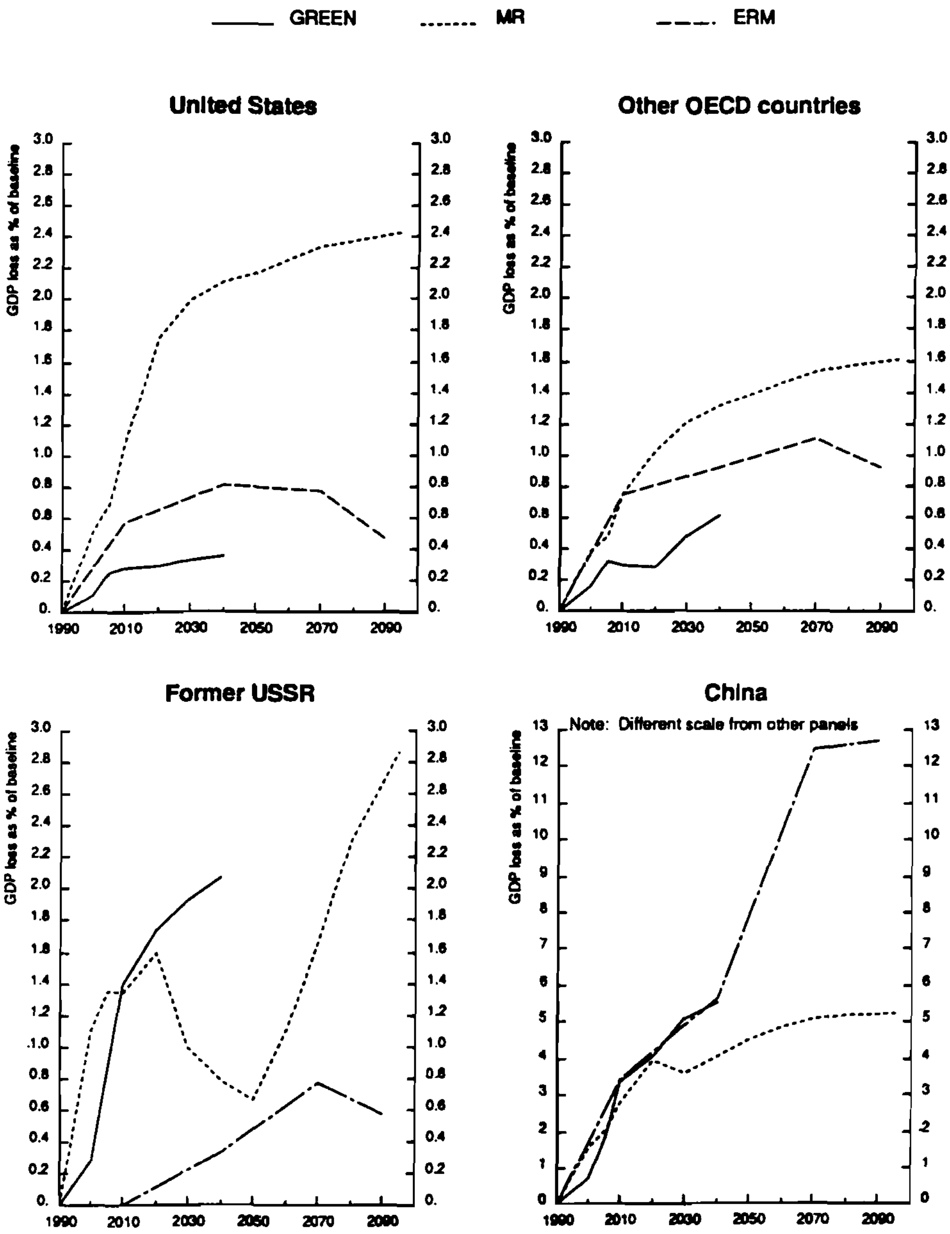
The main results for these scenarios are presented in Figures 4 and 5. Several general features stand out, as follows:

(i) The carbon tax for the *OECD regions* is highest in the IEA model and lowest for GREEN from 2010 onwards. The IEA result is as expected; baseline emission growth is relatively fast and the reduction scenarios indicate higher taxes than elsewhere for any particular reduction. The ERM result, in the middle of the pack, is also not surprising; the required tax was higher in the out years than for others, but baseline emission growth is much slower. The relatively low tax in GREEN is related to two factors: first, BaU emission growth for the OECD regions in GREEN is relatively low, even though world emissions are growing much faster than in the other models and, second, backstop technologies start to



Note: CRTM has been omitted because the series is very volatile and hence obscures the other series; it nevertheless has virtually the same terminal level as MR.

Figure 4. Carbon taxes in the stabilization scenario.



Note: CRTM has been omitted because the series is very volatile and hence obscures the other series; it nevertheless has virtually the same terminal level as MR.

Figure 5. GDP losses in the stabilization scenario.

become important in GREEN as from 2010, given both the assumptions on cost and the differences in base year relative energy prices across OECD countries. The CRTM and MR results lie between the extremes but are rather volatile before settling down at the backstop-related tax ($208 per ton) in the second half of the next century.

(ii) For *non-OECD regions*, a major feature is the erratic tax paths, especially for CRTM and MR in the case of the former Soviet Union and, to a lesser extent, for China. For the former Soviet Union, this is related to the slowing and then absolute fall in BaU emissions growth in the first half of the next century; for China it is related to backstop prices and the move to an equilibrium tax of $208 per ton of carbon by 2080. The GREEN and ERM tax curves are rather smoother and indeed rather close in the case of China, though the ERM tax climbs steeply in typical fashion.

(iii) The *GDP costs* associated with the stabilization scenario are relatively small in the case of the OECD regions and the former Soviet Union but very large in the case of China and RoW. These costs in general mirror rather closely the required tax rates. The taxes and costs are so much higher for China and RoW because the BaU emissions growth is so rapid and therefore the necessary cut-backs so large. The political reality, of course, is that these regions would not accept a stabilization target, at least not without massive compensating transfers from other countries.

(iv) *Backstop technologies*, in CRTM, GREEN and MR, put a limit on the carbon tax and GDP losses incurred in stabilizing emissions, although not for the former Soviet Union where emissions growth is anyway rather modest.

7. Cost-Effective Reductions in Emissions

The range of taxes and abatement costs across regions in the different reduction scenarios suggests the potential for savings in the global cost of reducing emissions. If, at the margin, it is more expensive (as reflected in the carbon tax rates) for one region to achieve the reduction objective than another, then it is in principle possible to achieve a mutually-beneficial redistribution of the emission reductions between regions. To achieve a globally cost-effective reduction in emissions, the marginal costs of abatement, as reflected in the regional carbon taxes, should be equated across regions. All the models indicate that equi-proportionate cuts in emissions are incompatible with this condition. A system of emission trading between countries or regions or a global carbon tax would allow cuts in emissions to be concentrated where abatement is cheapest. Emissions trading, for instance, if feasible, would allow for a more efficient distribution of emission reductions across region by letting the countries trade emission rights to the point where carbon taxes were the same in all countries. A global carbon tax would also lead to the marginal cost for reducing emissions being equal for all countries.

Three of the models in the comparison project (ERM, GREEN and MR) have carried out an emissions-trading scenario. The results for emissions trading for 2020, 2050 and 2100 in the case of the 2 percent scenario are shown in Table 3. The largest gain is for GREEN; with larger cuts in the regions where abatement is cheapest and smaller reductions elsewhere, the global output loss halves from 2 percent to one percent of GDP in 2020. All of the models point to gains from this type of emissions trading (Table 3). However, the gains are less in the models with a smaller dispersion in carbon taxes in the no-trade case, for instance ERM and MR. Furthermore, the dispersion of taxes narrows with time as backstop technologies come into play so that the gains from emissions trading diminish correspondingly. This can be seen from the GREEN results for 2050 where the gain from trading is less than in 2020. The sums involved in emissions trading are significant. In 2050, they range from $200 billion in GREEN to over $400 billion in MR, but the revenues fall off thereafter in MR as the backstops reduce the tax dispersion and hence the potential gains from trade. This underlines again the critical importance of the assumptions on backstop technologies for all aspects in assessing taxes and costs, including the gains from cost-effective agreements.

8. Summary and Conclusions

The major findings of the project are as follows:

1. There is a wide range of "business-as-usual" emission paths with worldwide carbon emissions in 2100 lying between $22\frac{1}{2}$ billion tons and 40 billion tons; these numbers are all above the IPCC's 1992 reference case (20 billion tons in 2100), although the IPCC also gives a wide spread for alternative scenarios.
2. Such a wide range of emissions, even with standardization of population and output assumptions, points to a considerable unresolved uncertainty about future emissions.
3. A factor identified as being particularly important in determining emissions is the rate of autonomous energy efficiency improvement which

Table 3. Cost differences for emission trading. Numbers refer to a 2 percentage point reduction in emissions from the baseline and are global aggregates.

		ERM[a]		GREEN		MR	
		Tax ($/tC)	GDP loss (%)	Tax ($/tC)	GDP loss (%)	Tax ($/tC)	GDP loss[b]
2020	No trade	283	1.9	149	1.9	325	...
	Trade	238	1.6	106	1.0	308	...
2050	No trade	680	3.7	230	2.6	448	...
	Trade	498	3.3	182	1.9	374	...
2100	No trade	1,304	5.7	...	...	242	8.0
	Trade	919	5.1	...	...	208	7.5

[a] End-year is 2095 for ERM.

[b] Consumption losses through 2100 – discounted to 1990 at 5 percent per year – in trillions of 1990 dollars.

ranges from zero to 1 percent per annum in the models surveyed; a difference of 0.5 percent in this parameter, given compounding, can lead to an outcome in 2100 which is as much as 20 billion tons different. Uncertainty about the size of this parameter is likely to remain large as it depends on future technical progress.

4. There are especially large differences in the projections of emissions for China; one particularly important factor seems to be the prices of fossil fuels used in the different models, with the fastest growth in emissions being projected by the GREEN model which takes account of the existing distortions in energy prices, hence building in relatively low prices.
5. Carbon taxes vary greatly across regions and across models. In most of the models there are rising tax curves, indicating that successive reductions in emissions can only be achieved by ever-larger increases in carbon taxes. The early cuts would be relatively cheap but substantial cuts would require very high taxes. For instance, cutting emissions in the United States in 2020 by 45 percent from baseline (as in the 2 percent reduction scenario) would require carbon taxes ranging from $200 to $350 per ton, compared with current energy taxes in the United States which are the equivalent of about $30 per ton of carbon. But deeper cuts would see taxes in both the United States and other regions rise towards $1,000 or more. An important exception is provided by the MR, GREEN and CRTM models which incorporate carbon-free backstop technologies. As soon as large supplies of newly-developed carbon-free fuels become available, their price puts a ceiling on the required carbon tax. More

information on the likely costs and speed of diffusion of such backstop technologies is needed.

6. The economic costs, measured here as GDP losses, also vary greatly across models and regions. The GDP loss is generally rather high for the Rest of the World region which includes the major oil-producing developing countries, but for the other regions the losses are less and there are different regional rankings of abatement costs across models. In the case of the 2 percent reduction scenario, the GDP loss in 2020 ranges from one-half to 2 percent of GDP in the OECD regions and from roughly one-half to 3 percent of GDP in China and the former Soviet Union. In the case of a stabilization scenario (keeping emissions at 1990 levels), the GDP loss in the year 2020 ranges between about zero and 2 percent of GDP for the OECD regions and the former Soviet Union, but is more likely to be 3 to 3.5 percent of GDP for China, where the cuts needed to stabilize emissions would be greatest. As with regard to tax curves, the GDP losses tend to rise more steeply as the degree of reduction increases, except when backstop technologies limit the tax, even though it is assumed that carbon taxes are offset by tax cuts elsewhere and are hence revenue-neutral.
7. Emissions trading has the potential to greatly reduce both the global and regional cost of emission reductions because there is a wide dispersion of carbon taxes and abatement costs across regions. The abatement costs are almost halved in the GREEN model, but the gains in two other models (ERM and MR) are less significant.

A word of caution is necessary regarding the nature of model comparisons in this paper. None of the scenarios presented here are in any way a policy prescription. The scenarios have been used as an expositional device to illustrate technical differences in the models. There are important policy messages from this work but none of the scenarios is being actively proposed in the current negotiations. Stabilization of emissions, however, has been adopted as a goal in the draft framework agreement but only for the developed countries. Furthermore, the costs of reducing energy-related CO_2 emissions are only one part of a complex problem which must take into account other sources and sinks of CO_2, other greenhouse gases, and the uncertain estimates of the impact of climate change.

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Tentative Conclusions from Energy Modeling Forum Study Number 12 on Controlling Greenhouse Gas Emissions*

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Concern about the extent of global climate change and its potential consequences has increased dramatically in recent years. Many believe that unprecedented climate changes are – or soon will be – occurring as the result of man-made emissions of greenhouse gases. There remain large uncertainties, however, about the relationship between emissions of greenhouse gases and their atmospheric concentrations, about the link between atmospheric concentrations and global climate change, about whether extraordinary changes in climate are actually occurring, and about the impacts of climate changes on people and ecosystems.

The largest man-made source of greenhouse gases is carbon dioxide produced by the combustion of fossil fuels in utility and industrial boilers, and in internal combustion engines. Thus, any effort to reduce greenhouse gas emissions will start with efforts to restrict these activities. Therefore, it seems essential to develop a range of projections of the likely costs of alternative levels of control of carbon emissions from the energy sector.

A fundamental challenge facing policy makers is the need for all or most of the world's large countries to co-operate in restricting greenhouse gas emissions; greenhouse gas emissions anywhere affect atmospheric concentrations (and climate) everywhere. The 24 developed countries that are members of the Organization for Economic Cooperation and Development (OECD) currently produce slightly less than half of the world's carbon dioxide emissions, and that percentage, even in the absence of emissions controls, is projected to decrease dramatically by the middle of the next century (to one third or so

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*D.W. Gaskins was Chairman of the EMF 12 Working Group, and J.P. Weyant is Director of the Energy Modeling Forum. The full EMF 12 working group report is to be published as a book entitled Reducing Carbon Dioxide Emissions; Costs and Policy Options in late 1993. The contributions of the almost one hundred individuals who contributed to the EMF 12 study are acknowledged there. The conclusions reported here have been reviewed by the working group several times, but have not yet been finalized.

of the world total). Thus, if only the OECD countries control emissions, that may have only a very minor impact on world emissions and world climate. If only part of the OECD participates the impact would be even less.

The twelfth Energy Modeling Forum (EMF) working group met five times from September 1990 to May 1992 to compare alternative projections of the impacts of a number of greenhouse gas emission control scenarios. The working group specified thirteen standardized scenarios reflecting a range of carbon emission control levels, as well as sensitivities on key standardized inputs. These scenarios were ultimately implemented by fourteen modeling teams employing a wide variety of techno-economic models (see Appendix), although not every model could implement every scenario. In addition to these model comparisons, ten study groups were formed to analyze issues not being addressed by the fourteen models and thirteen scenarios. These groups used additional models and methods to analyze issues not addressed in the thirteen original scenarios.

1. Basic Control Scenarios

Six of the thirteen EMF 12 scenarios employed the same GDP, population, resource availability, and technology assumptions, but consider different levels and rates of CO_2 emissions control.

1. *Reference* – no control;
2. *20% Reduction* – a 20% reduction in CO_2 emissions in the developed countries and no more than a 50% increase in the developing countries relative to 1990 levels by 2010;
3. *50% Reduction* – the same as (2), but with an additional reduction in CO_2 emissions in the developed countries to 50% below their 1990 levels by 2050;
4. *Stabilization* – hold CO_2 emissions in the developed countries to their 1990 levels by the year 2000, with the developing countries again constrained to no more than 50% above their 1990 levels;
5. a *Phased-In Carbon Tax* that escalates from $15 per ton in 1990 at 5% real per year; and
6. a *2% Points Per Year Reduction* in emissions relative to the Reference case.

In implementing these scenarios, the modeling teams generally used taxes based on the carbon content of fossil fuels to achieve the emissions reductions (except for the government revenues a carbon tax would produce, this formulation is equivalent to a system of carbon emissions permit trading). These carbon tax projections provide us with a rough estimate of the degree of market intervention that will be required to achieve the carbon emission reductions. Most of the models included anticipated results from new technology development and conservation programs in the Reference case. However, in these models there is no explicit consideration of market imperfections that may be causing current energy consumption patterns to differ from what perfectly functioning competitive markets would produce. More efficient, but more expensive, technologies are generally selected in the control scenarios, but no additional technology development is generally assumed to occur. Only one model adds additional conservation programs explicitly in those scenarios, and only one other model includes endogenously determined rates of technological change. Finally, in their initial implementation of these scenarios the modeling teams assumed no international emissions trading, lump sum rebate of any tax revenues collected, and no carbon offsets, such as those that might result from tree planting. A number of general points can be made from examining cost of control projections for these scenarios.

The impact of these control options on global climate change over the next twenty years may be quite limited. Even in the most tightly controlled scenarios, the reduction in cumulative CO_2 emissions over this period are projected to be no more than 25% relative to the *Reference case.* The impact of the control programs on atmospheric concentrations of CO_2 and climate change over that time period would be even less. By 2050, however, the *50% Reduction* scenario results in cumulative emissions that are as much as 100% below those projected in the Reference case.

Despite the inclusion of improved technologies and improved energy efficiencies in the Reference case, all models project that market intervention will be required to achieve each of the emissions targets in all regions. When the more stringent carbon limits are considered, many models project the intervention required would be equivalent to carbon taxes of hundreds of dollars per metric ton. For example, the projections of the average carbon tax required during 2000 to 2020 to reduce U.S. carbon emissions by 2010 by 20% with respect to their 1990 level range from $50 to $330 dollars per metric ton. The projections of the average carbon tax required during 2000 to 2020 to limit carbon emissions in China to no more than 50% more than 1990 emissions range from $25 to $200 per metric ton.

These carbon taxes would generate substantial tax revenues that could be used for a number of purposes including reducing other taxes, deficit reduction, and additional government spending. For example, the projections of the average annual tax revenues raised in the U.S. from 2000 to 2020 to achieve the 20% reduction in CO_2 emissions range from $65 Billion to $300 Billion. Projections of average annual tax revenues raised in China from 2000 to 2020 to limit emissions to 50% above 1990 levels range from $20 Billion to almost $200 Billion.

The impact of a carbon tax on Gross Domestic Product (GDP) measures its costs to the economy in terms of lost output resulting from the increase in the price of goods requiring carbon emissions; those goods must either be produced with less carbon or by more expensive processes. The GDP loss also includes the impact of the carbon tax on capital stock accumulation and technological progress although not all models capture these phenomena. The models initially assumed lump-sum redistribution of tax revenues; that is, tax revenues are used to reduce total tax payments by individuals and corporations without affecting marginal tax rates (for example, by reducing the standard deduction). The GDP losses calculated in this manner measure the cost of the distortions to the economy caused by the imposition of the carbon tax without either adding a credit or subtracting a penalty for the way the revenues are used. Under this assumption, and assuming no adverse trade effects, the model projections of the cost of stabilizing CO_2 emissions at today's levels range from .1% to .5% of GDP in 2000 for the U.S. and the cost of achieving a 20% reduction in CO_2 emissions relative to today's level range from .9% to 1.7% of U.S. GDP in 2010. Although 1.7% of U.S. GDP in 2010 amounts to about $130 Billion 1990 dollars, the reduction in the GDP growth rate between 1990 and 2010 would only be reduced form about 2.3% per year to 2.25% per year. Thus, it is possible to reduce emissions significantly from their non-controlled level without eliminating the growth of the economy.

The way in which carbon tax revenues are used has an important impact on the GDP loss. The projected GDP losses could be reduced substantially (relative to those calculated for the lump-sum recycling case) by using the carbon tax revenues to reduce existing taxes that discourage economic activity, particularly capital formation. Simulations with 4 models of the U.S. economy indicate that from 35% to more than 100% of the GDP losses could ultimately be offset by recycling revenues through cuts in existing taxes.

Regardless of where a model ranks in terms of the cost for a particular level of control in a particular year, there is a great deal of similarity in how the models project costs will vary over time for a particular level of control, and with respect to the level of control in any particular year. First, the cost of a particular level of control generally increases over time as the reference level of emissions grows and more adjustments must be made to reach a fixed level of emissions. For example, assuming lump-sum recycling of carbon tax revenues, projections of the cost of stabilizing emissions in the U.S. range from .1% to .5% of GDP in 2000 and from .2% to 1.0% of GDP in 2010. In the longer term, say by 2050 or 2060, low-cost oil and gas reserves are near depletion and the cost of reducing emissions depends on the difference between the cost of carbon-free sources, like solar cells and advanced technology nuclear reactors, and carbon-based sources of energy, like synthetic oil and gas made from coal or advanced coal-fired power plants.

Second, the cost of control appears to be non-linear with respect to the level of control in any given year, especially up to about 2040 before old fossil-fuel based energy producing and consuming equipment can be fully retired and new carbon-free technologies can be fully introduced. That is, incremental reductions in allowable emissions cost more as the absolute level of allowed emissions in any particular year is reduced. For example, the cost of stabilizing emissions in the U.S. range from .2% to 1.0% of GDP in 2010, while the cost of reducing emissions by 20% in that year range from .9% to 1.7% of GDP. In fact, during the period up to 2040 sharply increasing costs for the more extreme control levels in any one year can even offset the tendency of the costs of controlling to any level to increase over time.

If the OECD, or any other group of countries unilaterally implements a carbon reduction program, resulting changes in international energy prices will cause carbon emissions in other countries to increase relative to reference case levels. Increased carbon emissions by non-participating regions occur both as a result of increased energy intensity of economic activity and through the migration of energy-intensive production into unconstrained regions. Carbon restrictions place countries who control at a competitive disadvantage in energy-intensive industries. Thus, the cost to countries who control increases with the level of cutback, but the impact on global emissions may drop off sharply if large groups of countries fail to co-operate in controlling emissions.

The non-linearity of year by year costs of control, the tendency of this non-linearity to decrease over time as new technologies can be more fully phased in, as well as potential problems with recycling large amounts of tax revenues and dealing with large international trade shifts suggest that there is a tradeoff between the cost of meeting an annual emissions target and the emissions generated before the target is reached. Moreover, the cumulative cost of meeting any cumulative emissions reduction target can be reduced if it is phased in over a longer period of time. If a fixed annual emissions rate target is specified, cumulative costs can be reduced with some increase in short-term emissions if: (a) more time is allowed for reaching the target, and (b) the instrument(s) used to achieve it – say a carbon tax – is phased in gradually rather than abruptly. The cost reduction can be particularly significant if the target date and rate of implementation are set to allow new carbon-free technologies to be phased in smoothly. If discounting of future costs is included in the calculation (as some would argue is required to insure an optimal allocation of society's resources over time), the reduction in costs resulting from a slower phase-in of controls is even greater.

More greenhouse gases in the atmosphere may impose additional costs on society, though, so it may not be optimal to delay the imposition of constraints indefinitely. These costs depend on atmospheric concentrations of greenhouse gases which depend on cumulative emissions over time rather than a single year's emissions rate. The *20% Reduction* scenario leads to high short run adjustment costs according to the models included in this study. They project that almost the same reduction in cumulative CO_2 emissions reductions (and no more than a 20% increase in cumulative carbon emissions) can be achieved with the *Phased-in Tax* by the middle of the next century with a 30-40% reduction in cumulative costs (even without discounting of future costs).

The models display a wide range of cost projections for the scenarios considered depending on both the features the modelers have incorporated in their models and the way they have implemented the scenarios. The cost of control projections are also sensitive to variations in standardized input assumptions. We begin by discussing the results for alternative policy scenarios.

2. Additional Policy Options

A combination of policies imposed on each of the major greenhouse gases and implemented in a way that allows new technologies to be developed and implemented in a smooth manner, will be much less costly than aggressive pursuit of a single policy option.

In the EMF 12 *Emissions Trading* scenario, a common carbon tax is imposed in all regions until the same amount of global emissions allowed in the *20% Reduction* scenario is achieved. In the near term, there is a moderate amount of emissions trading from the developing countries to the developed countries, resulting in a 30–60% reduction in the GDP loss that results from the *20% Reduction* scenario. However, by 2040 or so, the developing countries are assumed to have deployed the same large-scale technologies as the developed countries, so there are no additional gains to emissions trading beyond that point.

Both *carbon* and *Btu* taxes have a bigger impact on CO_2 emissions when imposed at the primary energy production level, e.g., at the point of extraction, rather than at the wholesale or retail level, whereas an *ad valorem* tax has the largest impact when imposed at the end-use level. In addition, stabilization of CO_2 emissions can be achieved at lower costs when imposed at the primary energy level than at the wholesale or retail level. Also, it is difficult to insure that any emissions target will actually be met if a permit trading system is implemented at the wholesale or retail level, because unintended shifts in upstream fuel choices may result.

The Energy Security study group examined the energy security implications of the alternative emissions control scenarios and concluded that they would have only a minor impact on energy security. The main short-run impact of the control scenarios is to substitute gas, conservation and alternative sources for coal, leaving oil use relatively unaffected.

A gradually phased in carbon tax with the tax revenues recycled proportionally does not appear to result in major impacts on the distribution of income by income level. With the exception of the coal industry, which would experience a significant contraction over the next twenty years, the impact on individual industries is also likely to be small.

3. Sensitivity Analyses

The cost of carbon constraints also depends significantly on the assumptions made about the cost of carbon free technologies relative to the cost of carbon emitting ones. To explore this sensitivity the group examined an *Accelerated Technology* scenario in which the cost of non-carbon energy supply technologies (e.g., solar or advanced nuclear) in the *20% Reduction* scenario are assumed to be reduced to the cost of carbon based ones (synfuels and coal-fired electric generation) by 2010. According to all the models, this scenario reduces the annual cost of achieving the carbon constraint to zero by the latter part of the 21st century. The costs of the constraint during the early part of the next century are not nearly as significantly reduced (only 10–30%), however, because conventional fossil fuel technologies are still being used and because of constraints on the introduction of the new carbon-free technologies that cause additional costs to be incurred until large scale introduction of the new technologies can be completed. This latter effect re-enforces the large cost-of-adjustment effect observed above. Up until about 2040 the required carbon tax exceeds by a substantial margin the zero difference in the costs of carbon-based and carbon-free backstop technologies.

The study design includes a 2.2% growth rate in Gross Domestic Product (GDP) for the U.S. over the next thirty years. Two of the models included in the study produced independent GDP projections of 2.0% and 1.4% per year over that time frame. This results in lower carbon taxes being required to meet any particular emissions target. Interestingly, though, the computed GDP losses are not significantly less than in the other models because high energy prices are projected to diminish productivity growth. The lower GDP growth rate was adopted for a *Low GDP Growth Sensitivity* scenario. This scenario does lead to a significant reduction in the cost of control because it directly reduces the reference level of emissions projected by each model. In addition, when all the models are run with the low GDP growth rate assumptions, they produce carbon taxes that are more closely consistent with those projected by the lower growth models.

The cost of the transition to the non-carbon based energy technologies can be significantly affected by the availability of natural gas resources. Since gas has a lower carbon emissions rate than oil or coal, more fossil energy can be consumed within any emissions constraint if the use of natural gas can be increased. The *High Natural Gas Resources* scenario postulates a quadrupling of natural gas resources in each region in the *20% Emissions Reduction* case. Although a number of analysts would now argue for more gas reserves than assumed in the EMF 12 study design, the quadrupling assumption is probably quite a bit more optimistic than anyone currently projects. This assumption does lead to a 30 to 40% reduction in the discounted cost of satisfying the emissions constraint over the next twenty years.

4. Differences in Model Projections

Estimates of the cost of achieving an emissions target relative to the 1990 level of CO_2 emissions by some future date are sensitive to the reference case emissions trajectory projected by the model. A model with a higher reference case projection of total emissions will require more adjustments to reach the fixed target than one with a lower reference case emissions projection.

Even when GDP growth rates are standardized, a very wide range of reference case emissions projections are produced by the models included in the study. By the year 2100, projections of CO_2 emissions range all the way from a 20% to a 200% increase over 1990 levels. Relatively small differences in model parameters lead to large differences when their effects are compounded over the study's 110 year time horizon. For example, much of the difference in projections from the models for 2100 can be explained by differences in the assumed rate of decrease in energy use per unit of economic output independent of energy price changes. The Global 2100 model uses a value of .5% per year for this parameter, while the Edmonds-Reilly model employs 1.0% per year assumption. The more disaggregate assumptions made in the Global Macro model implies about a 1.25% rate. When compounded over 110 years, these differences can explain aggregate energy use and emissions projections that differ by a factor of two or more. Estimates of this aggregate parameter based on historical data range from a rate of decrease of about .5% per year to an increase at about that rate. Researchers who have attempted to extrapolate the types and efficiencies of energy using equipment into the future have argued that the potential exists for a rate of decrease in energy use per unit of economic output from 1% per year to over 2% per year.

In the *Reference* scenario, all models project steady improvements (about one percent per year in the U.S.) in energy intensity over the study's time horizon, but no strong movement towards or away from non-carbon fuels. Increases in energy intensity and switching to less carbon intensive fuels are the major means of satisfying the requirements of the *20% Reduction* scenario, with the fuel switching response being greater in the models with more end-use technology detail.

5. Directions for Future Research

Additional research in several areas could significantly improve the estimation of the costs of greenhouse gas emission control strategies and the evaluation of alternative policy options.

This study has identified the amount of energy intensity changes that will take place independent of changes in energy prices over the coming decades as a major determinant of reference case emissions, a major source of differences between the models, and a major determinant of the cost of achieving any emissions target. Yet, information about the potential for improved efficiency energy technologies is incomplete and often inconsistent and there is little conclusive analysis regarding their likely rate of adoption. Particularly important here are assessments of market imperfections or distortions that impede the introduction of more efficient technologies. For example, energy pricing in the developing countries and the former Soviet Union has been far below world market levels.

The projections of baseline emissions also depend significantly on long-run GDP and population projections for the main regions of the world.

Although some excellent analyses of the outlook for economic growth in the United States are available, more work would help resolve the remaining differences, which are considerable. In addition, very little is known about likely economic and population growth in the future in such important and diverse countries as China, India, Brazil, and the independent states of the former Soviet Union.

The adjustment costs that result from any control strategy depend on the availability and cost of non-carbon emitting renewable energy sources, especially before they emerge as mature technologies. The models included in this study all represent these adjustment costs in one way or another, but the different approaches can lead to markedly different results. This suggests the value of additional work on data and models of new technology availability dates and introduction rates, as well as of technology transfer to the developing countries.

It is important to assess the potential of offsets to carbon emissions, like tree planting or slowing de-forestation, and of reducing other greenhouse gas emissions like methane from natural gas system leaks, coal bed seams, or ruminants, as these can be as effective as carbon emissions reductions in slowing climate change. In addition, carbon sequestration and removal technologies, while not now economic, could easily become competitive in the future especially if carbon taxes reach $100 per metric ton or more.

This study suggests the value of additional work on the linkages between energy and the environment, between environmental policies and world energy markets, and between environmental policies and trade in non-energy goods.

The design of an appropriate control strategy depends on the benefits as well as the costs of control. Although a great deal of work has been completed on the translation of CO_2 emissions into concentrations, on the dependence of climate on atmospheric CO_2 concentrations, and on the impacts of climate change on people, plants, and ecosystems, great uncertainties remain. Research on evaluating the impacts in economic terms has just begun.

Appendix. The Core Models of EMF 12.

Model name(s)	Author(s)	Model type	Distinguishing characteristics
MARKAL (MARKet ALlocation model)	Samuel Morris (BNL)	Optimization (linear program)	• Model-wide objective function • Minimize total energy sector costs of meeting exogenously-given energy service demands • No economic effects outside energy sector • No effects of higher cost of energy except introduction of more energy-efficient technologies
EDS (Energy Demand System)	Lakis Vouyoukis, Niko Kouvaritakis (IEA)	Generalized equilibrium	• Equilibrium in energy sector's markets: primary, secondary, electric, etc. • No markets for capital, labor, or other nonenergy goods • Reference GDP and/or energy service demand exogenously-given • Price and/or GDP effects on demand through aggregate "feedback equations"
ERM (Edmonds-Reilly Model)	Jae Edmonds David Barns		
FOSSIL2	Sharon Belanger, Roger Naill (AES)		
GEMINI	Dave Cohan, Adriana Diener (DFI), Joel Scheraga (EPA)		
GLOBAL MACRO-ENERGY	Bill Pepper (ICF)		

Appendix. Continued.

Model name(s)	Author(s)	Model type	Distinguishing characteristics
T-GAS (Trace Gas Accounting System)	Bob Kaufmann	Regression	• Exogenous inputs of prices, GDP, population, etc. • Energy intensity by sector determined from regression equation and given inputs • Some user control over parameters in functions
CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck Thomas Teisberg	Optimal growth	• Maximizes discounted consumer satisfaction subject to resource and technology constraints • Consumer determines labor supply, consumption, and investment • GDP produced from aggregate production function • Moderate detail in energy sector
GLOBAL 2100	Alan Manne Rich Richels		
CRTM (Carbon Rights Trade Model)	Thomas Rutherford	General equilibrium	• Market equilibria for all goods: capital, labor, materials, other goods • Consumers choose savings/investment levels • GDP, energy intensity changes determined by interactions throughout the economy • Less detail in energy sector
DGEM (Dynamic General Equilibrium Model)	Dale Jorgenson Peter Wilcoxen		
GOULDER	Larry Goulder		
GREEN (GeneRal Equilibrium ENvironmental)	John Martin Jean-Marc Burniaux (OECD)		

Source: R. Beaver, *A Structural Comparison of Models Used in EMF 12 to Analyze the Costs of Policies for Reducing Energy-Sector CO_2 Emissions*. Draft paper, Energy Modeling Forum, Stanford University, Stanford, CA.

The Global Consequences of Regional Environmental Policies: An Integrated Macroeconomic, Multi-Sectoral Approach[1]

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Abstract

In this paper we explore the link between environmental policies and international trade using a multisector, multiregion model with a fully integrated and rigorous treatment of international flows of financial assets. We focus on two questions. First, how do unilateral environmental regulations affect a country's real exchange rate, its trade accounts, and the domestic output of its industries? Second, do changes in trade patterns vitiate unilateral attempts to reduce global externalities such as carbon dioxide emissions? We investigate both questions by using the model to compare two carbon dioxide control policies: a unilateral carbon tax imposed by the United States, and a multilateral tax imposed throughout the OECD. We find that international flows of capital can overwhelm price-induced effects and lead to improvements in a country's trade balance when an analysis ignoring capital flows would predict a deterioration. We also find that a unilateral carbon dioxide control policy would be unlikely to be vitiated by changes in trade patterns.

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1. Introduction

Because environmental regulations differ across countries, environmental protection and international trade are inextricably linked. A country adopting relatively strict environmental standards will increase the costs of its domestic firms and may harm their ability to compete with overseas rivals. One effect of this may be to cause dirty industries to migrate to countries with the least environmental regulation. In fact, Kalt (1985) has argued that standard trade theory predicts this result because international differences in regulation can be thought of as differences in endowments of environmental cleanliness. On the other hand, strict regulations *per se* do not necessarily harm a country's competitiveness as long as its major trading partners have similar standards (Congressional Budget Office, 1985).

This issue is particularly important in the debate over policies to control global warming. Schelling (1992) has argued that developed and developing countries differ in their incentives to control greenhouse gas emissions and are unlikely to agree on a single international standard. Furthermore, Hoel (1991) has shown that a partial standard, adopted by developed but not developing countries, could actually raise world emissions by shifting production to countries with less efficient energy sectors. Felder and Rutherford (1992) have also examined the possibility that a geographically-limited greenhouse gas policy could be vitiated by changes in trade flows. They point out that policies adopted to control carbon dioxide emissions in developed countries could reduce world oil demand and lower oil prices enough to stimulate a substantial increase in oil consumption by developing nations. This would lead to increased emissions by developing countries, thus offsetting the emissions reduction in the developed world.

Although these studies show that changes in trade flows might, in theory, offset a limited global warming policy, they do not provide much guidance on the empirical question of whether the effect is large or small. Addressing this question requires an empirical model with three specific features: the model must have multiple regions linked by trade flows; each region must have multiple industries so that changes in the pattern of production can be detected; and all trade imbalances must be matched by corresponding flows of assets which should, in turn, affect the exchange rate.

None of the existing models used to study global warming have all of these features. Some, such as Jorgenson and Wilcoxen (1991a; 1991b) and Goulder (1991), focus only on a single country. Others, such as Edmonds and Reilly (1983), Barnes *et al.* (1992), Cline (1989), and Manne and Richels

(1990; 1992) have multiple regions but are highly aggregated with each region. Those models which do have multiple regions and multiple sectors, such as Whalley and Wigle (1990), Rutherford (1992), Felder and Rutherford (1992), and Burniaux *et al.* (1991a; 1991b), lack a complete integration of international asset flows and exchange rate determination.

In this paper we describe G-Cubed, a new model specifically designed to explore the link between environmental policy and trade flows. It is based on and substantially extends two existing models: the global dynamic general equilibrium modeling framework (the MSG model) developed by McKibbin and Sachs (1991) and the detailed, econometrically-estimated intertemporal general equilibrium model of the United States developed by Jorgenson and Wilcoxen (1990). Like the McKibbin-Sachs model, G-Cubed is geographically disaggregated: the world economy is divided into six independent regions linked by trade and financial markets. Like the Jorgenson-Wilcoxen model, within each region production is disaggregated: each of G-Cubed's regions contains twelve production sectors. An important feature of G-Cubed which sets it apart from other models is that all intertemporal budget constraints on households, governments and nations (the latter through accumulations of foreign debt) are imposed. Thus, any agent who borrows will have to service the ensuing debt as long as it is outstanding. A more detailed description of the model can be found in McKibbin and Wilcoxen (1992).

In the remainder of this paper we summarize the theoretical structure of G-Cubed and compare the results for two simulations illustrating the link between environmental policy and international trade: a unilateral carbon tax imposed in the United States, and a multilateral carbon tax imposed in all OECD countries.

2. The Theoretical Structure of G-Cubed

G-Cubed's six regions can be divided into two groups: three industrial regions – the United States, Japan and the rest of the OECD – and three others – oil exporting developing countries (OPEC), Eastern Europe and the former Soviet Union (EFSU), and all other developing countries (LDCs). For the industrial economies, the internal macroeconomic structure as well as the external trade and financial linkages are completely specified in the model. We begin by presenting the structure of a particular one of these economies: the United States. The other industrial countries have similar structure and differ only in the values of behavioral parameters. To keep our notation as simple as possible we have not subscripted each variable by country except where necessary for clarity.

Each industrial economy or region in the model consists of several economic agents: households, the government, the financial sector and 12 production sectors: electric utilities, natural gas utilities, petroleum refining, coal mining, and crude oil and gas extraction, nonfuel mining, agriculture, forestry and wood products, durable manufacturing, non-durable manufacturing, transportation and services. We now present an overview of the theoretical structure of the model by describing the decisions facing these agents.[2] For convenience we have normalized all quantity variables by the economy's endowment of effective labor units. This means that in the steady state all real variables are constant in these units although the actual levels of the variables will be growing at the underlying rate of growth of population plus productivity (we denote this rate by "n").

A. Firms

Each of the twelve sectors is represented by a single firm in each sector which chooses its inputs and its level of investment in order to maximize its stock market value subject to its production function and a vector of prices it takes to be exogenous. For each sector h, output (Q_h) is a constant elasticity of substitution (CES) functions of inputs of capital (K_h), labor (L_h), energy (E_h), materials (M_h) and a sector-specific resource (R_h).[3] Energy and materials, in turn, are CES aggregates of inputs of intermediate goods. The nature of the sector specific resource varies across sectors. In the coal industry, for example, it is reserves of coal while in agriculture and wood products it is land which can be transferred between these two sectors.[4]

The goods actually purchased by firms and households are a mixture of imported and domestic commodities which we take to be imperfect substitutes. Due to data limitations, we assume that all agents in the economy have identical preferences over foreign and domestic varieties of each commodity. We represent these preferences by defining twelve composite commodities

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[2] The reader is referred to McKibbin and Wilcoxen (1992) for more detail. A complete listing of the equations in the model, the parameters and data sources are contained in an Appendix to that paper.

[3] The model's database is still under development. For the simulations presented in this paper we have had to constrain all elasticities of substitution to be unity so the production functions collapse to Cobb-Douglas. In future work, this restriction will be eliminated.

[4] In the version of the model in this draft, we have assumed an infinite supply of these resources, but future work will explore the implications of exhaustible resources and sequestration of land for tree planting, etc.

that are produced from imported and domestic goods according to a set of CES production functions. For example, the petroleum products purchased by agents are a CES composite of imported and domestic petroleum. Each imported good entering this function is itself a CES composite of imports from different sources. By constraining all agents in the model to have the same preferences over the origin of goods we require that, for example, the agricultural and service sectors have the identical preferences over domestic oil and oil imported from the Middle East.[5]

A by-product of this approach is that it is straightforward for us to model several emissions permit schemes. In particular, we impose that domestic and imported inputs to the composite commodity be combined in fixed ratios with emissions permits. We include separate permits for domestic and imported inputs in order to be able to simulate either consumption-based permit systems, in which permits would be required for either input, or production-based systems in which permits are required only for domestic inputs. We assume the permits are initially owned by households, so the market value of the permits is included in the definition of household wealth. The permits introduce a potential cap on the use of each input in production of the composite good. For the simulations reported in this paper, however, we allow the supply of permits to be infinite so they have zero value and no effect on the use of commodities.[6]

Figure 1 summarizes the supply side of the economy by showing the relationship between inputs, domestic production, imports and emissions permits for an arbitrary commodity.

In each sector the capital stock (K_h) changes according to the following relation between the rate of fixed capital formation (J_h) and the rate of geometric depreciation (δ_h):

$$dK_h/dt = J_h - \delta_h K_h \tag{1}$$

Following the cost of adjustment models of Lucas (1967) and Treadway (1969), we assume that investment is subject to rising marginal costs of installation, with total real investment expenditures in sector h (I_h) equal to the value of direct purchases of investment goods (J_h) plus per unit installation costs. Installation costs, in turn, are assumed to be a linear function

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[5] This does not require that both sectors purchase the same amount of oil, or even that they purchase oil at all; only that they both feel the same way about about the origins of oil they buy.

[6] Future papers will explore marketable permit systems for various types of emissions across sectors, both within and between regions.

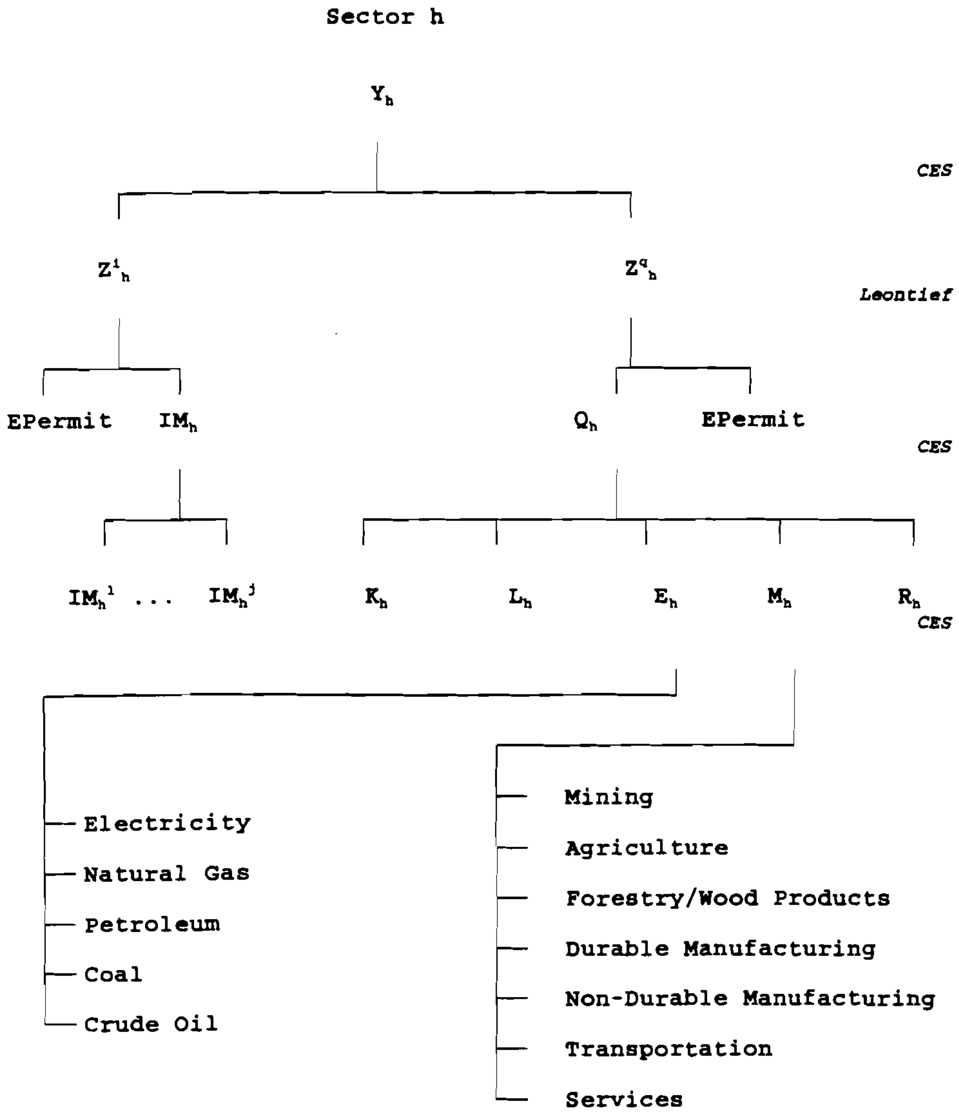

Figure 1. Production nesting.

of the rate of investment (J_h/K_h) so that adjustment costs can be represented by J_h $[(\phi_h/2)(J_h/K_h)]$. Total investment expenditure in sector h (of a particular country) is therefore:

$$I_h = [1 + (\phi_h/2)(J_h/K_h)]\, J_h \tag{2}$$

where ϕ is the parameter for adjustment costs (a high value implies large adjustment costs). One advantage of using an adjustment cost approach is that we can vary the adjustment cost parameter for different sectors to capture the degree to which capital is sector specific.

The goal of each firm is to choose investment and inputs of labor (L_h), energy (E_h), materials (M_h), and resources (R_h) to maximize intertemporal net-of-tax profits. For analytical tractability, we assume that this problem is deterministic.[7] Thus, the firm will maximize:[8]

$$\int_t^{\infty} \left[Profit_{hs} - (1-\tau_4) P^I_{hs} I_{hs} / (P_{hs} - \tau_3) \right] e^{-(rd_s - n)(s-t)} ds \tag{3}$$

where:

$$\begin{aligned} Profit_{hs} = \;& (1-\tau_2)\Big[(P_{hs} - \tau_3) Q_{hs} - W_{hs} L_{hs} - P^E_{hs} E_{hs} \\ & - P^M_{hs} M_{hs} - P^R_{hs} R_{hs} \Big] / (P_{hs} - \tau_3) \end{aligned} \tag{4}$$

$$rd_s = \frac{1}{s-t} \int_t^s r_v dv \tag{5}$$

is the long-term interest rate, and P is the price of domestic output, Q is the output of the domestic good, W is the nominal wage, and r_v is the real interest rate on government bonds in period v, subject to its production function and equations (1) and (2). The three taxes included in this specification are corporate income tax (τ_2), taxes on inputs that are proportional to output, such as carbon emissions, (τ_3)[9] and an investment tax credit (τ_4). All real variable are normalized by the economy's endowment of effective labor units, so profits are discounted adjusting for the rate of growth of population plus productivity growth (n). Solving the optimization problem facing this representative firm, we find the usual marginal product conditions for inputs

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[7] In other words, the firm believes its estimates of future variables with subjective certainty.

[8] The rate of growth of the economy's endowment of effective labor units, n, appears in the discount factor because the quantity and value variables in the model have been scaled by the number of effective labor units. These variables must be multiplied by exp(nt) to convert them back to their unscaled form.

[9] In the case of a carbon tax, τ_3, would be the ad valorem tax multiplied by the emission of carbon per unit of output of sector h. We assume that this tax is levied on only two sectors: Coal, and natural gas and oil extraction with different emission coefficients in each these sectors. This is discussed further in the section on results from a carbon tax.

of labor, intermediate goods and resources, plus the two conditions shown below:

$$\lambda_h = (1 + \phi_h J_h / K_h)(1 - \tau_4) P_h^I / (P_h - \tau_3) \tag{6}$$

$$\begin{aligned} d(\lambda_{hs})/ds = \quad & (r_{hs} + \delta_h)\lambda_{hs} - (1 - \tau_2)\left[d(Q_{hs})/d(K_{hs})\right] \\ & -0.5\phi_h \left[P_{hs}^I / (P_{hs} - \tau_3)\right](1 - \tau_4)(J_{hs}/K_{hs})^2 \end{aligned} \tag{7}$$

where λ_h is the shadow value of an additional unit of investment in industry h (again, in a particular country).

The marginal product equations are used to solve for the demand for variable factors of production. We assume that labor is mobile between sectors in each region, but is immobile between regions. Thus, within each region wages will be equal across sectors.[10] The wage is assumed to adjust according to an overlapping contracts model where nominal wages are set based on current and expected inflation and on labor demand relative to labor supply. In the long run employment is equal the supply of labor which grows at the exogenous rate of population growth. In the short run, employment is equal to the labor demanded at the given nominal wage.

Equations (6) and (7) can be interpreted as follows. Integrating (7) along the optimum path of capital accumulation (J_h, K_h) gives:

$$\lambda_{ht} = \int_t^{\infty} (1 - \tau_2)\left[dQ_{hs}^* / dK_{hs}^* + \Phi_{hs}\right] e^{-(rd_h + \delta_h)(s-t)} ds \tag{8}$$

where:

$$\Phi_{sh} = 0.5\phi_h (1 - \tau_4)(J_{hs}^* / K_{hs}^*)^2 P_s^I \; / \; (P_s - \tau_3) \tag{9}$$

and where dQ_h^*/dK_h^* (the marginal product of capital in production), J_h^*, and K_h^* are all evaluated along the optimal path. Φ_h is the marginal product of capital in reducing adjustment costs in investment in sector h. Thus, λ_h is the increment to the value of the firm in sector h from a unit increase in its investment. It is related to q_h, the marginal version of "Tobin's Q" (Abel, 1979) for sector h, as follows:

$$q_h = \frac{\lambda_h P_h}{P_h^I} \tag{10}$$

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[10] In the short run, this will overstate labor mobility between sectors. One solution would be to introduce an adjustment cost model of labor demand.

Thus we can rewrite (6) as:

$$J_h/K_h = \left[\frac{q_h}{(1-\tau_2)(1-\tau_4)} - 1\right]/\phi_h \tag{11}$$

Following Hayashi (1979), however, we modify the investment function in equation (11) to allow J_h to be a function not only of q_h, but also of the level of flow capital income at time t:

$$J_h = \alpha_2\left[\frac{q_h}{(1-\tau_2)(1-\tau_4)} - 1\right] K_h/\phi_h + (1-\alpha_2)Profit_h \tag{12}$$

This improves the empirical behavior of the specification and is consistent with the existence of firms that are unable to borrow and therefore invest purely out of retained earnings.

So far we have described the demand for new investment goods by each sector. We next assume that investment goods are supplied by a firm facing an optimization problem similar to those of the twelve industries described above (and not repeated here). Like the other industries, the investment sector demands labor and capital services as well as intermediate inputs. The only difference is that we assume there is no sector-specific resource (R) for the investment sector. The investment column in the input-output table is used to parameterize the investment sector's production function. As with the derivation above, there is a shadow "q" associated with investment in the investment goods sector.

B. Households

We assume that household behavior can be modeled by a representative agent with an intertemporal utility function of the form:

$$U_t = \int_t^{\infty} (\log\ C_s + \log\ G_s)e^{-\theta(s-t)}ds \tag{13}$$

where C_s is the household's aggregate consumption of goods at time s, G_s is government consumption at s, which we take to be a measure of public goods, and θ is the rate of time preference.[11] The household maximizes (13) subject to the constraint that the present value of consumption be equal to human wealth (H) plus initial financial assets (F), all defined in real terms:[12]

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[11] This specification imposes the restriction that household decisions on the allocations of expenditure among different goods at different points in time be separable.

[12] As before, n appears in (14) because the model's scaled variables must be converted back to their unscaled basis.

$$\int_t^{\infty}(P_s^c/P_s)C_s e^{-(rd_s-n)(s-t)}ds = (H_t + F_t) \tag{14}$$

Human wealth in real terms (that is, deflated by the price of aggregate output) is defined as the expected present value of future stream of after tax labor income of households:

$$H_t = \int_t^{\infty}\left[(1-\tau_1)\left(W_s^G L_s^G + W_s^C L_s^C + W_s^I L_s^I + \sum_{h=1}^{12} W_s^h L_s^h\right) + TR\right] / P_s e^{-(rd_s-n)(s-t)}ds \tag{15}$$

where TR is the level of government transfers, labor used directly by final consumption is L^C, labor used in producing the investment good is L^I, government employment is L^G, and employment in sector h is given by L^h. Financial wealth is the sum of real money balance (MON/P), real government bonds in the hand of the public (B), net holding of claims against foreign residents (A), the value of outstanding emissions permits (EP), and the value of capital in each sector:

$$F_s = MON_s/P_s + B_s + A_s + EP_s + q_s^I K_s^I + q_s^C K_s^C + \sum_{i=1}^{12} q_{is}K_{is} \tag{16}$$

where q_s^I is Tobin's Q for the investment good in period s, and q_s^C is Tobin's Q for the consumption of household capital in period s. Solving the household problem produces the familiar result that aggregate consumption is equal to a constant proportion of private wealth, where private wealth is defined as financial wealth plus human wealth.

$$C_t = \theta(F_t + H_t)P_t/P_t^c \tag{17}$$

However, based on the evidence cited by Campbell and Mankiw (1987) and Hayashi (1982) we assume that only a portion of consumption is determined by these intertemporally-optimizing consumers and that the remainder is determined by after tax current income (INC). This can be interpreted as liquidity constrained behavior or a permanent income model in which household expectations regarding income are backward-looking. Either way we assume that total consumption is a weighted average of the forward looking consumption and backward-looking consumption:

$$C_t = \alpha_8\theta(F_t + H_t)P_t/P^c_t + (1 - a_8)(INC_t)P_t/P^c_t \tag{18}$$

where α_8 is the marginal propensity to save for the liquidity-constrained or backward-looking households.

Once the level of overall consumption has been determined, spending is allocated among goods and services. Households demand each of the model's 12 commodities and also demand labor and capital services. Household capital services consist of the service flows of consumer durables plus residential housing. We assume that the household's preferences can be represented by a nested CES utility function.[13] At the top tier of the utility function, total consumption is allocated between capital and labor services, a basket of energy goods and a basket of non-energy goods. At the second tier, spending on energy and materials are disaggregated into demands for individual commodities according to CES functions. The result is a system of household demand equations which depend on the level of aggregate consumption and the price of the individual goods relative to the price of the consumption basket.

The supply of household capital services is determined by consumers themselves who invest in household capital, K^C_t in order to generate a desired flow of capital services, C^K_t according to the following production function:

$$C^K_t = \alpha K^C_t \tag{19}$$

where α is a parameter for the rate of flow of services from existing capital. Accumulation of household capital is subject to the accumulation equation below:

$$dK^C/dt = J^C_t - \delta^C K^C_t \tag{20}$$

We assume that changing the household capital stock is subject to adjustment costs so household spending on investment, I^C, is related to J^C_t by:

$$I^C = \left[1 + (\phi^C/2)(J^C/K^C)\right] J^C \tag{21}$$

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[13] This has the undesirable effect of imposing unitary income elasticities, a restriction usually rejected by data. Moreover, in the preliminary version of the model presented here, the elasticities of substitution have been constrained to be unity. We are in the process of estimating the elasticities econometrically using a long time series of input-output data. In future work we plan to replace this specification with one derived from the linear expenditure system to allow income elasticities to differ from one.

Thus the household's investment decision is to choose I^C to maximize:

$$\int_t^\infty \left(\alpha K_s^c - P_s^I I_s^C / P_s^{ck}\right) e^{-(rd-n)(s-t)} ds \tag{22}$$

subject to equations (19) through (21).

Solving this problem yields results similar to those discussed for firms above. However, since no variable factors are used in producing capital services, the first order conditions for the problem give investment as a function of the shadow price of capital:

$$J_h^C = \frac{(q_h^C - 1)K_h^C}{\phi_h^C} \tag{23}$$

and an equation for the shadow price of capital itself, where we have introduced $q^C = \lambda P^{ck}/P^I$:

$$\lambda_{ht}^C = \int_t^\infty \left(\alpha + \Phi_{hs}^C\right) e^{-(rd_h+\delta^C)} ds \tag{24}$$

where:

$$\Phi_{sh} = 0.5\phi_h(J_{hs}/K_{hs})^2 \tag{25}$$

Thus, the treatment of household capital is very similar to that used for producing sectors.

C. Government

We assume that the government in each country divides spending among final goods, services and labor according to the proportions in the input-output tables for 1987. The real value of this expenditure is assumed to be exogenous and constant in the future. The government finances this spending (plus interest payments on its debt and transfers to households) by levying sales, corporate and personal income taxes, and by issuing government debt. In addition, there can be taxes on carbon output and an investment tax credit. The government budget constraint can be written:

$$B_{t+1} = B_t + DEF_t \tag{26}$$

where the budget deficit (DEF) is defined in real terms and adjusted for inflation. The deficit is a function of interest payments (rB), total government spending on goods and labor (G), transfer payments to households(TR) and total tax collections from households and firms (T):

$$DEF_t = r_t B_t + G_t + TR_t - T_t \tag{27}$$

Assuming that agents will not hold government bonds unless they expect the bonds to be paid off eventually, we impose the following transversality condition:

$$B_t = \lim_{s \to \infty} B_s e^{-\int_t^s (r_v - n) dv} \tag{28}$$

If the government is fully leveraged, this allows equation (37) to be integrated and written as:

$$B_t = \int_t^\infty (T_s - G_s - TR_s) e^{-\int_t^s (r_v - n) dv} ds \tag{29}$$

Thus, the current level of debt will be equal to the present value of future primary budget surpluses.[14]

The implication of (29) is that a government running a budget deficit today must run an appropriate budget surplus at some point in the future. Otherwise, the government will be unable to pay interest on the debt and agents will not be willing to hold it. To ensure that (29) holds at all points in time we impose the following constraint: at every instant in time each government must levy an endogenously-determined lump sum tax equal to the value of interest payments on the outstanding debt.[15] In effect, therefore, any increase in government debt is financed by consols and future taxes are raised enough to accommodate the increased interest costs. Thus, any increase in the debt will be matched by an equal present value increase in future budget surpluses. Other fiscal closure rules are possible, such as always returning to the original ratio of government debt to GDP. These closures have interesting implications but are beyond the scope of this paper.

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[14] Strictly speaking, debt must be less than or equal to the present value of future budget surpluses. For tractability we assume that the government is initially fully leveraged so that this constraint holds with equality.

[15] In the model the tax is actually levied on the difference between interest payments on the debt and what interest payments would have been if the debt had remained at its base case level. The remainder, interest payments on the base case debt, is financed by ordinary taxes.

D. Financial Markets and the Balance of Payments

The six regions in the model are linked by flows of goods and assets. Flows of goods are determined by the import demands described above. These demands can be summarized to result in a set of bilateral trade matrices which give the flows of each good between exporting and importing countries. Thus, there is one 6 by 6 trade matrix for each of the twelve sectors.

Flows of financial assets are more complicated. The first difficulty is specifying the role of money in the model. It is a common dilemma in general equilibrium models to explain why agents hold money. A demand for money can only be derived from optimization if one of the following is true: money gives direct utility; money is a factor of production; or money must be used to conduct transactions. Following the approach taken in the MSG2 model,[16] we assume money enters via a constraint on transactions. This gives a money demand function in which the demand for real money balances is a function of GDP and short term nominal interest rates:

$$MON_t/P_t = (GDP_t)^{\alpha_3}(1+i_t)^{\alpha_4} \tag{30}$$

where α_3 is the income elasticity of money demand, α_4 is the interest rate elasticity of money demand, i_v is the nominal interest on government debt in period v. The supply of money is determined by the balance sheet of the central bank and is exogenous.

We assume asset markets are perfectly integrated across the OECD regions. With free mobility of capital, expected returns on loans denominated in the currencies of the various regions must be equalized period to period according to a set of interest arbitrage relations of the following form:

$$i_k = i_j + ({}_tER^j_{kt+1} - ER^j_{kt})/ER^j_{kt} \tag{31}$$

where ER^j_{kt} is the exchange rate between currencies of countries k and j. There is no allowance for risk premia on the assets of alternative currencies. The assumption of perfect capital mobility and zero risk premia for the major economies is chosen in light of the failure of the empirical exchange rate literature to demonstrate the existence of stable risk premia across international currencies. In the simulations of the model, this is equivalent to assuming that any risk premia are independent of both the shocks imposed on the model and of the subsequent adjustment of any endogenous variables.

Any trade imbalances are financed by flows of assets between countries. To determine net asset positions we make several simplifying assumptions.

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[16] See McKibbin and Sachs (1991) for more detail.

Some external financing will be exogenously determined by creditors. The remaining will be private capital for either portfolio or direct investment. Because all domestic assets are assumed perfect substitutes, the returns to these activities will be equalized. This implies that the composition of capital flows can be assumed to be in fixed proportions of portfolio investment, direct investment, and other capital flows. These proportions can be obtained from the allocation of assets in the model's base year dataset. All other net capital flows are restricted to be consistent by imposing the constraint that current account balances and trade account balances sum to zero for the world as a whole. For the major industrialized economies, the current account is determined under the assumption that domestic agents have free un-rationed access to international borrowing and lending at the international interest rate. For simplicity we assume that all international borrowing and lending takes place in the currency in which debt is denominated in the MSG database.

For the three non-OECD countries it is not reasonable to assume that exchange rates are free to float or that capital is freely mobile both within the regions and between the regions and the rest of the world. Instead we assume that these three regions peg their exchange rates to the US dollar. In addition, we assume that OPEC chooses its foreign lending in order to maintain a desired ratio of income to wealth. The EFSU and LDC regions are assumed to be constrained in what they can borrow from the rest of the world. Given their exogenously determined borrowing and endogenously determined exports and debt servicing costs, these regions then allocate any remaining funds to imports.

3. Data, Parameterization and Model Solution

The data used in G-Cubed comes from a number of sources which are listed in a technical Appendix available on request from the authors. The production and consumption parameters are still under development but are currently established by assuming unitary price elasticities and obtaining share parameters from a 1987 U.S. input-output table prepared by the Bureau of Labor Statistics. In lieu of obtaining input-output tables from Japan and the ROECD region, we currently create the tables for these regions based on the U.S. table and adjusted for actual final demand components from non-U.S. data. In effect, we are assuming that all industrial countries share the same production technology but differ in their endowments of primary factors and patterns of final demands. This assumption is a temporary necessity while we complete the model's database.

Next we assume the underlying long run rate of population growth plus productivity growth in 2.5 percent per annum. We also assume that the long run real interest rate is 4.5 percent in the baseline.

Trade shares are based on the United Nations SITC (Standard Industry Trade Classification) data for 1987 with sectors aggregated from 4 digit levels to map as closely as possible to the US Standard Industry Classification (SIC).[17] Trade price elasticities will be estimated in future work.

The parameters on shares of optimizing versus backward looking behavior are taken from the MSG model. These are based on a range of empirical estimates as well as a tracking exercise used to calibrate the MSG model to the experience of the 1980s.

G-Cubed is solved using software developed by McKibbin (1992) for solving large models with rational expectations on a personal computer.[18] The model has approximately 2100 equations in its current form with 47 costate (jumping or forward looking) variables. The first step in the solution algorithm is to use numerical differentiation to linearize the model around its 1987 database. Following this, linear algebra is used to transform the model into its minimal state-space representation. The eigenvalues of this reduced model are then calculated to ensure that the condition for saddle-point stability is satisfied (that is, that the number of eigenvalues outside the unit circle are equal to the number of costate variables). The algorithm then searches for the stable manifold which gives the adjustment of the costate variables in response to all inherited variables in the model. Once this is found the model can simulate various shocks.

4. Two Representative Simulations

We now present results from two simulations designed to investigate the link between trade flows and environmental policy. In each simulation an unexpected permanent carbon tax of $15 per ton of carbon is levied in the United States beginning in 1992. In one simulation, however, the US introduces the

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[17] A full mapping of SITC and SIC codes is contained in a technical appendix available from the authors by request.

[18] The software developed for solving this model has been written in the GAUSS programming language. See GAUSS (1992).

tax unilaterally while in the other simulation the tax is introduced simultaneously in all OECD countries.[19] In both cases we assume that carbon tax revenues are used to lower the budget deficit in the levying country.

Figures 2 and 3 show the macroeconomic effects of the two simulations on the United States over the next one hundred years.[20] Figure 2 presents results for GDP, the balance of trade, the fiscal deficit and the current account.[21] The change in GDP is expressed as a percentage deviation from the base case while changes in the remaining variables are shown as percentages of base case GDP. Figure 3 presents changes in short and long run interest rates (both real and nominal), changes in the nominal exchange rate relative to the Yen and the ECU, and changes in the rate of inflation. Changes in the exchange rate are expressed as percentage deviations from the base case while changes in the other variables are given in percentage points.

As an example of how the graphs may be interpreted, consider the upper left panel of Figure 2. That panel presents the results for U.S. real GDP as percentage deviations from the baseline. For the unilateral tax, real GDP falls by 0.4 percent at the announcement of the policy in 1991. By the year 2000 GDP has recovered slightly but is still below the value it would have had in the base case in 2000.

Figure 4 shows the effect of the unilateral US tax on US prices, output, employment, and capital stocks. Each variable is shown as its percentage deviation from the base case. Sectors are indicated by the fourth character of each variable name (e.g., OUP5UUNC is output in sector 5 in the US) and are numbered from 1 through 9 and then A to C, as shown in Table 1. At the industry level, the unilateral and multilateral taxes are very similar, so we have omitted the corresponding graphs for the multilateral case.

Our discussion of these results will first focus on the unilateral tax and will then move on to a comparison of the two simulations.

A. The Effects of a Unilateral Carbon Tax

The first panel of Figure 2 shows result familiar from other studies of carbon taxes: the tax reduces GDP by a small percentage, in this case by 0.55

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[19] A wider range of simulations are considered in McKibbin and Wilcoxen (1992).

[20] All figures have been drawn using the cellVision software program developed by Tomas Bok (1992).

[21] In each figure the key indicating the variable plotted refers to the variable name as it appears in the model. Definitions of these variables are given in the technical Appendix available from the authors.

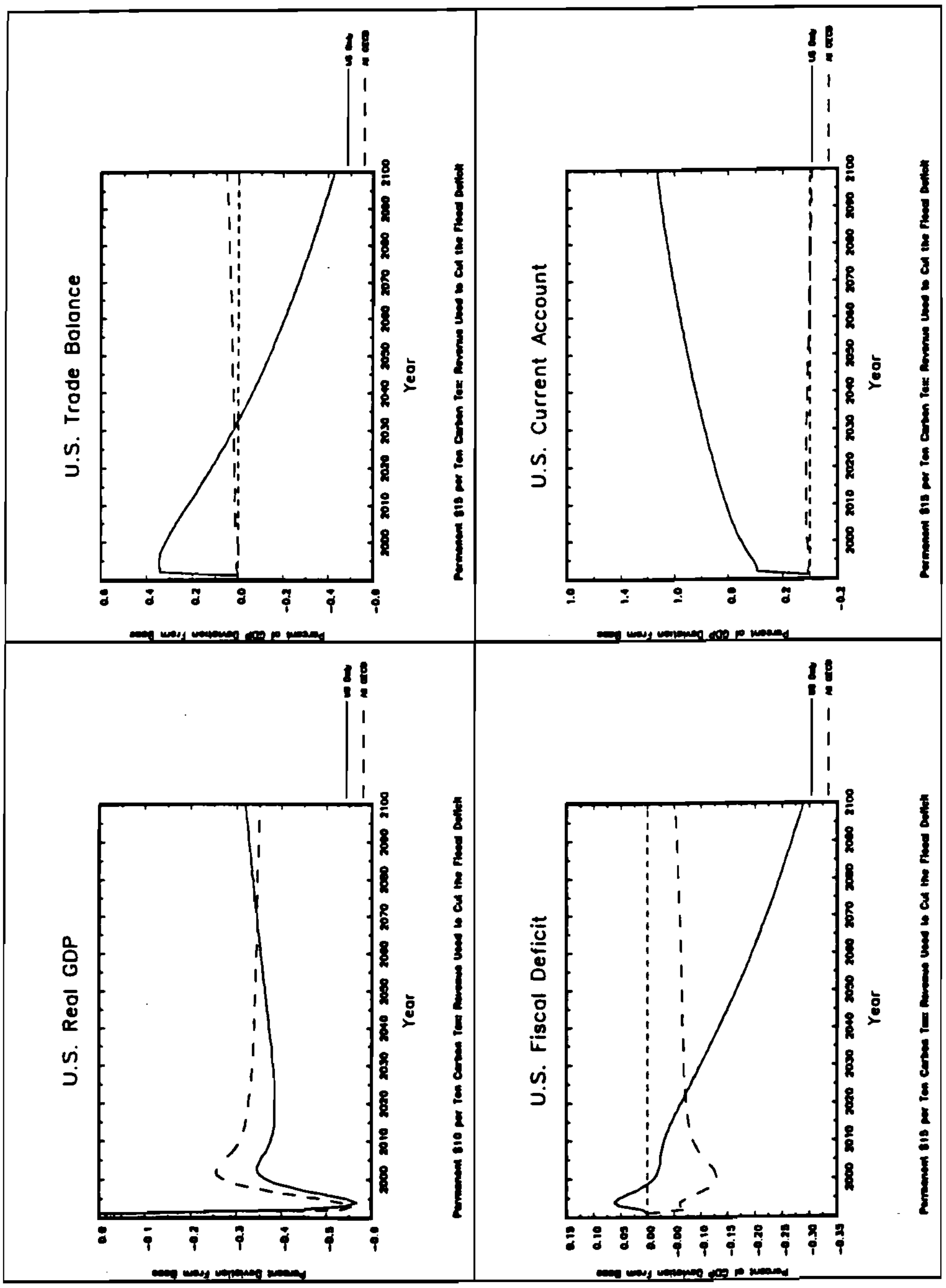

Figure 2. Permanent $15 per ton carbon tax.

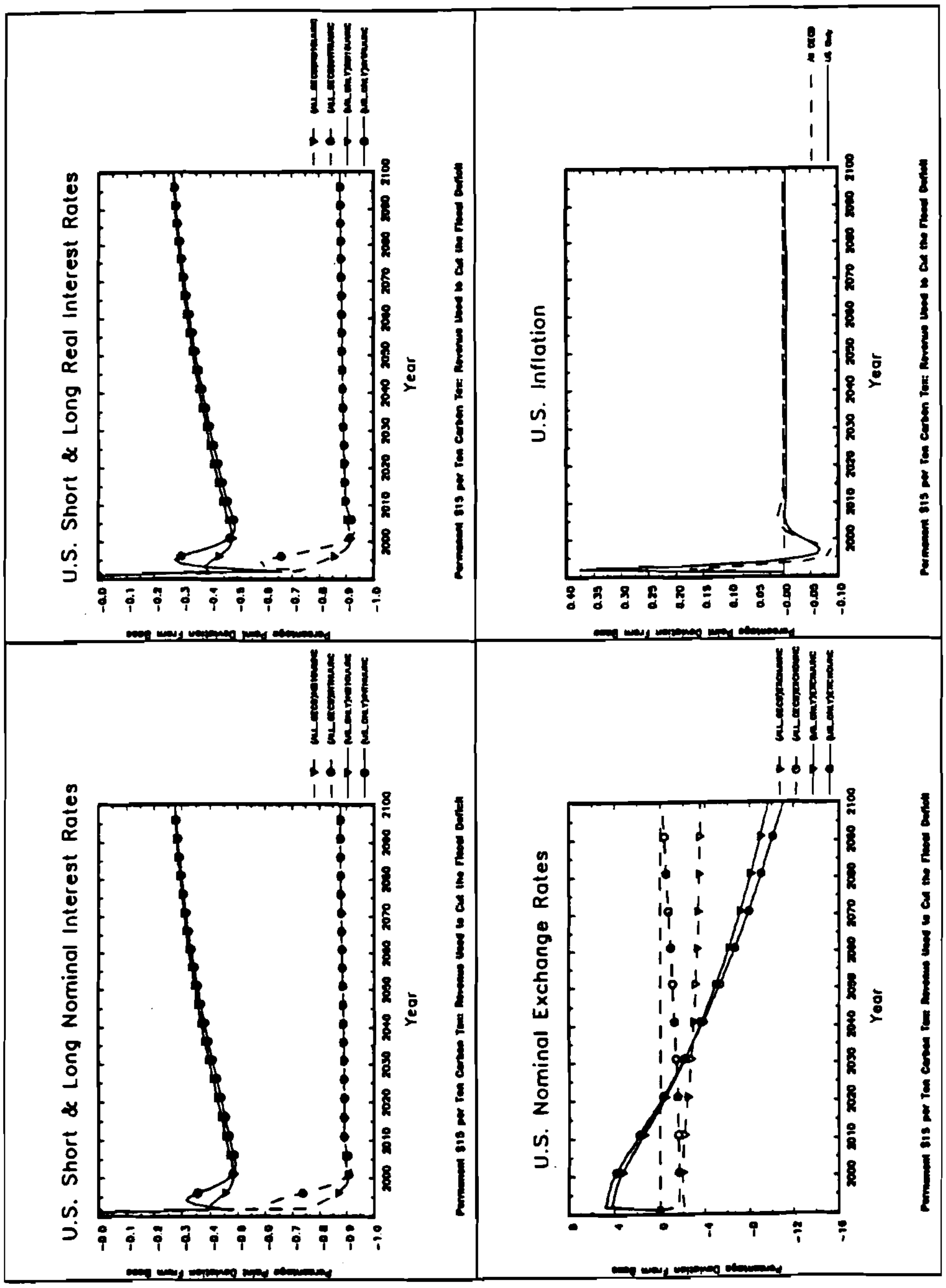

Figure 3. Permanent $15 per ton carbon tax.

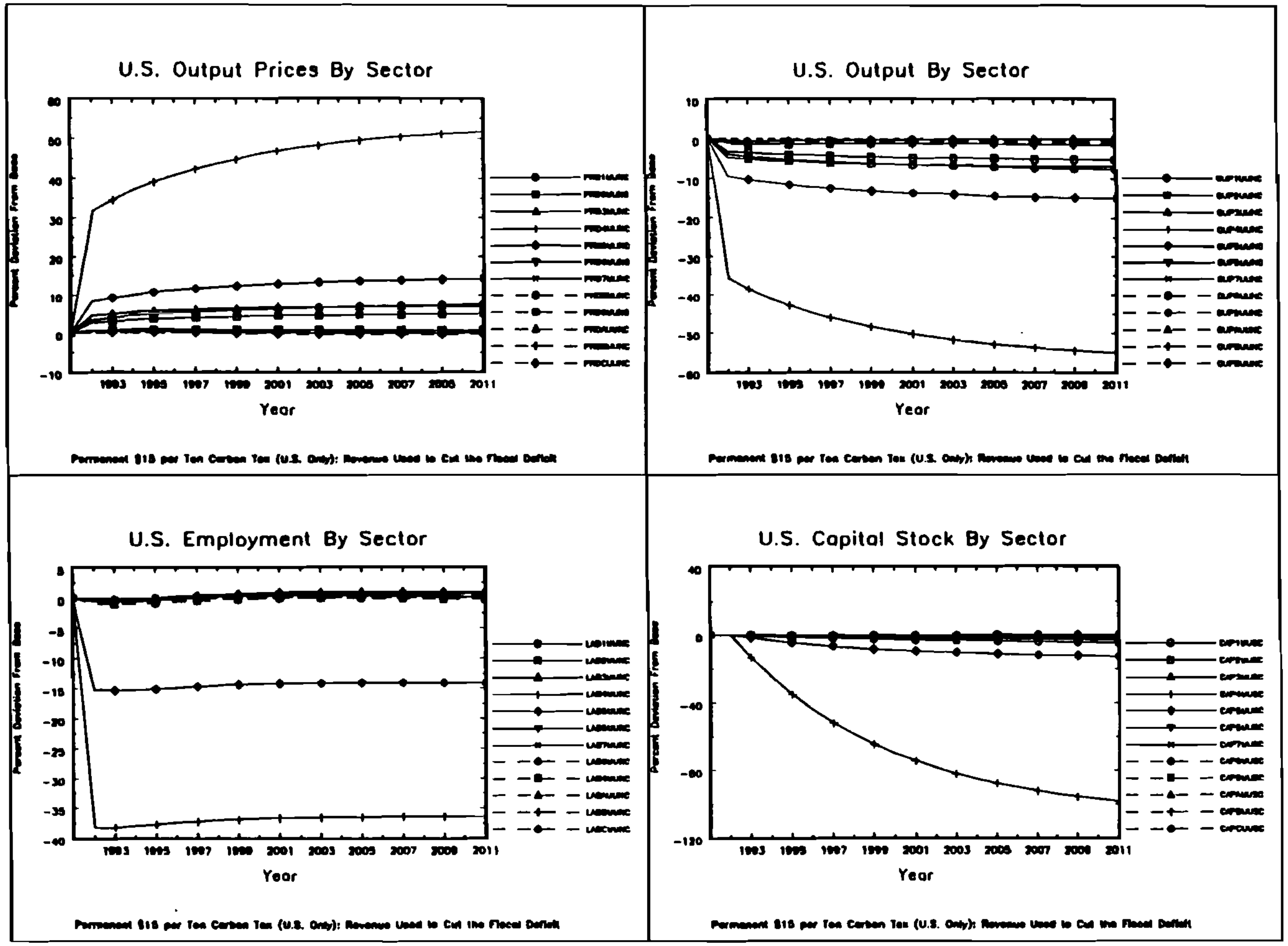

Figure 4. Permanent $15 per ton carbon tax in the U.S. only.

Table 1. Definition of sectors.

1	Electric Utilities
2	Gas Utilities
3	Petroleum Refining
4	Coal Mining
5	Crude Oil and Gas Extraction
6	Nonfuel Mining
7	Agriculture, Fishing and Hunting
8	Forestry and Wood Products
9	Durable Manufacturing
A	Nondurable Manufacturing
B	Transportation
C	Services

percent by 1994. After this, however, GDP recovers slightly. This recovery is due to a fall in real wages in response to the rise in unemployment, and as a consequence of lower real interest rates reflecting a decline in the marginal product of capital. Revenue from the tax is close to $26 billion (1992) dollars in 1992 and this revenue grows at the real growth rate of the economy. The fall in output reduces other tax revenue and despite the carbon tax, the deficit rises slightly for the first decade.

The fall in real interest rates in the United States leads to a capital outflow which has a counterpart in the improvement in the trade balance of 0.3 percent of GDP in 1992 (or close to $18 billion in 1992 dollars). This result is an important implication of our macroeconomic framework which explicitly incorporates international capital flows, and is strikingly different from the results of other studies in which capital flows are ignored. Other studies typically find that a carbon tax causes the U.S. balance of trade to deteriorate as U.S. exports become less competitive. In contrast, we find that in the short to medium term, the movement of capital in response to changes in real interest rates determines the effect on the overall trade balance. Substitution away from carbon intensive U.S. goods does occur but is overwhelmed by the capital flow effect. The fall in interest rates also depreciates the U.S. dollar by close to 4 percent. In addition there is a decline in U.S. domestic demand. Both factors enable the emergence of a trade balance surplus which is consistent with the capital outflow. The capital outflow also serves to lower world interest rates, stimulating real capital accumulation and lowering the foreign marginal product of capital.

The industry-level effects shown in Figure 4 make it clear that the coal industry (sector 4) will be the most strongly affected by the tax. The price of coal rises by 35 percent in 1992 and as the industry's capital stock falls the price rises even further, to over 50 percent above baseline by 2010. Natural gas prices rise by 10 percent and refined petroleum by 5 percent on impact. This result is similar to that found by Jorgenson and Wilcoxen (1991a).

These price increases translate directly into falls in output. Coal output falls by 35 percent when the tax is imposed in 1992 and then continues to decline as the industry's capital stock falls. By 2010, output is 50 percent below the baseline. The employment consequences of the tax are similar to the effects on output, but more severe in the short run (since capital is fixed). Employment in the coal industry declines by 37 percent. In the natural gas and crude oil extraction sectors employment falls by close to 15 percent.

Despite the rise in the relative price of carbon intensive goods in the U.S. the substitution into imported carbon-intensive goods is not sufficient to greatly offset the fall in global carbon emissions. The impact of the U.S. carbon tax on carbon emissions in the United States is to reduce these emission by 29.7 million tons in 1992. These emissions fall by 50.3 million tons relative to base by the year 2000. Using the same emission coefficients for the world as for the United States, global emissions fall by 32.6 million tons in 1992 reflecting the global fall in economic activity. By 2000 global emissions are down by 53.9 billion tons. These estimates of global emission probably overstate the decline because non-OECD production is likely to have a higher carbon output per unit of production than the U.S. production which is being reduced. However, the results strongly suggests that the impact effect of the U.S. tax would be to reduce global carbon dioxide emissions.

B. The Effects of a Multilateral Tax Imposed in all OECD Economies

The first difference between this simulation and the unilateral tax is surprising: the initial fall in U.S. GDP is larger for the OECD carbon tax – approximately 0.5 percent in 1992, a value not reached until 1994 under the unilateral tax. This comes about because the multilateral tax reduces global aggregate demand and hence the demand for U.S. exports. In the long run, however, the drop in U.S. GDP is smaller in the case of the OECD carbon tax: 0.3 percent by 2010 for the global tax versus nearly 0.4 percent for the unilateral U.S. tax. This occurs for two reasons. The first is that U.S. and foreign consumers and firms do not substitute away from high carbon U.S. goods to high carbon ROECD goods because both rise in price in the case of the multilateral tax. Secondly, the fiscal implications of the tax at the OECD level are larger for the OECD policy. Real interest rates fall by twice the amount they do when the United States acts alone. The fall in real interest rates of 80 basis points stimulates demand and offsets some of the contractionary effect of the carbon tax.

The unilateral and multilateral taxes also affect the U.S. trade account much differently: the multilateral tax essentially leaves the trade balance and the current account unaffected. This occurs because the multilateral regime eliminates most of the incentives for changes in the pattern of capital and goods flows. Under the multilateral tax, both U.S. and overseas rates of return on capital fall, so there is little change in the pattern of capital flows. At the same time, both U.S. goods and imports become more expensive, so there is little change in the pattern of goods flows. Thus, under the unilateral tax this improves the U.S. current account by over 0.3 percent of GDP in 1992, while under the multilateral tax, the improvement virtually disappears.

It is important to note that the accumulation of foreign assets plays an important role in the long run. This can be seen by comparing the paths for GDP and private consumption. In the case of the multilateral carbon tax, GDP fluctuates and then stabilizes about 0.35 percent below the baseline. Under the unilateral tax, however, GDP fluctuates but then gradually rises. This occurs because under the unilateral case, the U.S. trade balance improves, reducing the rate at which the U.S. borrows from abroad. This reduction in net foreign debt lowers future interest payments overseas, leading to a stronger long run real exchange rate, falling import prices and gradually rising output. By 2100 this effect has almost balanced the loss (measured in terms of GDP) between the unilateral and multilateral carbon taxes.

Calculating the impact of the OECD tax on carbon dioxide emissions produces several interesting results. The OECD-wide carbon tax reduces U.S. emissions by 29 million tons in 1992. This is 0.7 million tons less than for the U.S. only tax. Global carbon emissions fall by 92.3 million tons in 1992. By 2000 the global emission of carbon dioxide is reduced by 152 million tons.

5. Conclusion

In this paper we have presented the structure of G-Cubed, a model designed to explore the links between environmental policy and international trade.

We have also presented results for two simulations in which this link is apparent: a unilateral carbon tax imposed in the U.S. and a multilateral tax levied throughout the OECD. These results are still preliminary but clearly show both the feasibility and the importance of integrating macroeconomic and computable general equilibrium models into a consistent empirical framework for analyzing these kinds of policies.

A number of areas of the model need further work. The model's parameterization is preliminary and econometric work is currently underway to improve it substantially. In addition, more data is needed to parameterize the non-U.S. economies, which are now based on U.S. data. A further area where more work on the model's data set is needed is the treatment of trade in services. Data on trade in services is often unavailable so we are in the process of constructing a matrix of inferred bilateral trade in services by using information we currently have on individual country aggregate export and imports of services.

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The Likely Economic Impact of the Proposed Carbon/Energy Tax in the European Community[1]

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1. Introduction

The European Community has committed itself to the stabilization of its aggregate CO_2 emissions by the year 2000 at the 1990 level. The Commission of the European Communities has recently proposed a strategy for reaching this objective. This strategy consists of three main components:

- First, a set on regulatory, voluntary and research, development and demonstration measures. The main focus of these measures is on improving the rational use of energy, the diffusion of low-carbon technologies and the promotion of renewable energy sources.
- Second, a new combined carbon/energy tax to be gradually phased-in, reaching a level of US$ 10 per barrel of oil equivalent (ECU 0.7 per Giga-Joule and ECU 35 per ton of carbon) by the year 2000.
- Third, national programmes containing those CO_2 emission limitation measures which do not require Community involvement, but which can be taken independently at the national or even sub-national level.

All three components taken together are considered sufficient to allow the Community's carbon dioxide emission stabilization objective to be reached. Thus, although *the proposed carbon/energy tax is only one part of a comprehensive strategy*, it has nevertheless attracted by far the greatest attention in the media.

In this paper, a brief summary is provided of the analysis that has been undertaken concerning the likely economic impact of the proposed carbon/energy tax. In this analysis, the main emphasis is on the initial impact

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[1] This paper draws on "The Climate Challenge – Economic Aspects of the Community's Strategy for Limiting CO_2 Emissions", *European Economy* 51, May 1992. Views expressed in this paper represent the positions of the authors and do not necessarily correspond to those of the Commission of the European Communities.

of the tax. Although to some extent the analysis has a crude "back-of-the-envelope" character, it nevertheless allows a first assessment of the likely economic impact of the proposed tax to be made. Detailed results, as well as a discussion of the economic philosophy of the strategy, of alternative approaches and of the issues of practical implementation, can be found in two volumes of "European Economy" (Commission of the European Communities, 1992a; 1992b).

2. The Macroeconomic Effects

With respect to the macroeconomic effects, it is important to distinguish between the short or medium-term effects (up to seven years, say) and the long-term impacts (beyond seven years). Here, the focus is mainly on the short and medium-term effects, a choice that has also been partly determined by the analytical tools available.

Generally, three key factors are involved in determining the macroeconomic impact:

- First, the type of carbon/energy tax revenue use. *A priori*, there are two main options: either the tax revenues are used for improving the budget balance or adjustments are made to other parts of the budget so as to keep the budget balance unchanged. The latter could be done by using the carbon/energy tax revenues either for financing higher expenditures (budget balance neutral) or for cutting other taxes (revenue neutral). Without such a "recycling" of the tax revenues back into the economy, the introduction of the tax would tend to both raise the general price level and to slow down economic growth, at least in the short run.[2] Revenue neutrality, on the other hand, tends to restore aggregate demand even in the short run (as does budget neutrality), without necessarily reducing aggregate supply. It is therefore likely to be a particularly attractive option concerning the use of carbon/energy tax revenues.
- The second key factor is that, although adjustment will be necessary and entail some costs, these costs will be low if markets are flexible and the tax is phased in gradually and predictably.[3] Of particular importance is

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[2] In the long run, the picture may be different as an increase in national savings may lead to an acceleration in investment and eventually to an increase in GDP [see, e.g., U.S. Department of Energy (1991, Chapter 9)].

[3] The importance of the predictability aspect is clearly highlighted by Dale Jorgenson's and Peter Wilcoxen's conclusion that approximately 2/3 of the GDP losses attributed to the oil price shocks of the 1970s and 1980s are due to the surprise element and not to the price increase in itself [see Jorgenson and Wilcoxen (1990)].

the avoidance of a tax-induced wage-price spiral by orienting wage claims at real after-tax incomes rather than at gross wages. Thus, a societal consensus concerning the pursuit of such an environmental policy may significantly contribute to limiting its macroeconomic costs.

- Third, even when abstracting from the environmental benefits, the introduction of such a tax could also have a positive impact on economic welfare if the tax revenues were to be used for increasing the economy's structural adjustment potential and for lowering existing, strongly distortionary taxes. While for the United States some models suggest the existence of such positive welfare effects [see, e.g., Shackleton *et al.* (1992)], no such analysis has been undertaken for the European Community to date. Thus, more analysis is required for assessing quantitatively such a potential for welfare gains in the Community.

Although the illustrative macroeconomic simulation results presented in Table 1 allow a preliminary assessment, they nevertheless illustrate that the specific type of tax revenue redistribution has a significant influence on the macroeconomic impact of the carbon/energy tax.[4] While, for example, a revenue redistribution in the form of a reduction in income taxes tends to restore disposable income and thereby private consumption, the comparatively strong inflationary effect of the tax-induced increase in the general price level tends to lead to a noticeable slow-down in economic activity. A compensatory reduction in employers' social security contributions, on the other hand, reduces this price and cost increase and consequently favors private investment. Using the carbon/energy tax revenues for reducing value added taxes may lead to even more favorable effects.

The preliminary evidence emerging from the available simulation studies points to the conclusion that in some econometric models (for example, the QUEST model used here), economic activity is relatively sensitive to inflationary shocks. In these cases, a carbon/energy tax revenue "recycling" via a reduction in other indirect taxes (social security contributions or value added tax) tends to lead to significantly lower GDP losses (or even GDP gains) compared to alternative tax revenue redistribution schemes, at least in the short and medium-term.

Thus, according to the macroeconometric models used in this report, in the short to medium-term, a loss of GDP of the order of 0.5–1.0% compared to the reference scenario would appear the most likely scenario in the case of

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[4] This result is also confirmed by simulations undertaken with a different (macrosectoral) model for the four largest Member States of the European Community [see Standaert (1992)].

Table 1. Economic effects of a CO_2/energy tax of approximately 10$ per barrel of oil equivalent: Aggregate QUEST model results for all Member States.[a]

	Scenario			
	Without revenue redistribution[b]	Redistribution via personal income taxes[c]	Redistribution via employers' social security contributions[c]	Redistribution via VAT[c]
Volumes				
private consumption	-1.9	-1.0	-0.7	0.4
private investment	-2.2	-2.0	-1.9	0.7
exports	-2.0	-2.2	-1.4	-2.5
imports	-2.9	-2.1	-1.6	-2.3
GDP	-1.2	-1.1	-0.7	-0.1
employment	-0.4	-0.3	-0.0	0.1
Prices				
CPI	3.8	3.5	2.5	0.9
export deflator	3.2	2.8	1.8	3.0
import deflator	3.2	2.1	1.0	2.9
real unit labor costs	-0.3	-0.4	-0.6	-0.2
Ratios[d]				
budget balance	0.7	0.1	0.0	-0.1
current balance	0.3	0.2	0.3	0.0

[a] All variables, unless otherwise stated, in percentage change in the level after 5 years, compared to the reference case. All scenarios have been computed in linked mode.
[b] In these scenarios, the policy is pursued by all EC Member States, the USA and Japan.
[c] In these scenarios, the policy is pursued by all Member States.
[d] Differences in % of GDP.
Source: Commission Services.

a revenue neutral carbon/energy tax of approximately 10 US$ per barrel of oil equivalent. However, other models, in particular those assuming a higher degree of flexibility, may show smaller GDP losses. Thus, simulations of the proposed EC tax using the OECD Secretariat's GREEN model only result in GDP losses of 0.2% by the year 2000 (rising to 0.5 by the year 2050). Over the long run, both types of models tend to arrive at similar results.

The macroeconomic effects of the tax depend not only on the type of revenue "recycling", but also on the country concerned. Thus, as illustrated in Table 2, there are likely to be significant differences in the macroeconomic impact of the proposed tax on different Member States of the European Community. However, the evidence given by different econometric models is, at this stage, conflicting and therefore does not allow any firm conclusions to be drawn. This is illustrated, for example, by a comparison of the QUEST simulation results with the results of a simulation with the DRI econometric model (see Table 2). Although the definition of the scenarios differs somewhat between the two simulation exercises[5], it is nevertheless apparent that for some countries there are significant differences between both types of models, while the aggregate result for the Community as a whole is of the same order of magnitude. At the same time (but not shown here), the QUEST simulation results also indicate that a country's aggregate energy intensity (which tends to be higher in the less prosperous Member States of the Community) is a poor guide for assessing the likely macroeconomic effects, in particular in the case of a revenue neutral introduction of a carbon/energy tax.

3. The Sectoral Effects

As far as the sectoral effects are concerned, the analysis reveals that the likely impact on different industrial sectors depends not only on the specific type of tax revenue redistribution and the energy intensity of output of different sectors, but also on a whole chain of other determinants such as the magnitude of the effect on output prices, the intensity of international trade and the demand response to higher output prices. From this analysis it becomes clear that, in the short-term, the impact strongly depends on the initial sectoral cost structure, which in turn reflects the sectoral energy intensity as well as the existing level of energy prices. In the medium and long run, substitution possibilities are likely to change the picture to a considerable extent.

The sectoral impact of the tax can also be shown to depend strongly on the structure of the energy system, the size of existing tax rates on energy products and the modalities of the tax. The importance of differences in the national fuel mix is clearly illustrated in Figure 1, showing the carbon intensity of electricity generation in different Member States. As a result, the analysis reveals that a pure carbon tax would tend to imply larger differences as regards the sectoral impact than a pure energy tax. Similarly, it appears that in the case of a tax on final energy consumption, inter-country differences in the impact of the tax on energy prices generally tend to be smaller

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[5] The DRI scenario is a "mixed" scenario where the tax revenues are redistributed through a variety of tax cuts. Moreover, the DRI simulation also contains a series of non-fiscal energy saving measures.

Table 2. Impacts on Member States' GDP in various CO_2/energy tax cum "revenue recycling" scenarios with the DRI and QUEST Models.

		QUEST[a,b]		
	DRI[c] package	Personal income tax scenario	Social Security contributions of employers scenario	VAT scenario
B	-1.4	-0.3	-0.6	-0.3
DK	-1.3	-1.1	-0.4	-1.2
D	-0.8	-0.6	-0.3	-0.0
GR	-0.5	-1.8	-1.5	-1.3
E	-0.4	-1.2	-0.7	0.1
F	-0.6	-1.1	-1.3	-0.4
IRL	-0.8	-1.8	-0.6	-0.7
I	-0.9	-1.3	-1.0	-0.1
L	n.a.	-0.7	-0,2	-0.6
NL	-1.0	-1.6	-1.0	-0.3
P	-1,5	-1,6	-1,4	0.0
UK	-1.2	-0.7	+0.1	0.5
EC	-0.9	-1.0	-0.7	-0.1

[a] The aggregate results of these scenarios are presented in Table 1.

[b] Change in the level of GDP in the fifth year the – one shot – introduction of the CO_2/energy tax compared to the reference case.

[c] Change in the level of GDP in the fifth year in which the tax is fully in situ compared to the reference case.

Source: DRI and Commission Services.

than for a tax on the production or import of primary energy. This points to the fact that conversion losses also differ markedly between Member States.

A careful analysis of the present situation in manufacturing industry in those five Member States for which detailed statistics are available (Belgium, Germany, Spain, Denmark and United Kingdom) reveals that although there is a small group of potentially sensitive branches, most sectors have a low share of *direct energy costs* in total production costs. Thus, *for the great majority of manufacturing industry, direct energy costs only represent between 0% and 5% of total production value* (see Figure 2). According to the available – admittedly incomplete – data, these sectors represent approximately 85% of industrial employment. The average direct energy cost share for the manufacturing sector varies between 2.5% and 4%, respectively, according to the country considered.

Although there are a small number of energy intensive sectors which cluster around an average energy cost share of between 10% and 20%, these

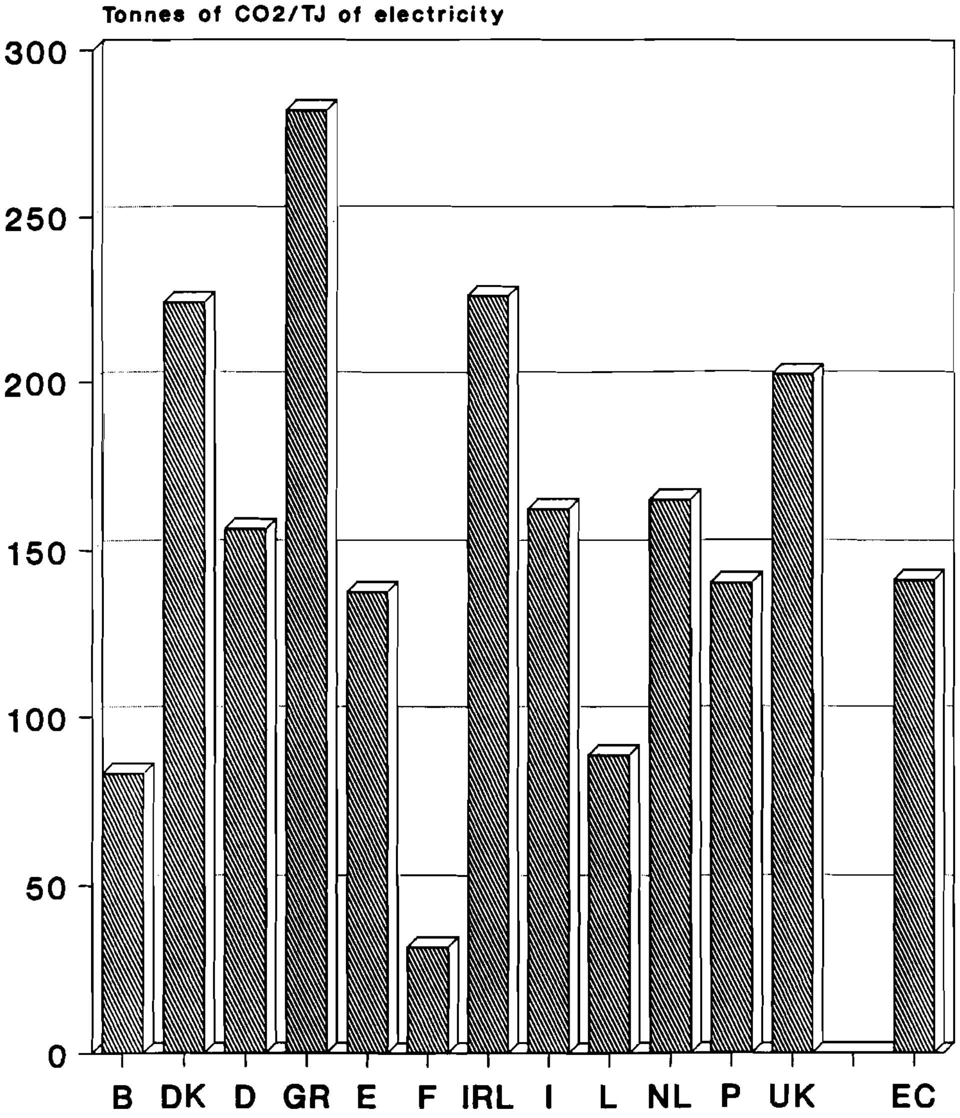


Figure 1. CO_2 emission intensity of electricity generation. Source: Commission Services.

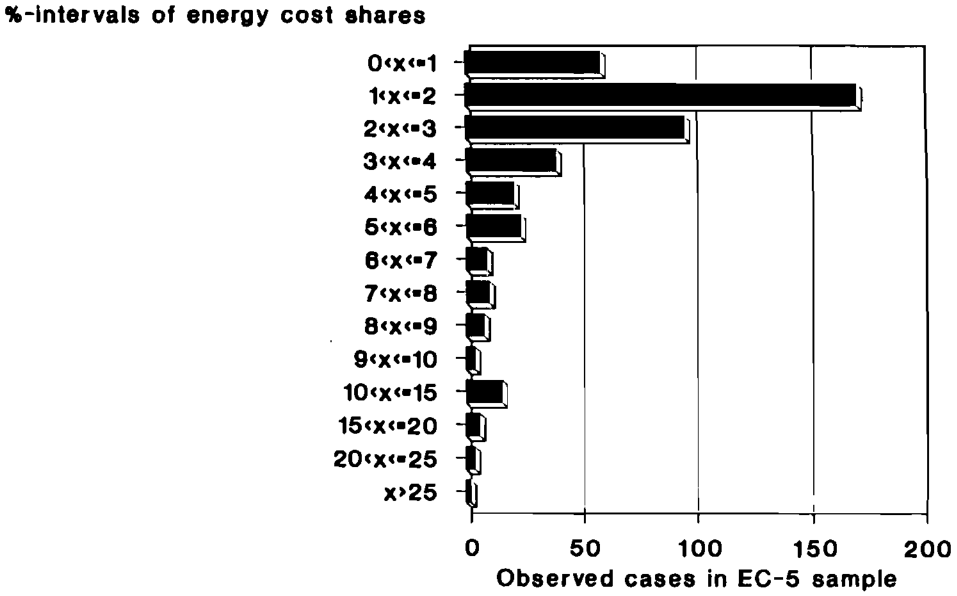


Figure 2. Sectoral energy cost shares. Frequency distribution of NACE 3 digit sectors over %-intervals of energy cost shares in industrial production. Note: The numbers of 1988 energy cost shares in total production cost of manufacturing industry in 5 EC countries (B, D, F, E, P) have been plotted over intervals of energy cost shares. Source: Commission Services, National Statistical Offices.

are only eight out of a total of 130 sectors. Moreover, some of these sectors cannot be classified as being exposed to strong international competition (e.g., heat generation and distribution, see below). On the basis of the available data, it appears that the branches with a share of energy costs in total costs of more than 10% ("potentially sensitive sectors") represent approximately 6% of industrial employment.

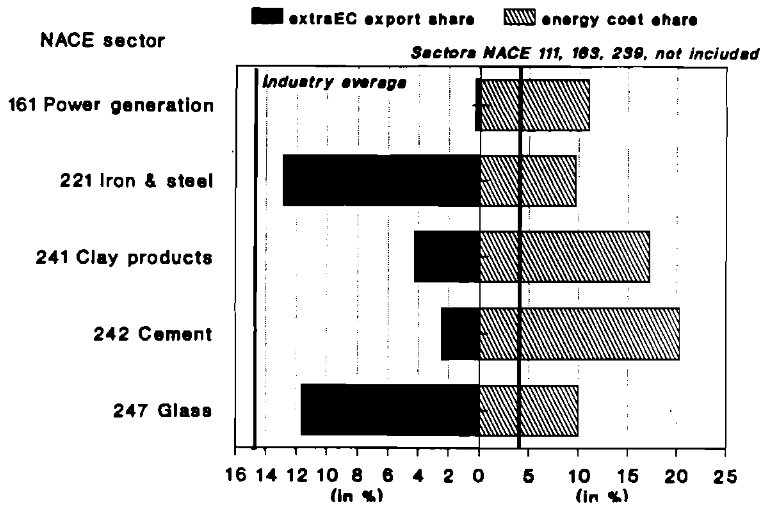
In a second group of (approximately twelve) branches, the energy cost shares lie between 5% and 10%, so that these sectors can be considered as being potentially moderately sensitive to energy cost increases. In terms of employment, these sectors represent approximately between 5% and 6% of industrial employment. Even if the available evidence is only sketchy, there is nevertheless the impression that, in these moderately sensitive sectors, the direct energy cost shares appear to be higher in Southern Member States compared to Northern Member States. Such differences do not appear to reflect differences in pre-CO_2/energy tax prices, but rather seem to be largely attributable to differences in production technologies.

It is interesting to note that for most industrial branches with a high energy cost share, exports represent a smaller share of production than on average in the manufacturing industry. This point is illustrated for the case of extra-EC *exports* in Figure 3. Only a few branches appear to be both energy and import intensive. For extra-EC imports, a similar observation holds. However, for an in-depth assessment it would be necessary to go beyond this static analysis and to also look at the degree of competition and the size of price elasticities on the respective markets.

Direct energy costs only represent part of the energy costs borne by companies. In order to investigate the *total incidence* of the introduction of carbon/energy taxes, an input-output analysis has been undertaken for a few selected Member States for which the necessary statistical information is available [France, Germany, Denmark and Italy; see also Martin and Velazquez (1992) for an application to Spain]. Although such an analysis has the disadvantage of implying a higher degree of sectoral aggregation (approximately 40 sectors compared to 130), it has the advantage of allowing an assessment to be made of the impact of energy costs embedded in companies' intermediate inputs and of the importance of the product structure of energy consumption for the overall tax incidence. For analytical purposes, the analysis – both for the case of a tax on primary energy and for a tax on final energy consumption – has assumed that no sector is exempted from the tax. Moreover, no macroeconomic feedbacks are taken into account.

It emerges from this input-output analysis that although for a significant number of energy price sensitive sectors the conclusions are, for most countries, quite similar when looking at total cost shares compared to only direct cost shares (e.g., cement, iron and steel), for others the picture may differ significantly (e.g., glass, hard coal extraction). Assuming that the increase in input costs would be fully passed through to output (production) prices – which, in turn, will have an effect on competitiveness – the following assessment can be made (see Table 3). Only iron and steel, special steel production and cement industries would experience production price rises of between 5% and 10%. For the other energy intensive branches, this increase would lie between 2% and 4%. A large number of – in economic terms very large – service branches would only experience price increases of significantly less than 1%. The analysis also showed that, in view of the strong differences in the fuel-mix used in electricity generation already referred to above, the precise impact of a carbon/energy tax may differ significantly among Member States, depending on the precise type of the tax.

a) Potentially sensitive sectors



b) Potentially moderately sensit.sectors

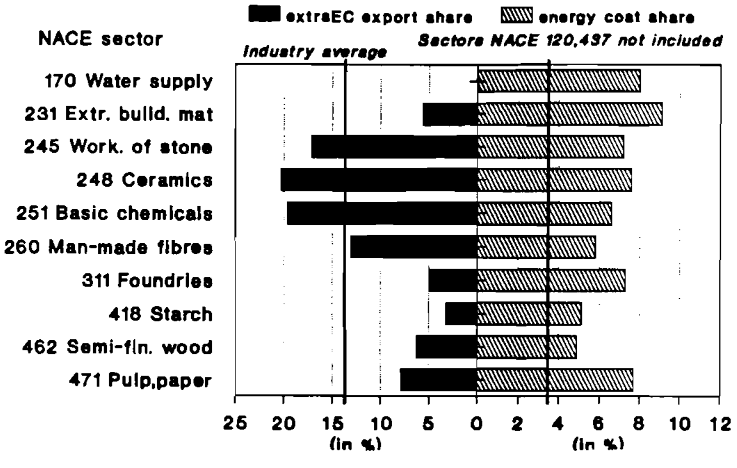


Figure 3. Share of extra EC exports in gross production (1987/1989) and energy cost shares - EUR5. Note: Sample includes Germany, Spain, France, Italy, and the United Kingdom. Source: Commission Services.

Table 3. Producer price increases in selected non-energy branches due to the introduction of a 10$ per barrel of oil equivalent CO_2 tax, estimates for 1990.

	% Producer price changes				
Branch	Denmark	Germany	Spain	France	Italy
Iron and steel	6.1	11.5	6.8	9.6	6.2
Special steel products	–	6.4	5.7	5.8	4.2
Non-ferrous metals	1.7	6.2	3.6	2.2	2.9
Cement, plaster	10.4	6.6	8.9	8.3	9.7
Glass	2.2	3.4	1.8	2.2	2.7
Clay and ceramics	4.5	2.8	2.7	2.6	2.5
Other minerals	3.0	3.8	2.6	1.3	1.8
Chemical	2.7	4.9	2.7	3.5	3.5
Metal products	1.8	2.9	2.1	1.7	1.8
Machines	1.1	1.3	1.3	1.0	1.1
Paper	4.8	5.3	2.5	2.0	3.2
Printed matter	1.6	1.7	1.1	0.7	1.2
Rubber, plastics	2.0	2.3	1.5	1.7	1.9
Other industry	1.1	1.8	1.2	0.7	1.7
Construction	1.2	1.4	1.3	1.0	1.1
Reparation	0.6	1.3	0.8	0.4	0.6
Trade	0.8	0.8	0.4	0.4	0.4
Railways	3.6	3.3	2.4	1.1	3.5
Road transport	2.1	1.5	2.0	1.6	2.1
Inland shipping	–	5.4	–	2.1	–
Maritime transport	5.2	7.3	2.7	6.8	6.5
Air transport	6.7	3.3	3.5	4.6	3.8
Other market services	0.6	0.5	0.5	0.3	0.3
Non-market services	0.7	0.9	0.4	0.5	0.4

Source: Own calculations on the basis of Eurostat I/0 tables for Denmark, Germany, France and Italy, and on Martin and Velasquez (1992) for Spain.

In the longer run, dynamic adjustment and substitution effects are likely to change the initial sectoral picture considerably. Moreover, the sectoral effects will also depend on the type of revenue "recycling". Generally, the total effect of the revenue-neutral introduction of a CO_2/energy tax is likely to be a relatively strong output price increase for energy intensive branches (unless, of course, these branches are partially or totally exempted in exchange for voluntary agreements), very moderate increases or even decreases for

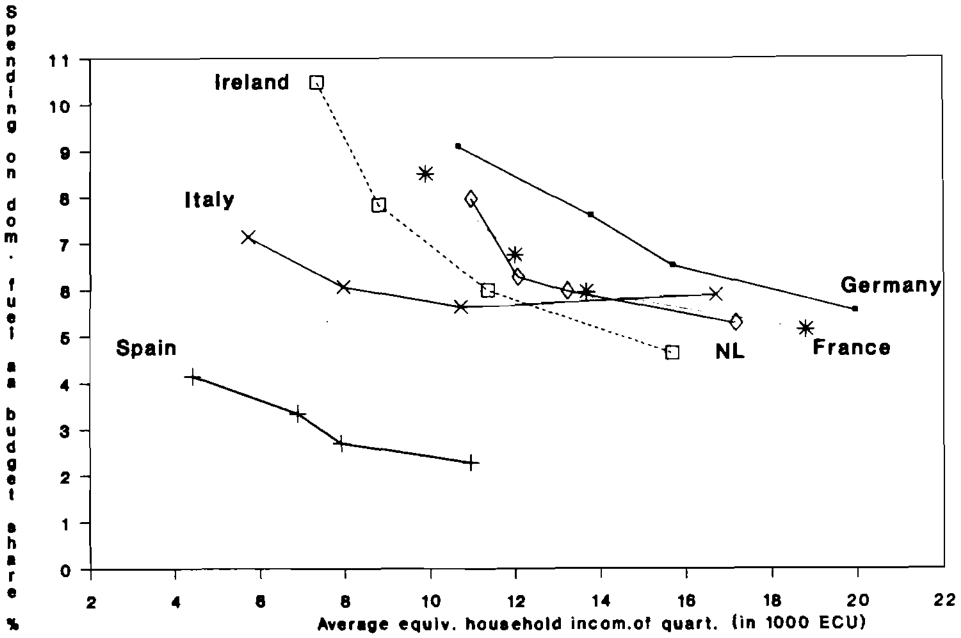


Figure 4. Budget shares for household expenditure on fuel and power in six EC countries by quartile groups of gross household income. Source: Eurostat (1990).

the other manufacturing branches and moderately strong price decreases for services.

4. The Effects in Terms of Household Income Distribution

Finally, as to the distributional impact of the introduction of a CO_2/energy tax on private households, several factors have to be taken into account [see Smith (1992) for more a detailed analysis]:

- Firstly, it has to be stressed that the overall impact of the additional carbon/energy tax payments on energy products on total household expenditures would only be modest. This direct impact would only represent between 0.5% and 1.3% of total household expenditure, depending on the Member State (see Figure 4).

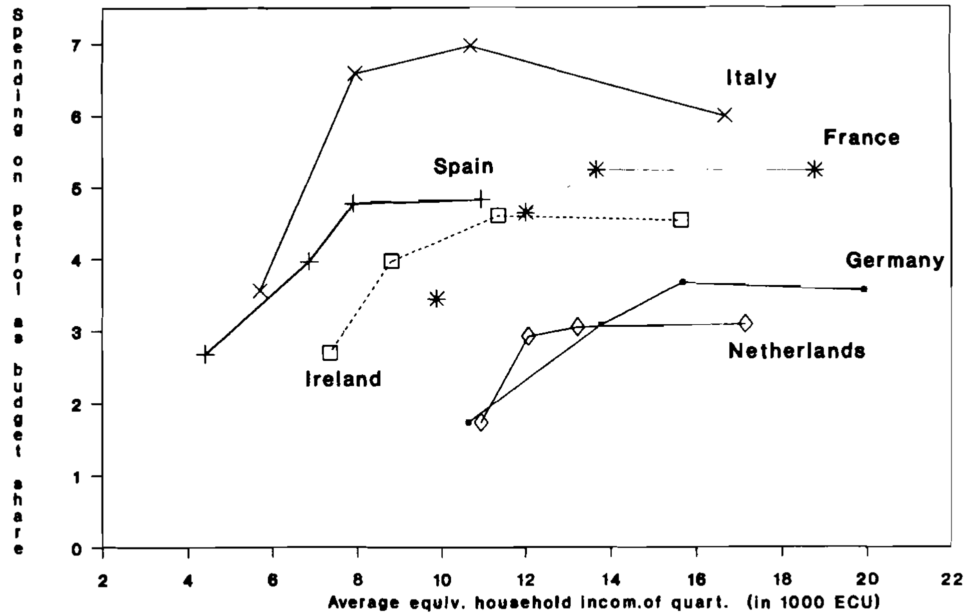


Figure 5. Budget shares for household expenditure on motor fuels in six EC countries by quartile groups of gross household income. Source: Eurostat (1990).

- Secondly, based on data from EC household expenditure surveys for six Member States (Germany, France, Spain, Ireland, Italy and the Netherlands), the evidence indicates that the poorest 25% of households tend to spend a relatively higher share of their expenditure on the direct purchase of domestic energy compared to the other three household quartiles. With the exception of Italy, the budget share of expenditure on domestic fuels declines steadily (see Figure 5). There is also a tendency for domestic fuel budget shares to be smaller in Southern Member States, which might be due to climatic circumstances.
- Thirdly, this contrasts with a lower budget share of expenditure on motor fuels for poorer households in comparison to richer ones. Thus, taxation of transport fuels would in fact be progressive in terms of household income classes (see Figure 6).
- Fourthly, as a result of these two opposing trends, and assuming unchanged spending patterns (i.e., a static analysis), a CO_2/energy tax is only slightly regressive in most Member States. However, there is some initial evidence pointing towards a more pronounced regressivity in some Northern Member States, in particular Ireland and the United Kingdom.

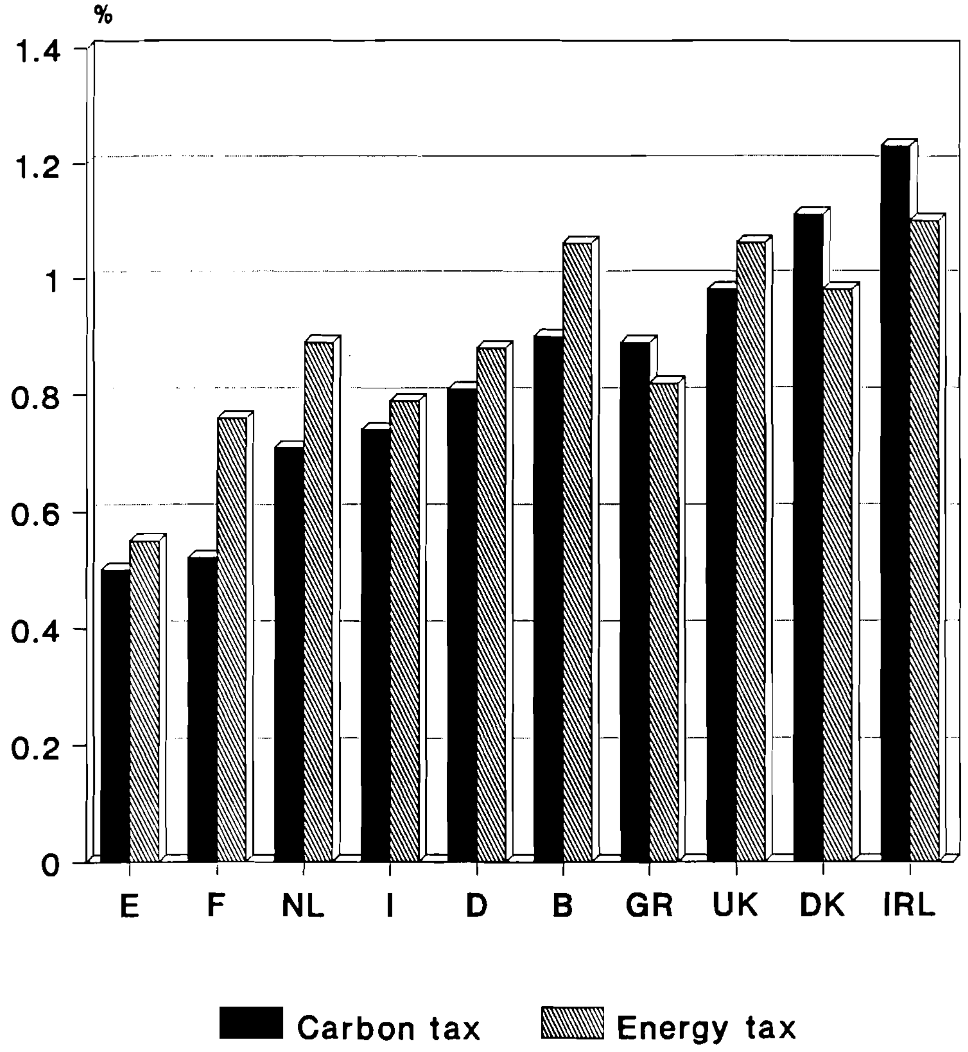


Figure 6. Carbon and energy tax payment as % of household total expenditure (all households). Source: Smith (1992).

It is interesting to note that the inter-country differences appear to be larger in the case of a pure carbon tax in comparison with a pure energy tax.

- Fifthly, over the medium and long run, households (and producers) will substitute away from highly taxed products. The short-run, static tax incidence may therefore be different from the long-run dynamic incidence due to a change in household spending patterns.

- Finally, the overall impact of a CO_2/energy tax on different household classes depends not only on this tax, but also on the incidence of the compensatory reduction in other taxes and charges implied by the revenue neutral introduction of a carbon/energy tax and on the incidence of the environmental benefits of such a tax, both of which are difficult to assess at this stage.

5. The International Dimension

Clearly, man-induced climate change being a global phenomenon, the policy response should preferably also be a global one. Acting alone, the Community with its 13% share in worldwide CO_2 emissions will only have a negligible impact on the atmospheric concentration of greenhouse gases. Nevertheless, both ethical and economic arguments would indicate that industrialized countries should take the lead. Not only do these countries have the resources as well as the technology to implement effective emission limitation policies, but they are also responsible for the overwhelming majority of the anthropogenic increase in atmospheric concentrations of greenhouse gases.

In this context, it is sometimes argued that the Community's exposure to international competition would imply high costs of European leadership in terms of CO_2 emission limitation. However, the analysis and evidence available to date do not support this view [see also Burniaux *et al.* (1992)]. Although any unilateral emission limitation policy implies some additional microeconomic costs compared to a global emission limitation policy, such a unilateral emission limitation by the European Community does not necessarily have to lead to major macroeconomic costs. This can be ascribed to three main factors:

- Firstly, *Member States' involvement in extra-EC trade of energy intensive products is relatively small.* On average, approximately 60% of each individual Member State's total trade is with other Member States. This trade would only be very moderately affected by the introduction of a Community-wide carbon/energy tax. Extra-EC exports of goods and services only contribute approximately 10% to the Community's GDP. Taking into account that other European OECD countries either have already introduced similar taxes or at least have announced their intention of doing so, one can conclude that trade with countries which have not taken (or are presently not willing to take) comparable action probably represents less than 8% of the Community's economic activity.

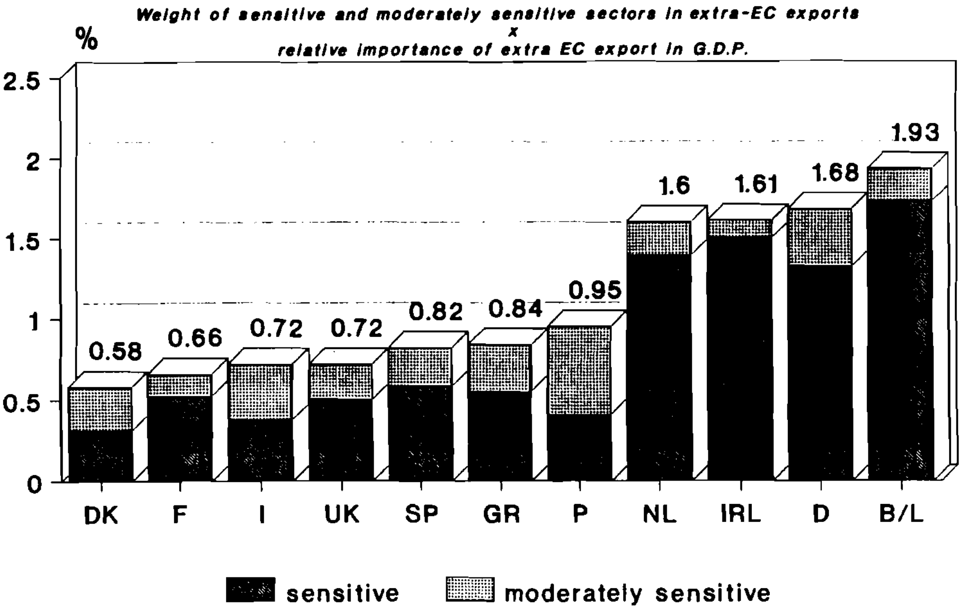


Figure 7. Importance of potentially sensitive and moderately sensitive sectors in extra EC exports in relation to GDP. Source: Commission Services.

Moreover, only a fraction of this trade consists of trade in energy intensive products. Thus, the channel through which a loss in international competitiveness caused by unilateral emission reduction could affect the Community's GDP is relatively small.

Combining information on the weight of energy intensive sectors in extra-EC exports with data on the relative importance of extra-EC exports in GDP, Figure 7 clearly demonstrates the limited macroeconomic importance (between 0.5% and 2% of GDP, depending on the country) of those sectors which could be considered as being potentially vulnerable to a unilateral increase in energy costs. For extra-EC imports, the picture is broadly similar. This is not to deny, of course, that individual companies or even branches might be significantly affected and that accompanying policies might, therefore, be required.

- Secondly, there are two main mechanisms through which external trade is affected by unilateral emission limitation policies: the Community's price competitiveness and the foreign trading partners' economic activity. As to price competitiveness, a certain deterioration might be difficult to avoid. However, a revenue-neutral introduction of a CO_2/energy tax would ensure that any losses in aggregate competitiveness would be limited, as the average tax burden in the economy would not increase. For avoiding a significant deterioration in international competitiveness it would, however, be necessary to ensure that no wage-price spiral is set in motion. On the other hand, the Community's exports are not only determined by export prices, but also by the volume of economic activity in the countries of destination. If, as indicated above, a CO_2 limitation policy may have a modest negative impact on economic activity at least in the short run, then the Community's exports could actually be higher if third countries did not embark on emission limitation policies than if they did. Thus, the total effect on Community exports is the combination of two opposing trends. Both the sign and the size of the net impact are difficult to predict.

- Thirdly, over the longer term, there may even be advantages in moving first. Although the empirical evidence on this issue is only sketchy [see e.g., Gerstenberger (1992)], the impression nevertheless emerges that there could by a positive feed-back from higher energy prices to energy efficiency-related innovation activity and trade performance in the field of energy technologies. However, further research is required to investigate this aspect.

In addition to these macroeconomic aspects, it is of course necessary to look at the broader welfare implications of such a policy. The analysis here has only focused on the environmental benefits in terms of CO_2 emission limitation (without even attempting to monetarize these benefits). There are, however, indications pointing towards the possibility that the secondary benefits of greenhouse gas emission control may exceed the direct benefits by between 8 to 30 times [see Pearce (1992)]. These benefits should be taken into account when making a comprehensive cost/benefit assessment of the Community's CO_2 emission limitation policy.

Of course, these arguments should not be misinterpreted in the sense of implying that it would make no difference whether other countries follow the Community in limiting their CO_2 emissions or not. On the contrary, as an isolated EC emission limitation policy will not be effective in noticeably slowing down climate change, the full benefits of such a policy can only be reaped in the context of a broader international agreement. This is even more so as emission reduction in only one world region may, due to dislocation and oil price feedback effects, even partly be compensated by an increase in CO_2 emissions elsewhere.[6] However, the important point to retain is that there are both costs and benefits of leadership and it may well be of economic advantage to start embarking on such a policy path, provided that such leadership improves the chance of success of a broader international agreement.

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[6] It is interesting to note, in this context, that GREEN model simulations of a unilateral EC carbon/energy tax point to only modest "carbon leakages" (11% by the year 2000). See Burniaux *et al.* (1992), p. 296.

The Regional Costs and Benefits of Participation in Alternative Hypothetical Fossil Fuel Carbon Emissions Reduction Protocols[1]

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1. Introduction

This paper examines the potential regional costs and benefits of participation in a set of hypothetical protocols to stabilize fossil fuel carbon emissions. This work is prompted by the observation that the particular construct of a stabilization agreement can greatly influence the potential acceptability and stability of that agreement.

The principal conclusion of this work is:

Any agreement to control fossil fuel carbon emissions, no matter how skillfully crafted, will require a process of constant revision in the terms of participation, because the economic needs of its participants will be evolving.

Additional conclusions are:

1. Costs of individual national emissions targets leading to a stabilization of global emissions will be much higher than the costs of efficient instruments such as a carbon tax or tradable permits. Overall costs of individual national targets were approximately double those of an efficiently administered global target in the reference case, although costs to developed nations were actually lower.

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[1] This paper is based on work that was undertaken for the United States Office of Technology Assessment (OTA) and the Pacific Northwest Laboratory (PNL) Global Studies Program (GSP), and which is forthcoming in reports to these organizations: Edmonds, J., Barns, D., and Ton, M., 1992, *Carbon Coalitions: The Cost and Effectiveness of Energy Agreements to Alter Trajectories of Atmospheric Carbon Dioxide Emissions*, Draft paper prepared for the United States Office of Technology Assessment and the PNL Global Studies Program. We draw upon that work and summarize its key findings in the present paper.

[2] Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO.

2. Conventional "equity-based" principles, such as equal per capita emissions rights, for allocating tradable permits may either
    (a) transfer too little wealth to developing nations, leading to a "dropout" problem, or
    (b) raise costs to developed nation participants to unacceptable levels.
3. Full participation by the world's nations may not be necessary to achieve most of the results of full participation. Perhaps as few as a dozen nations may be able to control atmospheric carbon concentrations.
4. Accelerated technology development and deployment to developing nations may greatly reduce costs.
5. Short delays, on the order of 10–15 years, in establishing an agreement may yield only small differences in long-term atmospheric concentrations.

In the remainder of this paper, we will briefly describe the approach taken to develop the assessment of the regional costs and benefits of participation in the alternative protocols, describe the hypothetical protocols examined, and finally discuss briefly each of the principal results.

While this paper uses a scenario approach to examine protocols, it should be noted that we do not predict the future. Results developed in this paper should be taken as indicative of the type of phenomena that may be encountered in the process of developing protocols for fossil fuel carbon emissions reductions. Results should not be taken literally. Furthermore, no attempt has been made to assess the net benefits of emissions reductions through changes in the expected rate of climate change. Only the net costs of emissions reductions within a hypothetical protocol structure are considered.

2. Approach

This paper examines both the rate of fossil fuel carbon emission and the consequent accumulation of carbon in the atmosphere. Two basic tools are used to address the issue of cost and effectiveness of potential future agreements to reduce fossil fuel carbon accumulation in the atmosphere: an energy-CO_2 emissions model and a carbon cycle model. Knowledge of both the processes that lead to fossil fuel carbon emissions and the processes that remove carbon from the atmosphere is surrounded by considerable uncertainty. This paper reports on only one emissions trajectory, Case A, and uses only one carbon cycle model, IPCC (1990).

We have used the Edmonds-Reilly-Barns Model (ERB), Version 4.01, modified for use in this exercise, to examine potential future fossil fuel carbon emissions. The ERB is a well-documented, frequently-used, long-term model of global energy and fossil fuel greenhouse gas emissions. The model consists of four parts: supply, demand, energy balance, and greenhouse gas emissions. The first two modules determine the supply of and demand for each of six major primary energy categories in each of nine global regions. For the purposes of this exercise, results from the nine regions have been aggregated to five regions:

No.	Region
1	United States (US)
2	Other OECD (OECD)
3	Eastern Europe and the Former Soviet Union (EEFSU)
4	China and other Asian centrally planned economies (CHINA)
5	Rest of the World (ROW)

The energy balance module ensures model equilibrium in each global fuel market. (Primary electricity is assumed to be untraded; thus supply and demand balance in each region.) The greenhouse gas emissions module is a set of three post-processors that calculate the energy-related emissions of CO_2, CH_4, and N_2O. The original version of the model is documented in Edmonds and Reilly (1985), while major revisions are discussed in Edmonds *et al.* (1986). The model is currently configured to develop scenarios for seven benchmark years: 2005, 2020, 2035, 2050, 2065, 2080, and 2095.

The carbon cycle model is a simple, single equation model of net ocean carbon uptake, taken from IPCC (1990). This model contains no process detail, but mimics the behavior of more sophisticated process models.

The ERB accommodates carbon taxes. Tax rates that achieve the goal of stabilizing fossil fuel carbon emissions are obtained. The total cost of an emissions reduction is computed using procedures described in Edmonds and Barns (1992). The total cost and the GNP loss will be the same under appropriate circumstances.[3] These procedures presume that there are no substantial market imperfections in the system.

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[3] The conditions considered in Edmonds and Barns (1992) include: a single homogeneous good used for both production and final consumption; a single fossil fuel and a single non-fossil fuel; a single and a closed economy, which is the case for the global economic system, but not for individual nations; and a system is in static equilibrium.

Table 1. Global population assumptions 1990 through 2095.

Year	Population (Millions)
1990	5,306
2005	6,579
2020	7,465
2035	8,725
2050	9,527
2065	9,916
2080	10,237
2095	10,420

Table 2. Labor productivity growth rate assumptions (in %/yr).

Region	2005	2020	2035	2050	2065	2080	2095
OECD[a]	1.62	1.62	1.36	1.36	1.08	0.98	0.98
EEFSU	1.45	1.45	1.17	1.17	0.97	0.93	0.93
CHINA	2.86	2.86	2.81	2.81	2.68	2.85	2.85
ROW	1.64	1.64	1.74	1.74	1.87	2.20	2.20

[a] United States included in OECD.

3. A Reference Case

While three cases were developed in the original analysis, we discuss only the central case in this paper. The ERB employs more than a thousand parameters to generate scenarios. Some of these parameters are more important than others. We have focused on a subset of parameters to build a reference case, Case A. Key parameters include: population, labor productivity, the rate of exogenous end-use energy efficiency improvement, the fossil fuel resource base, and the non-greenhouse environmental cost of fuels. Reference case population assumptions follow IPCC (1989). Global populations are given below in Table 1.

Labor productivity assumptions are given in Table 2.

Other assumptions are given in Table 3.

The consequent non-protocol reference case fossil fuel carbon emissions for the period 1975 through 2095 are shown in Figure 1.

Table 3. Other parameter assumptions, all cases.

Parameter	Value	Units	Notes
Exogeneous end-use energy intensity Improvement rate	1.0	%/yr	Applied to all regions and all sectors.
Fossil fuel resource base			Total available resource from discovered and undiscovered including those producible with current techniques and those which require advanced technologies.
Oil	16,511	Ej	
Gas	17,451	Ej	
Coal	217,000	Ej	
Solar/fusion cost	$40.21	1990 US $/Gj	Ultimate cost of delivered electricity with costs declining to this level by 2035.
Utility response to price change	-3.0	none	Logit elasticity parameter; value of 0.0 indicates no response in fuel share to cost; value of minus infinity indicates least cost option captures 100% of the market.
Income elasticity of demand for energy			% change in energy demand for each % change in income; values for non-OECD regions gradually reduced to those of the OECD by 2095.
OECD	1.00	none	
EEFSU	1.25		
ROW	1.40		
Price elasticity of demand for energy	-0.7	none	% change in energy demand for each % change in the price of aggregate energy. This input is used to calibrate the price elasticity of demand for energy services in the model.
Non-greenhouse environmental cost			Increased non-greenhouse environmental cost, over and above those in existence in 1975, in constant 1990 U.S. dollars. These costs reflect both explicit and implicit costs.
Oil	$0.00	$/Gj	
Gas	$0.00	$/Gj	
Coal	$1.70	$/Gj	
Nuclear	$10.65	$/Gj	
Biomass energy resource base	474	Ej/yr	Maximum potential supply of biomass from energy farms; minimum price is the minimum cost of solid energy needed to obtain any production; maximum price yields full utilization of the resource base.
Minimum price	$1.70	$/Gj	
Maximum price	$9.75	$/Gj	

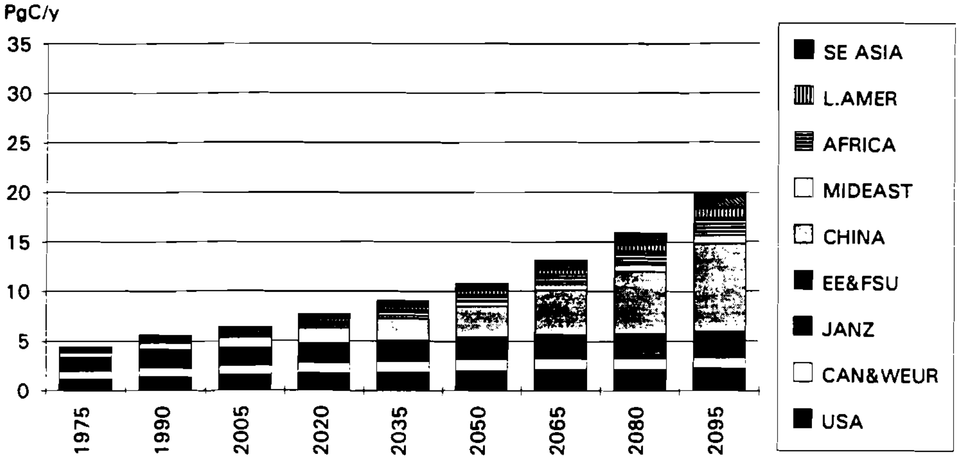

Figure 1. Non-protocol (reference) fossil fuel carbon emissions by region: 1975–2095.

4. Hypothetical Protocols

It has long been recognized that the reduction of global greenhouse-gas-related emissions requires international cooperation. No single country controls a sufficient share of global fossil fuel use to control total global carbon emissions.[4] The United States is responsible for the largest share of fossil fuel carbon emissions to the atmosphere, approximately 23% (Bradley *et al.*, 1991). Yet this share is anticipated to decline with time (Swart *et al.* 1991; Manne and Richels, 1990; IPCC, 1989; Lashof and Tirpak, 1989; Rotmans *et al.*, 1989; Edmonds and Reilly, 1983; Häfele, 1981).

While it is clear that some kind of protocol would be needed to establish control over anthropogenic greenhouse-gas-related emissions, governments have yet to agree on the nature, timing, or conditions of such an agreement.[5] Consideration nevertheless is being given to principles that might guide the development of a protocol and to broad potential terms and conditions that might be included in agreements (Ghosh, 1991; Grübler and Fujii, 1991; Barrett, 1990; Morrisette and Plantinga, 1990; Morrisette *et al.*, 1990; Sebenius, 1990; Grubb, 1989). Issues that need to be addressed in thinking about

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[4] By any measures, fossil fuel emissions are the single most important contributor to potential global climate change (Reilly, 1992; Wuebbles and Edmonds, 1991; Rotmans and den Elzen, 1991; IPCC, 1990; Nordhaus, 1990a; Lashof and Ahuja, 1990).

[5] The 1992 Rio Climate Convention does offer initial guidance, but contains no enforcement provisions.

emissions protocols include target levels, methods for achieving these levels, and the extent and timing of participation.

Targets: We have focused on fossil fuel carbon emissions rather than atmospheric concentrations. While it would be relatively simple to monitor the atmospheric concentration of CO_2, it would be extremely difficult to attribute changes in that concentration to individual counties. Furthermore, while it is possible to use carbon cycle models to infer required global emissions consistent with any desired annually and globally averaged atmospheric CO_2 concentration, the inferred emission requirement, for example to stabilize present concentrations, varies depending upon the particular carbon cycle model employed. Additional uncertainty is introduced by virtue of the fact the most desirable atmospheric concentration or rate of change of that concentration is unclear. Researchers including Nordhaus (1990b; 1990c), Peck and Teisberg (1991; 1992), and Cline (1990; 1991) have explored economically optimal strategies and have found dramatically different optimal paths under alternative assumed conditions.

There are a multitude of ways to specify global and national goals. For the purposes of providing a simple point of departure, we focus initially on the goal of stabilizing emissions. While this particular goal is arbitrary, it does appear as a voluntary objective of the Rio Climate Convention.

Implementation: Three alternative mechanisms of protocol implementation will be examined.

1. *Uniform taxes*: Each participant in the protocol is assumed to adopt a uniform set of taxes on carbon emissions to stabilize the combined emissions of all participants;
2. *Tradable permits*: The targets of participating nations are combined. Each participant is given an emission allowance. Allowances total to equal the participants' combined emissions target. Each participant must cover emissions with allowances. If a participant's emissions are less than the allowance the participant may sell excess emissions allowances. If a participant's emissions are greater than the allowance, then additional allowances must be obtained from other participants. A market is assumed to form in which allowances are traded in a manner similar to stocks, bonds, and international currencies.
3. *Individual targets*: Each participating region is assumed to be required to meet its own emission reduction target without being able to trade emissions allowances.

When tradable permits are examined, an issue arises as to the allocation of emissions allowances. As noted in the preceding discussion, much work has gone into the issue of allocating these allowances. Because tradable permits create a market for emissions rights, with a single price faced by all participants, they have efficient properties similar to a common tax. They also have income redistribution properties. Because considerable income can be redistributed, the distribution of emissions rights has substantial implications for the global income distribution. Of the great many options that have been suggested, we examine emissions allocations based on the following principles:

1. *"Grandfathered Emissions" Principle*: Emissions are allocated on the basis of rates at the time of joining the protocol;
2. *Equal Per Capita Emissions Principle*: Emissions are allocated on the basis of adult population, which we take to be the population 15 years prior to the allocation date;
3. *"No Harm to Developing Nations" Principle*: Developing nations receive sufficient emissions rights to cover their own emissions and to generate sufficient revenue to cover the economic cost of participation in the protocol;
4. *"No Harm to Non-OECD Nations" Principle*: Non-OECD nations receive sufficient emissions rights to cover their own emissions and to generate sufficient revenue to cover the economic cost of participation in the protocol.

Principle 1 is simple and needs no further explanations. Principle 2 uses lagged or adult population, rather than total population, to remove any incentive for nations to engage in programs to increase population in order to secure greater emissions rights. Furthermore, reliable same year population estimated are not presently possible. Some time is needed to build reliable population estimates.

Principles 3 and 4 are not intended to be pragmatically observable or calculatable allocation criteria. Such criteria can be examined with a model, however, and can be instructive with regard to potential negotiating positions that may be encountered. We calculate the implied distribution of emissions allowances that would leave developing and non-OECD nation participants no worse off in terms of GNP than had they not participated in the agreement. This calculation provides some guidance for comparison of other metrics in achieving this end. We have chosen not to examine an allocation of permits based on either GDP or per capita GDP. We consider the measurement of GDP to be too difficult at this time for such schemes to be a near-term possibility.

In our analysis, tradable permit rights are assumed to be usable only in the year in which they are issued. They cannot be saved and used later. Nations cannot borrow against expected future emissions. It is imaginable that an international system could accommodate saved emissions rights. During periods in which the real value of the emissions rights increase faster than the real interest rate, there would a tendency for emissions rights to be saved for use in the future. This intertemporal trading would tend to limit the rate of growth of the price of carbon emissions rights to the interest rate. It is more difficult to imagine a system in which it was possible to borrow against future emissions rights. As rights are accumulated annually with no end to the process, there is a potentially infinite store of rights against which to borrow. Borrowing could be restricted; that is, a nation could never be allowed to borrow more than a fixed number of years' emissions into the future. If borrowing could occur across more than a few years into the future, there would always be the danger that a participating nation might join, borrow against the future to finance current expenditures, and when the borrowing limit was reached, simply drop out of the process.

5. Results

Individual Targets: The simplest mechanism for stabilizing future fossil fuel carbon emissions - the mechanism espoused by the Rio Climate Convention would be for all nations to each agree to stabilize their respective emissions. This scheme is not without its own problems. First, individual targets shift the cost burden of emissions reductions away from developed nations and toward developing nations. By the year 2020, more than 80% of total global costs are borne by non-OECD regions.

Second, individual targets more than double the total global cost of emissions reductions, relative to the case in which a globally administered carbon tax is put into effect. (See Figure 2 which displays results for the reference emissions trajectory.) Ironically, costs are lower in the OECD region after the year 2005 than in the common tax case. This irony is the result of the fact that stabilizing individual emissions provides a non-tradable "grandfathered" emissions right to participants. Thus, there is no room for the increased emissions that would be expected to accompany the development process for currently developing nations. Under these circumstances, it is hard to imagine developing nations being attracted by such proposals.

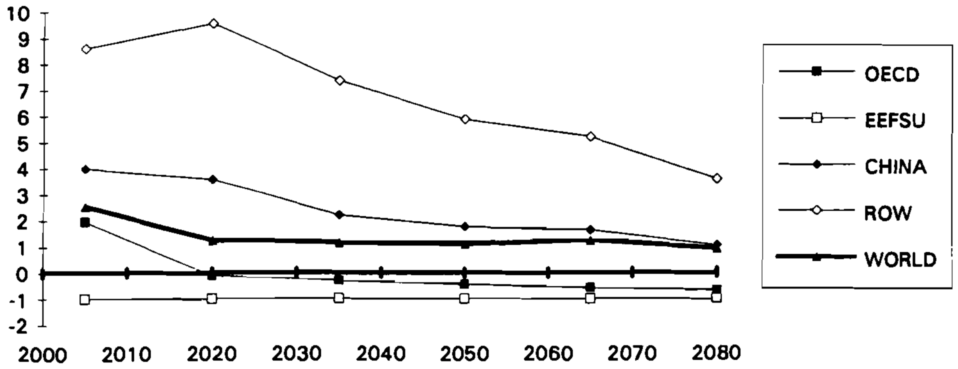

Figure 2. Percentage change in total cost of fossil fuel carbon emissions stabilization by individual region relative to the total cost of global fossil fuel carbon emissions with a common global tax, by region and by year (%).

Tradable Permits: An alternative mechanism for stabilizing global emissions is to create and distribute a tradable emissions permit. Like taxes, tradable permits can be shown to be economically efficient tools for reducing fossil fuel carbon emissions; that is, both provide identical incentives to emitters to reduce emissions. In the case of the common tax, all emitters see a common marginal cost of emissions reductions. Since the marginal costs of emissions reductions are identical across all human activities, there is no way to change the pattern of emissions slightly and reduce total emissions costs. Tradable permits have similar properties. A market is assumed to form, and permits are assumed to trade at a common market price. This price adds the same amount to the cost of using a fossil fuel as would a tax. To the user of the fossil fuel, there is no difference.

Other characteristics of the two systems are very different. In a tradable permit system, permits to release emissions into the atmosphere are owned as a property right. Ownership may be by the government or private parties. The emission right has value to an individual party. That value depends on the amount of emissions allowed to all parties and the amount allocated to the individual party.

In exploring the implication of tradable permit schemes, we examine the four very different rules for allocation of permits discussed above:

1. *"Grandfathered Emissions" Principle,*
2. *Equal Per Capita Emissions Principle,*
3. *"No Harm to Developing Nations" Principle,*
4. *"No Harm to Non-OECD Nations" Principle.*

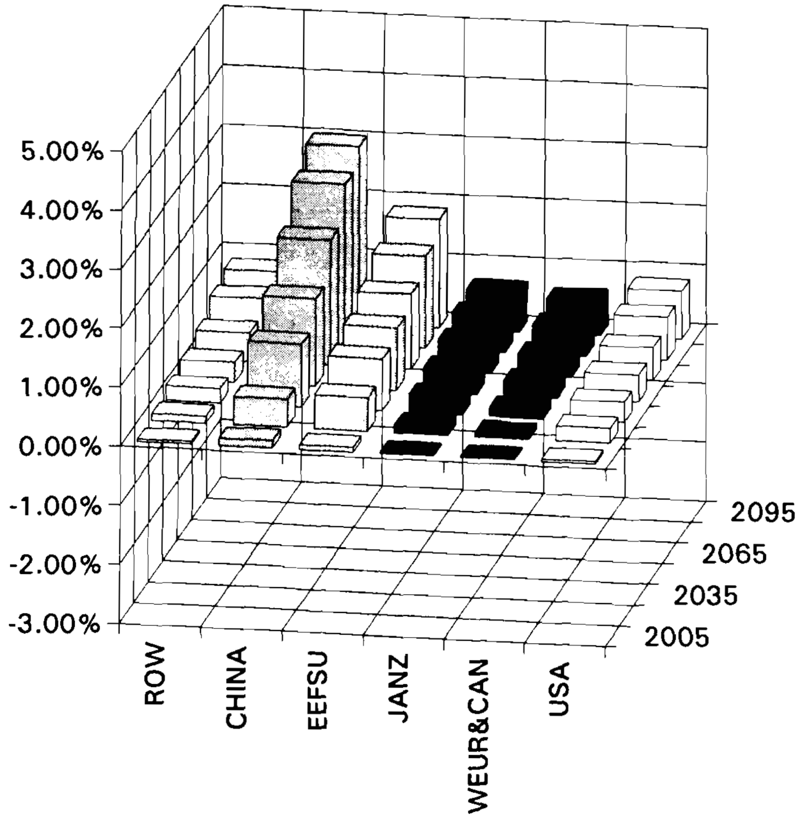

Figure 3. Common global carbon tax to stabilize emissions beginning in 1990: Total cost of emissions reductions relative to GDP by region and by year (%).

Tradable permits are assumed stabilize emissions. The principal issues are the associated distribution of costs and income transfers. The costs associated with a globally administered carbon tax are shown in Figure 3. This distribution of costs is taken to be the same as the case in which each region is allocated a share of emissions sufficient to cover its own emissions with no net trade.

The regional net costs, expressed as a fraction of GDP, for the Grandfathered Emissions case are given in Figure 4. Under this allocation of tradable permits, developing nations transfer wealth to the developed nations.

The regional net costs, expressed as a percentage of GDP, for the Equal per Capita Emissions allocation of permits is given in Figure 5. Here, wealth

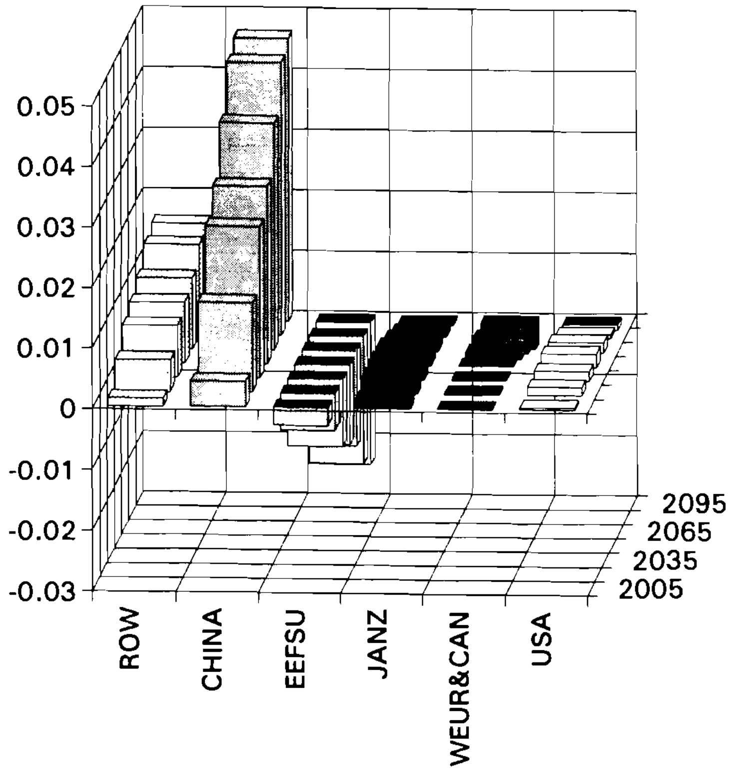

Figure 4. Total cost of emissions reductions relative to GDP plus net transfers of wealth from sale of excess emissions rights by region and by year: Tradable permits, "Grandfathered Emissions" Principle (%).

transfers flow from the developed regions to the developing regions. Interestingly, however, the particular set of assumptions examined in this case put China in a position where the value of its emissions allocation leaves insufficient excess rights to cover its costs after the first 15 years. This is surprising because of the large Chinese population. This result occurs because the assumed rate of growth of Chinese population is low, and the rate of labor productivity growth is high; that is, China is assumed to be successful in its development program. The irony is that this same success makes it unattractive to continue to participate in tradable emissions permit program after a short period of time. Of course, this scenario is not a forecast. China may fare perfectly well throughout the next century under a tradable permit system in which permits were distributed on the basis of population. The important lesson here is rather that this type of circumstance may emerge

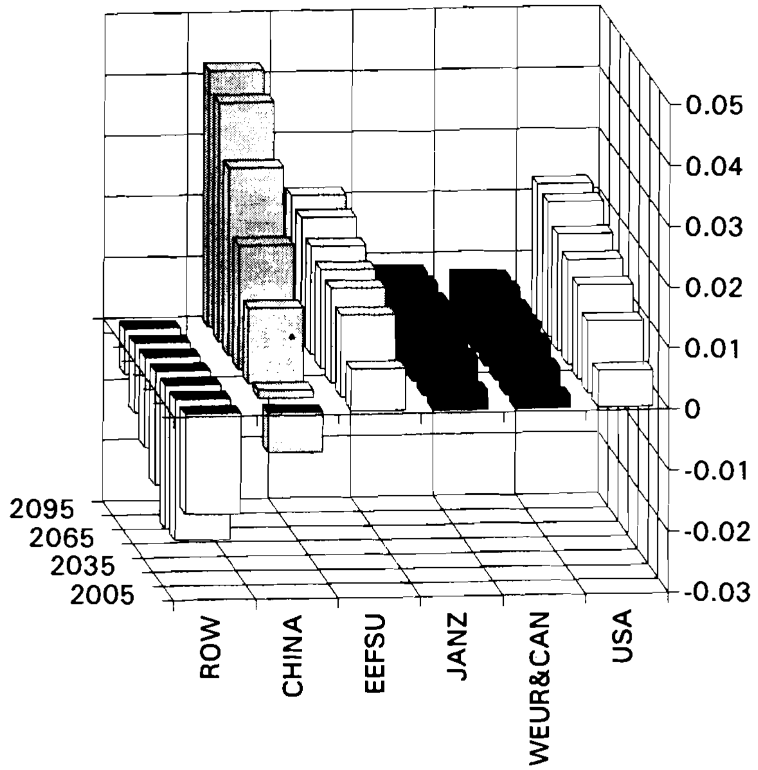

Figure 5. Total cost of emissions reductions relative to GDP plus net transfers of wealth from sale of excess emissions rights by region and by year: Tradable permits and "Equal per Capita Emissions" Principle (%).

for some important nation or nations. More generally, there is no particular reason to believe that the transfer of wealth via a tradable permit scheme based on equal per capita income will result in a permanent incentive for non-OECD nations to participate. Rather, it is likely that no matter how skillfully crafted initially, any agreement will require a long-term process of review and revision.

For contrast, we construct a case in which we compute the allocation of permits to developing nations necessary to leave developing regions just indifferent about participating or not participating in the protocol. The regional net costs, in terms of foregone GDP, associated with this case are displayed in Figure 6. We note that this case matches neither the Grandfathered Emissions permit allocation nor the Equal per Capita Emissions permit allocation. It is more similar to the former in the first period and

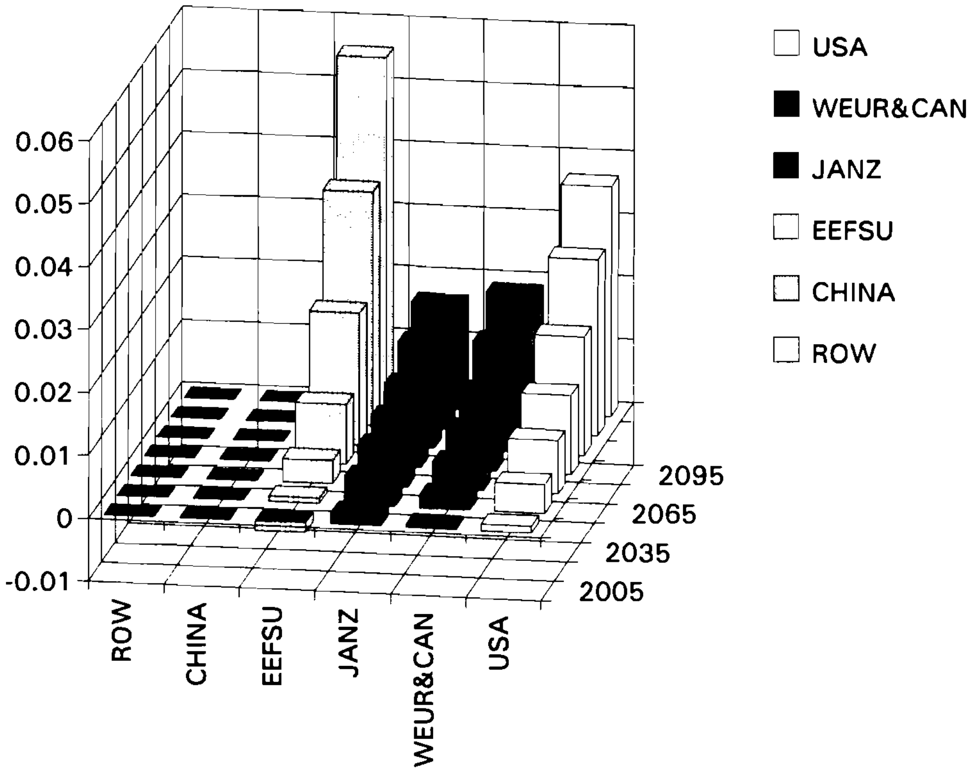

Figure 6. Total cost of emissions reductions relative to GDP plus net transfers of wealth from sale of excess emissions rights by region and by year: Tradable permits, "No Harm to Developing Nations" Principle (%).

ultimately more similar to the latter in later periods, but the match is not a good one.

For completeness, we have also constructed a case in which we compute the allocation of permits to non-OECD regions necessary to leave non-OECD regions just indifferent about participating or not participating in the protocol. The regional net costs, in terms of foregone GDP, associated with this case are displayed in Figure 7.

The Role of the "Big Three": The rapid acceleration of emissions of carbon into the atmosphere in the middle and latter half of the twenty-first century is the consequence of an accelerated use of coal resulting from the combination of continued rapid economic growth, particularly in the developing nations of the world, and limits to inexpensive conventional oil and gas resources. The world distribution of coal resources (not to be confused with reserves)

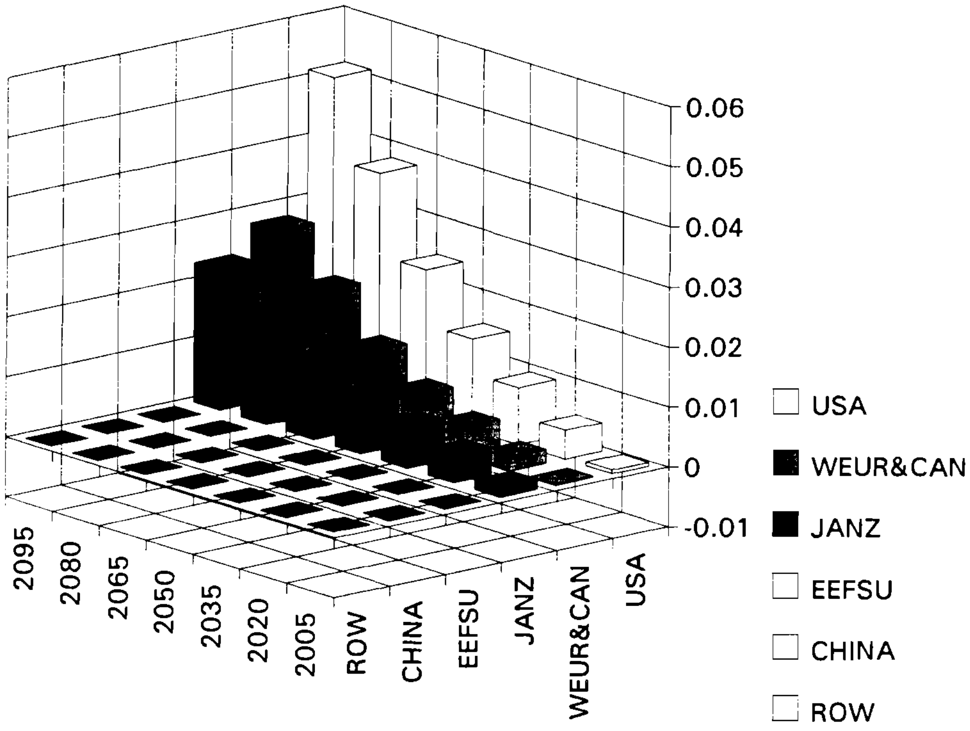

Figure 7. Total cost of emissions reductions relative to GDP plus net transfers of wealth from sale of excess emissions rights by region and by year: Tradable permits, "No Harm to Non-OECD Nations" Principle (%).

Table 4. Distribution of global coal resources. Source: Edmonds *et al.* (1986), Appendix A.

Region	Resource Base (ej)	(%)
OECD	107,158	40
EEFSU	114,328	42
CHINA	38,742	14
ROW	10,772	4
TOTAL	271,000	100

is not uniform. Table 4 shows the distribution of resources among world regions.

To explore the importance of participation by the Big Three regions – OECD, EEFSU, and China – we have constructed a scenario in which these regions engage in a coalition to stabilize combined emissions, but the rest of the world does not.

We have assumed that the Big Three institute a common two-part carbon tax with equal tax levels on production and consumption activities. In the analysis of a common global carbon tax, we found the issue of point of taxation (severance versus consumption tax) to be an unimportant issue. When some regions participate and others do not, the matter become important. If only consumption is taxed and production goes untaxed, then a protocol participant may simultaneously reduce its own emissions while supplying fossil fuels to the rest of the world and facilitating additional emissions by the rest of the world. On the other hand, when only a subset of nations participate and a severance tax is used without a consumption tax, the opposite propensity emerges; that is, there is a tendency for fossil fuel production to be reduced, but no direct incentive for the use of fossil fuels to be diminished.

Coupling production and consumption taxes is intended to address the problem of significant non-participating regions. The consumption component of the two-part tax directly stimulates reductions in the use of fossil fuels. The production tax component not only reduces domestic production of fossil fuels, but also affects the world price of coal to the rest of the world. It is not entirely clear how to report the two-part carbon tax. We have chosen to report the carbon tax rate as the simple sum of the production and consumption components. In the case in which a region is effectively closed, carbon would in fact be taxed twice. For economies that are dominated by either production or consumption, carbon could actually be taxed only once under such a scheme.

Big Three regional emissions are assumed to stabilize at 1990 levels throughout the period of analysis. Global fossil fuel carbon emissions grow through the year 2080, peaking at approximately 44% above 1990 levels. They decline sharply in 2095 (Figure 8). Within the region Chinese emissions grow to more than half of the regional total, while OECD and EEFSU emissions decline.

The "offshore" effect in the Big Three case is interesting. While this effect is generally thought to make global emission reductions relative to the reference case smaller than emissions reductions in participating regions, the Big Three case is more complex. In 2005, 2020, 2080, and 2095, the "offshore" effect actually leads to unintended emissions reductions by non-participants. This is effected by significant increases in energy prices. During the middle period, years 2050 and 2065, non-participants' emissions cause global emissions reductions relative to the reference case to be lower than

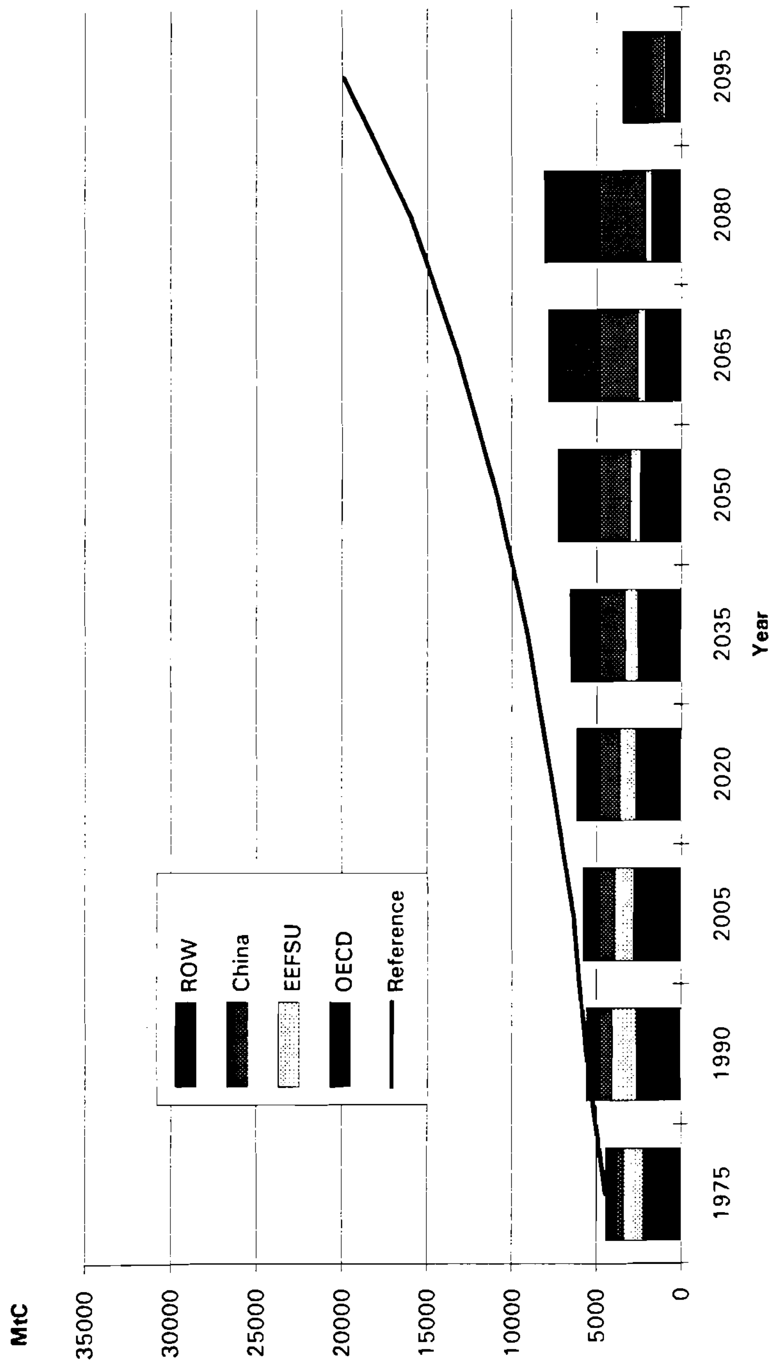

Figure 8. "Big 3" Protocol: Global fossil fuel CO_2 emissions by region and by year.

Table 5. Definition of delayed protocol cases.

Protocol 1a:	Initiation Date:	*1990.*
	Participation:	All nations initiate participation in 1990.
Protocol 1b:	Initiation Date:	*1990.*
	Participation:	Participation by the EEFSU is delayed until the year 2005, participation by CHINA to the year 2020, and ROW to the year 2035.
Protocol 2a:	Initiation Date:	*2005.*
	Participation:	All nations initiate participation in 2005
Protocol 2b:	Initiation Date:	*2005.*
	Participation:	Participation by the EEFSU is delayed until the year 2020, and participation by CHINA to the year 2035, and ROW to the year 2050.
Protocol 3:	Initiation Date:	*2020.*
	Participation:	No protocol is signed until the year 2020 and participation by non-OECD member states lags. The EEFSU joins in 2035, China joins in 2050, and the ROW joins in 2065.

emissions reductions by the Big Three. The unintended emissions reductions by non-participating regions were not expected.

The Consequence of Delayed Participation: We have examined a series of cases in which the initiation of the protocol and dates of entrance of participants are varied. The protocol under consideration is one in which participants agree to stabilize emissions at then-current levels using a common carbon tax. The variety of possible dates of protocol initiation and initial participation by various regional groups are defined in Table 5.

Short delays in reaching a meaningful agreement or staggered participation in a protocol that begins immediately with initial OECD stabilization of current emissions levels cause long-term (year 2095) concentrations of atmospheric CO_2 to be only slightly higher than is the case with immediate participation (Figure 9). Further delays in completion of an agreement exhibit increasingly higher long-term concentrations of atmospheric CO_2. These higher concentrations of atmospheric CO_2 trade against lower economic costs. The reduced economic costs appear to be generally disbursed among both immediate and delayed participants. We make no attempt in this paper to assess the benefits of emissions reductions and are therefore able only to describe the relationship between cost and atmospheric concentration. We are unable to provide a full economic assessment.

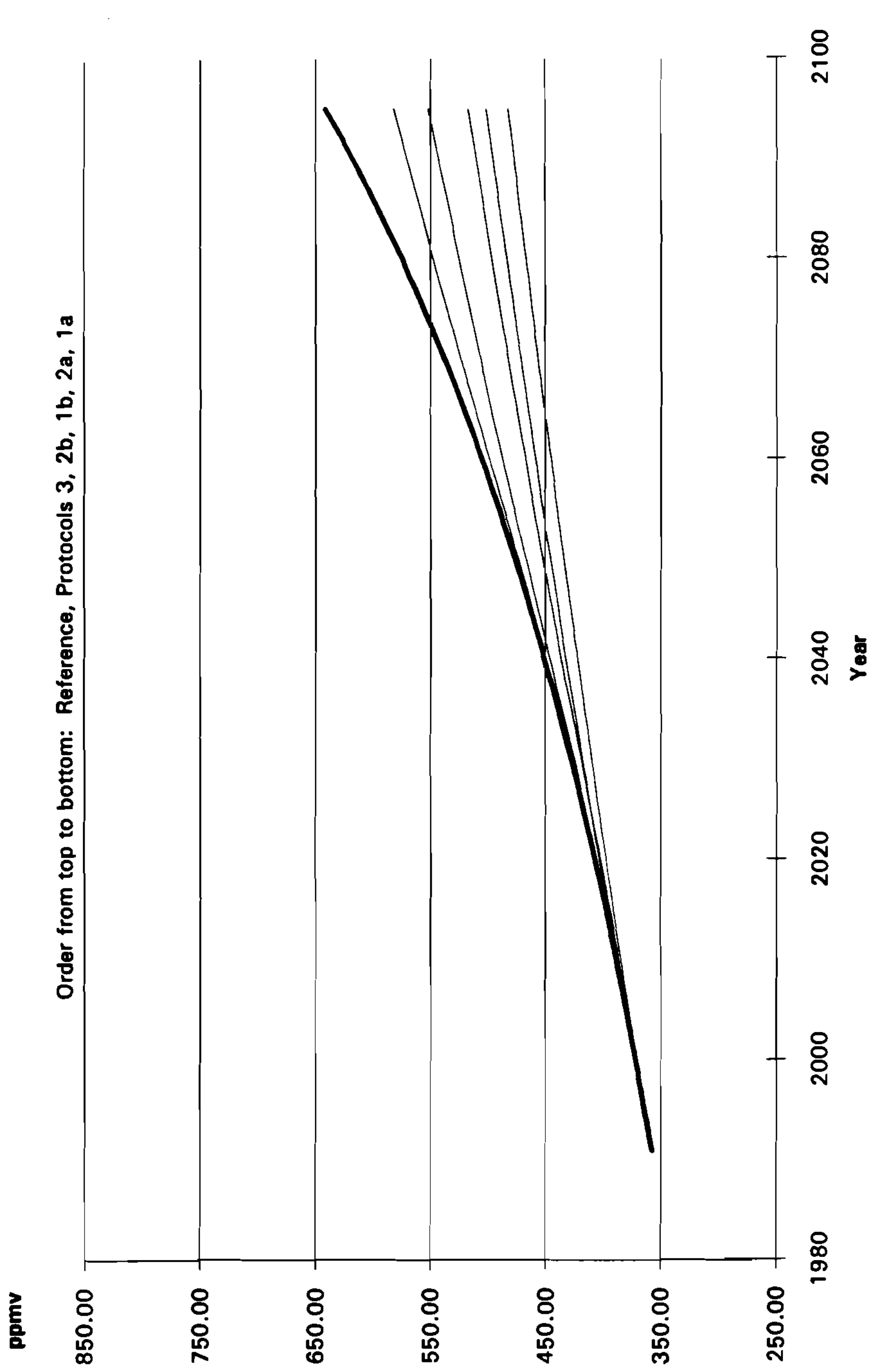

Figure 9. Atmospheric CO_2 concentration under alternative assumptions of initial dates and dates of individual regional participation.

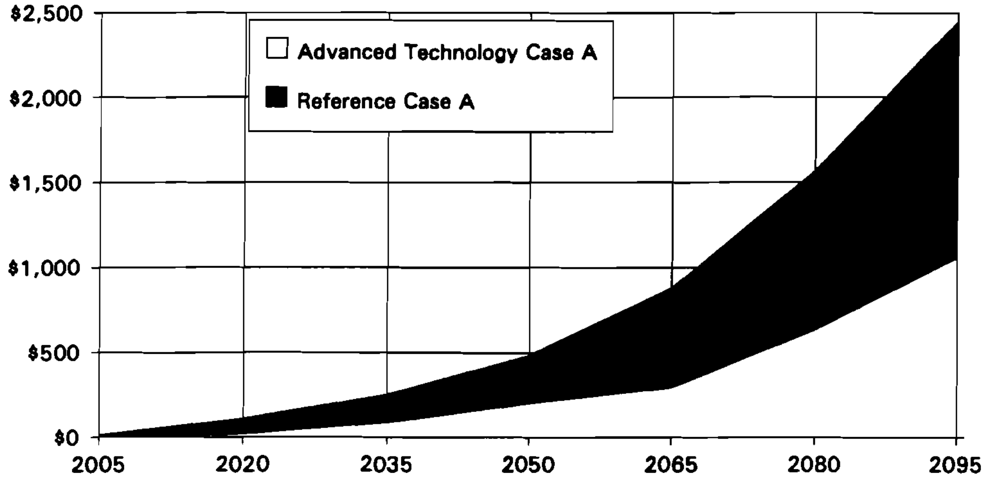

Figure 10. Total cost of stabilizing fossil fule CO_2 emissions at 1990 levels under Protocol 1a for reference and advanced technologies Case A (\$ × 10^9/yr).

Advanced Technology Development and Deployment: To explore the optimistic outlook for technology development, we assume that solar electric power becomes competitive (\$0.05/kWh) with fossil sources shortly after the turn of the century. Moreover, coal and gas have been assigned electrical generating efficiencies of 55% by the year 2020. This scenario change results in a 25% reduction in emissions in the final year, brought about by a 20% reduction in primary energy demand coupled with a growth in solar energy equal to nearly 2.5 times the growth projected in the reference case. At the same time, because of lower energy prices, secondary energy demand actually increases very slightly, accompanied by a substantial shift toward the electric mode.

Stabilization of fossil fuel carbon emissions at the 1990 level is correspondingly easier with taxes a bit more than one-half those in the standard scenario. In this exercise, primary energy demand is reduced still further, while the use of solar electric, now even more favorably priced compared to fossil fuels, nearly doubles again. The total costs to stabilize emissions, are reduced substantially, as seen in Figure 10. Total cost reductions under a globally common tax rate, range from \$14 × 10^9/yr in 2005 to more than 1.4 × 10^{12}/yr in the year 2095. The implied atmospheric concentration of CO_2 is the same in this case as in all other emissions stabilization cases.

6. Conclusion

The principal conclusion of the work reported here is that *any agreement to control fossil fuel carbon emissions, no matter how skillfully crafted, will require a process of constant revision in the terms of participation, because the economic needs of its participants will be evolving.* The examination of alternative protocol options here suggests that there will likely be a significant misalignment between the needs of the world's regions and nations and the two protocols examined here.

The notion that all nations will stabilize emissions independently looks to be costly, particularly for developing nations. Tradable permits and global uniform taxes can provide a significant reduction in global costs. The distribution of net costs depends only on the mechanism used to distribute emissions rights. Neither the allocation of rights on the basis of historical emissions nor allocation on the basis of population match the computed No Harm to Developing Nations case.

These conclusions notwithstanding, there is some hope for an agreement capable of making a significant impact on emissions and concentrations of atmospheric CO_2. Not all regions need to participate; a strategically chosen set of national actors, using appropriately chosen policy instruments, could jointly achieve global emissions reductions almost as great as a protocol with universal participation. There appears to be some time in which to craft an initial protocol and to bring members under the agreement. Long delays have significant implications for atmospheric concentrations of CO_2.

Finally, there appears to be very significant potential for reducing overall costs of emissions reductions available from the accelerated development and deployment of technologies.

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As always, even the best efforts of our colleagues may not be sufficient to keep us from erring. Responsibility for any errors remaining in this document remain with the authors.

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International Trade in Oil, Gas and Carbon Emission Rights: An Intertemporal General Equilibrium Model*

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Abstract

This paper employs a five-region intertemporal model to examine three issues related to carbon emission restrictions. First, we investigate the possible impact of such limits upon future oil prices. We show that carbon limits are likely to differ in their near- and long-term impact. Second, we analyze the problem of "leakage" which could arise if the OECD countries were to adopt unilateral limits upon carbon emissions. Third, we quantify some of the gains from trade in carbon emission rights. Each of these issues have been studied before, but to our knowledge this is the first study based on a multi-regional, forward-looking model. We show that sequential joint maximization can be an effective way to compute equilibria for intertemporal general equilibrium models of international trade.

Keywords: carbon emission limits, international trade, intertemporal general equilibrium

1. Introduction

This paper concerns three issues related to carbon dioxide emission emissions. First, we examine the possible impact of emission limits upon future oil prices. We show that carbon limits are likely to differ in their near- and long-term effects. Second, we analyze the problem of "leakage" which could arise if the OECD countries were to adopt unilateral limits upon carbon emissions. Third, we quantify some of the gains from trade in carbon emission rights. We do our analysis in the context of a five-region forward-looking

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model. These three issues (oil price effects, free-riding and gains from trade in emission rights) have been explored in several earlier papers. All three issues are addressed by Burniaux *et al.* (1992) in the context of a recursively dynamic multi-region model. Perroni and Rutherford (1991) and Pezzey (1992) consider the "leakage" issue in a static multi-region context, while Felder and Rutherford (1992) explore the same question using a recursively dynamic model. Both Kverndokk (1992) and Manne and Richels (1992) are concerned with the issue of trade in emission rights.

The present study is based on a model which has disaggregated intertemporal, interregional and technological dimensions. The time dimension is crucial for representing forward-looking exhaustible resource allocation decisions for oil and gas, and for the introduction of new energy technologies. Interregional disaggregation is crucial for determining the effects of carbon-dioxide restrictions on trade flows and terms of trade. Both of these dimensions are present in previous studies, but not together. The recursive-dynamic studies (Burniaux *et al.*, 1992, and Felder and Rutherford, 1992) are well-suited for investigating international trade issues, but the oil- and gas-extraction profiles in these models are based on the somewhat dubious assumption that production and reserve additions depend only on current but not future prices. Earlier versions of Global 2100 involved multiple regions with forward-looking agents, but the assumption of a fixed international oil price is clearly suspect in the face of dramatic reductions in carbon-based fuel consumption.

The present model leaves much room for improvement. For example, it would be useful to incorporate interindustry and regional details which are covered by Burniax *et al.* (1992). It would also be useful to address these issues in a multi-regional framework using a decision-making under uncertainty approach. We leave these extensions for future research.

The next section describes a range of issues related to the formulation and solution of intertemporal equilibrium models of international trade. We provide some motivation for the sequential joint maximization algorithm which turns out to be an effecitve technique for solving large-scale models.

For the sake of brevity, we describe only those modifications needed to convert the Global 2100 model structure and input data into a general equilibrium format. The remaining sections of the paper present our findings. The results are based on comparisons of alternative scenarios: business-as-usual and three proposals for carbon emission limitations. Because of the uncertainties connected with the numerical input parameters, the absolute levels of the solution values should not be taken too literally. We are concerned primarily with the insights that can be obtained by comparing the scenarios with each other.

2. Model Formulation

2.1. Dynamic General Equilibrium models

In AGE (applied general equilibrium) models of international trade, it is customary to employ a static framework. One may then ask questions of the following type: Suppose that regions A and B agree to lower their barriers to trade. What then will be the consequences to different sectors within each of these countries? Intertemporal equilibrium involves the simultaneous determination of prices and quantities during a sequence of time periods. This is a convenient fiction, but it is a debatable idea. Aside from financial instruments, there are no actual markets for purchases and sales in the distant future. There is a further difficulty with numerical models involving intertemporal equilibrium. This type of formulation can greatly increase the difficulties of computation.

Why not solve multi-period trade models recursively? This is the approach taken, for example, by Burniaux *et al.* (1992) and Felder and Rutherford (1992). Both of these models solve for an international equilibrium in year t, update the "stock" variables such as capital and exhaustible resources, then solve for a new equilibrium in year t+1. Rutherford (1992a) reports, however, that his recursive trade model can be ill-behaved when it is based upon an activity analysis description of production and there is a rapidly changing world.

For additional examples of these difficulties, see the numerical solutions obtained through "systems dynamics", e.g., Meadows *et al.* (1972). Typically, such models have a tendency toward overshoot and collapse. We have found that many of these inconsistencies can be overcome through an intertemporal approach. Clairvoyance is an implausible assumption, but myopia seems even worse.

In the present study, we project international trade flows through a five-region intertemporal equilibrium model. Each region is viewed as though it were a single consumer and producer with an infinite planning horizon. The regional, intertemporal and energy-environment features are based upon those employed in Global 2100. See Manne and Richels (1992). They employed an informal decomposition procedure to examine interregional trade linkages. Here we report on a formal AGE (applied general equilibrium) solution method. In addition to trade in oil, gas and carbon emission rights, there is international trade in a numeraire good.

2.2. Issues in model solution

With an intertemporal formulation, there is a date attached to each commodity. When such a model is solved simultaneously, it therefore has much higher dimensions than a static trade model. The equilibrium computations reported here are based upon Negishi weights and sequential joint maximization (SJM). For the general theory underlying this approach, see Negishi (1972). Dixon (1975) and Ginsburgh and Waelbroeck (1981) have shown that trial-and-error (tatonnement) techniques are effective ways to solve for these weights in medium-sized models of international trade. We are doubtful, however, that such an approach would be practical in this extension of Global 2100 where we are solving simultaneously for about 2300 prices and 3100 activity levels.

In our model, there are five endowment-holding agents, one in each region. The SJM procedure operates through solving a sequence of constrained nonlinear optimization problems. In this iterative process, successive problems differ only in the numerical values of the weights attached to the utility functions of the various agents. Between iterations, the weights are revised so as to bring each region's consumption expenditures into balance with the value of its endowment. The SJM method is based upon an aggregate welfare function which controls the shares of expenditures allocated to each region. This is possible when: (i) individual utility functions are linearly homogeneous, and (ii) the aggregate welfare function is expressed as a weighted sum of the logarithms of the individual utility indices. For technical details, see Rutherford (1992b). To our knowledge, Rutherford was the first to propose the specific procedure, and this paper represents its initial large-scale application. For a small-scale application, see Manne and Rutherford (1992).

2.3. Capital flows

Capital flows are endogenous in a fully intertemporal trade model. When embedding a single sector within a model of the economy as a whole, it is customary to analyze the sector in considerable detail, and to describe the balance of the economy in terms of a single numeraire good, e.g., dollars of constant purchasing power. Real prices, e.g., those of oil or wheat, may then be expressed in terms of dollars per ton. A similar convention is often adopted when there is international trade. With either static or recursive models, this form of aggregation seems appropriate. However, with intertemporal AGE models, difficulties are encountered unless the rate of return is identical in all regions. When there are differences in the rates of return, capital movements and arbitrage would tend to reduce them to zero.

To illustrate the problem, assume that there are two regions called North and South (abbreviated N and S, respectively). Let prt be the present-value price of the numeraire good in region r during period t, and let the initial period's prices $p_{N1} = p_{S1} = 1$. If, for example, the marginal productivity of capital in both regions were 5% per year, the present value price of both regions' output in the following year would be .95. Alternatively, if the rate of return on capital were higher in the South than in the North, then $p_{N2} > p_{S2}$. The terms of trade have moved in favour of the North and against the South. The converse would hold if $p_{N2} < p_{S2}$. There is no way to define an international numeraire unless we assume that the returns on capital are identical in all regions.

In their parallel five-region computations (hereafter abbreviated 5R), Manne and Richels benchmarked the production function parameters so that if all other prices remain constant, the real rates of return are uniformly 5% in all regions. In our AGE extension of Global 2100, the same approach was adopted. With this convention, there is no incentive for significant interregional capital flows.

2.4. A summary of model structure

An algebraic formulation of Global 2100 is presented in Manne and Richels (1992) (Chapter 7). This section presents a general overview of the AGE extension of this model, but omits many of the details from the original 5R formulation. In Global 2100, the world is divided into five major geopolitical regions: the United States, other OECD nations, the former USSR, China, and the rest of the world. These are abbreviated, respectively, USA, OOECD, USSR, China and ROW. The model is benchmarked for a base year of 1990, and the projections cover ten-year time intervals extending from 2000 through 2100.

Supplies and demands are equilibrated within each individual period. Since this is an intertemporal equilibrium model, there are "look-ahead" features to allow for consistent expectations of changes in relative prices. Price changes may be particularly important if one is modeling a future in which there are increasingly tight constraints on the emissions of carbon dioxide, conventional hydrocarbon resources are subject to depletion, and there are costly options for accelerating the introduction of new technologies.

In the AGE extension of Global 2100, there is a single representative producer-consumer within each of the five regions. Savings decisions are modeled by choosing each region's consumption sequence so as to maximize a linearly homogeneous function: the sum of the discounted logarithms of consumption. Capital is fully mobile between regions. Although there are interregional capital flows, they have a negligible overall impact. This is a direct result of benchmarking the model so that the rates of return on capital are approximately equal between regions.

Labor is immobile between regions. To allow for increases in productivity, the labor force is measured in "efficiency units". For shorthand, the growth of the labor force is described as an index of potential GDP. Technical progress is introduced into the macroeconomic production function in a Harrod-neutral form. At constant prices for capital, labor and energy, these assumptions determine the rate of GDP growth. Depending upon the pattern of changing relative prices, there are general equilibrium feedback effects. The realized growth may therefore exceed or fall short of the potential.

The potential GDP growth rates constitute some of the key numerical inputs. Through 2050, these values are significantly different between regions, and they are identical to those used in the original 5R model. Thereafter, in order to reduce horizon effects within the AGE framework, we have lowered the growth rates in China and ROW so that they converge to the same rate as in the industrialized regions: the USA, OOECD and former USSR. This type of simplification was not needed for the parallel analyses conducted within the 5R framework.

Global 2100 allows for energy efficiency gains, some that are autonomous and others that are price-induced. There is a nested CES (constant elasticity of substitution) functional form that provides for long-run substitutability between the inputs of labor, capital, electric and nonelectric energy. There are short-run rigidities, and adjustment costs are modeled through a "putty-clay" form of this production function.

2.5. Parameterization

In this study, we have tried to employ as many parameters as possible from the Global 2100 dataset. Certain changes were made to improve the representation of the international markets for oil and gas during the era preceding the transition to backstop technologies. Except for these modifications, the AGE version employs the same structure and numerical parameters as 5R:

(i) We have eliminated the arbitrary quantity limits previously imposed upon the import and export of crude oil. International oil prices are projected endogenously rather than taken as an exogenous assumption. The model now has the capability of exploring the impact of carbon emission limits upon both the international oil price and also the quantities traded at these prices. No specific allowance is made for OPEC. In effect, we assume a competitive international oil market. Our approach is consistent with the conclusions of Griffin (1992). For the cartel's "core" members, he shows that the optimal long-term pricing strategy is much closer to a competitive outcome than to that of a monolithic cartel.

(ii) We have allowed for the endogenous determination of natural gas prices and the quantities traded via pipelines between the former USSR and the OOECD region. This change has led us to introduce representative transport cost coefficients: \$2/GJ for natural gas and \$2 per barrel for crude oil shipments between regions. We do not analyze interregional coal trade.

(iii) The five regions differ with respect to existing taxes and subsidies on petroleum consumption. See Hoeller and Coppel (1992). In 1990, the USA's prices were close to international levels. Within the OOECD, there were substantial existing taxes on petroleum (here taken to be \$3/GJ), and these will make it increasingly expensive to impose additional taxes on carbon emissions. Conversely, within the former USSR, China and the ROW there were substantial subsidies. The elimination of these subsidies could improve economic efficiency, and could also have a major impact upon global carbon emissions (see Burniax *et al.* (1992)). For purposes of the AGE model, we assume that the existing OOECD petroleum taxes will remain in effect, but that the subsidies will be eliminated rapidly in the other three regions. It is straightforward to incorporate this type of tax-subsidy analysis within the SJM framework – provided that we assume lump-sum recycling of revenues and expenditures for the representative agent within each region.

(iv) Under assumptions (i)–(iii), the former USSR has the potential to become a major exporter of oil and gas. To avoid excessive optimism on this score, we have lowered the region's resource depletion factor (RDF) while retaining the same assumptions regarding the magnitude of oil and gas resources and reserves. The RDF represents the maximum fraction of the remaining undiscovered oil and gas resources that may be converted into proven reserves during any one year. The RDF has also been lowered for the ROW region.

(v) There are two new classes of constraints. The first is a remedy for a logical defect in the original formulation of 5R. This is a condition ensuring that each region's oil exports cannot exceed its domestic production. Within each region, there are then separate markets for oil and natural gas with endogenous prices for each of these fuels. As non-electric energy sources, oil and gas are perfect substitutes except that we specify limits upon interfuel substitution. Natural gas can no longer supply more than 50% of any region's nonelectric energy. Together, these two modifications have the direct or indirect effect of imposing more realistic limits upon international oil trade than those employed previously.

2.6. Details of implementation and solution

Both the 5R and the AGE versions of Global 2100 are solved as nonlinear optimizations written in GAMS (a generalized algebraic modeling system). See Brooke *et al.* (1988). In order to convert 5R into its AGE counterpart, we took advantage of modularity and inserted regional subscripts into the unknowns and constraints for each of the five regions. These regional blocks are semi-autonomous systems, and each consists of about 450 linear and nonlinear constraints. The five blocks are linked to each other through just 44 coupling equations. There is one for each of the 11 projection periods $(2000, 2010, \ldots, 2100)$ and for each of the four tradeable commodities: crude oil, natural gas, carbon emission rights and the numeraire good.

The reader should be alerted to a technical difficulty relating to the post-2050 backstop phase whenever there are carbon emission constraints and there is free trade in carbon emission rights. In Global 2100, it is assumed that a carbon-free nonelectric backstop is more expensive than one that is carbon-emitting. Moreover, there are no interregional differences between the costs of these two backstops. These assumptions did not affect 5R because the informal decomposition procedure was not extended beyond 2050.

Within the AGE version of Global 2100, there are difficulties created by these backstop assumptions. Although the equilibrium price of carbon emission rights is determined uniquely, there is non-uniqueness in the backstop quantities produced within each region. The location of backstop production is indeterminate, and the regional shares may fluctuate erratically over time. These difficulties can be overcome in a reasonably straightforward way. It requires only a small amount of judicious experimentation to identify those years and regions for which it is redundant to allow for international trade in carbon emission rights. We then assign a zero value to the level of the carbon trade activities for these years and regions. Because the procedure is somewhat arbitrary, this paper reports annual results only during the transition phase – that is, through 2050.

3. Scenarios for Business-As-Usual and Carbon Emission Limits

In this and the following sections, the AGE model will be employed to compare four alternative scenarios. These are abbreviated and identified as follows:

BAU:	business-as-usual;
CLM:	carbon emission limits designed to achieve global stabilization; by 2010, a 20% cutback from 1990 levels in the USA, OOECD and former USSR; increase not to exceed 50% in China and the ROW regions;
UNL:	unilateral 20% emission cutbacks within the USA and OOECD; no limits upon the former USSR, China and ROW;
NCT:	no carbon emission rights trading; otherwise same as CLM.

For the regional distribution of carbon emissions under BAU, see Figure 1. Note that the currently industrialized nations (USA, OOECD and USSR) account for most of the world's carbon emissions in 1990, but that their share is projected to drop to less than 50% by 2050. This is consistent with the conventional wisdom that the developing nations are likely to account for much of the world's increase in carbon emissions over the next half century.

Our BAU projections for the former USSR are less conventional. In view of the dramatic changes in this region's political structure since the fall of the Berlin Wall in 1989, there is a realistic potential for "no regrets" energy and environmental policies. With the elimination of constraints on international trade in oil and gas, there is a dramatic increase in the domestic price of energy. Even if economic growth is maintained at roughly the same percentage rates as in the USA and OOECD, price-induced energy conservation (together with a shift toward natural gas) could lead to the virtual stabilization of carbon emissions from the former USSR through 2050.

Next we compare BAU with the CLM scenario which involves a global agreement on carbon limits and international trade in emission rights. Figure 2 shows the regional distribution of percentage GDP losses. With international carbon emission quotas based largely upon 1990 levels, the biggest

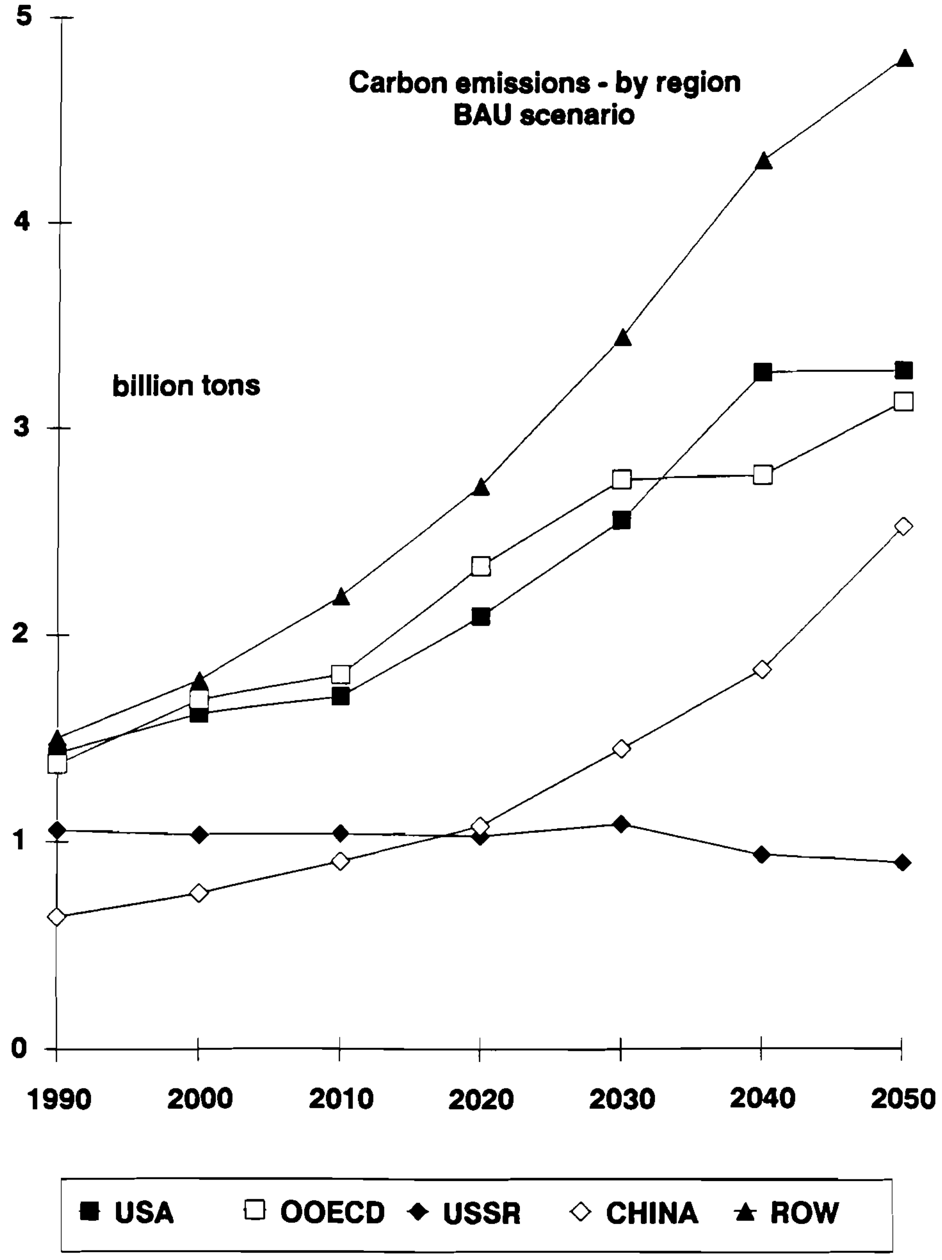

Figure 1. Carbon emissions by region: BAU scenario.

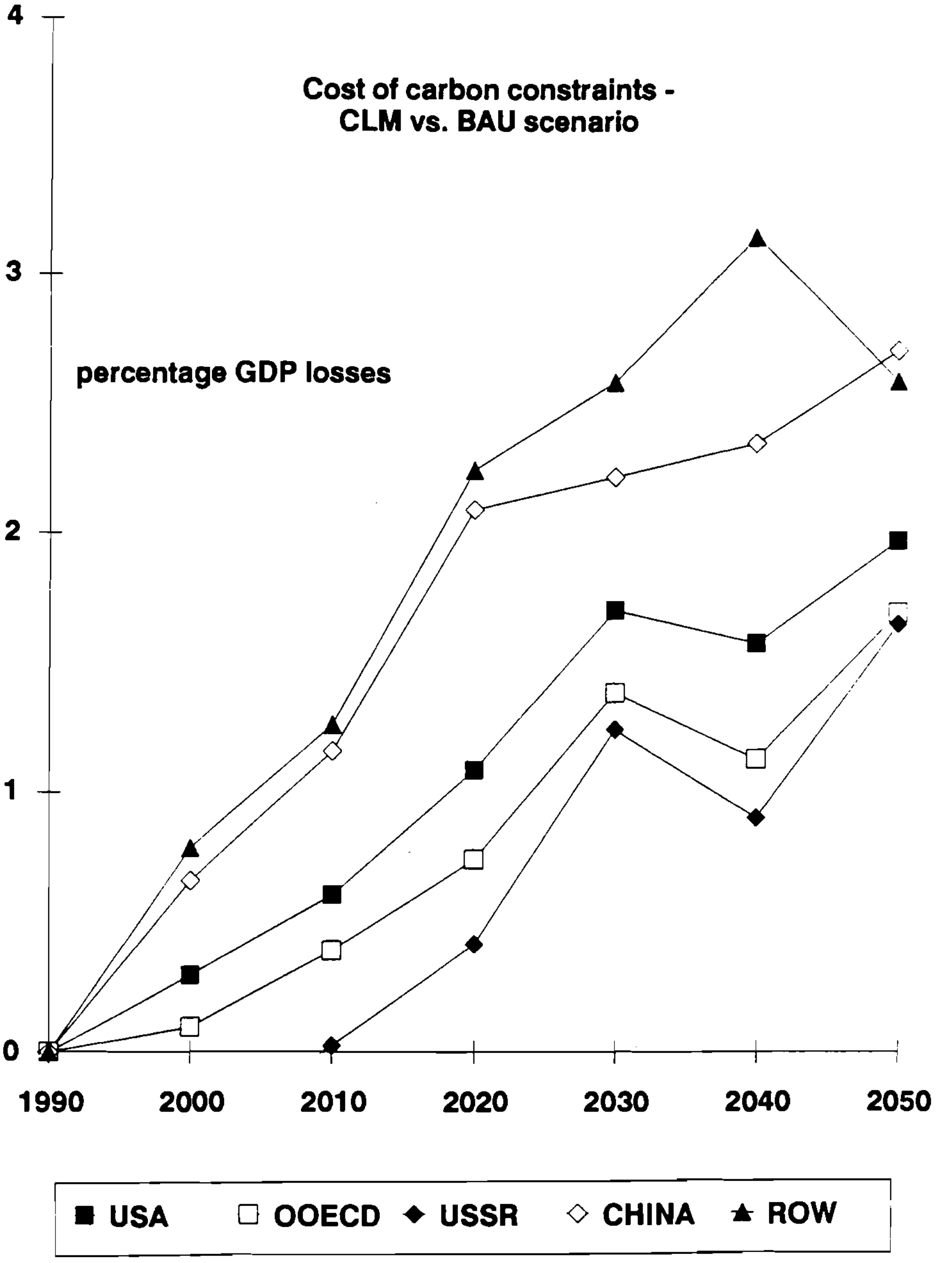

Figure 2. Cost of carbon constraints: CLM vs. BAU scenario.

losers are the rapidly growing regions: China and the ROW. The percentage losses in the USA and OOECD regions are roughly comparable with each other. The USA remains more carbon-intensive than the OOECD, but it has the advantage of lower preexisting taxes on nonelectric energy. The smallest loser is the former USSR. This is the region whose emissions remain nearly constant under BAU.

Two caveats related to these estimates of GDP losses: (1) Global 2100 measures only the costs of emissions abatement. It does not measure any of the benefits that might accrue from reducing the atmospheric accumulation of carbon dioxide. (2) Because of endogenous changes in the international prices of oil, gas and carbon emission rights, the AGE model leads to a somewhat different regional incidence of gains and losses than the original 5R. Some of these changes are attributable to changes in numerical values of the input parameters, and others can be traced to differences in model structure.

With trade, there is an internationally uniform carbon tax and an efficient allocation of carbon rights between regions. According to Figure 3, the tax begins at a relatively low level in 2000 (about $50 per ton). During the first two decades of the 21st century, it is optimal to delay the exercise of emission rights. This is why the tax rises at a real rate of 5% annually, following the rate of return on the international numeraire good. It is not until 2030 that electric backstop technologies become widely available, and there is a temporary drop in the value of emission rights. Thereafter, there is a transition away from conventional oil and gas toward backstop nonelectric technologies. From 2050 onward, the carbon tax stabilizes at just over $200 per ton. This is the rate required in order to make the carbon-free backstop competitive with coal- or shale-based synthetic fuels.

Under the CLM scenario, there is a significant volume of international trade in carbon emission rights. This could lead to strains within the domestic political coalitions that support emission limits. During the entire transition period through 2050, the OECD nations are net importers of carbon rights from China and the ROW. The financial transfers are $20 billions in 2000, and would range between $50 and $80 billions annually thereafter.

According to our model, the dollar value of interregional oil trade is likely to be far higher than that of natural gas and carbon emission rights. Oil exports originate primarily in the ROW region (which includes OPEC), but there is a growing share provided by the former USSR. There are systematic differences between the export quantities under BAU and CLM. Under BAU, the ROW exports more oil during the first two decades of the 21st century

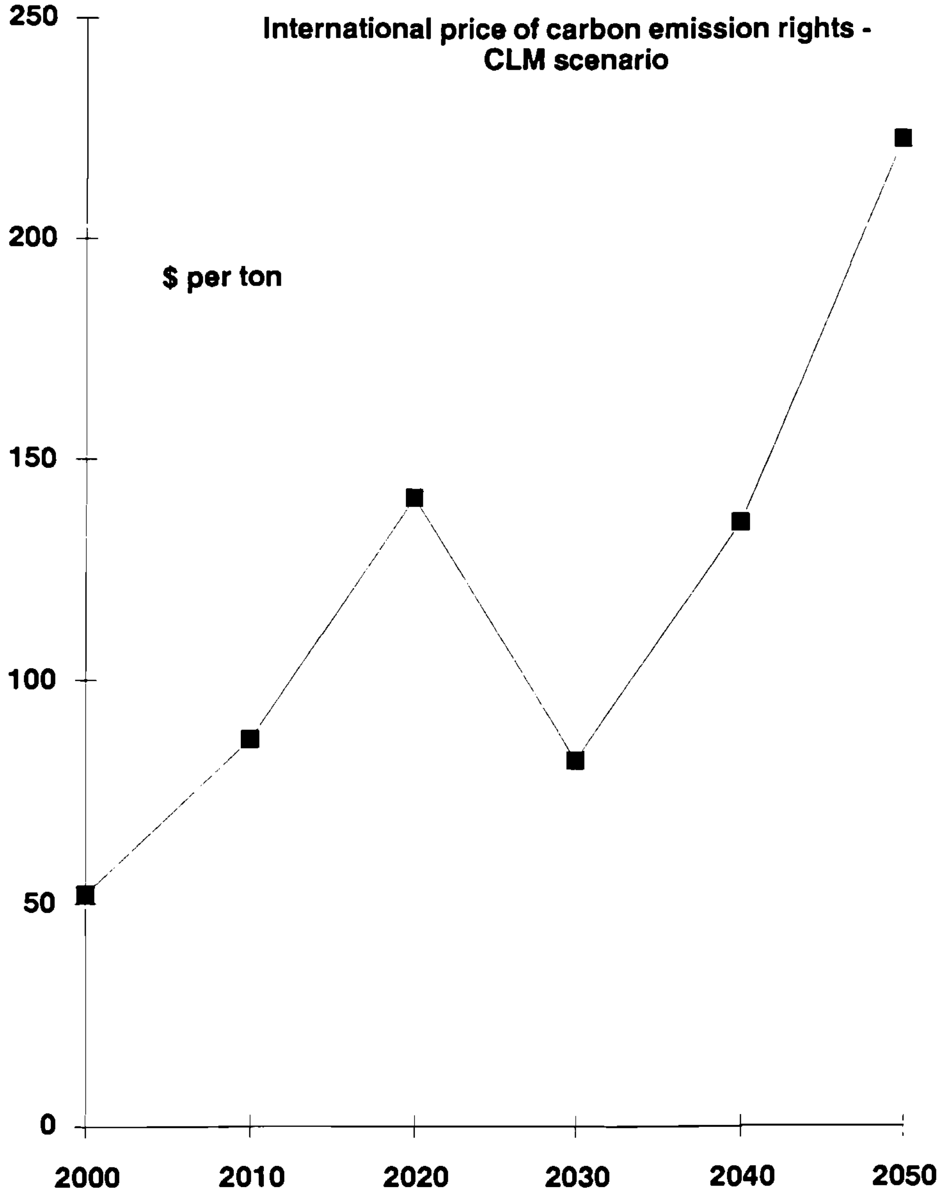

Figure 3. International price of carbon emission rights: CLM scenario.

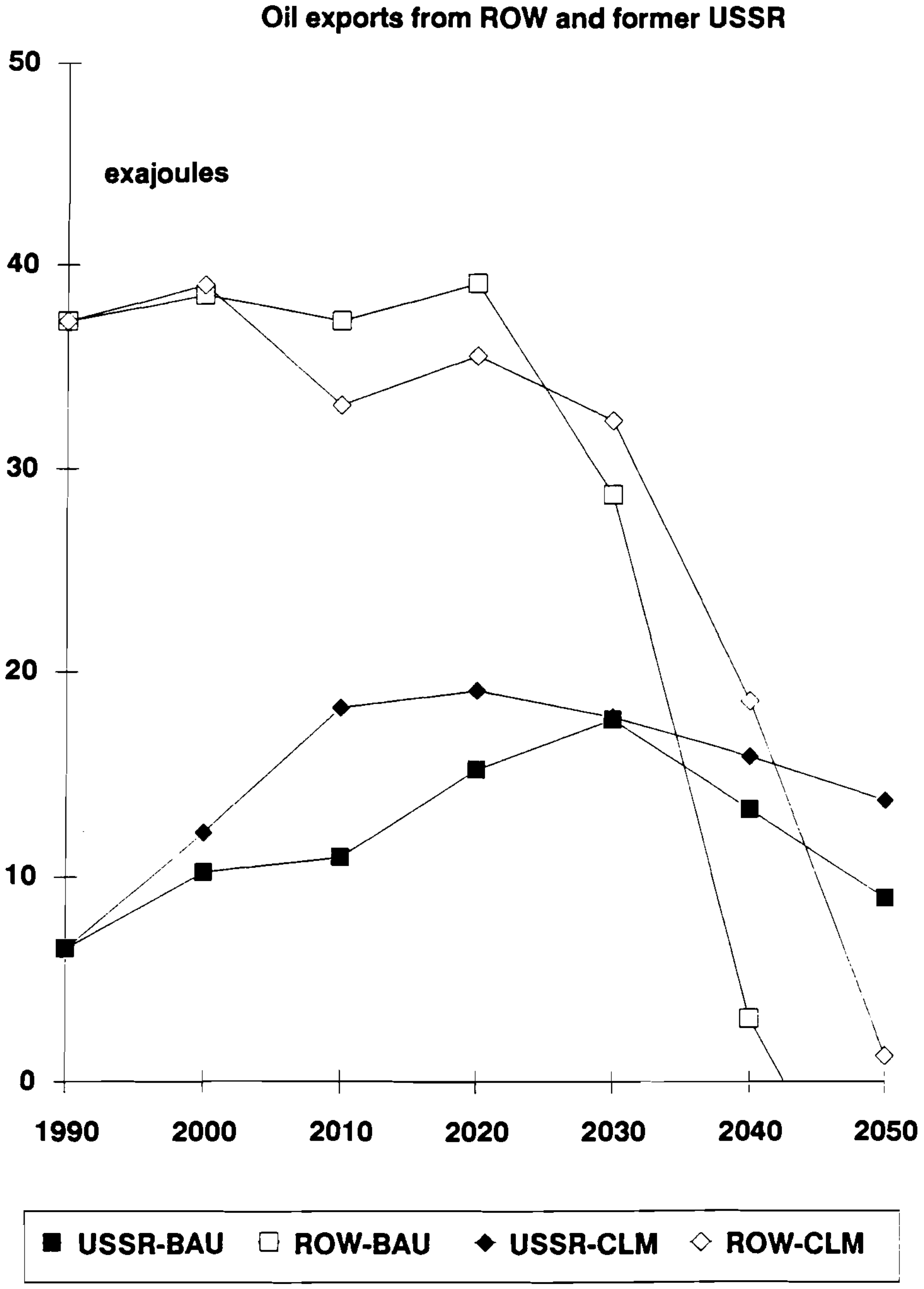

Figure 4. Oil exports from ROW and former USSR.

but less thereafter than under CLM. Under BAU, the former USSR exports less oil at almost all points in time. See Figure 4.

4. Unilateral OECD Carbon Emission Cutbacks

Because of the difficulties of inducing China and the ROW to reduce their carbon emissions, it has been proposed that the OECD nations take the first step toward global reductions. The UNL scenario (a unilateral 20% OECD emissions cutback) could be effective for a few decades, but probably not beyond. Figure 5 provides a three-way comparison between BAU, CLM and UNL. From 2020 onward, there is no way to stabilize global emissions unless the developing nations are somehow induced to join an international agreement. Their growth is too important to be ignored.

There is a further difficulty. Because of international trade links, a one ton unilateral OECD reduction will not be translated automatically into a one ton reduction in global emissions. Carbon emissions may increase elsewhere. To quantify this idea, we calculate the average "leakage rate" as the ratio of carbon emission increases outside the OECD to carbon emission cutbacks within the OECD, in each future year measuring increases and cutbacks relative to the BAU scenario. (See Felder and Rutherford, 1992.) So long as the leakage rate is less than 100%, unilateral action produces a decrease in global emissions. According to Figure 6, the leakage rates would be low initially, but could reach over 30% during the transition period away from oil and gas.

In order to understand why this might occur, see Figure 7. There are interactions between international oil prices, the quantities traded and the presence or absence of carbon emission limits. Through 2010, either an international or a unilateral carbon limitation agreement would put downward pressure on the international price of oil. This has the perverse effect of stimulating oil consumption – particularly within China and the ROW in the UNL scenario.

Over the long term, conventional hydrocarbons become exhausted, and oil prices increase toward their backstop level. Under BAU, oil prices are capped by coal-based synthetic fuels, and it is assumed that these cost $50 per barrel of oil equivalent. With CLM, oil enjoys a premium relative to coal-based synthetic fuels. Since oil's carbon emissions coefficient is half that of synthetic fuels, its international price eventually reaches $75 per barrel halfway between the cost of synthetic fuels and the carbon-free backstop.

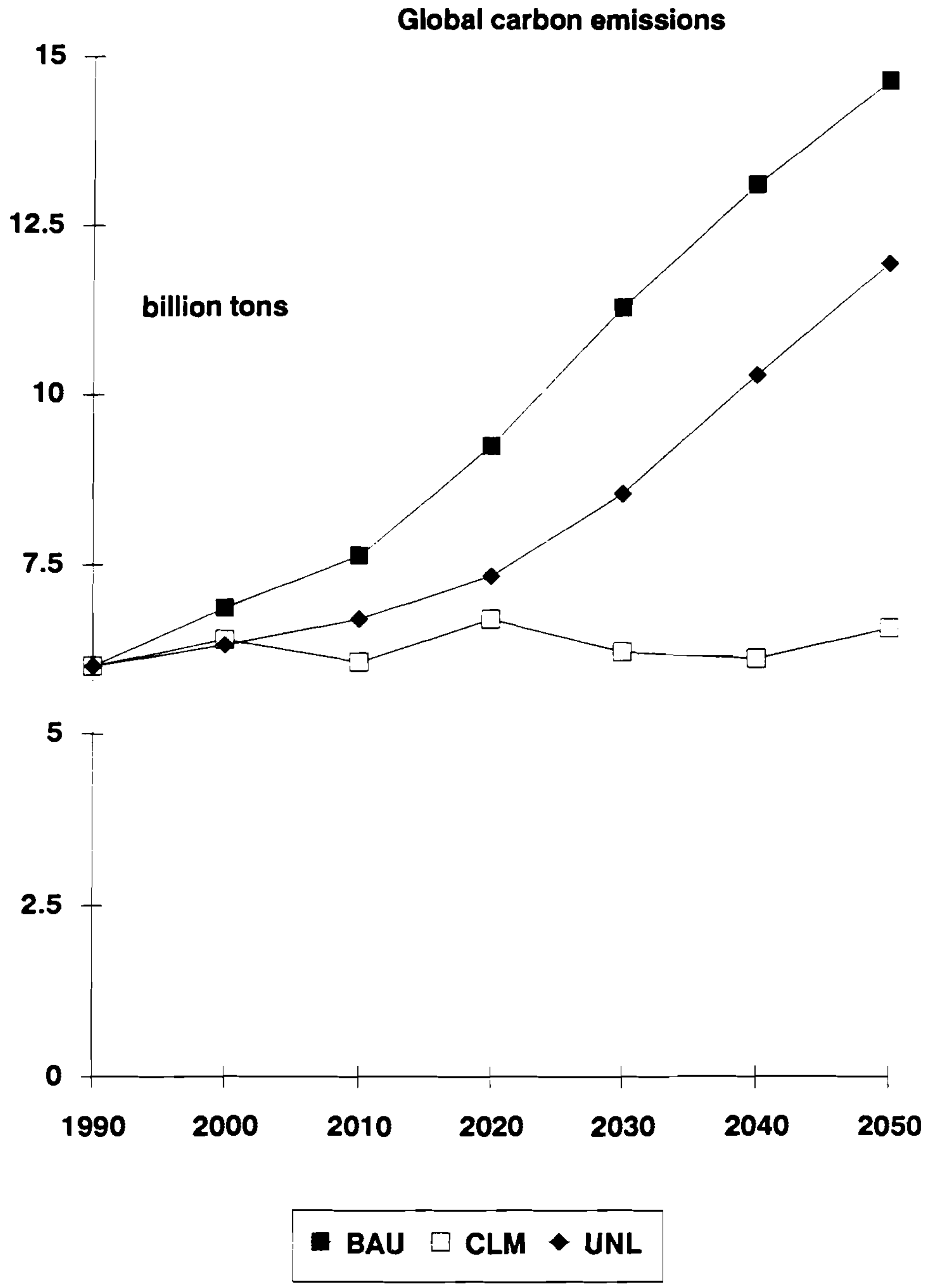

Figure 5. Global carbon emissions.

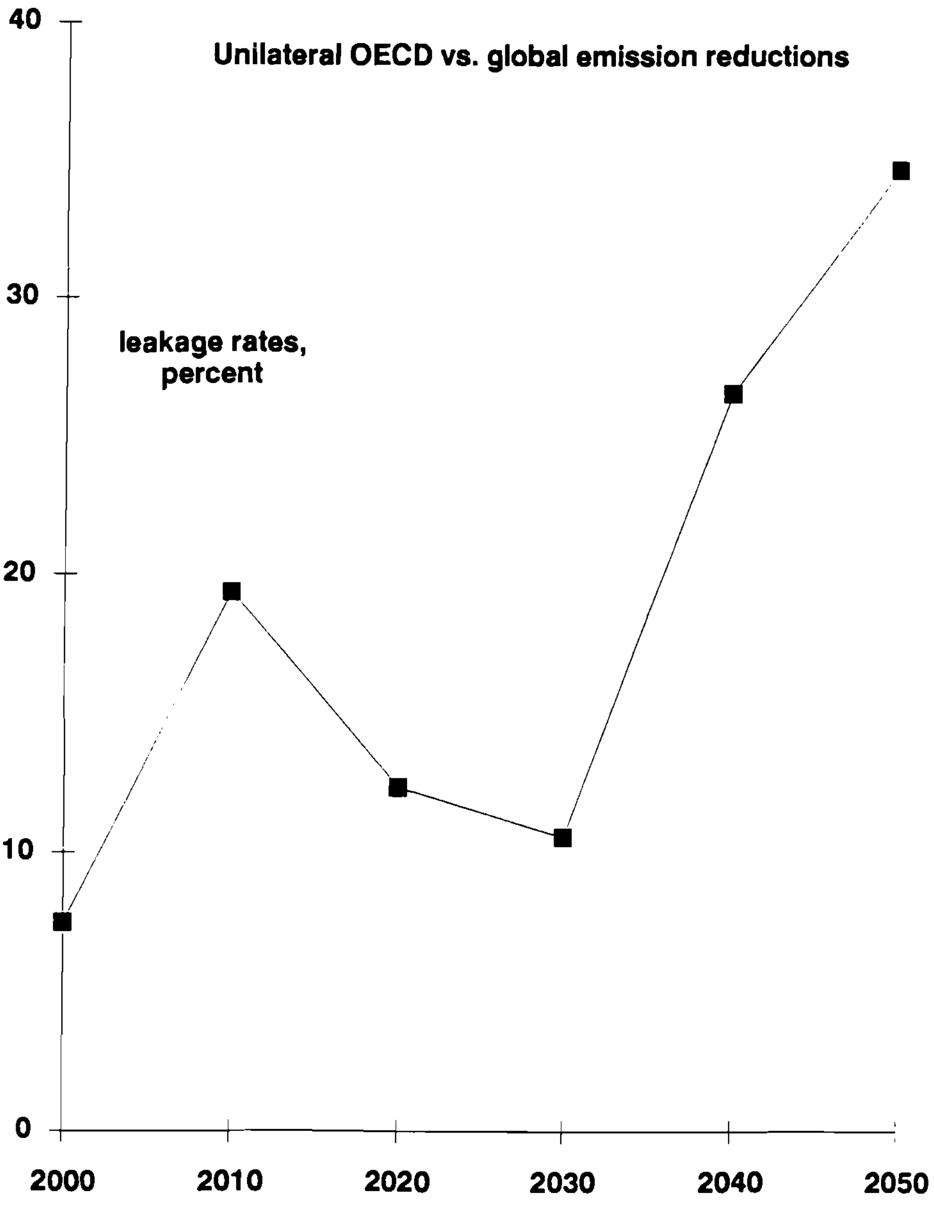

Figure 6. Unilateral OECD vs. global emission reductions.

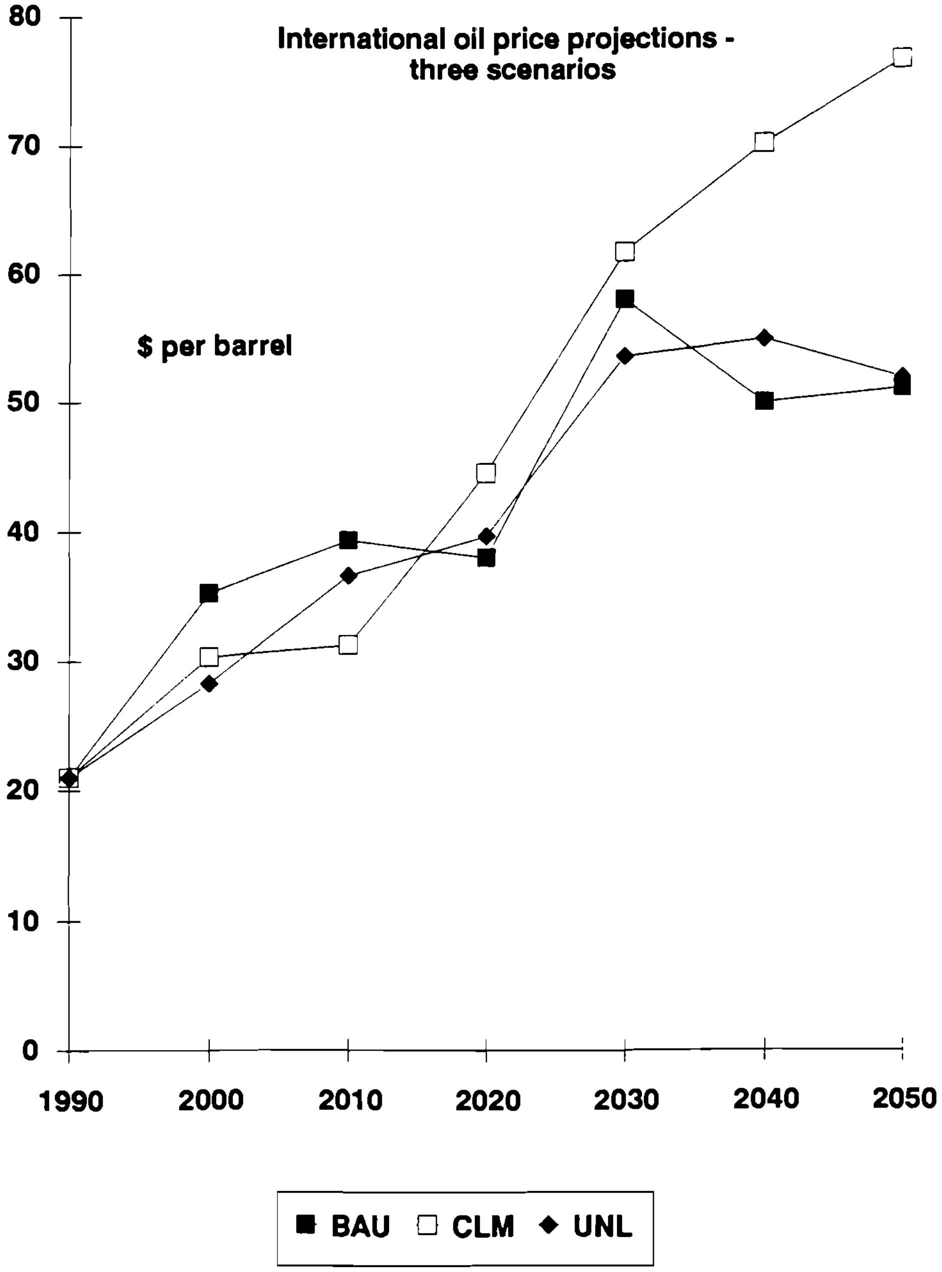

Figure 7. International oil price projections: three scenarios.

With the unilateral reductions scenario, there are incentives for locating synthetic fuels production outside the OECD region during the period of transition away from exhaustible resources. At that time, China and the ROW could supply much of their domestic nonelectric energy needs through synthetic fuels, and they would compete to export their oil production to the OECD countries. This keeps the international price of a barrel of oil down to the $50 backstop level, but it leads to the high leakage rates that have already been noted. Overall, these calculations suggest the implausibility of a unilateral OECD emissions cutback as a viable long-term global option.

Our leakage analysis leads to different results than those reported by others. We believe that many of these differences can be traced to the handling of dynamic linkages. Perroni and Rutherford (1992) and Pezzey (1992) employ static general equilibrium frameworks. Felder and Rutherford (1992) use a recursively dynamic model. Both of these approaches miss out on the role of price expectations in the determination of short-run supplies and demands for energy.

5. The Gains From International Trade in Carbon Emission Rights

International trade would lead to an economically efficient allocation of carbon emission rights, and it would help to separate efficiency issues from those of equity. This type of trade would, however, require a totally new set of institutions. There could be futures as well as spot markets. Some sort of banking system might have to evolve in order to monitor international transactions in these rights. Because of the difficulties in setting up these institutional arrangements, it is instructive to see what might happen if the same region-by-region limitations were imposed as in CLM, but there is no carbon trade. This scenario is abbreviated NCT.

Figure 8 compares the price paths of carbon emission rights. Under CLM there is a uniform international price, but with NCT there is a separate price in each region. Through 2020, the value of carbon is much higher in the USA and OOECD region than elsewhere. NCT provides a strong incentive for carbon trade either directly or indirectly. After 2020, there are four regions in which the value of carbon rights tends to converge toward the identical backstop price. The only exception is the former USSR. Because of its huge natural gas resources, it is in a rather different position than the other regions. See the cross-scenario comparison of its gas exports to the

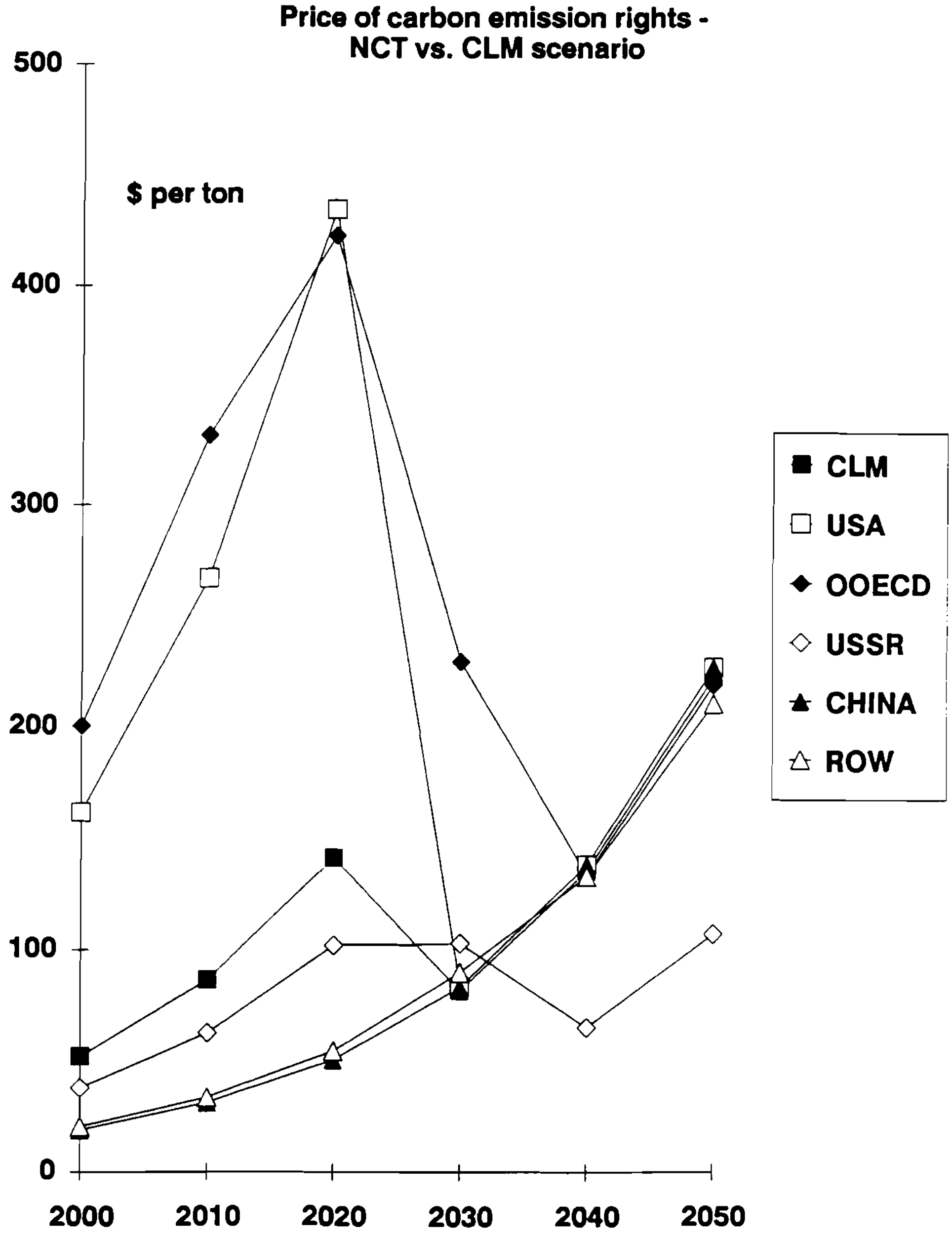

Figure 8. Price of carbon emission rights: NCT vs. CLM scenario.

OOECD (Figure 9). Note that these exports represent quantities over and above the relatively small amount of actual shipments (2 exajoules) in 1990.

Through 2020, when there is trade in carbon emission rights, the OOECD region finds it profitable to import these rights rather than to pay the \$2/GJ costs required to transport gas from the former USSR. Both under the BAU and CLM scenarios, large-scale gas trade does not begin until 2030. With NCT, the starting date is 2010. Natural gas has a carbon emissions coefficient 30% below that of oil and 66% below that of synthetic fuels. This provides a strong incentive for gas trade to serve as a substitute for trade in emission rights. Even with high exports, the former USSR does not exhaust its gas resources during the 21st century. Its allocation of emission rights is too small for it to be economical to produce synthetic fuels. Natural gas is the best domestic alternative to the high-cost, carbon-free nonelectric backstop. This means that the marginal value of carbon emission rights is lower than in other regions through 2050. Thereafter, it rises sharply because of competition between natural gas and the carbon-free backstop. The gas resources of the former USSR do not become exhausted until after 2100.

We are now in a position to estimate the gains from trade in carbon emission rights. Perhaps the simplest summary measure is to compare the losses from carbon restrictions both with and without trade. For this purpose, we employ a 5% real discount rate and cumulate the macroeconomic consumption losses through 2100. The region-by-region results are shown in Figure 10. All regions gain from trade. There would have been still greater gains from trade if the regional distribution of carbon allocations had been based upon an egalitarian criterion such as 1990 population rather than a status quo criterion such as 1990 emissions.

According to Figure 10, four of the five regions incur losses from carbon restrictions, but the former USSR is an exception to this pattern. Because of the net effect of changes in the international prices and the quantities traded, it is a small gainer from carbon restrictions.

6. Conclusions and Suggestions for Further Research

This AGE extension of Global 2100 provides insight into a number of policy issues. First, our model shows how carbon emission restrictions might affect crude oil prices and the quantities traded. Carbon restrictions tend to depress oil prices in the near term, but to increase them in the long term.

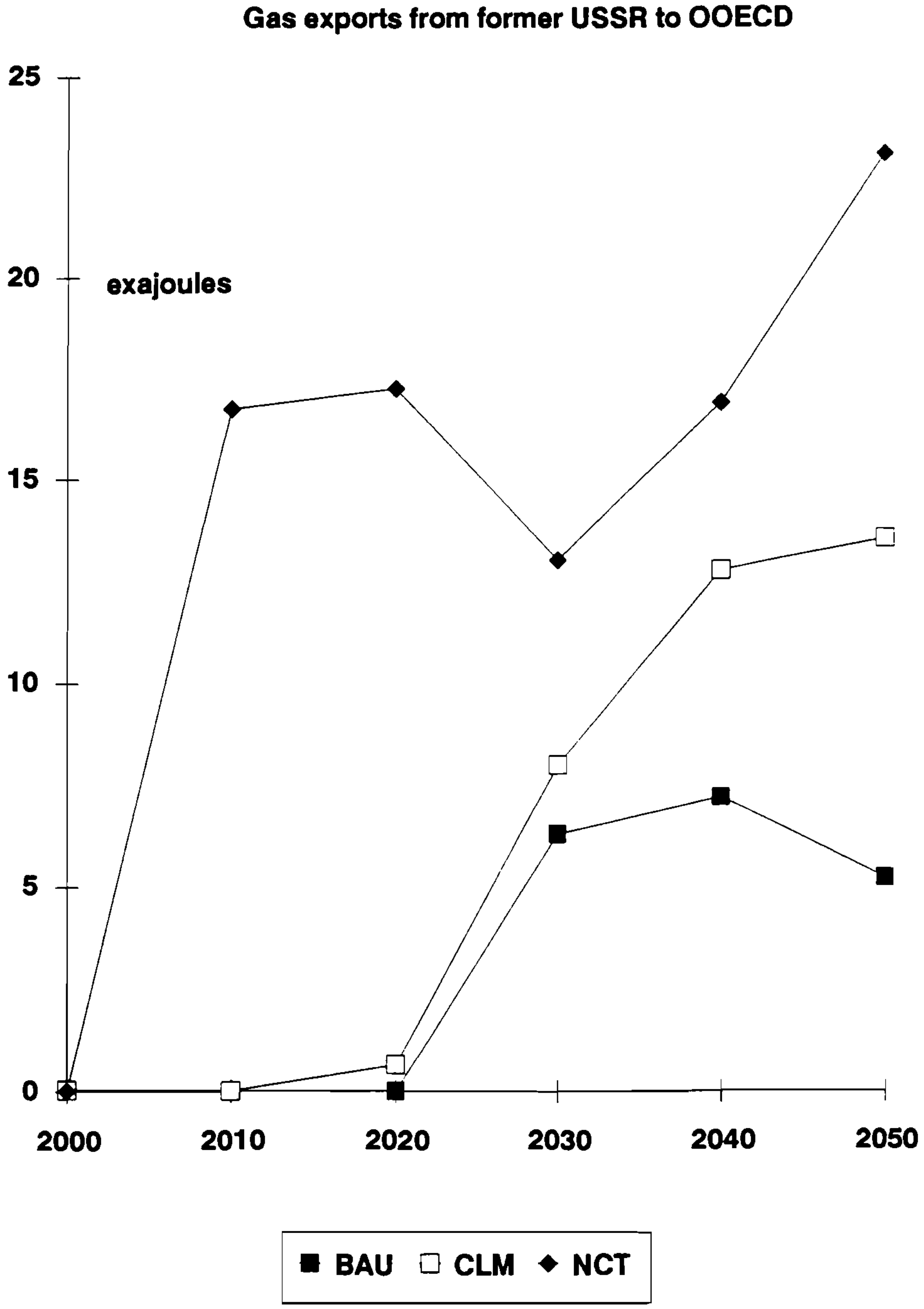

Figure 9. Gas exports from former USSR to OOECD.

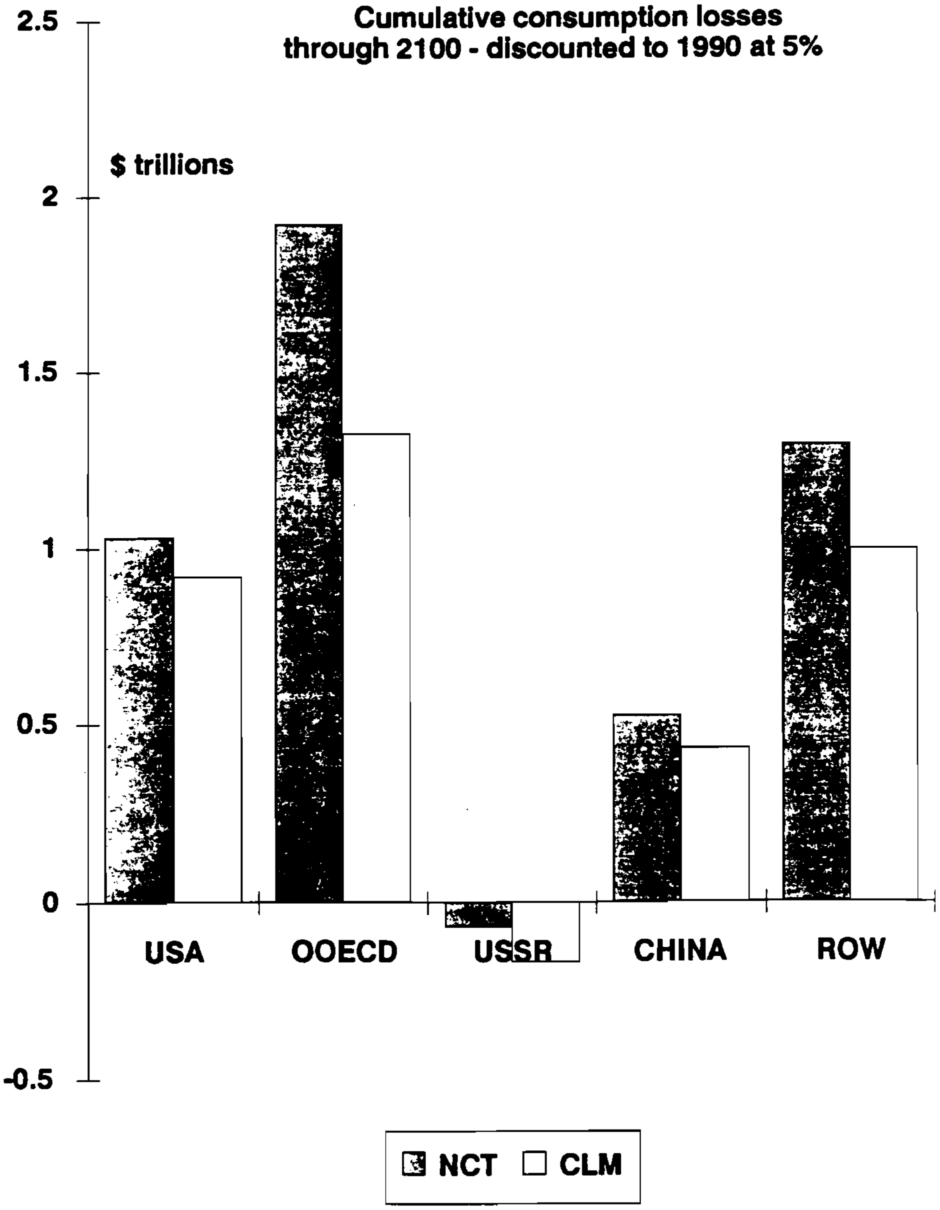

Figure 10. Cumulative consumption losses through 2100, discounted to 1990 at 5%.

Oil is less carbon-intensive than coal-based synthetic fuels, hence oil enjoys a premium in periods when carbon taxes are high.

Second, we find that carbon limits affect the prospects for pipeline trade in natural gas between the former USSR and Western Europe. This could be particularly important in scenarios when there is no trade in emission rights. In these cases, natural gas trade would provide a direct substitute for trade in emission permits.

Third, our estimates of the costs of carbon restrictions are roughly comparable with those of Manne and Richels (1992). Unlike their heuristic decomposition procedure based upon parallel single region projections, our algorithm is fully automatic.

Finally, we find that the free-rider problem limits the effectiveness of unilateral carbon reductions by the OECD nations. From 2020 onward, there is no way to stabilize global emissions unless the developing nations are somehow induced to join an international agreement. There are further difficulties with a unilateral approach. A 20% unilateral cutback would lead to average leakage rates of the order of 10-20% through 2030. Thereafter, the leakage rates would rise even higher with the emergence of coal-based synthetic fuels.

This study provides an important lesson in AGE methodology, particularly for activity analysis models that incorporate inequalities and point-to-set mappings. Our experience indicates that the sequential joint maximization procedure can process a problem which would have involved about 5300 inequality constraints if it had been formulated as a complementarity problem. SJM provides us with the ability to deal with five to ten times as many constraints as those that can be handled reliably by Newton-based methods such as the SLCP algorithm of Mathiesen (1985).

There are a number of directions for further research. First, the present model might be extended to distinguish additional regions. This would make the model more useful in assessing the negotiating positions of various countries in their bargaining over a comprehensive global agreement.

A second type of extension would be to disaggregate non-energy tradeable commodities. In their recursively dynamic model, Felder and Rutherford (1992) estimate that about half the total leakage arises from the impact of unilateral OECD emissions constraints upon the international oil market, and that another half can be traced to changes in the location of production of energy-intensive commodities. It would be useful to evaluate whether this estimate would remain valid with the intertemporal framework adopted here.

Perhaps the most challenging direction for future work would be an explicit analysis of decisions under uncertainty. It is easy enough to trace out various futuristic scenarios, but it is more relevant to see how these might affect today's policy decisions. To analyze hedging strategies in a rigorous way, we will need to specify dates for the resolution of uncertainties, and to assign numerical probabilities to various future states-of-the-world. In principle, it is straightforward to do this type of analysis, but these ideas have just begun to emerge within the greenhouse policy debate.

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Simulation Study on Tradable CO_2 Emission Permits

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Abstract

This paper presents a simulation study on the feasibility of global CO_2 emission control through international trading in emission permits, which is theoretically expected to be an institutional scheme for achieving globally efficient CO_2 control while maintaining a fair sharing of the burden among regions. The "Edmonds–Reilly Model" is used for simulations, with some modifications such as the introduction of an international market for emission permits, regional CO_2 taxation, and regional CO_2 absorption options. Simulation results illustrate the effectiveness of the proposed global system for CO_2 reduction.

Key words: global warming, tradable CO_2 emission permit, CO_2 tax, world energy model

1. Introduction

Global environmental problems, particularly global warming caused by greenhouse gases, have attracted considerable attention lately in international energy policy studies. Carbon dioxide is responsible for about half of the total contribution of greenhouse gases to global warming. However, reducing CO_2 emissions will be extremely difficult because CO_2 emissions occur mainly as a result of burning fossil fuels which supply almost 90 percent of world energy requirements. World energy systems should change significantly to cope with the global warming problem. It is required that the socioeconomic impacts caused by the introduction of policy measures to reduce CO_2 emissions are assessed in advance of their implementation.

A variety of economic measures to reduce CO_2 emissions can be classified into CO_2 taxation and emission permit trade. The CO_2 taxation introduces a penalty in the market optimization process, while the emission permit trade forms an optimization process itself with an explicit constraint on CO_2 emissions.

To achieve globally efficient control while maintaining fair burden sharing among regions, a scheme of global CO_2 emission control through international trading in emission permits has been proposed. In this scheme, the total world emission limit determined by scientific knowledge is allocated to each of the members which represent each region in the world under a certain rule. Then the allocated emission permits are traded through an international market. When the member's CO_2 emission in a region exceeds the initial allocation of its emission permit, then the member must reduce its emission by regional measures or buy emission permits through the international market.

This paper proposes a global CO_2 emission control scheme with a combination of international emission permit trade and regional measures which consist of regional CO_2 taxation and regional CO_2 absorption by afforestation. The effectiveness of the proposed global CO_2 emission control scheme is illustrated by simulations.

2. Global Energy Model

A computer model which is utilized in this simulation is based on the IEA/ORAU long-term global energy mode, namely the "Edmonds–Reilly Model" (Edmonds and Reilly, 1983). This model is a mathematical model which integrates economic, demographic and technological factors to make long-term projections of global energy and CO_2 emissions.

The model divides the world into 9 regions as shown in Figure 1 and can assess alternative energy strategies up until the year 2100 with an interval of 25 years. The model computes energy demands for 6 major primary energy sources (1 = oil; 2 = gas; 3 = solids, e.g., coal and biomass; 4 = resource-constrained renewable, i.e., hydroelectric power; 5 = nuclear, 6 = solar). Energy demand is a function of population, labor productivity, economic activity, technological changes, energy prices, and energy taxes and tariffs in each region. Energy supply is dependent upon resource constraints, technological progress, and energy prices for the various regions. The prices and quantities of three fossil fuels are determined at an equilibrium point of world energy markets. After a world energy balance has been reached, CO_2 emission associated with the consumption of fossil fuels is evaluated with appropriate carbon emission coefficients.

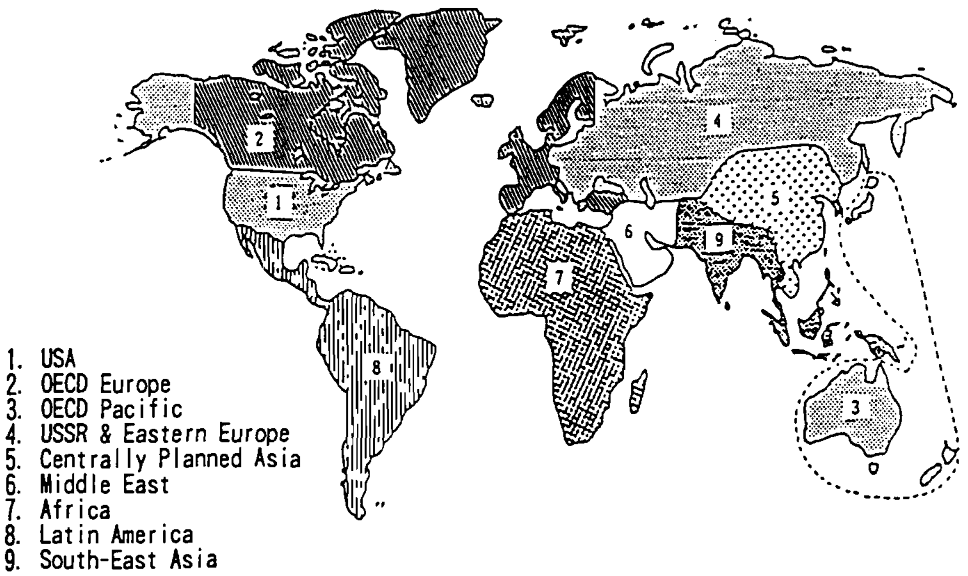

Figure 1. The nine regions in the Edmonds–Reilly Model.

3. Modeling of Absorption Options

It is difficult to estimate the exact amount of land available for afforestation. Matthews estimated that 702 million hectares of forest land had been lost by human activity as of 1980 (Matthews, 1983). Williams estimated that a total of 806 million hectares of forest plus woodland had been converted to other uses by 1978 (Pitelka, 1990; Marland, 1988). In this study, we assume that the maximum amount of land available for afforestation is equal to the amount of forest destroyed by past human activities. Thus, a world maximum potential is set at approximately 800 million hectares based on these reports. A geographical breakdown of this maximum potential is reproduced in Table 1.

There are also limits for the annual rate of afforestation reflecting the constraints of manpower and related facilities. For example, the average worldwide annual afforestation of land in 1980 is about 15 million hectares which is 1.86 percent of the maximum potential. In this study, it is assumed that the limit of annual afforestation of land is 1 percent of the maximum potential.

The rate of CO_2 absorption by afforestation is different for kinds of vegetation. In this study we assumed an average annual rate of carbon absorption in each region as shown in Table 1.

Table 1. Regional maximum potential for afforestation and rate of CO_2 absorption.

Region	Max. potential (Mha)	Rate of CO_2 absorption (t-C/ha/year)
USA	45	5.9
OECD Europe	104	3.3
OECD Pacific	53	5.9
USSR & Eastern Europe	122	3.6
Centrally Planned Asia	86	5.9
Middle East	3	5.4
Africa	76	9.9
Latin America	121	9.9
Southeast Asia	197	9.9

Table 2. Regional afforestation cost functions.

Region	Area (Mha)	Cost (\$/t-C)
USA	0 - 11.3 - 45.0	9.3 - 92.9 - 594.7
OECD Europe	0 - 26.0 - 104.0	15.2 - 152.3 - 974.7
OECD Pacific	0 - 13.3 - 53.0	9.3 - 92.9 - 594.7
USSR & Eastern Europe	0 - 30.5 - 122.0	15.2 - 152.3 - 974.7
Centrally Planned Asia	0 - 21.5 - 86.0	7.1 - 71.3 - 456.5
Middle East	0 - 0.8 - 3.0	10.1 - 101.5 - 649.8
Africa	0 - 19.0 - 76.0	4.2 - 42.5 - 272.0
Latin America	0 - 30.2 - 121.0	4.2 - 42.5 - 272.0
Southeast Asia	0 - 49.2 - 197.0	4.2 - 42.5 - 272.0

For the cost function of afforestation in each region, we assumed a two-part, linear cost curve which increases slowly up to a quarter of the maximum potential and then increases sharply in the latter part (see Table 2).

4. Modeling of International Market for CO_2 Emission Permits

4.1. Initial allocation of CO_2 emission permits

In this paper it is assumed that an initial permit is allocated in proportion to the population of each region in the year 2000 as follows:

$$CQ_m = CQ \cdot Z_m \; / \; \sum_{i=1}^{9} Z_i \tag{1}$$

where CQ is a given world CO_2 emission limit, CQ_m is an initial CO_2 emission permit for region m, and Z_m is the population of region m in the year 2000.

4.2. Coordination of tradable emission permits, CO_2 taxation and afforestation

For a particular region, where CO_2 emissions are larger than the region's initial permit, the CO_2 emissions must be reduced either by purchasing a permit from an international permit market or by a regional strategy such as CO_2 taxation and absorption. Here, we assume that such a region is called a "permit import region". In permit import region m, the following regional constraint must be satisfied:

$$CE_m(t_m) = CQ_m + CP_m + CW_m \tag{2}$$

where $CE_m(t_m)$ is the CO_2 emission (Mt-C) under a CO_2 tax of t_m (\$/t-C). CP_m is the purchased permit (Mt-C) from the market. CW_m is CO_2 absorption by afforestation (Mt-C).

On the other hand, a region which has an initial permit larger than its CO_2 emissions is called a "permit export region". These regions supply CO_2 emission permits to the international market.

We assume that in the permit import region, the cost of purchasing permits and afforestation is covered by the revenue of CO_2 taxation. The following cost constraint is given:

$$CE_m(t_m) \cdot t_m = CP_m \cdot P + CW_m \cdot PW_m \tag{3}$$

where P is the price of a CO_2 emission permit in the international market (\$/t-C) and PW_m is the unit cost of afforestation in region m (\$/t-C).

If a permit export region introduces afforestation, the cost of afforestation is covered by the revenue of selling CO_2 permits in the international permit market. Thus, it must satisfy the following cost constraint:

$$P \cdot (CQ_m - CE_m) \geq CW_m \cdot PW_m \ . \tag{4}$$

Figure 2 shows the framework of our simulation model. As described in Figure 2, the GNP of a permit export region is increased by the amount of net revenue (permit sales minus afforestation cost).

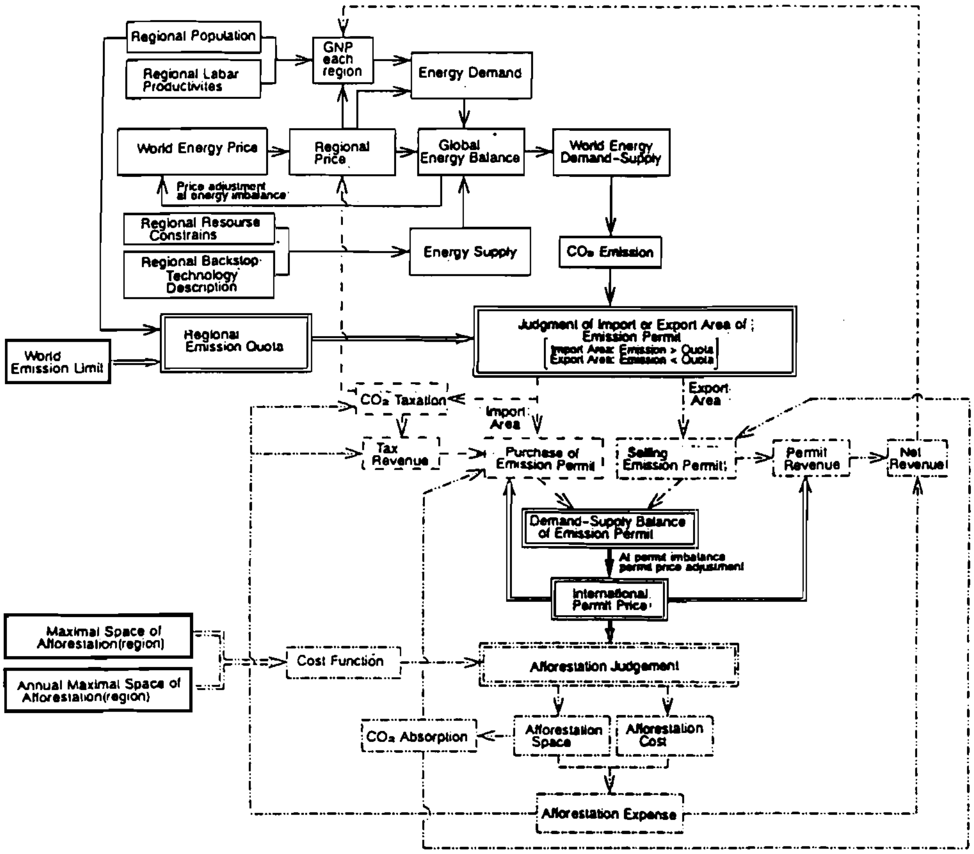

Figure 2. Flow-chart of CO_2 permit trade simulation with the Edmonds–Reilly Model.

4.3. Supply–demand equilibrium in the permit market

The CO_2 emission permits are traded in the international market. In this permit market, a balance of permit supply and demand must be satisfied. In the case of the introduction of afforestation, the following constraint on the permit market should be kept between the demand of permit import regions and the supply of permit export regions:

$$\sum_{m=1}^{n}(CQm + CW_m - CE_m(t_m)) = \sum_{m=1}^{(L-n)} (CQ_{n+m} + CW_{n+m} - CE_{n+m})$$

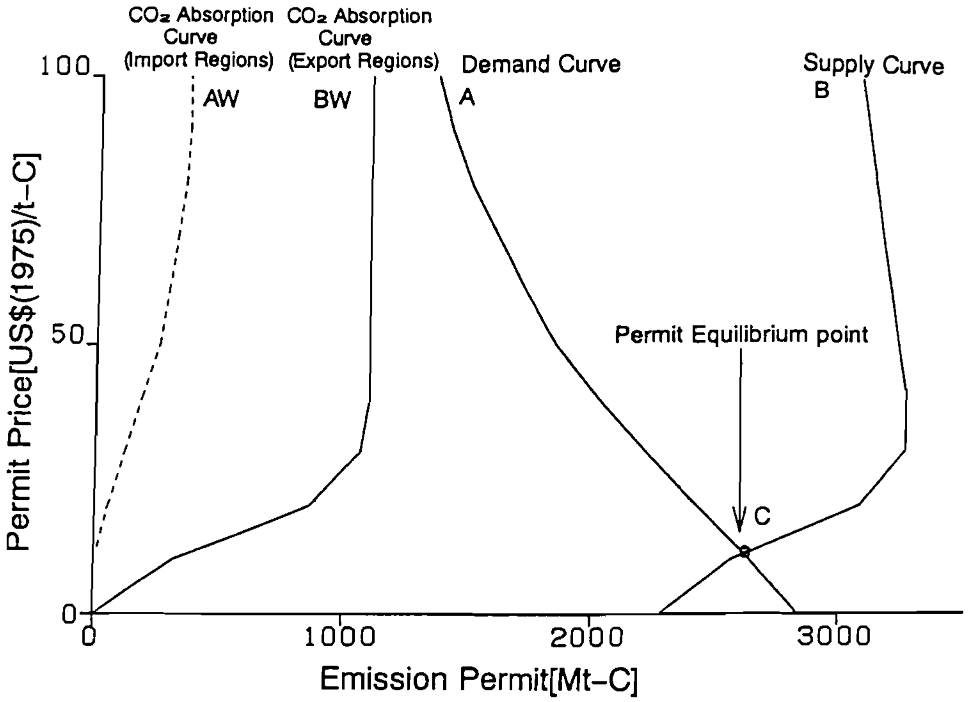

Figure 3. Demand-supply curves in the international CO_2 emission permit market with an absorption option (world CO_2 emission limit of 6Gt-C in the year 2000).

$$(\text{total demand}) = (\text{total supply}) \tag{5}$$

where L is the total number of regions and n is the number of permit import regions.

Figure 3 shows the demand-supply curve of CO_2 emission permits in the international market with the absorption option. In this figure, curve A is the total permit demand of import regions (USA, OECD Pacific, OECD Europe, Middle East, Centrally Planned Europe), and curve B is the total supply of export regions (Centrally Planned Asia, Latin America, Africa, Southeast Asia). Curve AW is the total CO_2 absorption by afforestation in all import regions and curve BW is the total absorption in export regions. Afforestation in permit export regions is introduced even when the market price of permits is low because of low afforestation costs in these regions. Where the permit price is higher, the rate of afforestation is limited by the annual afforestation constraint. The demand and supply of permits are in equilibrium at point C.

Table 3. Simulation cases.

Case name	CO_2 taxation	Tradable permit	Absorption option
(1) Reference	–	–	–
(2) Taxation	Available	–	–
(3) Equilibrium	Available	Available	–
(4) Absorption option	Available	Available	Available

5. Simulation Results and Discussions

5.1. Simulation cases

Table 3 shows simulation cases which are selected from different combinations of CO_2 control strategies. In all cases, the original database of the Edmonds-Reilly Model (NIEA.DAT dated 22 August 1989) was used.

The case with no CO_2 limit and no specific CO_2 control measures is the reference case of the simulation study. In the taxation case, import regions have to reduce their CO_2 emissions to the level of the initial permits allocated only by regional CO_2 taxation strategy. In the permit equilibrium case, the international emission permit trade and regional CO_2 taxation are introduced to keep within the world CO_2 limit. In the absorption option case, regional afforestation is added to the permit equilibrium case. Simulation was carried out up to the year 2025.

5.2. Simulation results

Figure 4 shows CO_2 emissions for 1975–2025 in the reference case. World CO_2 emissions increase from 3.8 Gt-C in 1975 to 9.9 Gt-C in 2025. In 1975, industrialized regions including the USSR and Eastern Europe produced more than half of the world CO_2 emissions. In 2025, however, due to population growth and economic growth, the share of the developing regions becomes higher than that of industrialized regions.

Figure 5 shows the flows of tradable permits at an equilibrium point under a world CO_2 emission limit of 5 Gt-C in the year 2000 in the permit equilibrium case. Five permit import regions (USA, OECD Pacific, OECD Europe, USSR and Eastern Europe, and Middle East) purchase emission permits from the market. Tradable permits are provided from four permit export regions (Southeast Asia, Africa, Latin America, and Centrally Planned Asia). Southeast Asia supplies 80 percent of the total tradable permits (967 Mt-C), and the USA purchase about 40 percent of the total permits provided.

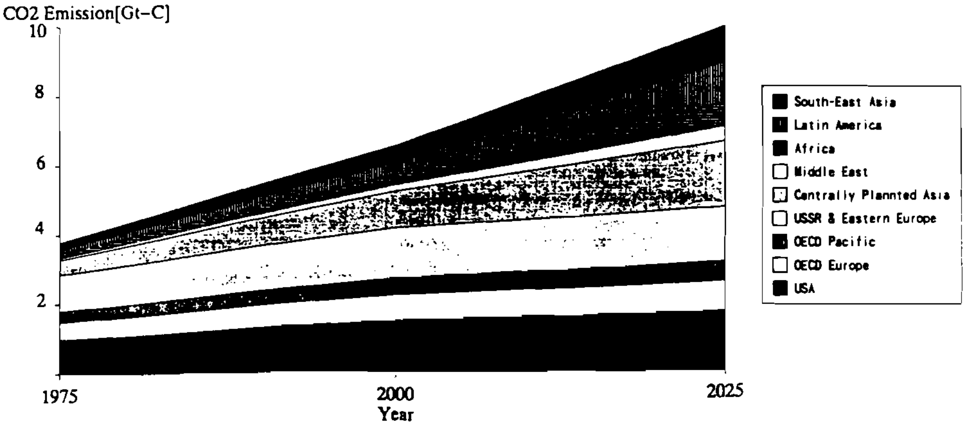

Figure 4. CO$_2$ emissions by each region (1975–2025) in the reference case.

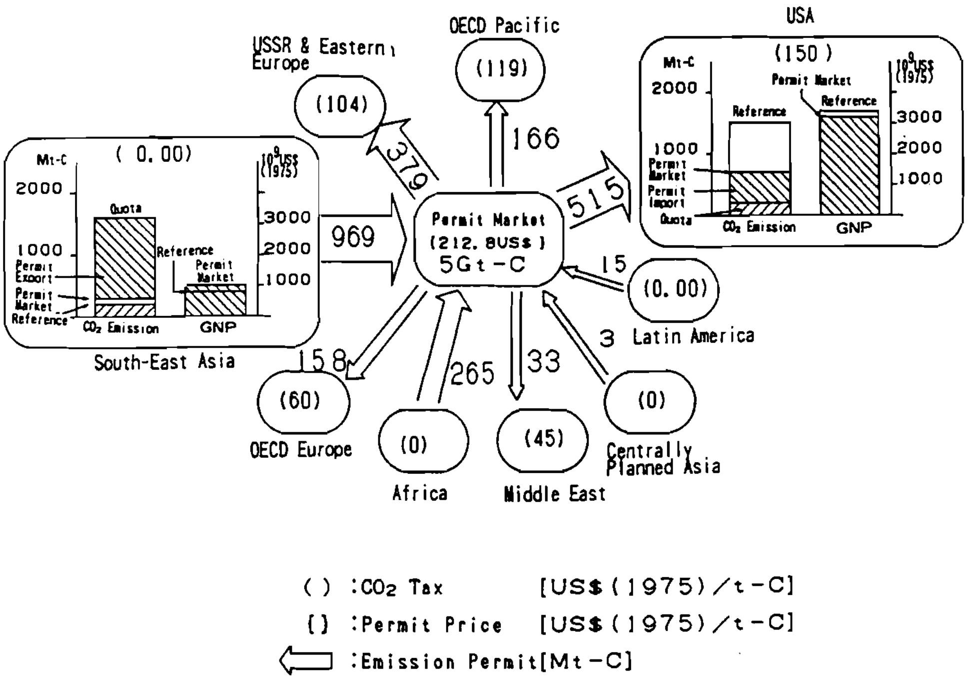

Figure 5. Flows of permits at an equilibrium point in the permit equilibrium case (world CO$_2$ emission limit of 5Gt-C in the year 2000).

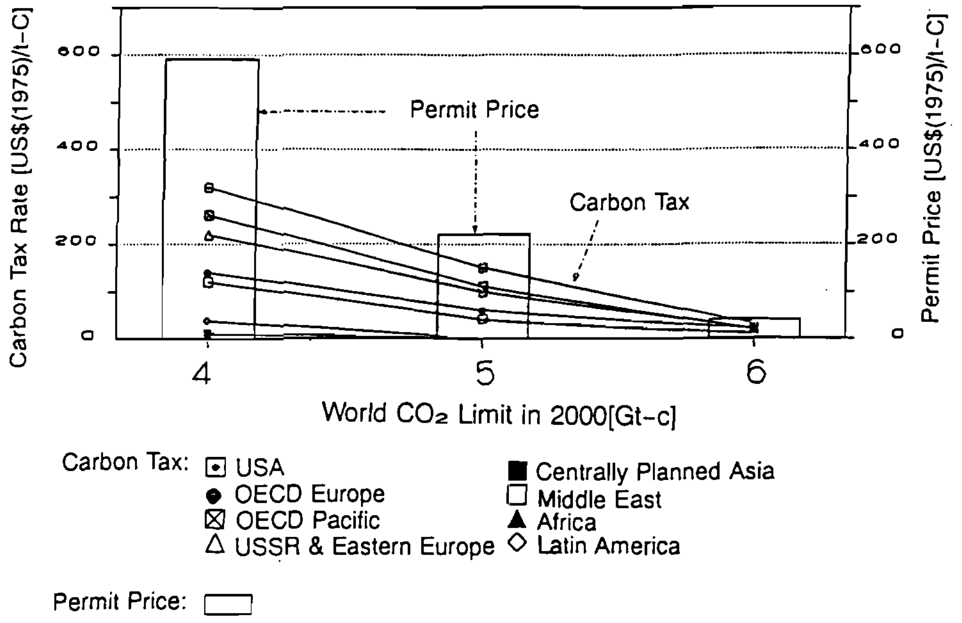

Figure 6. CO_2 tax rates of each permit import region and permit prices at equilibrium points of the market in the year 2000.

Figure 6 shows CO_2 tax rates in each permit import region and permit prices at equilibrium points in the market for a world CO_2 limit of 4, 5, and 6 Gt-C in the year 2000, respectively. The lower the world emission limit, the higher CO_2 tax rates and permit prices. Regional CO_2 tax rates in the permit equilibrium case can be reduced to one-tenth to one-fifth of those in the taxation case.

Figure 7 shows the flows of tradable permits at an equilibrium point under a world CO_2 emission limit of 5 Gt-C in the year 2000 in the absorption option case. In this case, the equilibrium permit price in the market is 25.2 US$(1975)/t-C. The total amount of CO_2 absorption by afforestation is 1131 (Mt-C). The permit price is substantively lower than that in the permit equilibrium case. Also, the total number of traded permits in the market is larger than that in the permit equilibrium case because of the large amount of regional afforestation.

Figure 8 shows the control of CO_2 emissions and absorptions, respectively, in the permit import regions and in the permit export regions for the reference case, the permit equilibrium case, and the absorption option case. The CO_2 reduction caused by regional taxation decreases when the

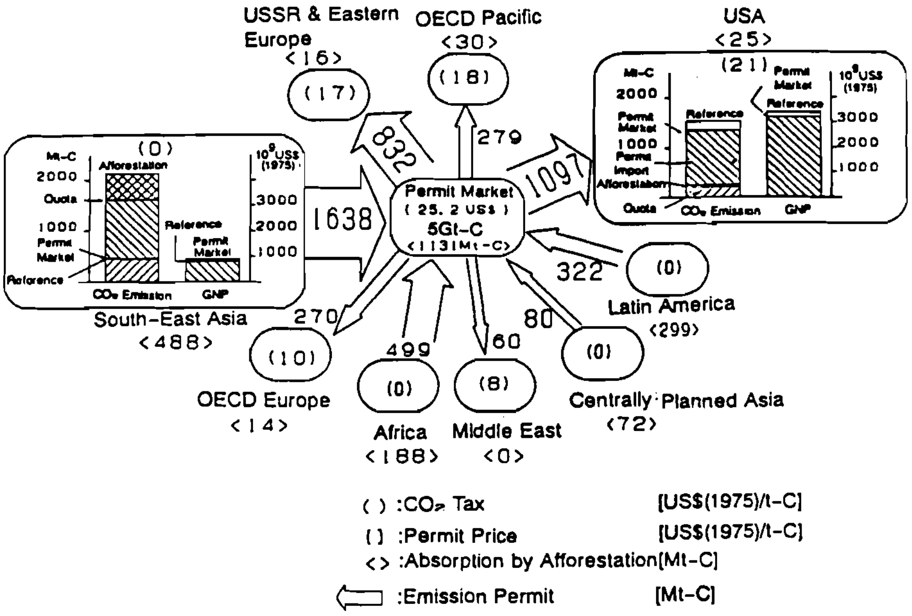

Figure 7. Flows of permits at an equilibrium point in the permit absorption option case (world CO_2 emission limit of 5Gt-C in the year 2000).

Table 4. Permit prices at the equilibrium point in the market for 2025. Unit: US$(1975)/t-C.

CO_2 limit (Gt-C)	Year 2000		Year 2025	
	Equilibrium case	Absorption case	Equilibrium case	Absorption case
4	586.7	80.8	–[a]	1190.5
5	212.8	25.2	–[a]	418.7
6	42.3	11.2	989.9	21.4

[a] In this case there are no permit export regions, thus all regions must reduce their CO_2 emissions to the level of the permit allocated initially by employing CO_2 taxation.

number of tradable permits in the market increases as a result of regional afforestation.

Table 4 shows permit prices at equilibrium points in the market for each world CO_2 limit in 2000 and 2025. In the absorption case, permit markets exist under all world CO_2 limits, even in 2025. However, in the case without an absorption option, there exists no permit export region for a world CO_2 limit of less than 5 Gt-C in 2025.

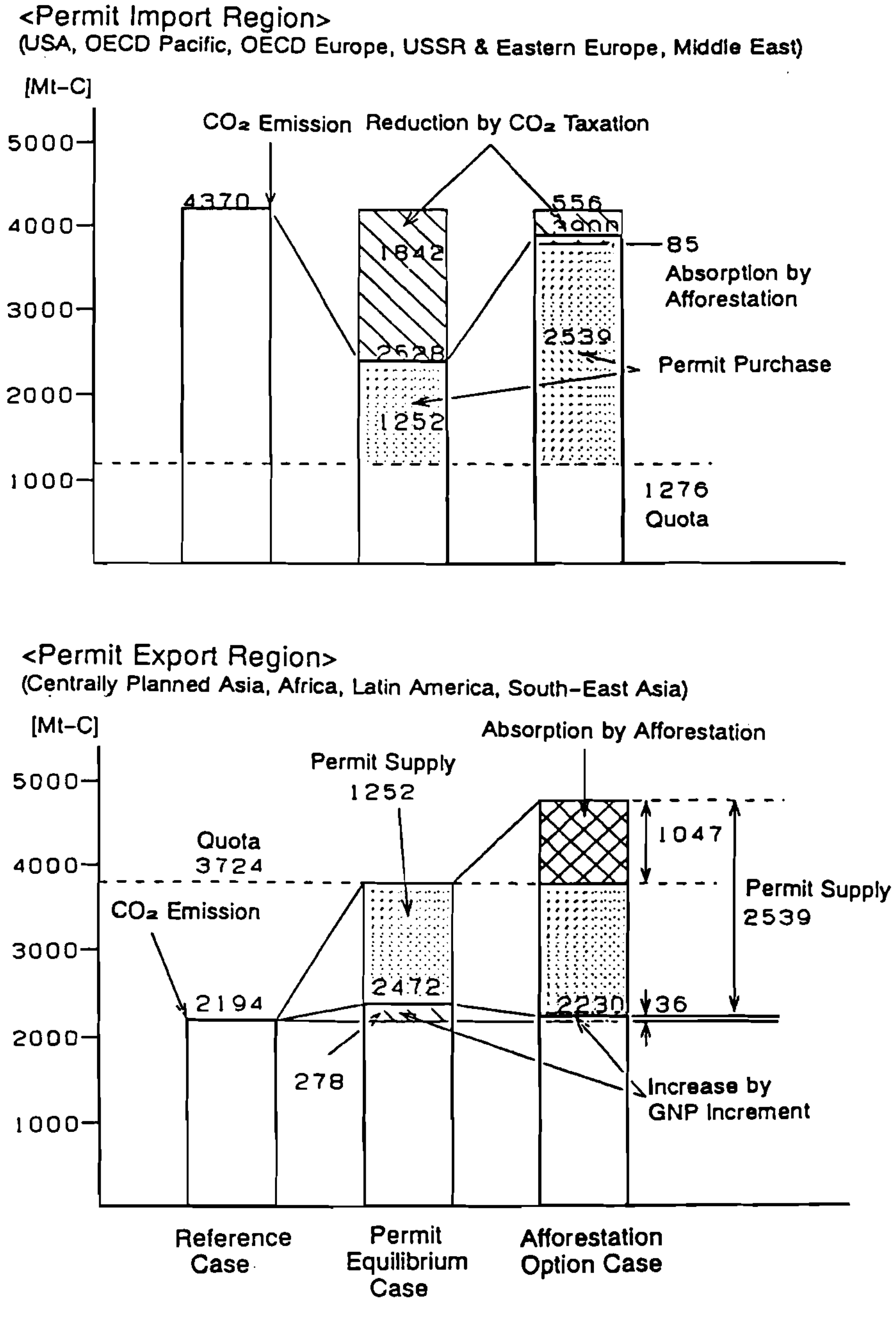

Figure 8. CO_2 emissions in the permit export regions for the reference case, the permit equilibrium case, and the absorption option case (world CO_2 emission limit of 5Gt-C in the year 2000).

6. Concluding Remarks

Feasibility of an international market for CO_2 emission permits combined with regional CO_2 taxation and regional afforestation options is demonstrated numerically through simulations. Major findings are summarized as follows:

1. Equilibrium points exist in the international market for CO_2 emission permits for most cases examined in the study.
2. Through the international permit market, a significant amount of money, more that 100 billion dollars per year in some cases, is transferred from developed regions to developing regions.
3. Levels of regional CO_2 tax rates and associated GNP losses are significantly reduced by the introduction of an international permit trade, compared with the case in which each region independently achieves its CO_2 limit by having a regional CO_2 tax.
4. The introduction of CO_2 absorption options (afforestation) reduces levels of regional CO_2 tax rates and associated GNP losses even further by increasing permit supply in the market; but, on the other hand, the equilibrium permit price is also lowered significantly and reduces the total revenue of developing countries.

As to future work concerning modeling, the following are identified: explicit modeling of optimization processes in each region, and incorporation of other inter-regional interaction schemes such as technology transfer.

We should take care in deriving practical implications from the simulation results. One of the most controversial points is related to the initial allocation of emission permits. There are many arguments, particularly about the fairness of initial allocation. While fairness is a very attractive criterion in the appropriate allocation of emission quotas, which can be achieved by the appropriate allocation of emission quota, most schemes for initial permit allocation which have been proposed to keep fairness seem infeasible under the reality of present international politics. There are also many other obstacles in the implementation of tradable permits; for example, monitoring of and accounting for regional CO_2 emission/absorption, sanctions for nonparticipants, software for adjusting prices and quantities of traded permits, etc. Along with studies on the performance of tradable permits, we should also explore more practical institutional schemes which have similar effects to those of a permit market.

Acknowledgments

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Top Down – Bottom Up: A Systems Engineer's View

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1. Introduction

Top-down macroeconomic and bottom-up engineering descriptions of the energy system tend to give different estimates of future energy demands and effects of efforts to increase energy efficiency. For similar macroeconomic activities, the two approaches may provide widely different cost estimates to control CO_2 emissions from the energy system [see, e.g., Manne and Richels (1990); Williams (1990)].

The top-down/bottom-up controversy is not uncommon in the world of science. Blatt and Weisskopf (1952) commented on the relative success of two nuclear models which seemed to hold two mutually exclusive pictures of the nucleus: "We are facing here one of the fundamental problems of nuclear structure which has not yet been solved." Eventually, both the Top Down Liquid Drop and the Bottom Up Independent Particle models of the nucleus have been proven to be consistent with basic principles [see, for instance, Gomes *et al.* (1957); Bohr and Mottelson (1969)]. The liquid drop model describes the global properties of the nucleus while the independent particle model is necessary to understand local structures. A marriage between the two approaches can be achieved by a renormalization procedure whereby the bottom-up model is calibrated to reproduce the average behavior of the top-down model. For an example of the procedures for investigating nuclear fission, see Strutinsky (1968).

The example from nuclear physics indicates that bottom-up models have to be constrained by information available from top-down analysis in order to be able to reproduce the properties of higher lying systems. This should not come as a surprise to the system scientist. The system paradigm assumes an hierarchical structure where new properties emerge as one passes on to higher lying systems. The properties of the system elements determine which configurations are possible. The higher lying system controls which of the possible configurations of the system elements will be realized [see, for instance, the discussion about hierarchy, communication and control in Checkland (1981)]. Ashby's law of requisite variety also provides a rationale for a coordinated top-down/bottom-up approach (Ashby, 1964). The regulator here is the scientific community and the system to be regulated is the body of scientific knowledge.

An earlier effort integrating the top-down and bottom-up analysis in energy economics was made by Hoffman and Jorgenson (1977). As a working hypotheses for our purposes, one could assume that the top-down models are better tools for understanding average trends in the demands for useful and primary energy, and the coupling of these demands to macroeconomic activities. This is consistent with the assumption that the general economy controls the energy system through the shape of demand curves for different energy services and through the total amount of resources it is willing to spend in order to secure these services. But the bottom-up engineering models are necessary to understand how new technology, and ultimately technological R&D, affects the productivity of the energy system, including the ability to control the emissions of potentially harmful substances.

The purpose of this paper is to illustrate how a top-down/bottom-up approach can give insights into the coupling between technological R&D and demands for energy carriers.

The following section indicates how engineering data on technological R&D can be used to understand the results from top-down econometric analysis. The bottom-up field data are sparse and lie within one sector of industrial energy usage. However, the engineering analysis provides useful insights into how technological R&D set long range conditions for the demand of electricity and fuels.

One prerequisite for an integrated bottom up–top down modeling system is a renormalization prescription. Following the earlier work by Manne (1981) and Manne and Richels (1992), Manne and Wene (1992) linked a systems engineering model to a macroeconomic growth model. The systems engineering model, MARKAL, is a dynamic and technology-rich model (Fishbone *et al.*, 1983). The macroeconomic growth model, MACRO, was earlier used in conjunction with Energy Technology Assessment (ETA), a highly aggregated model. MARKAL–MACRO are linked together formally and solved as one model by a non-linear optimizing algorithm. One advantage of the hardlinking is that there is no external renormalization needed in order to compare the two models. The effect of the built-in renormalization on the demands in MARKAL is illustrated in Manne and Wene (1992). The user has one parameter available to simulate the effects of the saturation of old demands and the emergence of new demands. In Section 3, MARKAL–MACRO is used to study the interplay between technology and demands.

2. Bias for Electricity Use in Technological R&D

An analysis of fuel and electricity use for the Swedish industry between 1980–1988 shows that the electricity to fuel ratio has increased by 25%, in spite of the fact that the ratio between the price for electricity and a weighted fuel price has doubled during the same period. To the best of my knowledge, there is no econometric analysis available in Sweden to give a macroeconomic explanation of these trends. In Norway, however, such analysis has been made within the framework of the SAMMEN project (Mysen, 1991). The analysis shows the same trends in all of the investigated industrial sectors: increasing electricity to oil ratio between 1980–1988, in spite of the fact that price ratio between electricity and oil also increased during the same period. The data are estimated with models that assume non-homeothetisity and non-neutral technical change. In all industrial sectors, the best fits were obtained with a model with non-neutral technical change. For the public sector, the non-homeothetic models were preferred.

I would want to argue that technological R&D is an important driving force behind the non-neutral technical change. I cannot provide a complete analysis, but I will present some technical evidence to support my case.

R&D results usually have long lead times. If the electricity to fuel ratio in the 1980s was driven by R&D, then we should look for actions taken in the 1970s.

In Sweden during the 1970s, the occupational hazards and workplace safety were important issues requiring special efforts to develop safe and clean industrial technologies and technical systems. Special funding was provided to support this development. The R&D activities were carried out by universities and branch institutes but also at selected enterprises that acted as front runners.

Some form of ventilation is included in all available options to reduce the risk for harmful airborne pollutants to enter the respiratory tract. Ventilation is one of the most energy-intensive measures used to control occupational hazards. About 10–15% of all electricity consumed in the Swedish industry is used for ventilation. The air flows created by ventilation can, however, be used in a more or less efficient manner.

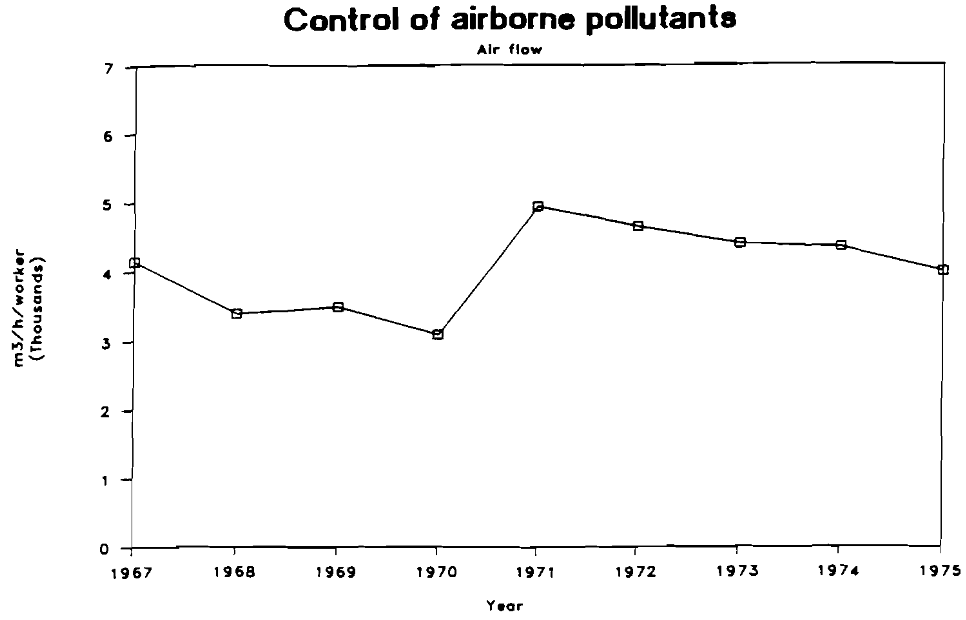
Figure 1 shows the air flow and use of electricity for ventilation in one of the selected enterprises acting as front runners (Wene, 1976; 1977). This enterprise had been the focus for several technological development projects over the years; it was pointed out to the investigator by several independent actors within the field that it represented the state-of-the-art. It was a small factory, employing about 100 workers. The factory produced details for consumer capital goods in polystyrene. The airborne pollutants consisted of plastic particulates and styrene. Styrene has later been shown to be carcinogenic. During the time period covered by the investigation, the enterprise had reduced the concentration of harmful pollutants in the respired air by one order of magnitude.

It is interesting to compare the effects of the technology development on the demand for electricity and fuels. The demand for electricity per worker increases by 150%. But the total flow of air to the workplace remains constant; the change in air flow over the period is due to business cycle and not to changing technology. Low temperature heat is needed to heat the air. If all the heat is directly supplied by burning fuels, the demand for fuels will remain constant. However, there are many options to reduce the demand for fuels such as recuperation or using waste heat from industrial processes.

Figure 2 indicates why concentrations of airborne pollutants can be reduced by increasing electricity use and keeping fuel use constant. The initial control technology in A is based on dilution. Outside air is heated and forced into the workplace, exchanging old air which is vented through fans placed in the walls or in the roof. This is not a very efficient way of controlling air streams or airborne pollutants. Figure 2B indicates the development that was done. Small ventilation gears, individually adapted to each workplace, were placed very close to the source, K, of the pollution. The small jetstream from the ventilation gear worked as a vacuum cleaner controlling the pollution at the source. The technique does not need any extra air supply.

The described technical solution has two properties. Firstly, it must be individually developed for each type of workplace. This indicates substantial lead times. Secondly, although the technique does not demand any increased air flow, it demands a substantial amount of extra electricity (see Figure 1). The reason for this is the large pressure differential needed to sustain the jetstream.

Wene (1976) made a survey of the Swedish industry, identifying emerging techniques to control workplace airborne pollution. The survey indicated that tailor-made ventilation gear, controlling the pollution at the source, provided the most efficient solution. By Bernouillis law, this would demand larger pressure differentials and thus more motive power. An estimate was



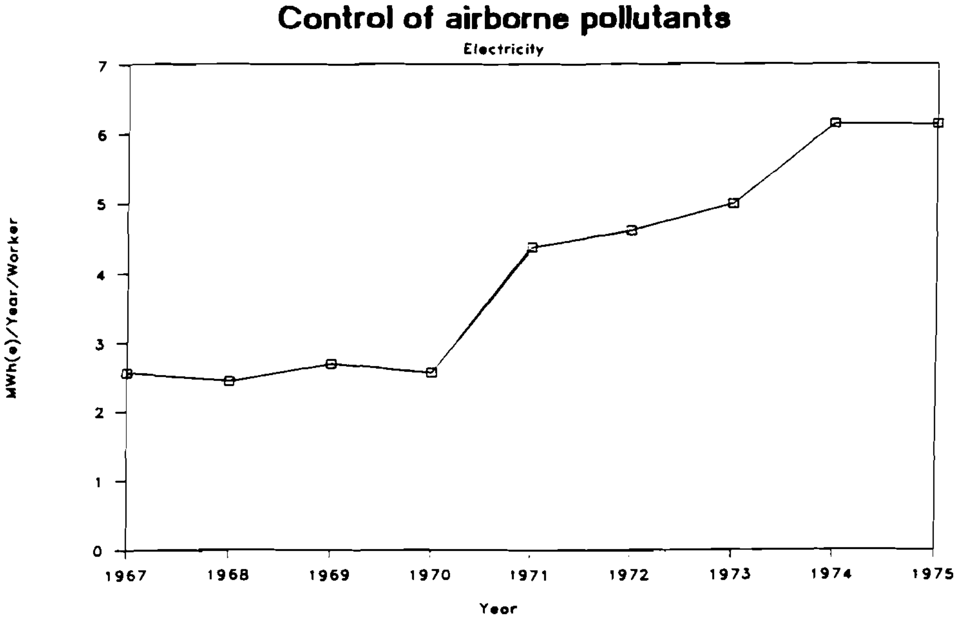


Figure 1. Air flows and demand of electricity for ventilation in the factory for hard plastics, Trelleborgplast, Ljungby, Sweden. Time period 1967–1975.

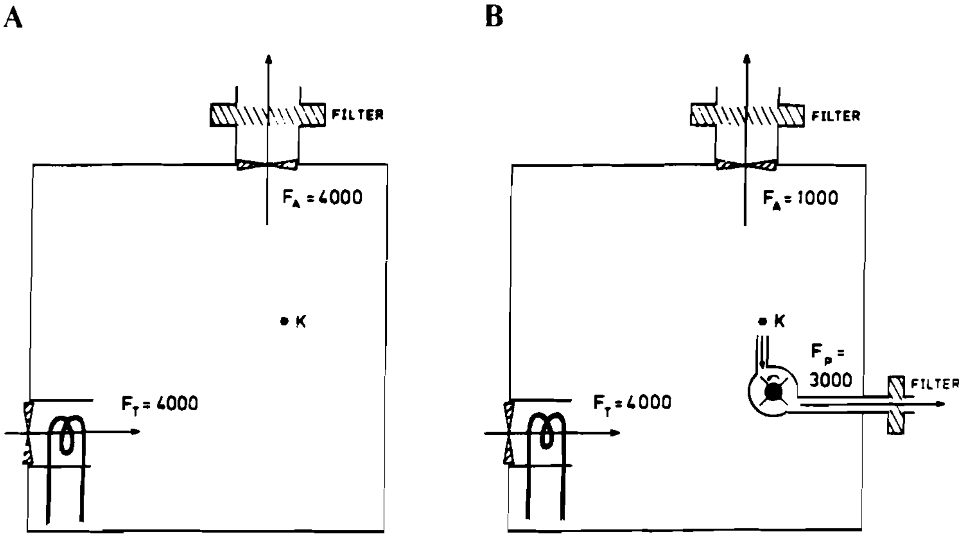


Figure 2. Schematic drawing of two alternatives for ventilation in a closed space with one source of airborne pollution, K. The numbers refer to the airflow measured in m^3/hour.

made for the whole Swedish industry based on the experience by factories using state-of-the-art technology such as described above. The estimate showed that, over a 10-year period, controlling airborne pollution at the workplace would lead to an increased demand for electricity in industry by 3–5 TWh/year. The fuel demand could probably be reduced. Later information has supported this estimate. The total demand for electricity in the Swedish industry was 39 TWh/year in 1977 and 50 TWh/year in 1987.

Obviously, the measures to reduce airborne pollution in the Swedish industrial workplace explain neither all the Norwegian results nor all the concordant Swedish data. However, they explain a substantial part of the increase for electricity demand in the Swedish industry. Most important, however, they provide a bottom-up example of non-neutral technological development, with the properties seen in the top-down Norwegian model. The relative prices of fuels and electricity do not influence the choice between the two energy carriers. The new technology is based on motive power and electricity provides the most efficient and trouble-free means to obtain motive power in industry.

It is easy to find other examples of industrial R&D where electricity provides the key to a smarter solution. The example above is interesting, because it shows the effect of a generic technology that runs through the whole industry.

3. MARKAL–MACRO: Technologies and Demands

MARKAL (Fishbone *et al.*, 1983), EFOM (van der Voort *et al.*, 1984) and Message (Agnew *et al.*, 1979) are examples of systems engineering models. They are based on extensive data bases for new and existing energy technologies. The data bases contain forecasts for improvements in the existing technologies and for costs and efficiencies of the emerging new technologies. If there are no new constraints on the energy system, such as emissions caps, the average costs and prices for energy services in the future will be determined by technology development and prices for the primary energy carriers supplied to the system. Engineering forecasts usually show improved efficiencies and reduced costs for energy technologies, while prices for energy carriers increase. In the simplified model world, the average costs and prices for energy services decrease or increase depending on whether or not the rate of technological improvement is higher than the rate of price increase for primary energy carriers.

What can we learn about the effect of technological improvements on fuel demands from coupling the systems engineering model to a top-down macroeconomic model? E.g., what is the total effect on demand for a case where improvements in efficiency lead to reduced prices and reduced average cost? Or, when expected improvements in a key technology do not materialize?

The MARKAL–MACRO provides one framework for discussing such questions. Figure 3 demonstrates the demand for primary energy in two extreme cases. The MARKAL database is the same restricted U.S. database used in Manne and Wene (1992) with some changes made in the description of new automobiles and of windpower potential and cost. The two cases differ in the assumptions made about autonomous improvements in energy efficiency (AEEI). For the case "AEEI=0", it is assumed that AEEI=0 for each of the 13 energy demand categories in the model (see caption to Figure 5 for a listing of these demand categories). For the other case, AEEI=2.5% per annum for each category. For both cases, the potential GDP growth is 2% annually and the elasticity of substitution (ESUB) is assumed to be 0.5. The price of imported oil is assumed to grow by 3%/year.

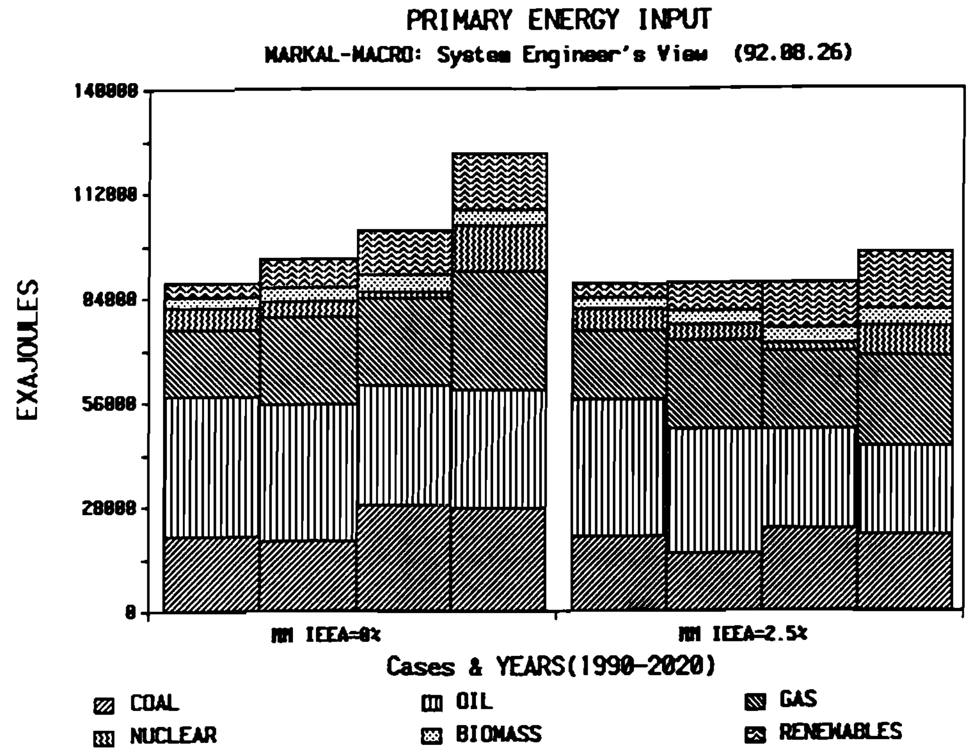


Figure 3. Demand for primary energy.

Without any changes in energy technology and in the price of primary energy carriers, the Primary Energy Demand (PED) in "AEEI=0" should grow at the same rate as GDP. Figure 3 shows that with the changes in GDP, prices and technology result in a PED growth of only 0.7%/year during the first 20 years, and 1.9%/year in the last 10-year period. Renewable and nuclear energies are accounted for through their fossil equivalence.

PED is the total energy supplied to the technical energy system. This system uses energy technology to convert the primary energy in one or more steps into useful energy for distribution to the consumer. Figure 4A compares the rates of growth in GDP, total Useful Energy Demand (UED) and total Primary Energy Demand (PED) for the "AEEI=0" case. The total UED is the sum of the UED for the thirteen demand categories which are very different from each other. The total UED is an indicator of the energy services provided by the technical energy system to the rest of the economy. For the first 10 years it grows by 1.3%/year. But for the period 2000–2020 the growth rate of the total UED is closer to the GDP growth rate.

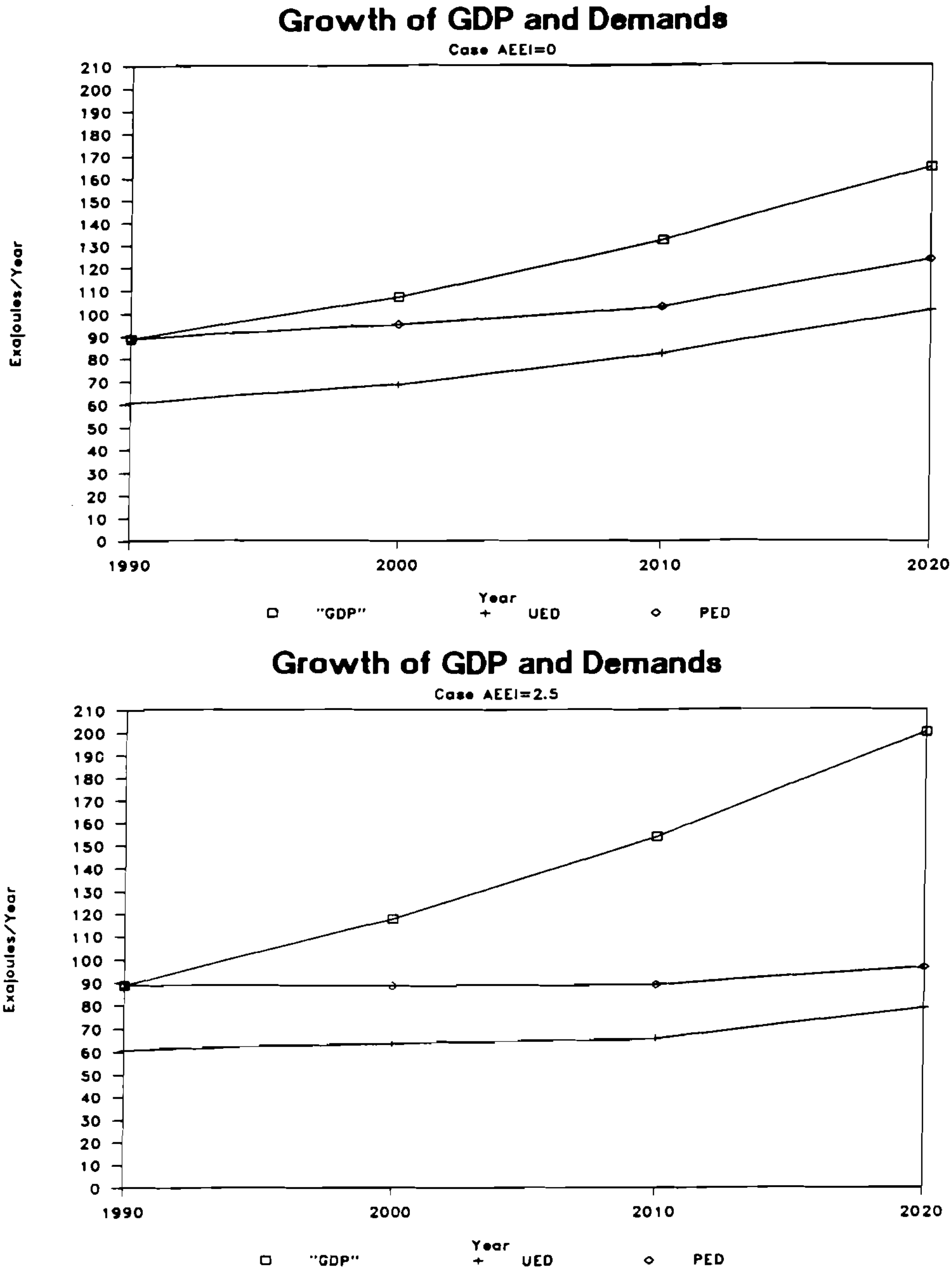


Figure 4. Growth of total useful energy demand and primary energy demand for "AEEI=0" and "AEEI=2.5". The line marked "GDP" indicates what the primary energy demand would be if it grew at an annual rate identical to the rate of GDP.

Figure 5 explains the behavior of UED growth rates. During the first part of the 30-year period, most prices increase. As more new technology becomes available, the prices are reduced. Note, however, that the technical energy system quite generally is a good "buffer" against increases in fuel prices; category "IH", hydrocarbons for non-energy use, is the only end user which experience the full 3% annual rise in the price of imported oil. As ESUB=0.5, the average annual increase in demand for hydrocarbons for non-energy use is roughly $1.02*1.03^{-0.5}=1.005$ or 0.5%. In the category "T4" (automobile), technical development offsets most of the increase in fuel price. The average annual increase in UED for automobiles is 1.9%.

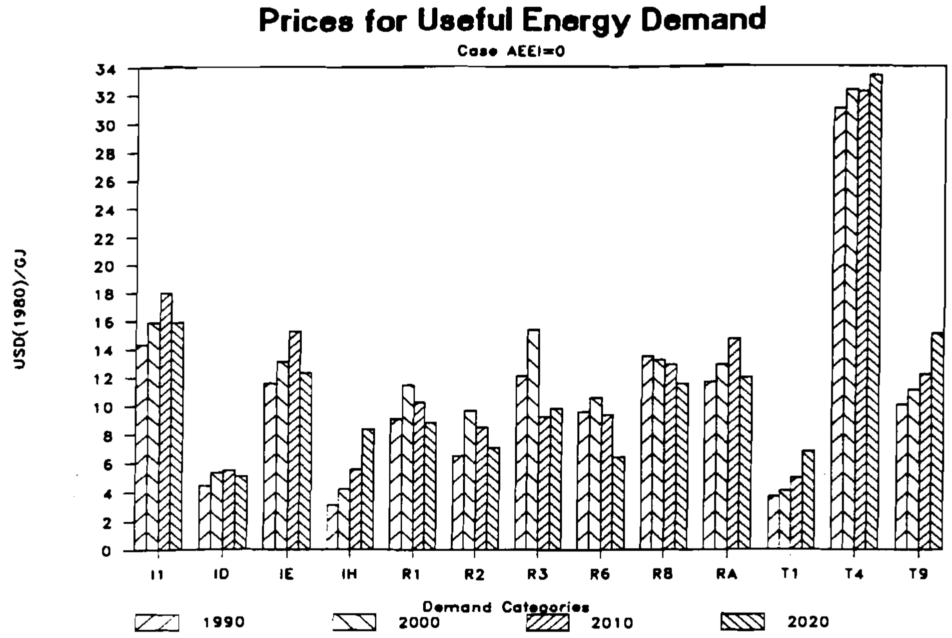
Price-induced conservation in UED explains part of the slow rise in PED. The rest is explained by the introduction of more energy-efficient technologies in the technical energy system. Changes in the ratio UED/PED can be used as an indicator for improving the total energy efficiency of the energy system. In the example studied here, the ratio increases from 0.68 in 1990 to 0.82 in 2020, or by 20%. During the same time the fossil fuel content of the total PED has been reduced from 0.85 to 0.75.

"AEEI=2.5" represents a case with considerable amount of autonomous conservation. However, Figure 4B indicates that the total effect on UED and PED is a reduction in growth rates of 0.7–1.0%. One reason for this is that the released resources are used in other parts of the economy, leading to a slightly higher economic growth. But there is also a "take-back effect" due to the reaction in the technical energy system. Prices are reduced because the most expensive marginal technologies can be avoided, and expansion investments can be postponed until more efficient technologies are available. The increase in UED/PED ratio is the same as in the "AEEI=0" case.

Increased prices for primary energy carriers and new technology leads to a reduction in PED. In the example presented here, this reduction is of the same order of magnitude as the reduction expected from an across-the-board annual increase in autonomous energy efficiency increase of 2.5% in all demand categories.

Figure 6 compares the CO_2-emissions from the energy system. The reduction in emissions is the same as the reduction in PED between the two cases; there is no preference for fossil or non-fossil technologies.

With the MARKAL–MACRO tool, it is possible to identify cost-efficient technologies to satisfy each type of demand, and follow energy flow paths through the conversion and distribution network to find the resulting effect on PED and CO_2 emissions. The restricted U.S. data base is not rich enough in technologies to provide results beyond the obvious. Figure 7 is included only to demonstrate the type of possible analysis. The example is taken from



Demand Category	Description
I1	Iron and Steel Metallurgy
ID	Industrial Process Heat
IE	Industrial Electricity
IH	Hydrocarbons for Non-Energy Use
R1	Residential Space Heat
R2	Residential Hot Water
R3	Residential Air Conditioning
R6	Commercial Space Heat & Hot Water
R8	Commercial Air Conditioning
RA	Residential and Commercial Appliances
T1	Rail/Truck/Bus Transport
T4	Automobile Transport
T9	Air and Ship Transport

Figure 5. Prices in 1990, 2000, 2010 and 2020 for the 13 demand categories. Case "AEEI=0".

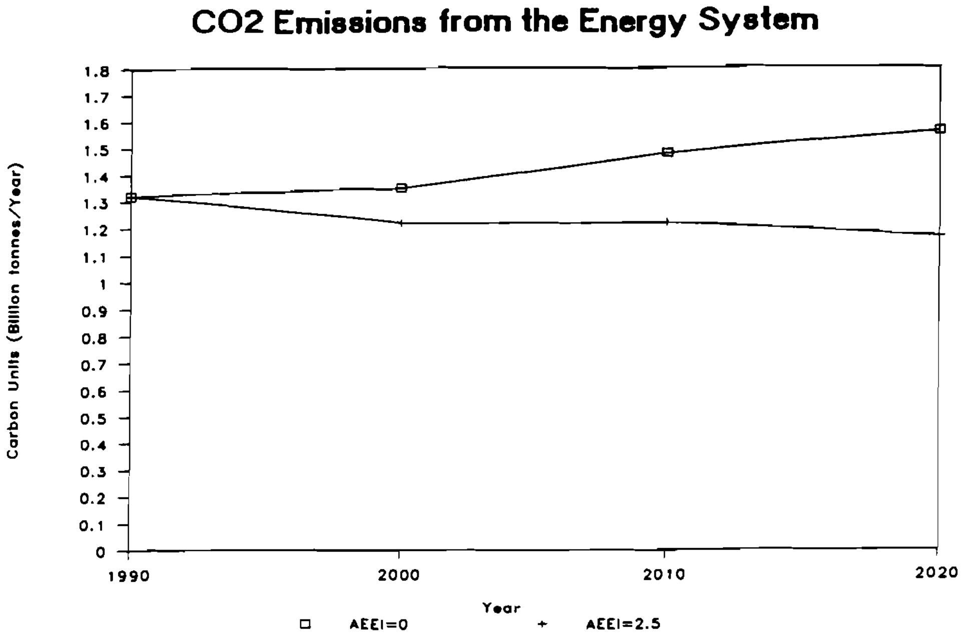


Figure 6. CO_2-emissions for "AEEI=0" and "AEEI=2.5".

the transport sector and shows the effect on fuel demand for automobiles if a key technology fails.

The purpose of the discussion in this section is to show the use of an integrated model to understand the effect of specific energy technology development on demands and emissions. There are two important caveats: one regarding the data base and another on market penetration.

Without a validated, goal-oriented database, a systems engineering model provides limited insights for the strategic or policy level. The reason is that the generic or data-independent information in the model is rather small. There are balance equations for fuels which take the shape of annual averages and seasonal/diurnal averages for electricity, gas, and district heating. There are also theoretical considerations about the periodicity of investments, fuel cycles, maintenance, and the shape of physical constraints.

The restricted data base used here is appropriate for demonstration purposes, but more details are needed for the systems engineering approach to prove its value. The validation of a technology-rich data base is, however, a large task for which methodologies need to be developed. A problem area may be the cost estimates for new technologies versus existing technologies. Developers of new technologies have the best information. However,

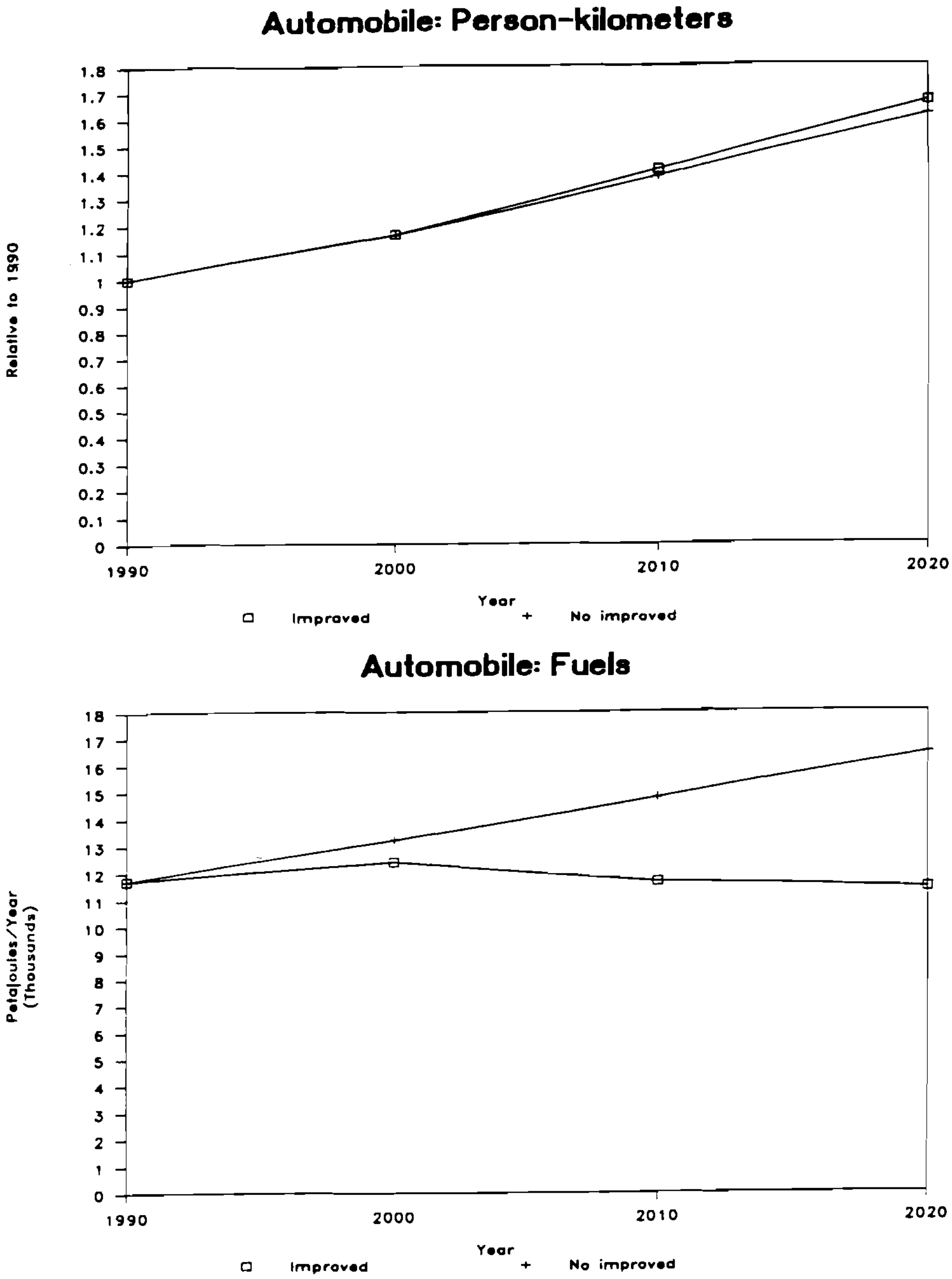


Figure 7. Growth in person-kilometers (A) and demand for fuels (B) for automobiles with and without improved Otto-engine. The improved Otto-engine increases the mileage by 100% by 2010 for an extra investment cost of 15%.

they are also stakeholders and their cost estimates may be biased, with or without intention. This is not a major problem in a stand-alone systems engineering model which is used to rank technologies; the ranking between different new technologies may be correct although total cost may be underestimated. However, in a linked energy-economic model, the growth of GDP and demands depend on intertemporal comparisons of costs and prices. Cost estimates must therefore be internally consistent, not only within one time period but from the first through the last period. For instance, the previous discussion about demands is meaningful only if cost estimates in the restricted data base are consistent over time.

The model runs presented here use the original MARKAL options to constrain the rate of market penetration of a new technology. These consist of maximum growth rates or upper limits on the total capacity or investments. Manne and Richels (1992) introduces a penalty for above-normal expansion activities, connecting the high rates of implementation with an extra cost. This is an attractive option which also makes it possible to avoid spurious large swings in the prices for UED.

Work is underway at Brookhaven National Laboratory and Stanford University to improve the U.S. data base and the description of market penetration in MARKAL–MACRO. This work will also increase the availability of the model (Hamilton *et al.*, 1992).

4. Conclusion

The systems paradigm embraces the top-down/bottom-up approach; both as an efficient way of gaining knowledge about the system and as a description of the way the system organizes itself. In the present context, the systems engineer approach represents the bottom-up direction and the economist approach represents the top-down direction. The existing energy system and technological R&D provide a wide range of options. Through demand and resource allocation, the economic system controls the realization of different options.

The coupling between R&D and demands has been discussed in two cases.

In the case of airborne pollutants, the technology R&D did not provide the economic system with a real choice between electricity and fuels. The demand for electricity in the emerging technical solution was controlled by an over-riding system, "the laws of physics". For the economic system to regain control, the price advantage of fuels must be large enough to make local production of motive power by heat engines an attractive option. In this case, the top-down analysis isolated the symptoms, but the bottom-up analysis provided a diagnosis.

Linking systems engineering and economic models provides a framework for more systematic studies of technology development, emissions control, demand, and costs. MARKAL–MACRO is used in this paper to give a bird's-eye view of the interaction between technology development and demand. But much more details are expected from the systems engineers analysis. For such analysis, a technology-rich data base is necessary together with a more realistic description of the market penetration of new technologies. The validation of the data base is a challenging task that still needs methodological development. Recent developments in computer hardware and software facilitate the design of PC-based integrated energy-economic models with the potential to handle detailed technological information.

Acknowledgment

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On the Uncertainty of Estimating Global Climate Change

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Abstract

To evaluate the policy options for preventing global climate change, it is necessary to develop models that estimate global greenhouse gas emissions, atmospheric concentrations, and temperature rise. For this purpose, we are developing the Asian–Pacific Integrated Model (AIM) for assessing options in policy making to cope with global climate change.

With this model, we estimate CO_2 emissions based on future predictions of socioeconomic and natural factors. The results show that CO_2 emissions in 2025 would be 1.4 to 2.4 times as large as those in 1990, and CO_2 emissions in 2100 would be 2 to 7 times as large. To stabilize CO_2 emissions at the 1990 level by introducing a carbon tax, it is estimated that the required carbon tax would be 180 to 440 1990US$/t-C in 2025 and 310 to 1,250 1990US$/t-C in 2100. The decrease in world GNP caused by the carbon tax is estimated to be 1.5% to 2.8% in 2025 and 2.8% to 7.3% in 2100.

1. Introduction

In estimating global warming effects, there are so many problems left unsolved. The difficulties come from the uncertainty of natural factors such as carbon circulation, effects of clouds, and ocean heat uptake, as well as that of socioeconomic factors such as population growth, economic growth, and improvement of energy efficiency. To evaluate policy options for stabilizing global climate, it is necessary to estimate global warming responses based on future scenarios.

The purpose of this study is to develop computer simulation models for estimating greenhouse gas emissions, their atmospheric concentrations, and the rise in temperature with several scenarios (Matsuoka, 1992; Morita, 1991a). We have designed the total system, implemented the basic programs, and simulated some effects of the countermeasures.

2. Structure of the Asian–Pacific Integrated Model (AIM)

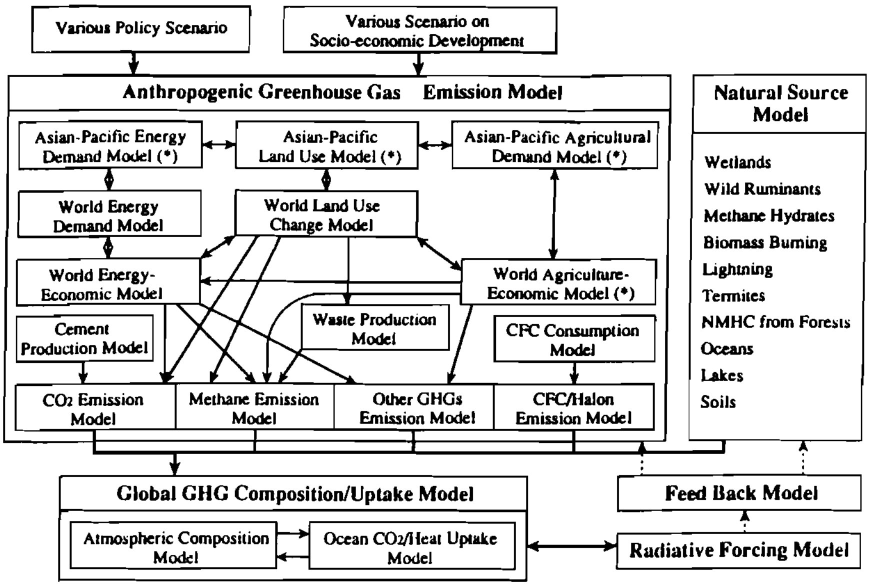
The purpose of AIM is to estimate greenhouse gas emissions in the Asian–Pacific region, to evaluate their socioeconomic impacts, and to assess options in policy making (Morita, 1991b). It consists of the World Model and models for each individual country in this region. The World Model is based on the Atmospheric Stabilization Framework (ASF) designed by ICF Incorporated for the US Environmental Protection Agency, and is modified to be linked to the models of each country.

The structure of AIM is outlined in Figure 1. There are three main submodels: the Anthropogenic Greenhouse Gas Emissions Model, the Natural Source Model, and the Global Greenhouse Gas Composition/Uptake Model. The Anthropogenic Greenhouse Gas Emission Model is composed of submodels, such as the Energy Economic Model, the Land Use Model, the Agricultural Demand Model, the Waste Production Model, and the Cement Production Model, and estimates greenhouse gas emissions from socioeconomic activities. The World Energy Economic Model is based on the Edmonds–Reilly Model (Edmonds and Reilly, 1983) and was modified to analyze the effects of various countermeasures as shown in Figure 2.

3. Main Scenarios for Predictions

Global climate change based on future predictions of socioeconomic factors and natural factors are estimated. First, greenhouse gas emissions are estimated based on the following scenarios.

Figure 3 shows the recent results of world population estimations. In this figure, the dotted lines show high population estimates and solid lines show low ones. The world population is estimated to be about 5 billion in 1990 and to range from 3.6 billion (World 3) to 109.4 billion (UN1990) in 2100. The high estimation by the United Nations (1992) is calculated assuming constant total fertility rate. The high estimate by Mesarovic is calculated assuming the population growth rate to be constant. The low estimation with World 3 is calculated assuming that the death rate will increase because of environmental pollution. We excluded these extreme cases and used the projection by the World Bank (1991), 11.3 billion, as the



* in process of development

Figure 1. Outline of the Asian-Pacific Integrated Model (AIM) to evaluate policy options.

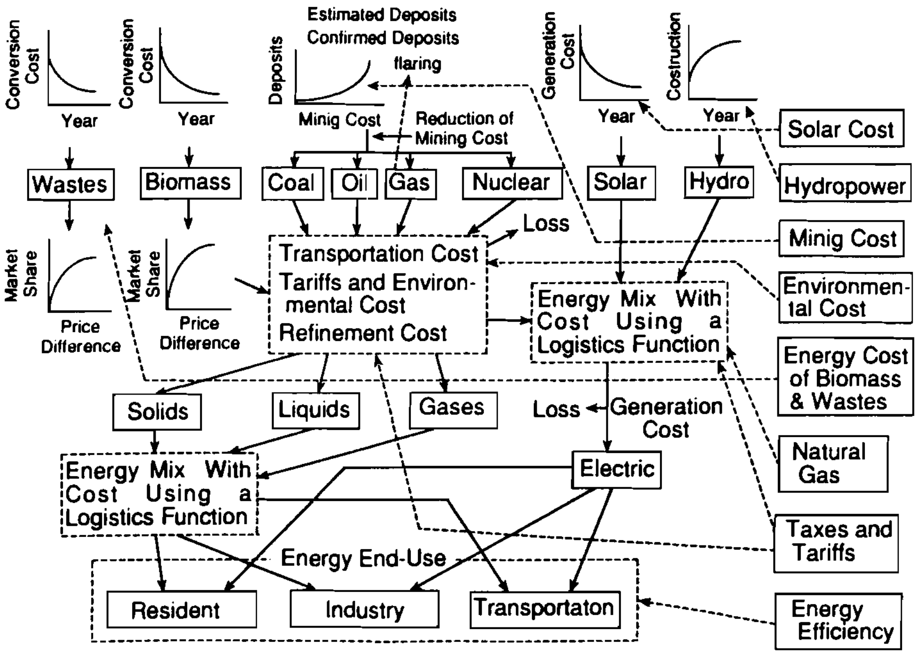


Figure 2. Countermeasures to reduce energy demand.

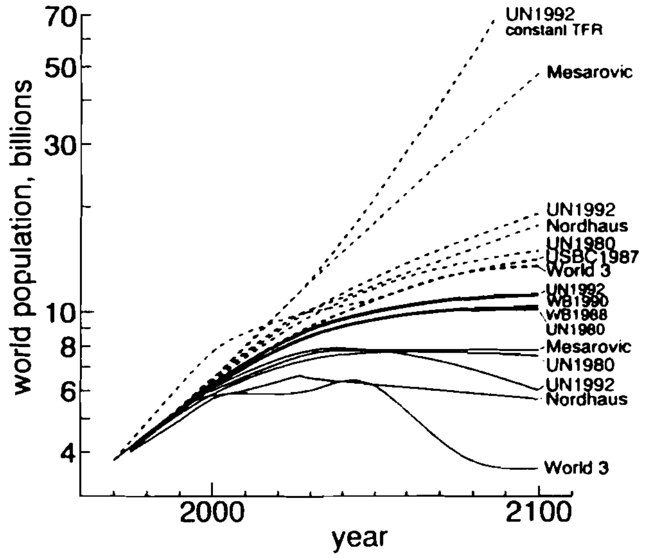


Figure 3. Estimation of world population.

lower limit of the world population in 2100 and that by the US Bureau of the Census (1987), 13.5 billion, as the upper limit.

Figure 4 shows the recent results for GDP per capita. In this figure, the dotted lines show the estimates in OECD countries and the solid lines show those in Southeast Asian countries excluding Japan. The "90BAU" line shows the results by IPCC in 1990 (RSWG, 1990) assuming "Business as Usual". The line marked "IRS91" also shows the results by IPCC in 1991 which predicts that the growth rate of GDP per capita would be 2.5% per annum in OECD countries, 4.1% in developing countries, and a world average of 2.9% by the early part of the 21st century, and would decrease 0.8 to 1.4% after that. The dotted area shows ±20% around "IRS91a" and is used in our simulation study.

As for the improvements in energy efficiency, we use the end-use energy based on the rapid change scenario as the lower limit and that based on the slow change scenario as the upper limit (Lashof and Tirpak, 1990). The end-use energy demand for the developed countries is estimated by Mintzer (1988) and that for the developing countries is estimated by Sathaye *et al.* (1987).

Emissions of CFCs are estimated based on the Montreal Protocol. The rate of participation in the developed countries is estimated to be 100% and that in the developing countries is estimated to the 85%. HCFC-22 is

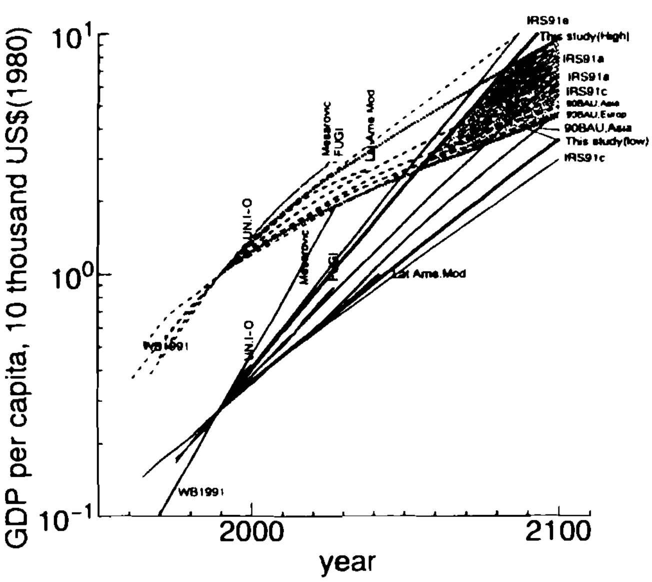


Figure 4. Estimation of GDP per capita.

estimated to increase by 5% per annum by the end of this century, by 2.5% by the middle of the next century, and to be constant after that. More strict regulation of CFCs and Halons will be discussed at the fourth meeting of the Montreal Protocol in November 1992.

As for land use changes, projections of future deforestation and reforestation in the tropics (Houghton, 1990) are used. The rate of deforestation increases exponentially and the deforested area is estimated to be 34 million ha per annum by the middle of the next century.

The amount of methane from municipal wastes, CO_2 from cement production, greenhouse gases from agricultural activities are estimated based on population growth and GDP per capita increase.

Scenarios of the global warming mechanism are based on climate sensitivities and feedback mechanisms. The missing sink is one of the main unknown factors. We assume three scenarios concerning the missing sink. The first is to assume that the size of the missing sink is constant during the prediction period (1.43 billion tons of carbon per annum). The second is to assume that it increases in proportion to the atmospheric concentrations. This corresponds to a negative feedback. The third is to assume that it decreases. The rate of decrease may be, for example, 2%.

The standard climate sensitivity is assumed to be 3°C, the low sensitivity to be 2°C, and the high sensitivity to be 4°C, respectively.

As for feedback effects, we take five factors. The first is the fertilization effect of CO_2. This effect is a negative feedback. The amount of carbon taken up by plants is assumed to increase in proportion to the atmospheric CO_2 concentration and to be 90 billion tons of carbon in the case of CO_2 doubling. The second feedback effect is the effect of carbon release from terrestrial ecosystems due to the temperature increase. We assume it to be 0.5 billion t-C/year/°C. The third effect is the increase in CH_4 caused by the temperature increase. We assume it to be 200 million t-CH_4/year/°C. The fourth effect is caused by methane hydrates. We assume it to be 0.11 billion t-CH_4/year/°C, half of the figure in the Lashof report (Lashof, 1989).

Finally we take into account the effect of ocean heat uptake. For example, when the surface temperature of the ocean increases 2°C compared with that before the Industrial Revolution, the amount of ocean heat uptake may change significantly.

Combining these scenarios, we estimate greenhouse gas emissions in the following cases. First, we assume two standard "Business as Usual" cases:

1. *Low Standard Scenario.*
   Low Population Scenario + Low GNP Scenario + High Efficiency Scenario
2. *High Standard Scenario.*
   High Population Scenario + High GNP Scenario + Low Efficiency Scenario

Then we estimate the cost of stabilizing and decreasing greenhouse gas emissions by introducing a carbon tax. The tax rate is assumed to be equal worldwide. The rate of the carbon tax depends upon the scenario. Two tax rates corresponding to low and high standard scenarios are estimated.

As for missing sink and feedback effects, we added their effects to the standard cases. For high estimates, three effects are considered. The first is the 2% decrease per annum in the missing sink. The second is forward feedback such as carbon release from terrestrial ecosystems, the increase in CH_4 from wetlands, and the release of methane from methane hydrates. The third effect is the change in ocean circulation. For low estimates, two effects are considered, increase in the missing sink and negative feedback effects such as fertilization effects of CO_2.

4. Simulation Results

Global climate change based on future predictions of socioeconomic factors and natural factors are estimated. The results show that CO_2 emissions in

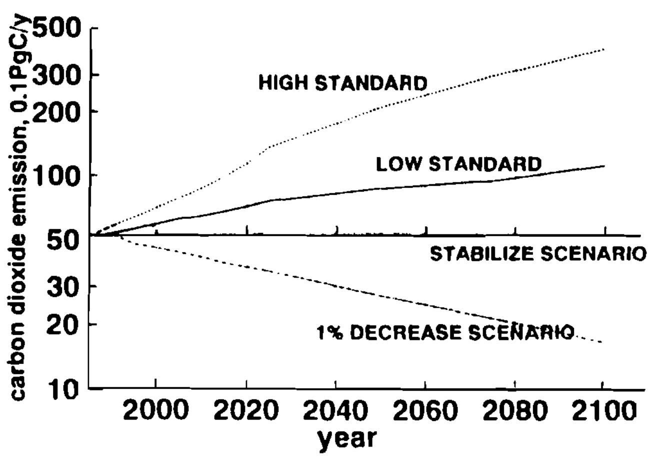


Figure 5. Projections of CO_2 emissions from fossil fuel consumption.

2025 would be 1.4 to 2.4 times as large as those in 1990, and CO_2 emissions in 2100 would be 2 to 7 times as large. Figure 5 shows the prediction of CO_2 emissions. The total CO_2 emission from fossil fuel consumption in 1985 is assumed to be about 5.1 PgC. CO_2 emissions are estimated to be about 39.6 PgC in 2100 with the Low Standard Scenario and 11.2 PgC with the High Standard Scenario. Figure 6 shows the results of recent reports on future CO_2 emissions. The dotted area shows the range of these simulation results. The area is within the recent reports.

Figure 7 shows the trajectories of energy consumption based on the High Standard Scenario. The vertical axis represents energy resources and the horizontal axis represents their extraction cost. On the resource–extraction cost curves, the points for 2025 and 2100 are indicated. Based on the "Business as Usual" case, energy resources of oil and gas have almost all been consumed (about 90%) and coal has been about 37% consumed. This shows that we cannot predict that a lack of energy resources would solve global warming problems.

Figure 8 shows the amount of carbon tax for the cases of stabilization and a 1% decrease. To stabilize CO_2 emissions at the 1990 level by introducing the carbon tax, it is estimated that the required carbon tax would be 180 to 440 1990US$/t-C in 2025 and 310 to 1,250 1990US$/t-C in 2100. The effects on world GDP are shown in Figure 9. The decrease in the world GNP caused by the carbon tax is estimated to be 1.5% to 2.8% in 2025 and 2.8% to 7.3% in 2100. We can conclude that the impacts on the world economy are not so high, even in the high standard case.

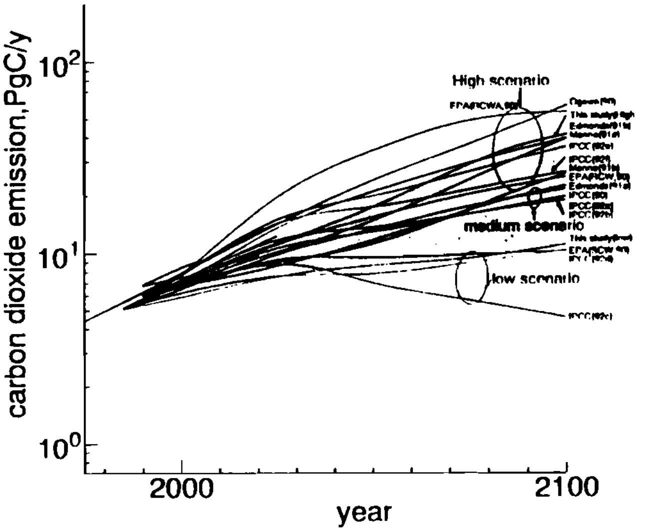


Figure 6. Recent estimates of future CO_2 emissions from fossil fuel consumption.

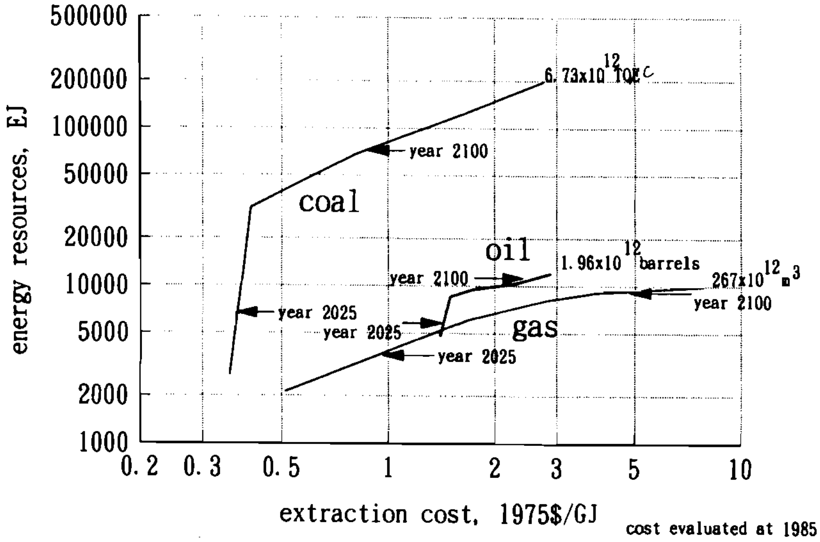


Figure 7. Estimates of energy resources.

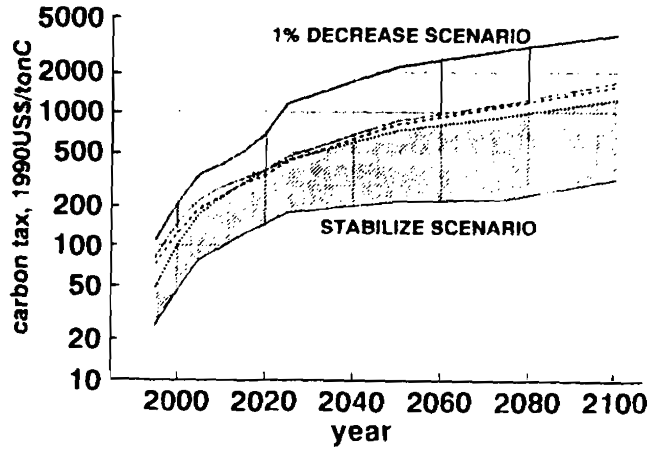


Figure 8. Estimates of carbon tax.

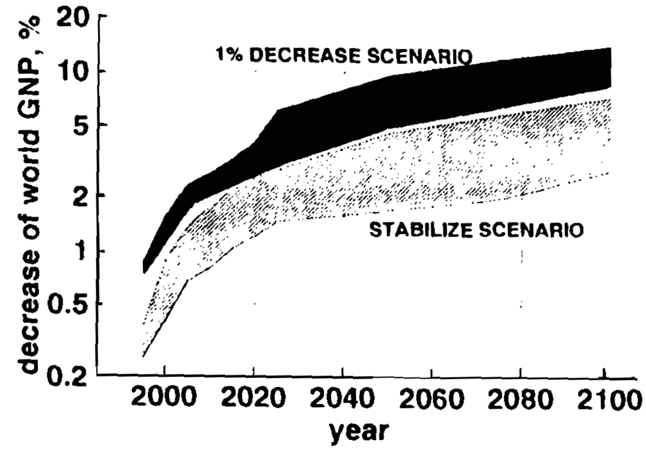


Figure 9. Estimates of world GDP decrease.

Global warming cannot be stopped only by stabilizing CO_2 emissions. Another political option will be necessary. Even if the carbon tax were to be more than 2,000 1990US$, the world temperature might increase. Countermeasures such as plantation and the use of solar energy and biomass should be taken.

Figure 10 shows the greenhouse gas concentration. Figure 10(a) shows the results of "Business as Usual" cases. Missing sink (MS), positive and negative feedbacks, and the effects of changes in ocean circulation are also considered. The greenhouse gas concentration is estimated to be 819 to 1,846 ppmv with the High Standard Scenario and to be 690 to 2,379 ppmv with the Low Standard Scenario. In cases of stabilization scenarios, it ranges from 617 to 872 ppmv. Greenhouse gas concentration would be 713 ppmv without considering natural factors [Figure 10(b)]. Figure 10(c) shows the case of a 1% annual decrease. In this case, greenhouse gas concentration is estimated to be 573 ppmv without considering natural factors and ranges from 518 to 780 ppmv with natural factors.

Figure 11 shows the temperature increase caused by greenhouse gas emissions. Figures 11(a), (b), and (c) correspond to "Business as Usual", "Stabilization", and "1% decrease" cases, respectively. The effects of ocean circulation are estimated to have significant effects on global warming. In Figures 10 and 11, climate sensitivity is assumed to be 3°C. In Figure 12 climate sensitivity ranges from 2 to 4°C. In the case of a climate sensitivity of 4°C, the temperature increase is estimated to range from 2.2 to 10°C in 2080.

5. Conclusion

AIM has been developed to evaluate the impacts of policy options in each country from the Asian–Pacific region by simulating global environmental changes and world socioeconomic trends. The prototype model developed this year will be improved and applied to other countries in the Asian–Pacific region. This model will be integrated into the global warming impact models in the Asian–Pacific region and will be used to estimate global warming impacts in this region.

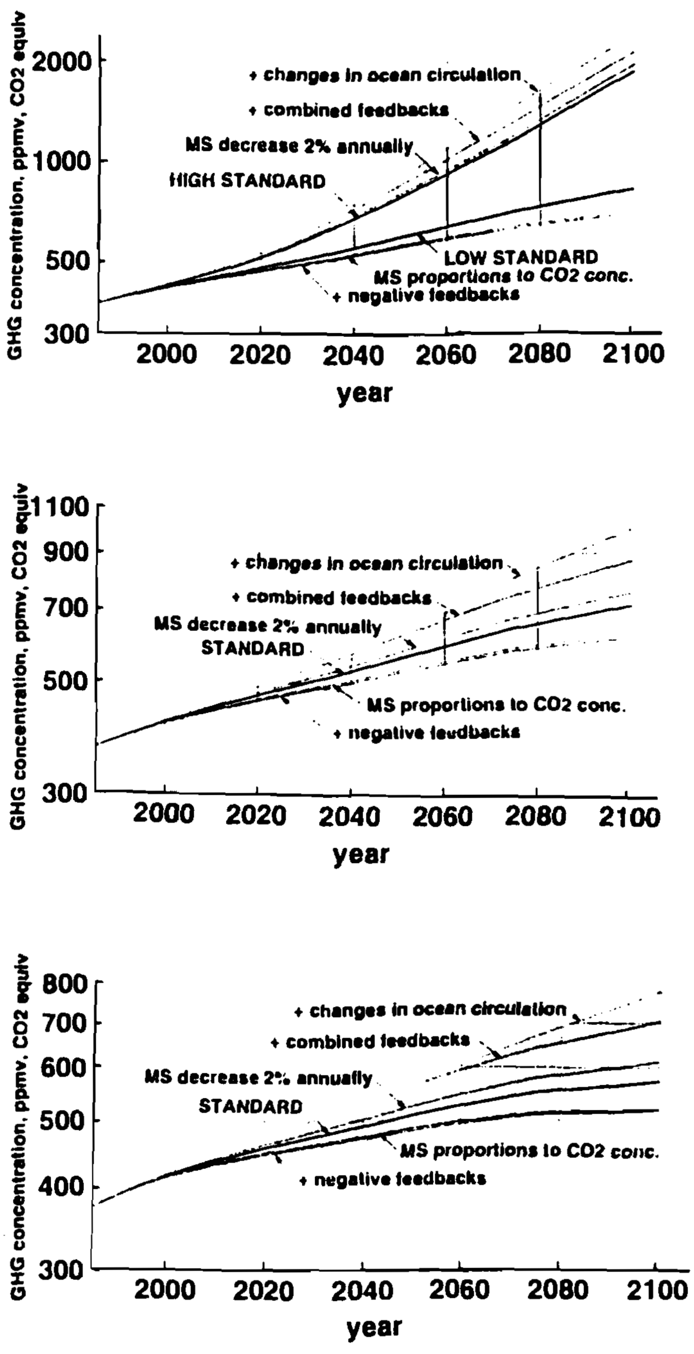


Figure 10. Estimates of greenhouse gas concentrations. (a) Business as usual; (b) constant CO_2 emission; (c) 1% annual decrease of CO_2 emission.

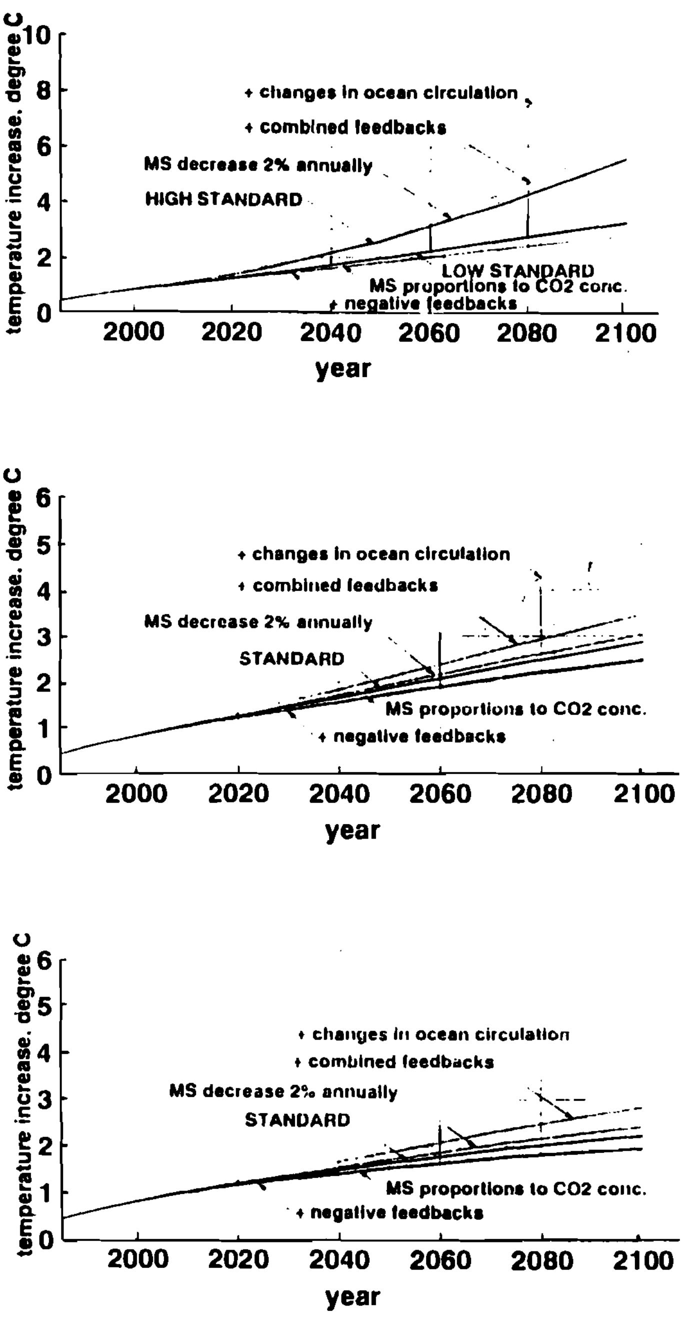


Figure 11. Temperature increase caused by greenhouse gas emissions. (a) Business as usual; (b) constant CO_2 emission; (c) 1% annual decrease of CO_2 emission.

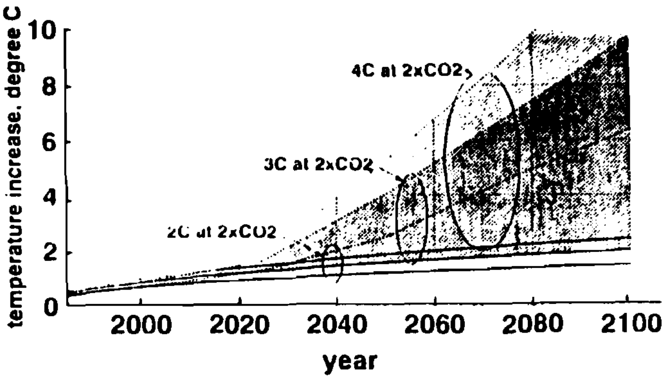


Figure 12. Temperature increase estimations with different climate sensitivities.

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Part 4

Costs: National and Regional Estimates

Reducing US Carbon Dioxide Emissions: An Assessment of Different Instruments

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Abstract

The possibility that CO_2 emissions from fossil fuel use might lead to global warming has become a leading environmental concern. Many scientific and environmental organizations have called for immediate action to limit CO_2 production. For the most part, however, public debate has focused on a single policy instrument: a carbon tax applied to fossil fuels in proportion to their carbon content. In this paper we present a detailed model of the US economy and use it to compare carbon taxes with two other instruments which could achieve the same reduction in carbon dioxide emissions: a tax on the energy content of fossil fuels (a BTU tax) and an *ad valorem* tax on fuel use. We find that carbon taxes can achieve a given reduction with the least overall effect on the economy, but with a large effect on coal mining. Energy taxes are fairly similar to carbon taxes but with slightly less impact on coal mining and slightly greater overall cost. In contrast, *ad valorem* taxes fall much more lightly on coal mining at the expense of having much greater effect on the economy as a whole.

1. Introduction

The possibility that carbon emissions from fossil fuel combustion might lead to global warming has emerged as an international environmental issue.[1] Multilateral action to reduce emissions will be discussed under the United Nations Framework Convention on Climate Change, signed by the United States and many other nations at the United Nations Conference on Environment and Development in Rio de Janeiro. The U.N. Framework Convention

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[1] A very thorough discussion of global warming and numerous references to the literature are given by EPA (1989). Overviews of the economics of global warming are presented by Nordhaus (1991) and Schelling (1992).

calls for stabilization of carbon dioxide emissions at 1990 levels, but leaves the choice of policy instruments to be used for this purpose to each of the signatory nations.

The policy instrument for reducing carbon dioxide emissions in the United States most often recommended by economists is a carbon tax,[2] a tax on the carbon content of fossil fuels. A carbon tax would lead to substitution away from these fuels and toward other inputs, such as capital, labor, and materials. In addition, a carbon tax would result in less intensive use of coal, which has a high carbon content, and more intensive use of natural gas, which has a low carbon content. The European Community has proposed an energy tax, levied on primary fuels in proportion to their energy (BTU) content. Finally, taxes proportional to the value of individual fuels, such as an *ad valorem* tax on gasoline, have also been discussed.

A great deal of valuable information about the economic impact of policies to limit the emissions of greenhouse gases has been accumulated.[3] However, the analysis of the impact on US economic growth of restrictions on these emissions is seriously incomplete. Alternative tax instruments, such as carbon, energy (BTU), and *ad valorem* taxes are intended to reduce fossil fuel use by inducing producers and households to substitute toward other inputs. In order to capture these effects it is essential to model the responses of businesses and households at a highly disaggregated level. A disaggregated model of producer behavior is required to incorporate differences among sectors in response to energy taxes. A disaggregated model of the household sector is necessary to include differences in responses among households.

Taxes on fossil fuels affect carbon dioxide emissions by changing relative prices. These price changes affect capital formation and the rate of economic growth, so that assessment of the impact of alternative tax instruments requires a model with endogeneous capital formation. In addition, these taxes will increase the price of energy to purchasers, which may reduce or accelerate the rate of productivity growth. In this paper we present a detailed model of the US economy with endogeneous economic growth. We use this model to compare the economic impact of alternative tax instruments for

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[2] A carbon tax was first analyzed by Nordhaus (1979) and has recently been discussed by the Congressional Budget Office (1990). Jorgenson and Wilcoxen (1992) have examined the economic impact of using a carbon tax to achieve different restrictions on carbon dioxide emissions. Poterba (1991) and Jorgenson *et al.* (1992) have considered equity and efficiency impacts of a carbon tax.

[3] Detailed surveys of estimates of the impact of restrictions on carbon dioxide emissions are given by Cline (1992), Hoeller *et al.* (1991), and Nordhaus (1990).

stabilizing US carbon dioxide emissions at 1990 levels, as stipulated in the U.N. Framework Convention.

The organization of the paper is as follows. In Section 2 we describe the model of the US economy employed in our evaluation of the economic impact of alternative tax instruments for stabilizing carbon dioxide emissions. In Section 3 we compare these alternative instruments and find that a carbon tax will achieve the objective of stabilizing emissions with the least overall impact on the US economy. However, such a tax will have a severe negative impact on coal production. An energy tax is fairly similar in its economic impact to a carbon tax, but has less effect on coal mining and greater overall cost. By contrast, an *ad valorem* tax on fossil fuels has a smaller impact on coal mining, but a much greater negative impact on the growth of the US economy. In Section 4 we assess the alternative tax instruments and summarize our conclusions.

2. An Overview of the Model

Our analysis of the incidence of carbon, energy (BTU), and *ad valorem* taxes is based on simulations of US economic growth, using an intertemporal general equilibrium model of the US economy described in detail by Jorgenson and Wilcoxen (1993). Jorgenson and Wilcoxen (1990b) have employed this model to assess the impact of environmental regulations in the United States. In this section we outline the key features of the model and describe its application to alternative tax instruments for the control of carbon dioxide emissions.

2.1. Producer behavior

Since carbon dioxide emissions are generated by fossil fuel combustion, a disaggregated model is essential for modeling differences in the response to alternative policies for controlling these emissions. Our submodel of producer behavior is disaggregated into thirty-five industrial sectors, listed in Table 1. The model determines levels of output for thirty-five separate commodities, each produced by one or more industries. The industries correspond, roughly, to two-digit industry groups in the Standard Industrial Classification (SIC). This level of industrial level makes it possible to measure the effect of changes in tax policy on relatively narrow segments of the economy.

We represent the technology of each of the thirty-five industries in our model by means of a hierarchical tier structure of econometric models of producer behavior. At the highest level, the price of output in each industry

Table 1. Definitions of the industries.

No.	Description	No.	Description
1	Agriculture, forestry, and fisheries	19	Stone, clay, and glass products
2	Metal mining	20	Primary metals
3	Coal mining	21	Fabricated metal products
4	Crude petroleum and natural gas	22	Machinery, except electrical
5	Nonmetallic mineral mining	23	Electrical machinery
6	Construction	24	Motor vehicles
7	Food and kindred products	25	Other transportation equipment
8	Tobacco manufacturers	26	Instruments
9	Textile mill products	27	Miscellaneous manufacturing
10	Apparel and other textile products	28	Transportation and warehousing
11	Lumber and wood products	29	Communication
12	Furniture and fixtures	30	Electric utilities
13	Paper and allied products	31	Gas utilities
14	Printing and publishing	32	Trade
15	Chemicals and allied products	33	Finance, insurance, and real estate
16	Petroleum refining	34	Other services
17	Rubber and plastic products	35	Government enterprises
18	Leather and leather products		

is represented as a function of prices of energy, materials, and capital and labor services. Similarly, the price of energy is a function of prices of coal, crude petroleum, refined petroleum, electricity, and natural gas; the price of materials is a function of the prices of all other intermediate goods. We derive demands for inputs of capital and labor services and inputs of the thirty-five intermediate goods into each industry from the price function for that industry.

We have estimated the parameters of production models for the thirty-five industries econometrically. For this purpose, we have constructed a set of consistent inter-industry transactions tables for the US economy for the period 1947 through 1985.[4] Our econometric method for parameterization stands in sharp contrast to the calibration method used in almost all applied general equilibrium models. Calibration involves choosing parameters to replicate the data for a particular year.[5]

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[4] Data on inter-industry transactions are based on input-output tables for the U.S. constructed by the Bureau of Economic Analysis (1984). Income data are from the U.S. national income and product accounts, also developed by the Bureau of Economic Analysis (1986). The data on capital and labor services are described by Jorgenson (1990b). Additional details are given by Wilcoxen (1988, Appendix C) and Ho (1989).

[5] See Mansur and Whalley (1984) for more detail. An example of the calibration approach is Borges and Goulder (1984) who present a model of energy policy calibrated

The econometric approach to parameterization has several advantages over the calibration approach. First, by using an extensive time series of data rather than a single data point, we are able to derive the response of production patterns to changes in prices from historical experience.[6] This is particularly important for the analysis of alternative tax policies to control carbon dioxide emissions, since energy prices have varied widely during our sample period. The calibration approach imposes responses to price changes on the data through the choice of functional forms. For example, elasticities of substitution are set equal to unity by imposing the Cobb-Douglas functional form or zero by imposing the Leontief form. Similarly, all elasticities of substitution are set equal to each other by imposing the constant elasticity of substitution functional form.

Empirical evidence on substitutability among inputs is essential in analyzing the impact of alternative tax policies to control carbon dioxide emissions. If it is easy for industries to substitute among inputs, the effects of these policies will be very different than if substitution were limited. Although calibration avoids the burden of data collection required by econometric estimation, it also specifies the substitutability among inputs by assumption rather than relying on empirical evidence. This can easily lead to substantial distortions in estimating the effects of alternative policies.

A second advantage of the econometric approach is that parameters estimated from time series are much less likely to be affected by the peculiarities of the data for a particular time period. By construction, parameters by calibration are forced to absorb all the random errors present in the data for a single benchmark year. This poses a severe problem when the benchmark year is unusual in some respect. For examples, parameters calibrated to data for 1973 would incorporate into the model all the distortions in energy markets that resulted from price controls and rationing of energy during the first oil crisis. Econometric parameterization greatly mitigates this problem by reducing the influence of random errors for any particular time period.

An important feature of our producer submodel is that an industry's productivity growth can be biased toward some inputs and away from others. Biased productivity growth is a common feature of historical data, but is often excluded from models of production. By allowing for biased productivity growth, our model provides a separation between price-induced

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to data for the year 1973. Surveys of applied general equilibrium modeling are given by Bergman (1985; 1990).

[6] A detailed discussion of our econometric methodology is presented by Jorgenson (1984; 1986).

reductions in energy utilization and those resulting from changes in technology. In addition, the rate of productivity growth for each industry in our model is determined endogeneously as a function of relative prices.[7]

In summary, the salient features of our production model are, first, that it is disaggregated into thirty-five industries. Second, all parameters of the model are estimated econometrically from an extensive historical database developed specifically for this purpose. Third, the model determines rates of productivity growth endogeneously and allows for biased productivity change in each industry. Fourth, the model incorporates extensive historical evidence on the price responsiveness of input patterns, including changes in the mix of fossil fuels. We turn next to a brief discussion of our modeling of final demands - consumption, investment, government expenditure, and foreign trade.

2.2. Consumption

Alternative tax policies to control carbon dioxide emissions have very different impacts on different households. For example, the imposition of a tax on energy affects the relative prices faced by consumers. An increase in the price of energy resulting from the tax adversely affects those consumers who devote a larger share of total expenditure to energy. To capture these differences among households, we have subdivided the household sector into 672 demographic groups that differ by characteristics such as family size, age of head, region of residence, race, and urban versus rural location. We treat each household as a consuming unit, so that the household behaves like an individual maximizing a utility function.

We represent the preferences of each household by means of an econometric model of consumer behavior. The econometric approach to parameterization enables us to derive the response of household expenditure patterns to changes in prices from historical experience. This approach to modeling consumer behavior has the same advantages over the calibration approach as those we have described for modeling producer behavior. Empirical evidence on substitutability among goods and services is essential in analyzing the impact of alternative tax policies to control carbon dioxide emissions.

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[7] Our approach to endogeneous productivity growth was originated by Jorgenson and Fraumeni (1981). A general equilibrium model of production that incorporates both substitution among inputs and endogeneous productivity growth is presented by Jorgenson (1984). The implications of this model have been analyzed by Hogan and Jorgenson (1991). Further details are given by Jorgenson (1986) and Jorgenson and Wilcoxen (1993).

If it is easy for households to substitute among commodities, the effects of these policies will be very different than if substitution were limited.

Our model of household behavior is generated by a three-stage optimization process. At the first stage, each household allocates full wealth, defined as the sum of human and nonhuman wealth, across different time periods. We formalize this decision by introducing a representative agent who maximizes an additive intertemporal utility function, subject to an intertemporal budget constraint. The optimal allocation satisfies a sequence of necessary conditions that can be summarized by means of an Euler equation.[8] This allocation is determined by the rate of time preference and the intertemporal elasticity of substitution. The Euler equation is forward-looking, so that the allocation of full wealth incorporates expectations about all future prices and discount rates.

After households have allocated full wealth to the current time period, they proceed to the second stage of the optimization process – choosing the mix of leisure and goods. We represent household preferences between goods and leisure by means of a representative agent with an indirect utility function that depends on the prices of leisure and goods. We derive demands for leisure and goods as functions of these prices and the wealth allocated to the period. This implies an allocation of the household's exogeneously given time endowment between leisure time and the labor market, so that this stage of the optimization process determines labor supply.

The third stage of the household optimization problem is the allocation of total expenditure among capital and labor services and the thirty-five commodity groups included in the model. At this stage, we replace the representative consumer approach by the approach of Jorgenson *et al.* (1982) for deriving a system of demand functions for each household. We distinguish among household types cross-classified by attributes such as the number of household members and the geographic region in which the household is located. For each type of household, we employ a hierarchical tier structure of models of consumer behavior to represent demands for individual commodities.[9]

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[8] The Euler equation approach to modeling intertemporal consumer behavior was originated by Hall (1978). Our application of this approach follows Jorgenson and Yun (1986).

[9] Our model of personal consumption expenditures can be used to represent the behavior of individual households, as in Jorgenson and Slesnick (1987), or the behavior of the household sector as a whole, as in Jorgenson (1990a). Jorgenson *et al.* (1992) have employed the results for individual households to separate the overall impact of a carbon tax into equity and efficiency improvements.

The parameters of the behavioral equations for all three stages of our consumer model are estimated econometrically.[10] This includes the Euler equation, demand functions for leisure and personal consumption expenditures, and demand functions for individual commodities. Our household model incorporates extensive time series data on the price responsiveness of demand patterns by consumers and detailed cross section data on demographic effects on consumer behavior. An important feature of our household model is that we do not require that demands are homothetic. As levels of total expenditure increase, patterns of expenditure on individual commodities change, even in the absence of price changes. This captures an important feature of cross section data on household expenditure patterns that is usually ignored in applied general equilibrium modeling.

2.3. Investment and capital formation

Our investment model, like our model of saving, is based on perfect foresight or rational expectations. Under this assumption, the price of investment goods in every period is based on expectations of future capital service prices and discount rates that are fulfilled by the solution of the model. In particular, we require that the price of new investment goods is always equal to the present value of future capital services.[11] The price of investment goods and the discounted value of future rental prices are brought into intertemporal equilibrium by adjustments in prices and the term structure of interest rates. This intertemporal equilibrium incorporates the forward-looking dynamics of asset pricing by producers.

For tractability, we assume there is a single capital stock in the economy that is perfectly malleable, so that it can be reallocated among industries, and between industries and final demand categories at zero cost. Under this assumption, imposition of alternative tax policies can affect the distribution of capital and labor supplies among sectors, even in the short run. In each time period, the supply of capital in our model is completely inelastic, since the stock of capital is determined by past investment. Investment during the period is determined by the savings made available by households. The relationship between capital stock and past investment incorporates backward-looking dynamics into our model of intertemporal equilibrium.

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[10] Details on the econometric methodology are given by Jorgenson (1984; 1990a). Additional details are provided by Wilcoxen (1988), Ho (1989), and Jorgenson and Wilcoxen (1993).

[11] The relationship between the price of investment goods and the rental price of capital services is discussed in greater detail by Jorgenson (1989).

We assume that new capital goods are produced from individual commodities, so that the price of new capital depends on commodity prices. We have estimated the price function of new capital goods using final demand data for investment over the period 1947–1985. Thus, our model incorporates substitution among inputs in the composition of the capital. This feature can play an important role in the evaluation of alternative tax policies. Jorgenson and Wilcoxen (1990a) have found, for example, that an increase in the price of automobiles resulting from mandatory installation of pollution control devices shifts investment away from motor vehicles and toward other types of capital.

In summary, capital formation in our model is the outcome of intertemporal optimization by households and firms. Optimization by households is forward-looking and incorporates expectations about future prices, wages, and interest rates. Optimization by producers is also forward-looking and depends upon these same expectations. Both types of optimization are very important for modeling the impact of future restrictions on carbon dioxide emissions. The effects of these restrictions will be anticipated by households and firms, so that future policies will have important consequences for current decisions.

2.4. Government and foreign trade

The two remaining final demand categories in our model are the government and foreign sectors. We determine final demands for government consumption from the income-expenditure identity for the government sector. The first step is to compute total tax revenue by applying exogeneous tax rates to appropriate transactions in the business and household sectors. We then add the capital income of government enterprises, determined endogeneously, and nontax receipts, also determined exogeneously, to tax revenue to obtain total government revenue.

We assume that the government budget deficit can be specified exogeneously. We add the deficit to total revenue to obtain total government spending. To arrive at government purchases of goods and services, we subtract interest paid to domestic and foreign holders of government bonds together with government transfer payments to domestic and foreign recipients. We allocate the remainder among commodity groups according to fixed shares constructed from historical data. Finally, we determine the quantity of each commodity by dividing the value of government spending on the good by its price.

Foreign trade has two components – imports and exports. We assume that imports are imperfect substitutes for similar domestic commodities.[12] The goods actually purchased by households and firms reflect substitution between domestic and imported products. The price responsiveness of these purchases is estimated econometrically from historical data. In effect, each commodity is assigned a separate elasticity of substitution between domestic and imported goods. Since the prices of imports are given exogeneously, intermediate and final demands implicitly determine imports of each commodity.

Exports, on the other hand, are determined by a set of export demand equations, one for each commodity, that depend on exogeneously given foreign income and the foreign price of US exports. Foreign prices are computed from domestic prices by adjusting for subsidies and the exchange rate. The demand elasticities in these equations are estimated from historical data. Without an elaborate model of international trade, it is impossible to determine both the current account balance and the exchange rate endogeneously. In the simulations reported below, we take the current account to be exogeneous and the exchange rate to be endogeneous.

2.5. Estimating energy production and carbon emissions

The most important remaining feature of the model is the way in which carbon dioxide emissions and the energy content (BTU) of fossil fuels are calculated. For tractability, we assume both are produced in fixed proportions to fossil fuel use. This implicitly assumes that nothing can be done to reduce the carbon dioxide emissions or increase the energy produced by a given combustion process.[13] For each fuel, Table 2 gives total domestic production, heat content per unit and total heat produced. Heat production is measured in quadrillion BTU (quads or QBTU).

We have calculated the carbon content of each fuel by multiplying the heat content of the fuel by the carbon emitted. We obtain the average heat content of each fossil fuel in millions of BTU per quantity unit from the

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[12] This is the Armington (1969) approach. See Wilcoxen (1988), Ho (1989), and Jorgenson and Wilcoxen (1993) for further details on our implementation of this approach.

[13] This is largely the case in practice since carbon dioxide is one of the natural products of combustion. Little can be done to change the amount produced when burning any particular fuel. Similarly, the energy content of fossil fuels is largely unaffected by the combustion process, although the useful work that can be performed may be affected by the process. For comparability with other studies, we measure carbon dioxide emissions in tons of contained carbon. To convert to tons of carbon dioxide, the reader can multiply by 3.67.

Table 2. Domestic production and heat content of fossil fuels.

	Unit	Domestic output	Heat content (MBTU/unit)	Total heat (QBTU)
Coal	ton	916.9×10^6	21.94	20.1
Oil	bbl	3033.2×10^6	5.80	17.6
Gas	kcf	17.8×10^9	1.03	16.8

Table 3. Carbon emissions data for 1987.

	Fuel		
Item	Coal	Oil	Gas
Unit of measure	ton	bbl	kcf
Heat content (10^6 BTU per unit)	21.94	5.80	1.03
Emissions rate			
(kg per 10^6 BTU)	26.9	21.4	14.5
(kg per unit)	590.2	124.1	14.9
Total domestic output (10^9 units)	0.9169	0.3033	17.8
Total carbon emissions (10^6 tons)	595.3	414.1	268.6

Energy Information Administration (1990). We then obtain data from the Environmental Protection Agency (1988) on the amount of carbon emitted per million BTU generated from each fuel. Multiplying the emissions figures by the heating value gives the carbon content of each fuel. Total carbon emissions can then be calculated from fuel production. Table 3 gives data for each fuel in 1987.

All prices in our model are normalized to unity in a common base year, so that quantities do not correspond directly to physical units. Moreover, the model has a single sector for oil and gas extraction. To convert the data for this industry into a form appropriate for the model, we have added carbon production for crude petroleum and natural gas, and divided by the industry's output for 1987 to obtain the carbon coefficient for this industry. Similarly, the coefficient for coal was obtained by dividing total carbon production from coal by the model's 1987 value for coal mining output. These coefficients were used to estimate carbon emissions in each simulation. We now turn to a brief discussion of the model's base case.

2.6. The base case

To simulate the US economy, we must provide values of the exogeneous variables for all time periods. We have accomplished this in two steps. First, we have adopted a set of default assumptions about the time path of each exogeneous variable in the absence of changes in government policy. These assumptions are used in generating a simulation of US economic growth called the "base case". Our second step is to change certain exogeneous variables to reflect the introduction of alternative tax policies and simulate US economic growth again to produce an "alternative case". We then compare the two simulations to assess the impact of the policy change. Obviously, the assumptions underlying the base case are important in interpreting the results.

Since our model is based on agents with perfect foresight, we must solve the model indefinitely far into the future. To do this, we project values for all exogeneous variables over the period 1990–2050. After 2050 we assume the variables remain constant at their 2050 values, which allows the model to converge to a steady state by the year 2100.[14] First, we set all tax rates to their values in 1985, the last year in our sample period. Next, we assume that prices of imports in foreign currency remain constant in real terms at 1985 levels before US tariffs are applied.

We project a gradual decline in the government deficit through the year 2025, after which the nominal value of the government debt is maintained at a constant ratio to the value of the national product. Finally, we project the current account deficit by allowing it to fall gradually to zero by the year 2000. After that we project a current account surplus sufficient to produce a stock of net claims on foreigners by the year 2050 equal to the same proportion of national wealth as in 1982.

The most important exogeneous variables are those associated with growth of the US population and corresponding changes in the economy's time endowment. We project population by age, sex, and educational attainment through the year 2050, using demographic assumptions consistent with Social Security Administration projections.[15] After 2050 we hold population constant, which is approximately in line with these projections. In addition, we project the educational composition of the population by holding the

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[14] Some of the most important projections are noted briefly below; a more detailed discussion is given by Jorgenson and Wilcoxen (1992).

[15] Our breakdown of the US population by age, sex, and educational attainment is based on the system of demographic accounts compiled by Jorgenson and Fraumeni (1989). The population projections are discussed in detail by Wilcoxen (1988, Appendix B).

level of educational attainment constant, beginning with the cohort reaching age 35 in the year 1985. We transform our population projection into a projection of the time endowment by taking relative wages across different types of labor input to be constant at 1985 levels. Since capital formation is endogeneous in our model, our projections of the time endowment effectively determine the size of the economy in the more distant future.

3. An Assessment of Different Instruments

A strategy for controlling carbon dioxide emissions consists of a target path of emissions and a tax instrument to be used to attain the target. We compare the economic impacts of three different sequences of tax instruments for holding US carbon dioxide emissions constant at the 1990 level of 1,576 million tons. All three instruments are taxes on fossil fuels. The specific taxes we considered are the following:

1. A tax on the carbon content of fossil fuels.
2. A tax on the energy (BTU) content of fossil fuels.
3. An *ad valorem* tax of fossil fuels.

To measure the impact of adopting sequences of taxes that hold US carbon dioxide emissions constant, we have constructed a number of alternative simulations of US economic growth. In the base case, we simulate US economic growth with no limits on emissions. In the alternative cases, we simulate growth with emissions of carbon dioxide held constant. To hold the level of emissions constant, we introduce endogeneous sequences of taxes applied to fossil fuels in proportion to their carbon content, their energy content, and their monetary value.

Since each of the tax sequences produces substantial revenue, we hold government spending constant at its base case level. We allow the average tax rate on labor income to adjust in order to keep the government deficit constant. We hold the marginal tax rate on labor income constant, so that adjustments in the average rate reflect changes in the implicit zero-tax threshold. This tax adjustment is equivalent to a lump sum transfer to the household sector.

3.1. Long run effects

The direct effect of all three tax policies is to increase purchasers' prices of coal, oil, and natural gas. However, the tax bases for these policies are substantially different, so the alternative taxes will produce quantitatively different results. We next present the qualitative results of using a carbon tax to maintain emissions at 1990 levels in the year 2020. We then discuss how the results vary with alternative tax policies.

In order to achieve 1990 carbon emissions in the year 2020, a 14.4 percent reduction in emissions is required from the base case level. This requires a tax of $16.96 per ton of carbon contained in fossil fuels.[16] Using the data in Table 2, this amounts to a tax of $11.01 per ton of coal, $2.31 per barrel of oil, and $0.28 per thousand cubic feet of gas. A carbon tax would generate additional government revenue of $26 billion annually, so that the average labor tax rate could be reduced by 0.45 percent.

The rising price of fossil fuels results in substitution away from these fuels and toward other energy and nonenergy commodities by both firms and households. Total energy consumption falls to about 68 quadrillion BTUs. This substitution toward nonenergy inputs results in a drop of 0.7 percent in the capital stock and 0.5 percent in the national product by the year 2020.

The impact of a carbon tax differs considerably among different types of fossil fuels. Figure 1 shows changes in the supply price of the 35 commodities measured as percentage changes relative to the base case. The largest change occurs in the price of coal, which rises by forty percent. Electricity prices rise considerably less than coal prices because coal accounts for only about thirteen percent of total electric utility costs. Other prices showing significant effects are those for crude and refined petroleum, and gas utilities. These rise, directly or indirectly, because of the tax on the carbon content of oil and natural gas.

Changes in relative prices affect demands for energy and nonenergy commodities and lead to a restructuring of industry outputs. The second panel of Figure 1 gives percentage changes in quantities produced by the thirty-five industries by the year 2020. Although most sectors show only small changes in output, the production of coal falls by 26.3 percent. Coal is strongly affected because its demand is elastic. Most coal is purchased by electric utilities. In our model these utilities can substitute other fuels for coal when the price rises. Moreover, the utilities also have some ability to substitute other inputs, such as labor and capital, for energy, further reducing the demand for coal.

We next consider energy (BTU) and *ad valorem* tax policies that could be used to control carbon dioxide emissions. Neither of these taxes is as efficient as a carbon tax in controlling emissions. However, both taxes have

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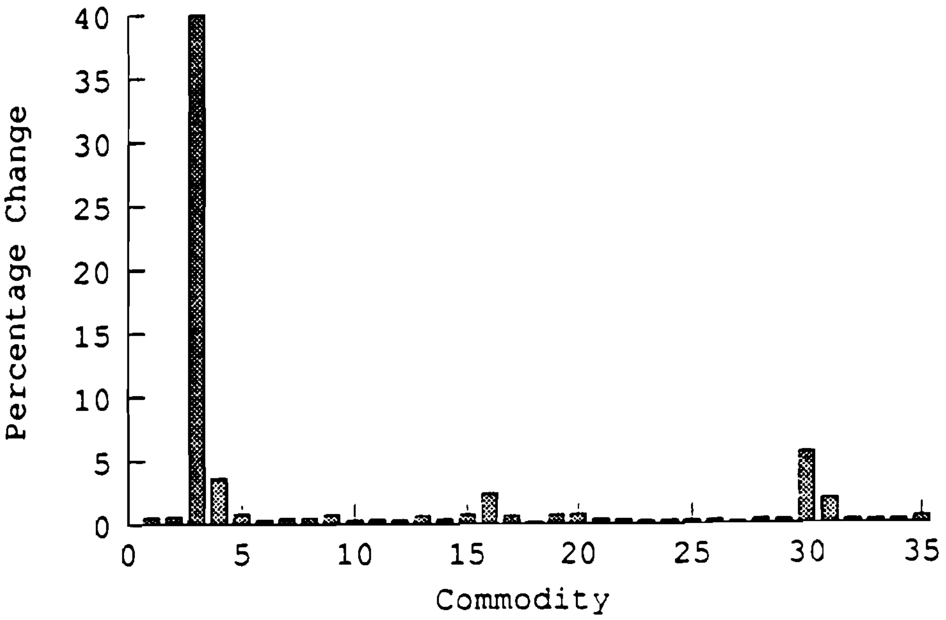
[16] Unless otherwise indicated, all dollar amounts are in 1989 prices.



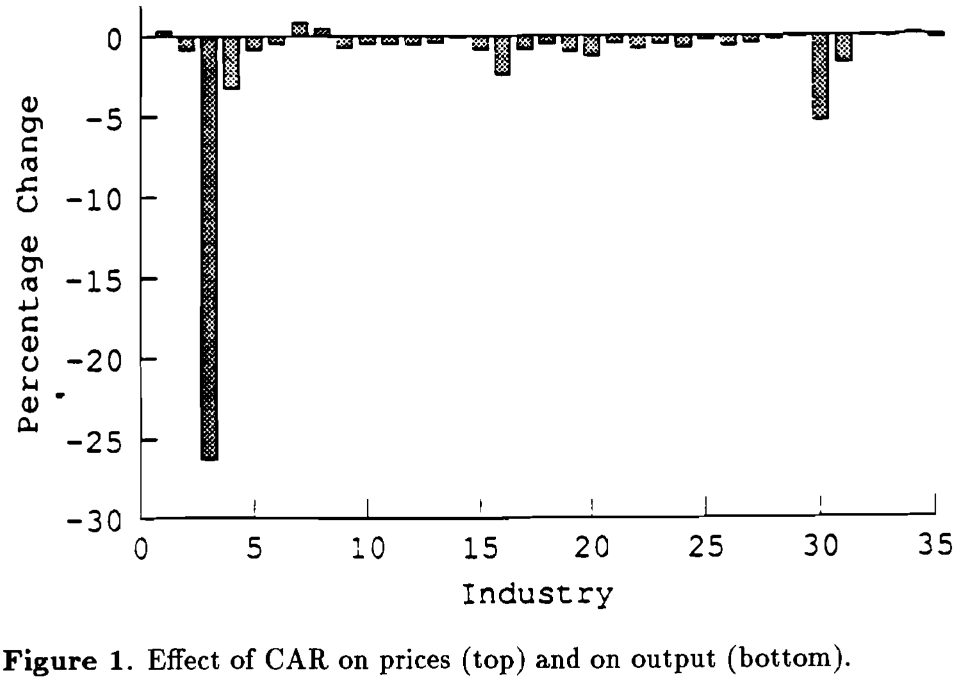


Figure 1. Effect of CAR on prices (top) and on output (bottom).

substantial impacts on fossil fuel use and might be preferable to a carbon tax in achieving other objectives. For example, an energy tax would reduce combustion of fossil fuels, providing environmental benefits other than lower carbon dioxide emissions. An *ad valorem* tax, on the other hand, may be easier to implement. In this section we discuss the impact of these alternative taxes in holding emissions at 1990 levels.

For the first alternative tax simulation, we show that limiting carbon dioxide emissions in the year 2020 to 1990 levels would require an energy (BTU) tax of $0.47 per million BTU. Using data from Table 2 this can be converted to $10.21 per ton of coal, $2.70 per barrel of oil, and $0.48 per thousand cubic feet of gas. Compared to coal, oil and gas have greater heat content for a given amount of carbon dioxide emissions, so that an energy tax falls more heavily on oil and coal than a carbon tax. The difference between the energy and carbon taxes is a negative $0.80 per ton of coal, a positive $0.39 per barrel of oil, and a positive $0.20 per thousand cubic feet of gas.

Total government revenue from an energy tax that would stabilize carbon dioxide emissions at 1990 levels is $31 billion by the year 2020, allowing the average labor tax rate to be lowered by 0.54 percent. Higher energy prices lead to a decline in the capital stock of 0.8 percent and fall in the national product of 0.6 percent, relative to the base case. These declines are slightly higher than for the carbon tax simulation, since the energy (BTU) tax creates greater distortions in the US economy. The impacts on commodity prices and industry outputs are given in Figure 2. The most important difference between this simulation and the carbon tax simulation given in Figure 1 is that an energy tax has less effect on coal price and output and more effect on prices and outputs of petroleum and natural gas. However, the two simulation results are quite similar.

Finally, we consider US economic growth with an *ad valorem* tax on fossil fuels that stabilizes carbon dioxide emissions at 1990 levels. Coal is much less expensive per BTU than petroleum or natural gas. Coal was selling around one dollar per million BTU in 1989, while the price of oil was $2.75 per million BTU.[17] This difference means that an *ad valorem* tax falls much more heavily on oil than carbon or BTU taxes, so that the price of oil rises far more than in the previous simulations. This eliminates much of the interfuel substitution we have discussed above. In particular, it reduces

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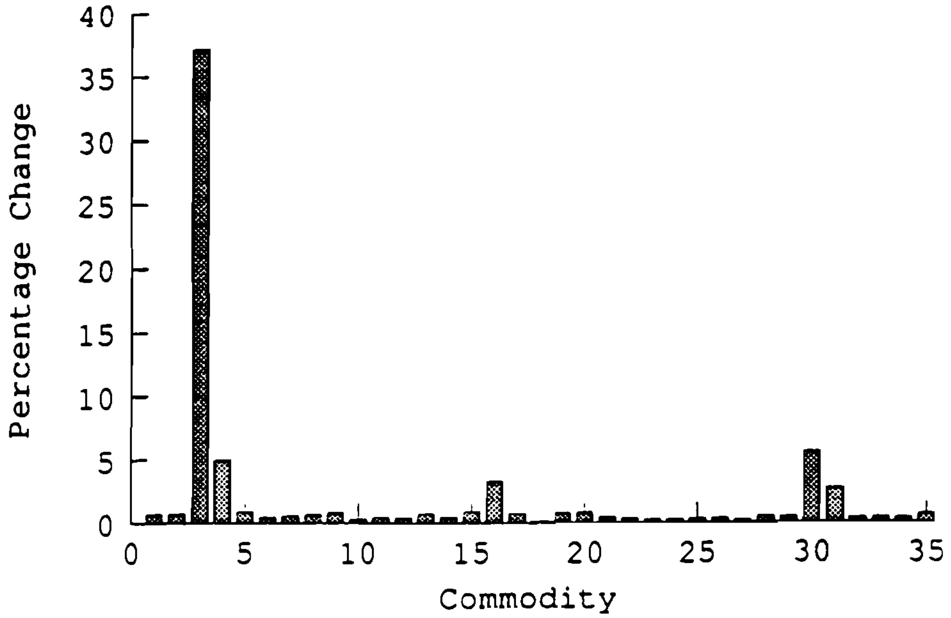
[17] In 1989, the price of coal was $21/ton f.o.b. at the mine mouth. From Table 2, the heating value of a ton of coal is 21.94 MBTU, so the price per million BTU was $0.96. In the same year, the price of crude petroleum was $15.85/bbl, while its heating value is 5.80 MBTU/bbl, yielding a price of $2.73 per million BTU.



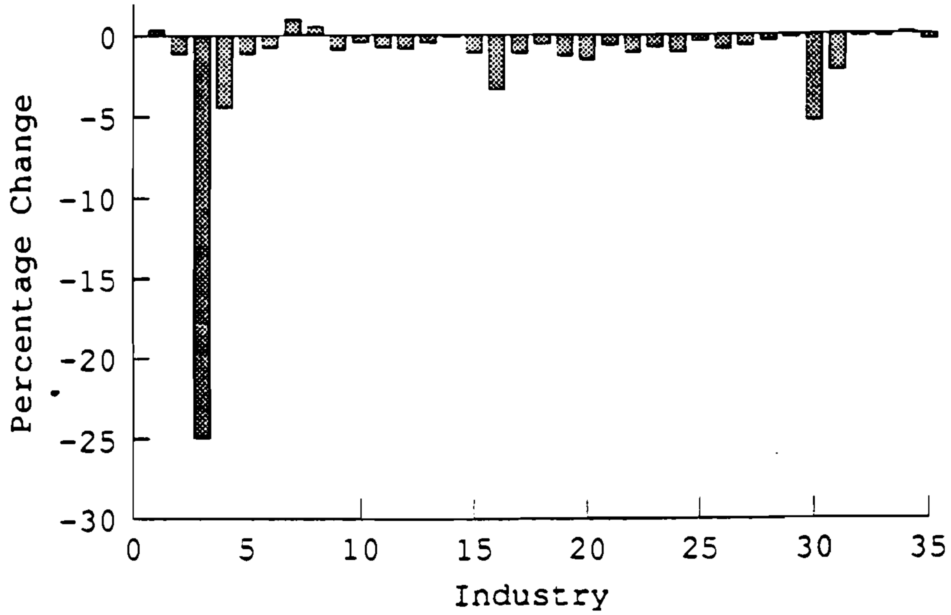


Figure 2. Effect of BTU on prices (top) and on output (bottom).

substitution of oil for coal by electric utilities, so that all energy prices rise substantially.

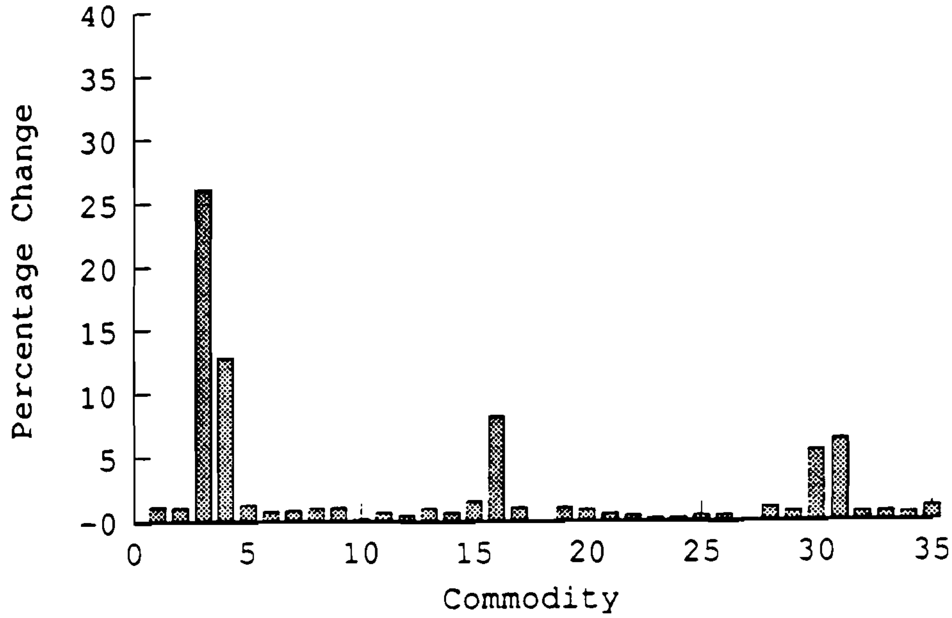
In order to achieve 1990 carbon dioxide emissions rates in 2020 an *ad valorem* tax rate of 21.6 percent would be required. This would raise almost $53 billion in tax revenue, which is considerably more than the revenue raised by either carbon or BTU taxes. As a consequence, the average labor tax rate could be lowered by 0.90 percent. An *ad valorem* tax produces much greater economic distortions than either of the alternative taxes, so the capital stock falls by 1.4 percent and the national product drops by one percent, relative to the base case.

Figure 3 gives the impacts of an *ad valorem* tax on commodity prices and industry outputs. The increase in coal prices is still substantial, but less drastic. The price of crude oil, however, rises much more than under carbon or energy taxes. This, in turn, raises prices of refined petroleum, electricity and natural gas. In the bottom panel of Figure 3, we show that higher energy prices have a marked effect on the outputs of the energy sectors. Both crude and refined petroleum decline by nearly ten percent, while gas and electric utilities fall somewhat less. As in earlier simulations, outputs of a few sectors, notably food and tobacco, actually increase with restrictions on carbon dioxide emissions. This results from lower personal consumption expenditures and shifting patterns of household consumption.

Table 4 summarizes the results of all three simulations. A comparison among alternative tax instruments shows that a carbon tax, as expected, achieves the target reduction in carbon dioxide emissions with a minimum impact on the US economy. However, this tax has a very substantial negative effect on the output of the coal industry. The other end of the spectrum is provided by the *ad valorem* tax, which produces the greatest distortions in the economy and the least impact on coal mining. The difference arises from the fact that coal is much cheaper than oil for a given heat content. Carbon and energy taxes change the price of coal substantially, while affecting the price of oil only a little.

3.2. Economic dynamics

Carbon dioxide restrictions adopted today will have effects far into the future. At the same time, anticipated future restrictions will have effects today. To assess the intertemporal effects of alternative tax policies, we now turn to the model's dynamic results. As with the long run results, we begin by discussing a carbon tax designed to maintain emissions at 1990 levels.



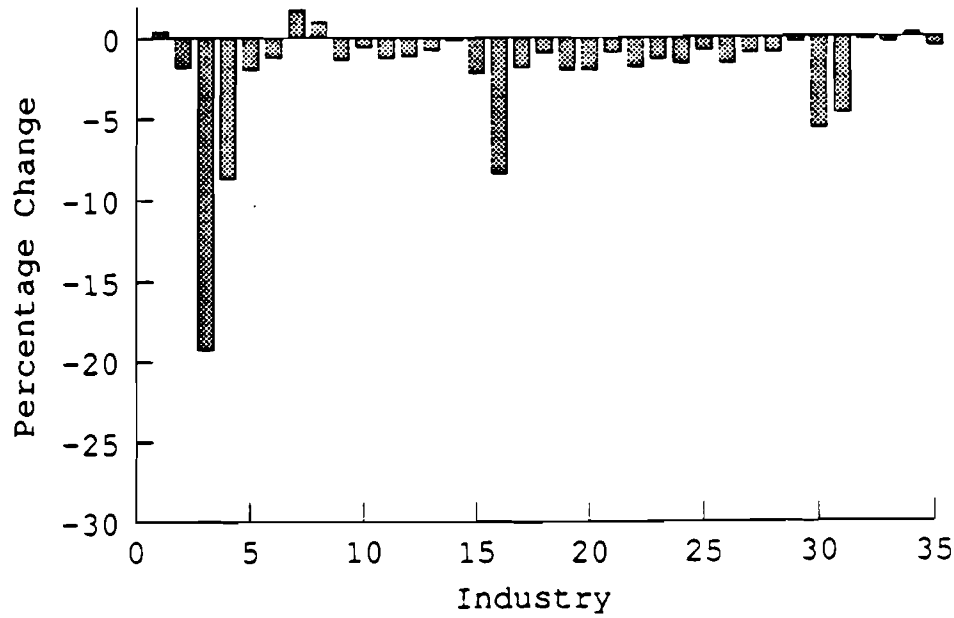


Figure 3. Effect of ADVAL on prices (top) and on output (bottom).

Table 4. Long run effects of different tax instruments.

		Instrument		
Variable	Unit	Carbon tax	BTU tax	*Ad Valorem*
Carbon emissions	%Δ	-14.4	-14.4	-14.4
Carbon tax	$/ton	16.96	–	–
BTU tax	$/MBTU	–	0.47	–
Ad valorem tax	%	–	–	21.6
Tax on coal	$/ton	11.01	10.21	–
Tax on oil	$/bbl	2.31	2.70	–
Tax on gas	$/kcf	0.28	0.48	–
Labor tax rate	Δ	-0.45	-0.54	-0.90
Tax revenue	Bil.$	26	31	53
BTU production	%Δ	-12.2	-12.4	-13.5
Capital stock	%Δ	-0.7	-0.8	-1.4
Real GNP	%Δ	-0.5	-0.6	-1.0
Price of coal	%Δ	39.9	37.2	26.1
Quantity of coal	%Δ	-26.3	-25.0	-19.5
Price of oil	%Δ	3.6	5.0	12.8

Following that, we examine the dynamic response of the US economy to alternative tax policies to lower emissions of carbon dioxide.

The paths of the three taxes needed to maintain 1990 carbon dioxide emissions are shown in Figure 4. Base case emissions increase over time, so that each tax rate rises gradually over the next several decades. Since the alternative tax policies stabilize emissions at 1990 levels, they produce identical reductions in emissions, relative to the base case. These reductions are shown in Figure 5 as annual percentage changes from the base case. Emissions begin dropping immediately and are 14.4 percent below the base case level by the year 2020.

The principal effect of the alternative tax policies is to reduce the output of the coal industry. This is shown clearly in Figure 6, which gives percentage reductions in coal production from the base case. The impact of a carbon tax is shown as a solid line, an energy (BTU) tax as a dashed line, and an *ad valorem* tax as a line of dots and dashes.[18] As each tax is phased in, production of coal gradually falls. It does not, however, return to its 1990 level, since some of the reduction in carbon dioxide emissions is due

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[18] We employ this convention in all subsequent figures.

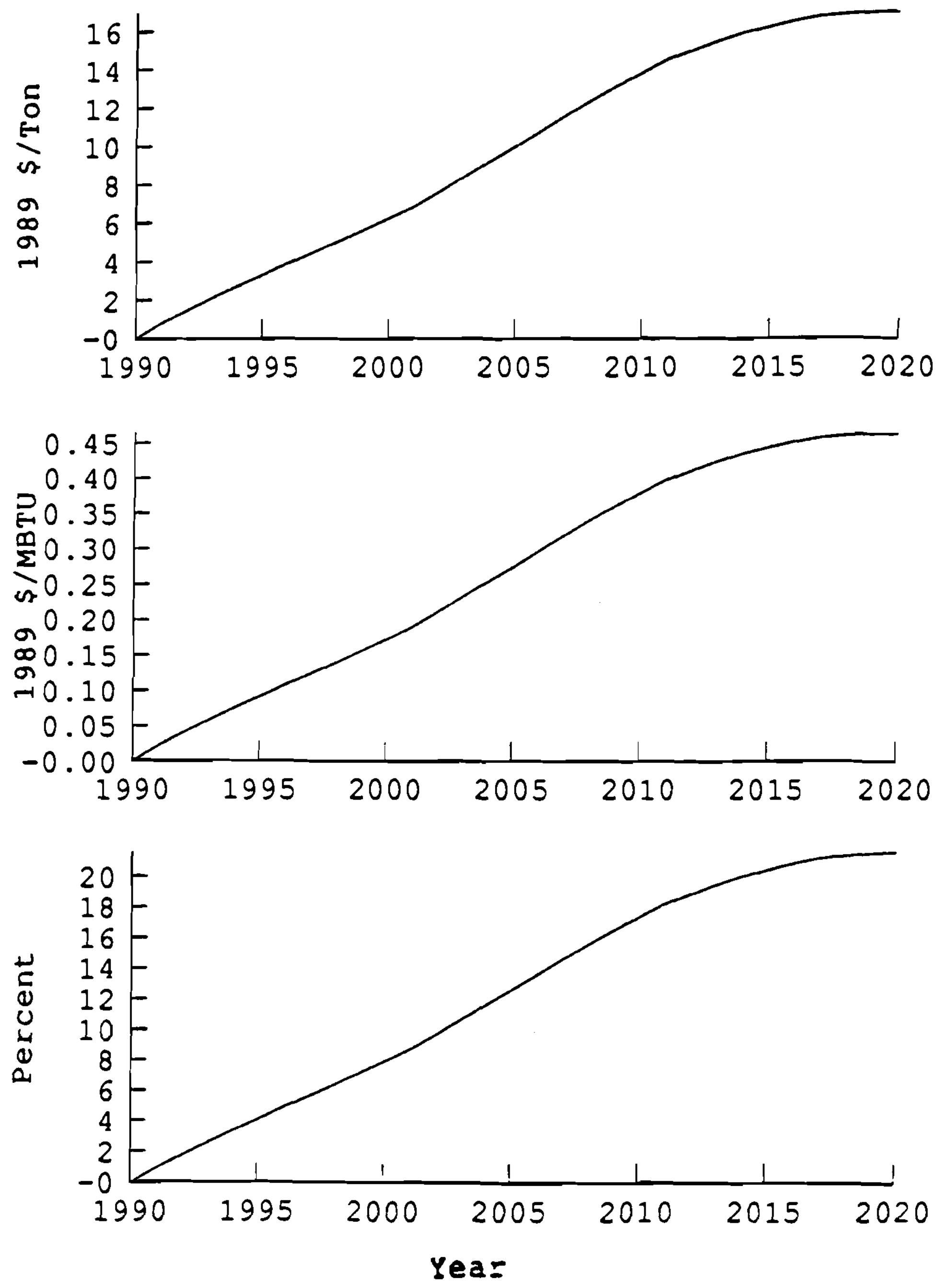

Figure 4. Carbon tax required (top), BTU tax required (middle), and *Ad Valorem* tax required (bottom) to maintain 1990 carbon dioxide emissions.

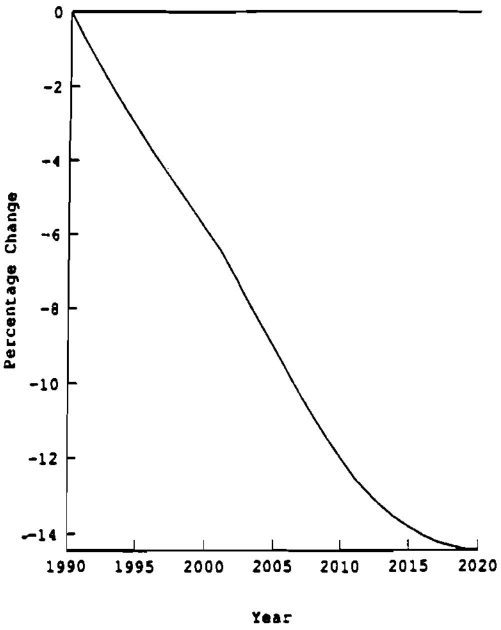

Figure 5. Carbon emissions relative to the base case.

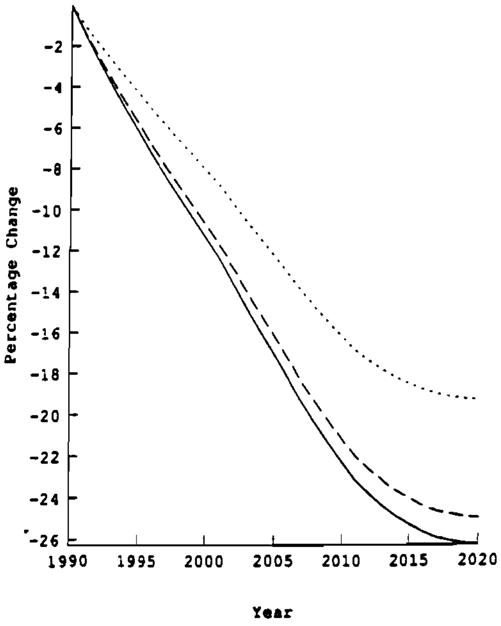

Figure 6. Coal production relative to the base case.

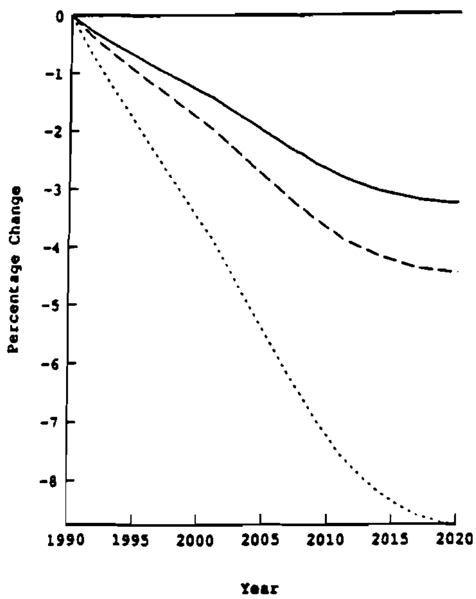

Figure 7. Oil and gas extraction relative to the base case.

to reductions in oil consumption. This can be seen in Figure 7, which gives percentages changes in crude petroleum and natural gas extraction.

The rising price of energy reduces the rate of capital formation, as shown in Figure 8, giving percentage changes in the capital stock from the base case. The capital stock does not decline immediately; instead, it remains near its base case level for the first few years. This reflects intertemporal optimization by households. The household treats higher taxes as a reduction in wealth and reacts by lowering consumption in all periods. However, the drop in consumption leads to an increase in saving and helps to maintain capital formation. Eventually, however, the impact of the taxes is to reduce capital stock relative to the base case.

The decline in growth of the capital stock leads to a drop in the growth of the national product, as shown in Figure 9. Over time, the national product gradually falls relative to the base case. Slower capital stock growth is not the only factor contributing to the decline. Higher energy prices reduce the rate of productivity growth, leading to slower growth of output. Under the carbon tax, average annual growth of output over the period 1990–2020 is 0.02 percentage points lower than in the base case. About half of this is due to slower productivity growth and half due to reduced capital formation. Figure 9 shows that the most important difference among the three tax

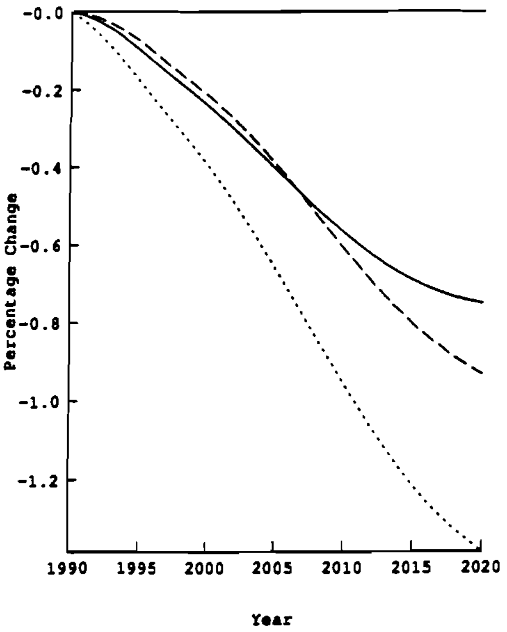

Figure 8. Capital stock.

Table 5. Effects of carbon reduction policies on GNP growth. (Differences from base case annual average growth rates over 1990–2020.)

Tax	Effect on growth
Carbon	-0.02
BTU	-0.02
Ad valorem	-0.03

policies is that the *ad valorem* tax produces greater distortions in the US economy.

Our final step in comparing the three alternative tax policies is to estimate the effect of each on the average rate of growth over the period 1990–2020. The results of this calculation are shown in Table 5. An *ad valorem* tax is by far the most expensive in terms of economic growth. None of the tax policies, however, has a substantial impact on the growth rate.

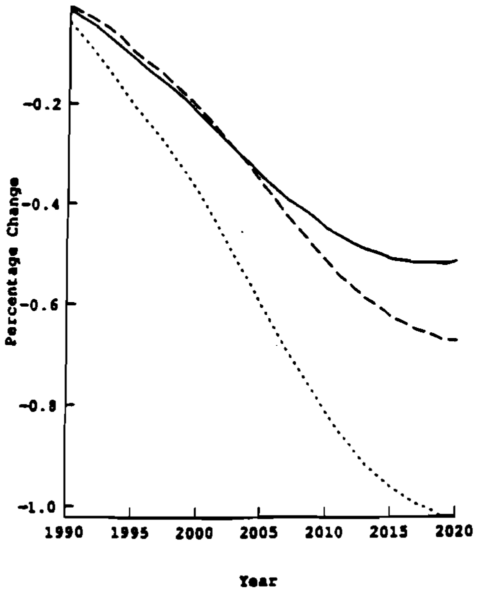

Figure 9. Real GNP.

4. Conclusion

The purpose of this section is to evaluate the usefulness of econometric general equilibrium modeling as a practical guide to assessment of the impacts of alternative tax policies for controlling emissions of carbon dioxide. The framework for the econometric approach to modeling the impact of alternative tax policies is provided by intertemporal general equilibrium. We have distinguished among thirty-five industrial sectors of the US economy and have also identified thirty-five commodity groups, each one the primary product of one of the industries. In modeling consumer behavior, we have distinguished among 672 different household types, broken down by demographic characteristics. Aggregate demand functions for components of consumer expenditures are constructed by summing over individual demand functions.

The econometric method for parameterization used in modeling technology and preferences has important advantages over the calibration approach. The main advantage is that the responses of production and consumption patterns to changes in prices of fossil fuels are derived from historical experience. In Section 2 we have outlined a highly disaggregated model of the US economy suitable to analyzing alternative tax policies for controlling carbon dioxide emissions. An important mechanism for adjusting to changes in tax policy is through altering rates of capital formation. A second mechanism is the pricing of capital assets through forward-looking expectations of future prices and discount rates. This illustrates the critical importance of intertemporal equilibrium in modeling the dynamics of the response of the US economy to alternative tax policies.

In Section 3 we have analyzed the economic impact of three alternative tax policies for controlling carbon dioxide emissions – a carbon tax, an energy (BTU) tax, and an *ad valorem* tax on energy. Each of these taxes results in price-induced energy conservation that has important feedbacks to the rate of US economic growth through capital asset pricing and capital formation. The principal effects of each of these policies to control carbon dioxide emissions would be to reduce coal production and consumption. Other energy sectors would be significantly affected if a tax policy other than a carbon tax is adopted. The precise form of tax policies to control carbon dioxide emissions will be vitally important to the energy industries that are affected.

The alternative tax policies for controlling carbon dioxide emissions have fairly modest impacts on the US economy. Even though large amounts of government revenue are raised by these taxes, the overall impact on the US economy occurs through introduction of distortions resulting from fossil fuel taxes. This conclusion is supported by the relatively small impact of the alternative policies on growth of the national product. Capital formation and the rate of productivity growth are affected only slightly, so the change in US economic growth is modest. However, there are important differences in economic impact among the alternative tax policies.

Finally, our overall evaluation of three alternative tax policies for controlling carbon dioxide emissions is that a carbon tax has the smallest negative impact on the US economy as a whole. Carbon taxes do, however, have the most severe effect on coal mining. An energy (BTU) tax would shift some of the burden to oil extraction but would be more costly to the US economy. The worst policy is clearly an *ad valorem* tax on primary fuels. It would increase energy prices far more than either of the other taxes in achieving the goal of stabilizing emissions.

Acknowledgments

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New Challenges for Energy–Environment Long-term Modeling: Lessons from the French Case

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In this paper I will venture to draw some lessons from a study carried out in a very specific context, the French "Commissariat Général du Plan" (CGP)[1], because I think that these lessons should be borne in mind while discussing our research agenda as regards modeling tools for long-term environmental issues.

1. Which Factors are Flexible and which are Rigid in the Long Term? The Critical Role of Transportation

1.1. Specific questions in the French context

To date, studies on the flexibility of our energy systems concentrated on how to increase energy efficiency and how to promote carbon-free energies. This could not be the question posed by the French planning body, CGP, for two obvious reasons:

- Firstly, the lowest cost potential energy savings have been tapped in France since 1973 and most of the remaining parts could be tapped rather easily in the next 15 years, according to the conclusions drawn by "Atelier de prospective énergétique", a subgroup within the CGP planning body (CGP, 1991).
- Secondly, substitution of carbon-based electricity with carbon-free electricity has been achieved (90% of electricity is based on hydro and nuclear power).

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[1] In order to avoid any possible misinterpretation, let us recall that the French CGP does not aim for mandatory "command and control" decisions. Bringing experts, business and trade union representatives together with public administration, it tries to attain some consensus on which to base long-term policies.

Consequently, the crucial question was: "Will there remain any room for maneuver beyond 2005?" This is why the "French case" may bring lessons for the future of other countries, as the Japanese case does in its own way. Although it is generally admitted that some emission abatement options exist over the next two decades (with more or less optimism on the range of magnitude of these possibilities), the critical issue raised by concern over the climate is whether or not, beyond these two decades, our countries will be faced with ultimate technical limits. The subsequent question is how far ahead they are and which signals are likely to shape innovation trends to push these limits further in the future.

The very nature of these questions implies that the issue can no longer be addressed through a description of the economic behavior given the set of techniques currently available. It is necessary to account for changes in expectations which are likely to generate new sets of techniques, of goods and of services. Some analytical progress has been made in this direction, owing to the conceptual distinction between "price induced" and "autonomous" technical progress; but from a decision-making perspective, the difficulties in accurately assessing their relative role are exacerbated by two considerations, as follows.

- First, the theoretical necessity of separating, in the price effect, the relative weight of short-term, optimizing behavior (the substitution effect given a set of goods and techniques) from innovative behavior driven by changes in long-term expectations.
- Second, autonomous progress encompasses structural changes in global output and in final demand, as well as non-price-induced technological progress. It also results directly from policies designed to enhance uptake of efficient techniques. Lack of analytical knowledge of the links between economic forces, institutions, and technical trajectories makes it difficult to bridge the gap between economic pessimism and engineering optimism, which tends to add up favorable assumptions to write low-cost abatement scenarios. The apparent economic pessimism is due to the consciousness of the risks associated with some sort of "technological forcing" to account for feedbacks between technology and economic behavior and for the economic and political costs of removing market imperfections.

However, conversely, models calibrated econometrically in the past, useful for catching the aggregate outcome of these contradictory factors over the short term, are less suitable over the long term. Moreover, the current economic data register the reactions to non-anticipated energy price movements resulting from external oil shocks. The incentive tools currently considered here, such as a carbon taxation scheme respecting a fiscal neutrality principle, are not meant to create an external shock on a system characterized by a given elasticity but to act as a signal aimed at upgrading this elasticity.

In the absence of a ready-made model, we designed a tool, IMACLIM (see Appendix), to explore contradictory assumptions about technical choices and structural change in industry and life styles, treating them not as being uniquely based on current trends but depending on general, controversial expert statements about the relative potential of each technical option, its long-term development costs, and the related social and political constraints that will ultimately determine its pace of penetration.

The variants in technical options were then used for deriving the energy efficiency scenarios, one denoted by ME[2], and another denoted by REF from *reference laissez faire.*

An alternative set of assumptions about long-term development patterns was accounted for only in the *structural change scenario* (MS). These scenarios focus on new orientations to be taken in two main fields: a growth based less on energy-intensive industries and a reduced demand for freight and passenger transportation.

The three baseline scenarios (REF, ME, MS) on development strategies beyond 2005 up to 2030 were submitted to the planning body, CGP, as an experiment to determine a minimum consensus on their political and social acceptability. A carbon tax was then applied to each baseline scenario. The tax increases progressively up to about 200 \$/t-C. The scenarios derived with a carbon tax are denoted REF1, ME1 and MS1.

1.2. Numerical results: the evidence of possible bifurcations

The first numerical conclusion of the simulations is obviously the reversal of the current trend in decreasing CO_2 emissions; in the REF scenario, the total CO_2 emissions between today and 2030 increase even though the CO_2/GDP ratio decreases about 46%.

This outcome is clearly related to the timing of the nuclear programme. Beyond 2005, electricity has indeed exhausted all its penetration niches and the French energy strategy hits a "hard core" of fossil fuel consumption for motor fuels and chemical uses, both among the most dynamic end-uses.

The second set of numerical conclusions is related to the range of possible emissions. As shown in Figure 1, the range is quite wide, from 1 to 2. It is

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[2] ME is for "maîtrise de l'énergie", literally energy mastership, a concept that originated from the name of a state agency: Agence Française pour la Maîtrise de l'Energie.

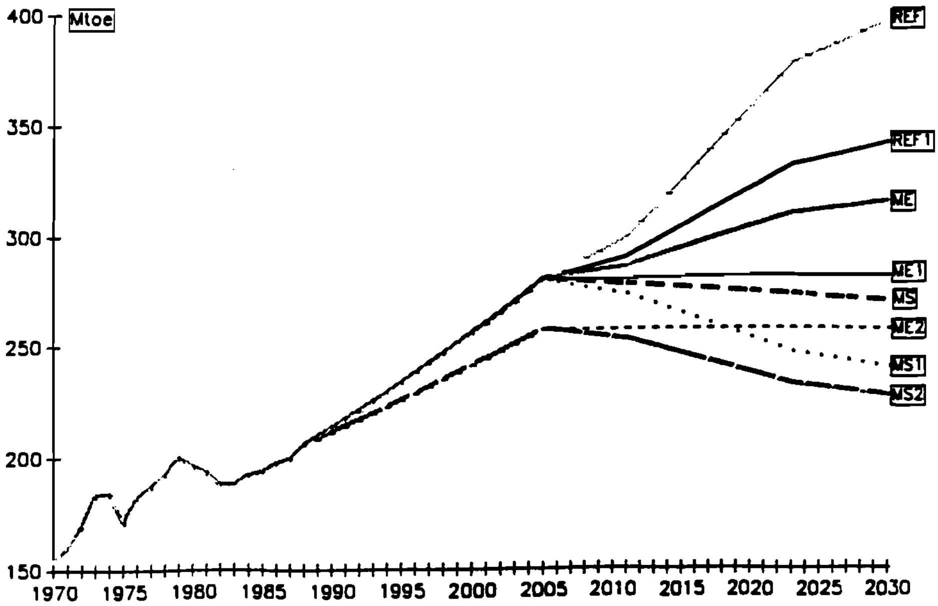

Figure 1. France: CO_2 emission scenarios (1970–2030).

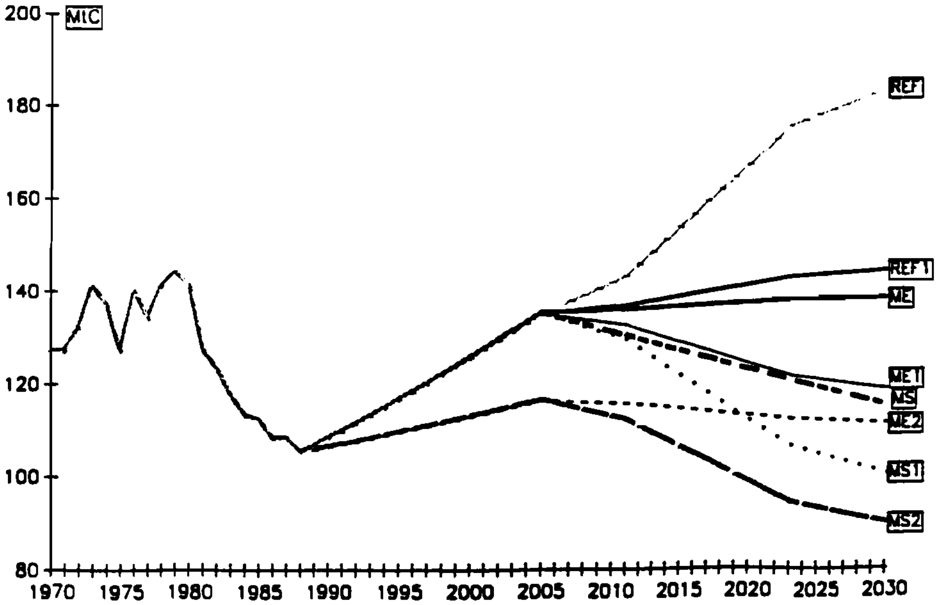

Figure 2. France: primary energy consumption scenarios (1970–2030).

noteworthy that France would fail in meeting the Toronto target[3] even in the best case (ME2), when action is engaged immediately and not beyond 2005 – under this hypothesis, abatement would reach only 17% between 1988 and 2030.

These findings can nevertheless be interpreted in a more positive way. France would be able to significantly reduce its CO_2/GDP ratio simply by riding its current energy trend, an achievement which if generalized to all industrialized countries would stabilize global CO_2 emissions by the middle of the next century. However, on the other side, this perspective can be seen as unsatisfactory for two reasons. Firstly, an effective, preventive strategy requires more ambitious abatement levels; secondly, during a negotiation process, France cannot expect special treatment because of its previous achievements and therefore cannot ask for other countries to act first.

Obviously, more satisfactory results could be obtained through more optimistic technical hypotheses; however, in terms of policy implications, the most challenging conclusion is that shifting from the highest to the lowest scenario requires a mix of hypotheses encompassing price signals, no price incentives, and long-term development patterns.

The implementation of the carbon tax alone (from REF to REF1) only leads to a 21% abatement of GHG emissions (see Figure 2).

An energy efficiency policy relying on incentives other than taxation (subsidies, information, standards, research and development programmes, etc.) would be able to stabilize emissions at the current level, but only if implemented together with a carbon tax. Although it is efficient in promoting energy savings in other sectors, this policy, however, fails in drastically lowering the total amount of emissions because of the rigidity in the transportation sector. This rigidity is due to three factors:

- A carbon tax has a low impact on consumer prices because of current taxation levels in France: there would be an 8% increase of the gasoline price.
- The rail for road or rail for air substitutions are both slow and have low sensitivity to pure price incentives as long as specific measures are not taken to enhance the consumer's preference for railways.
- Gains in energy efficiency observed since 1973 have taken advantage of the easiest technical improvements. From now on, opposing factors such as the improvement in the power of cars and the worsening of traffic conditions are expected to offset a good part of the additional gains in motor efficiency. These negative factors were clearly captured by the

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[3] Abatement of about 50% in 2030.

flatness of the logistic curve (see Appendix) describing the evolution of energy efficiency in this sector.

Then, more ambitious abatement targets can only be met by resorting to additional structural hypotheses, as described in the MS family scenarios: intermodal substitution of rail transportation for freight, urban public transportation, etc.

The critical point is that MS scenarios are "spontaneously" better in terms of CO_2 emission even if the choices behind them are likely to be taken irrespective of energy and climate change issues.

The case of gasoline provides a good illustration. The increase in the final price due to a high tax level is too marginal, and the competitive advantage of oil-based car fuels is high enough to discourage automobiles and refining industries from taking the risk of large-scale production of alternative motors and fuels. This does not rule out the possibility of technological breakthroughs, it simply means that these breakthroughs would be fostered by factors other than a concern for the greenhouse effect: the electrical car as a solution to local pollution in big cities, biofuels as an attempt to secure new markets for agricultural production, etc.

Far from minimizing the advantages of a carbon tax, the above remarks help to point out how critical it is to specify in which overall context the implementation of the tax is being considered. They lead to some methodological issues.

2. Some General Methodological Implications

The methodological lessons from this "French case" are likely to be of interest in other contexts. They come from the fact that once the substitution between fossil and non-fossil fuels in the energy sector is achieved, and once energy efficiency is brought up to reasonable levels, the *key role of structural factors beyond the energy price becomes obvious,* be it for transportation and also for the substitutability between materials, or for lifestyles. The fact that measures in non-energy fields not related to greenhouse issues are likely to have a strong consequence on the long-term flexibility of our productive systems raises two main methodological questions: the first one is related to the use of several baselines for long-term scenarios, and the second is related to the definition of "no-regret strategies".

2.1. Cost assessment analysis and choice of baselines

Assessment studies of macroeconomic costs of greenhouse policies usually start from an optimized baseline projection and compute the shift induced by a taxation policy. However, the critical importance of non-energy-related and non-greenhouse-related factors on long-term development trends suggests than several "histories" are possible in the future, leading to different costs for preventive strategies. This clearly advocates the systematic use of several baselines scenarios reflecting the diversity of expertise and expectations. I will emphasize later that this necessity can be proved stringent in the case of bifurcation in the development trends, of which I will give an example.

Current trends in the French freight sector will lead to a doubling of road freight on highways within 15 years under the influence of the upcoming Single European Market. Abating this evolution will require decisions on infrastructures, but also on pricing and taxation systems in order to account for the full cost of road transportation (to charge the users for total road maintenance, congestion costs, etc.).

The critical problem comes from the fact that, if these decisions are not taken earlier, say, in 10 years' time, we will certainly have gone beyond a bifurcation point and be engaged in an irreversible process because of the amount of economic, social and political interest involved in the road system which would lead to an inflexible system without any economically efficient and politically acceptable alternatives. The narrow range of available choices and low flexibility of the economy would entail high economic and political costs in the case of future compulsory actions to curb GHG emissions.

The bifurcation issue is certainly broader. It also encompasses innovation choices on motor fuels and, surely the most difficult, the evolution of overall demand for transportation induced by alternative town-planning patterns. More generally, it concerns a lot of network industries where the market forces tend, beyond a point, to reinforce the first choice instead of correcting it in a self-fulfilling process.

This means that at date "t" several possible market equilibria can still be envisaged for the "t+n" future, corresponding to several contingent "states of the world" characterized by different technical contents, and not easily predictable from current trends. The only sound methodological answer is to work on the basis of several baseline scenarios, characterized by alternative assumptions on development patterns and innovation in contrast to the current practice of writing scenarios with high, medium or low versions. However, the implication of this evolution of analytical tools is that, in terms of collective decision making, a cost assessment analysis can be meaningful only at the margin of each scenario and can no longer give a clear-cut, univocal answer.

Economists, in order to put some objectivity in discussions, must accept that scientific or technical controversies and disagreements about value or political judgments mean several possible histories; otherwise, they risk being refuted as giving totally arbitrary answers and justifications in favor of preexisting choices. However, they are in a position to immediately recall that the viability of each scenario is conditional upon its economic consistency, i.e., its macroeconomic equilibrium and coordination of microeconomic behavior. *In order to play this role we need to elaborate appropriate tools for bridging the gap between economics, engineering and political sciences.*

New tendencies in long-term modeling take the right direction thanks to a more systematic use of the properties of the general equilibrium concept. This can indeed be helpful for the study of several baseline scenarios if we define a scenario as the final picture of each set of technical and economic expectations; with each set of explicit technical hypotheses can be associated a set of economic hypotheses insuring the economic consistency of the resulting scenario. Usually implicit or neglected, these economic hypotheses can then be discussed in terms of their implications for technical and consumption trends.

However, a more convincing progress is determined by two prerequisites:

A. Relaxing the Fixity of the Production Functions of the Non-energy Sectors

The dangers of the assymmetry between the current treatment of technical progress in the energy and non-energy sectors in the available macroeconomic energy models must be stressed. Technical change in macroeconometrics is indeed, whatever the level of disaggregation, a "proxy" which encompasses several factors: technical innovation in the engineering sense, intersectoral and intrasectoral structural changes, business cycles, and strategic behavior.

This makes it difficult to establish explicit links between production functions in economic models and projections on technology and to accurately determine the origins of the gaps between these two measures of "technical progress". Therefore, contrary to the case of the energy sector where it is possible to explore a wide range of alternative expert statements, the current practice of macroeconomic modeling is to use given production functions for each of the other sectors. This method is sound and reliable for short-term analysis, but there are few logical grounds for assuming that a set of price, or non-price, long-term incentives for innovation would have

Table 1. Macroeconomic impacts of compensated 1,000 FF/t-C carbon tax sensitivity tests.

	REF Scenario			
χ	0	0.5%	1%	2.8%
DGDP	+1.65%	+0.94%	+0.24%	-2.15%
DN in million	+574,000	+325,000	+83,000	-745,000
	MS Scenario			
χ	0	0.5%	1%	2.8%
DGDP	+0.88%	+0.18%	-0.4%	-2.61%
DN in million	+305,000	+64,000	-172,000	-970,000

no effect on the production functions of the non-energy sectors over the long term.

We have illustrated the high sensitivity of macroeconomic results to assumptions about global factor productivity (reflected in the price of the composite good of non-energy sectors) with a very simple model in which the macroeconomic effect of a carbon tax is the product of a quasi keynesian effect of lower taxes on labor and production, and of the regressive effect of higher energy costs. Thanks to a backward induction procedure combined with a general equilibrium approach (see Appendix), it was possible to solve the equilibrium equations without *a priori* restrictions on the implicit production function, and to carry out sensitivity tests.

χ denotes the increase of the composite good due to carbon tax. In the case of non-absolute substitutability between energy and other production factors, this increase is about 2.8% and the induced macroeconomic cost is between 2.15% and 2.61% of the GDP; it falls to between 1% and 1.5% if the substitution parameter between energy and other input to production is assumed to be the same in the baseline and "taxed" scenarios.[4] However, a very slight change in this function is enough to create a situation where the benefits of decreasing other taxes offset the deadweight costs of the carbon tax. The cost of the composite good could remain constant in the case of a higher but reasonable optimism; in this latter case, the positive effect of the taxation scheme would lead to a slight increase in GDP. These results cannot be used for concluding that a response to the greenhouse issue could be achieved at no cost or at negative cost, but they point out to what extent the cost assessment of anti-greenhouse strategies can be changed without

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[4] These results are of the same order of magnitude as most assessment studies for OECD countries (2% for the European countries in Manne and Richels, 1991).

drastic assumptions about the potential effect of a high tax on the long-term innovation process in the non-energy sectors.

B. Behavioral Models and Mechanical Trajectories

If we want to bridge the gap between the macroeconomic description of production, for example, Jorgenson and Landau (1989), and a fuller description of the long-term prospects for technology and development, we need to go beyond this type of linkages sketched out on the basis of long-term market equilibria. The description of transition paths between today and these possible future equilibria, and the analysis of their viability, obviously entails more challenging difficulties (Aubin, 1992).

This is the reason why some additional work is required to model technical trajectories, their response to economic and non-economic signals, and their socio-political viability. This calls for additional work on behavioral submodels adapted to each sector and technique beyond the simple solution we adopted here. For example, countering the intuitive idea of higher capital requirements for rail systems, some French experts pointed out that the total investment is 0.3 F/tkm for trucks and 0.12 for rail if one includes the investment in vehicles. To check these data and to include them in a general equilibrium model would obviously change the long-term macroeconomic cost of an abatement scenario. However, investment decisions are made by very different agents with different economic behavior and it could be misleading to carry out any cost assessment of rail/road substitution without a simplified description of these behavior.

C. Towards a More Encompassing Definition of the "No Regret" Concept

The debate on "no regret" strategies is currently strongly linked to the "efficiency gap" controversy. To date, theoretically, a road-dominant system or a rail/canal-dominant system can be assumed to be without any slack at their efficiency maximum, and the consumers can be assumed to be totally rational; but they are faced with a choice between the goods and services of either system, resulting from a long and cumulative process and characterized by very different energy contents.

Manne and Richels (1992) are right to underline the risks of technological forcing involved in a mere engineering vision of energy efficiency. Here, we have another type of "technological forcing": in network industries and infrastructure activities public intervention is always necessary prior to the realization of the technical projects, and this will in fact determine, directly or not, the range of options (often a single one) at the disposal of consumers.

Since these public choices determine in the long run a good part of the energy path embedded in transportation and urban structures, it is legitimate to question their underlying collective preference function. In France's freight system, for example, the long-term shift from rail to road comes from the flexibility of road transportation, the door-to-door services, but also the underpriced infrastructures for trucks, and the risk of strikes in the railway sector. However, having experienced last July the ease with which the truck drivers' corporation was able to block traffic all over France, and faced with local contestations against the extension of highways, the public authorities may be incited to introduce security and local environment as arguments of the collective preference curve and review some components of the present incentive structure.

From this perspective, climatic risks must be discussed as a new argument of this function. The "no-regret" concept then goes further than the mere accounting of the "negative costs" of the improved energy efficiency of a specific equipment; it encompasses the fact that GHG abatement becomes a joint product of improvements in other dimensions, such as the following.

- Reduction of other environmental costs at local levels (congestion, air pollution, noise).
- National security.
- Prevention of irreversible trends leading to uncontrolled fossil-fuel-intensive development patterns and technological paths.
- Macroeconomic benefits of removing existing distortionary taxes.

The research on "no-regret" strategies should therefore be focused on the core of actions where this "joint-product" of positive externalities is possible, and on the conditions for reaching a cooperative equilibrium from this basis.

3. Conclusion

As a conclusion, I would like to sketch here some ideas on the collaboration between energy and transportation economists, which has been proved to be necessary to address the key issues of long-term development–environment analysis.

In the past two decades, energy economists have carried out a paradigmatic revolution: they focused on energy-growth decoupling and elaborated demand-side approaches to complement the supply-side optimization, studying the external determinants of end-use demand. It seems that these types of questions have not yet reached the mainstream of transportation economics and they have not yet been used to focus on the difficult problem of the choices between the means of transportation and optimization of the network infrastructures.

Seizing the opportunity of climate change issues, energy modeling could play a provocative role, asking, for the sake of their own models, about the long-term determinants of transportation needs simply because the projection of their current exponential growth would drastically reduce the chance of success of preventive policies. Freight transportation does not raise the most difficult theoretical problem; it can be solved, on one hand, by a better understanding of the geographic trends of the economic activity and, on the other hand, by a study of incentive structures which are better able to reflect the external costs of this sector (congestion, security, infrastructure maintenance, etc.). The issue of individual transportation (for work or leisure) is quite different because we are confronted with the risk of imposing undue normative constraints on the consumer.

Similar approaches can be used in the energy field which aim to replace the cost-minimization of a given toe or kWh by the cost-minimization of end-use energy. The first problem is to substitute the maximization of accessibility by the maximization of mobility as the key argument of the collective objective function in infrastructure policies. Indeed, an increase in transportation needs can either reflect an increase in welfare, or a response to new, unexpected constraints, which unfold as a result of development patterns. The substitution between transportation and telecommunication is, however, a partial response since the first trends observed in the 1980s indicate that the explosion of new telecommunication tools has increased the geographical extent and the number of business contacts, inducing higher transportation requirements.

This is why we cannot avoid a thorough description of constraints which are likely to enable us to discover possible long-term saturation effects which are not reflected in the current trends. Given the uncertainty about these constraints, the time budget of an individual citizen could provide us with a solid accounting system which includes the ultimate constraints on the demand for individual transportation. There is a long way to go before any reliable results can be found on that issue. However, linked with economic balances and energy balances, this accounting system could be the more efficient way of connecting three types of expertise and of understanding some of the ultimate development issues raised by the climate concerns better.

Appendix

Linkages Between Technical Hypotheses and Economic Signals in the IMACLIM Model

For the 2005 scenarios, the "Atelier de Prospective Energétique" used a disaggregated, bottom-up model of the French energy system with 165 energy end-uses, a precise description of vintages of equipment for each category of energy consumers and modeling of induced investments.

Resulting from a consensus of the relevant scenarios to be constructed for the sake of strategic analysis, the 2005 balances provided numerical pictures of the range of opinions of experts on the international background, the available technical degrees of freedom, and the social and political constraints which will ultimately determine the viability of each scenario.

Taking the 2005 balances as starting points, the long-term scenarios (2030) written by the IMACLIM model are consequently strictly exploratory scenarios aimed at answering two sets of questions:

- Will France after 2005, having exploited the maximum possible substitution between carbon-based electricity and nuclear energy, be faced with limits to its further reduction of energy intensity, making it unable to accept any commitment to substantially reduce its CO_2 emissions? If not, how far can technical innovation push these limits?
- What would be the impacts of a 1,000 FF/t-C carbon tax, as proposed by the Groupe Interministériel sur l'Effet de Serre (Martin, 1990)? This tax level implies that the tax will be offset by a decrease in income taxes, value added taxes or any other social contribution so as to give fiscal neutrality; its implementation depends on a prior commitment involving the main OECD countries in order to avoid a distortionary effect on international markets.[5]

In order to bridge the gap, to whatever extent is feasible, between the engineering perspective and the economic perspective, while designing a tool able to explore controversial assumptions on technical progress, of structural changes in industry and lifestyles, we tried to design an instrument adhering to three basic principles:

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[5] This perspective is similar to the aborted proposal of the EC. It remained exploratory and was never adopted officially at the political level.

- to treat the assumptions on technology, structural changes and behavior not as based uniquely on current trends but as depending on controversial expert statements, and to be able to test the impact of the current controversies on the results of the scenarios;
- to distinguish explicitly the needs likely to reach saturation levels in the future from consumption trends with linear or exponential growth, at least given our current knowledge;
- to avoid the risks of a mere multiplication of technical assumptions by accounting for the effect of institutional inertia on the diffusion of technical and behavioral changes, verifying the consistency of the technological and structural assumptions with economic parameters such as personal income and relative prices.

We adopted a solution which may seem simple, but tried to take advantage of the institutional context of this study for which we had access to detailed exogenous expertise. It consists of using logistic functions in $y = f_k(r,p)$ and $y = g_k(t,p)$ with personal income (r) and prices (p) as arguments for the segments of demand expected to reach saturation $(dy/dr>0)$[6], and time (t) and energy prices (p_e) for the energy efficiency coefficients of each technology $(dy/dt<0$ and $dy/dp<0)$. In the latter case, the role of time is to encompass the capital turn-over effects of the progressive diffusion of new technologies.

The exogenous technical expertise determines the asymptotes "k" for these logistic curves which means that they can be changed in case of non-consensus. Given the value of the saturation levels[7], each curve can be benchmarked for a corresponding technique or end-use, based on past observations (1973–1988) and on future data, in this case A.P.E.'s 2005 scenarios. For a given set of expert statements, the price of energy acts mainly as an accelerator in the technical diffusion (Figure 3) and the benchmarking of the curve catches the non-economic and non-technical inertia observable in the past and accounted for (or expected) by the experts of the A.P.E in their 2005 scenarios.

Because of the scarcity of factual findings about the possible range of long-term variation of the production function coefficients of non-energy sectors, we used a backward induction procedure connected with a general equilibrium approach. Each scenario was considered consistent with a long-term

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[6] For the other segments, we worked with the usual log-linear functions of income and prices.

[7] In the case of energy efficiency, the long-term saturation levels can be changed, if necessary, resulting from the reaction of the innovation process to drastic increases in energy prices.

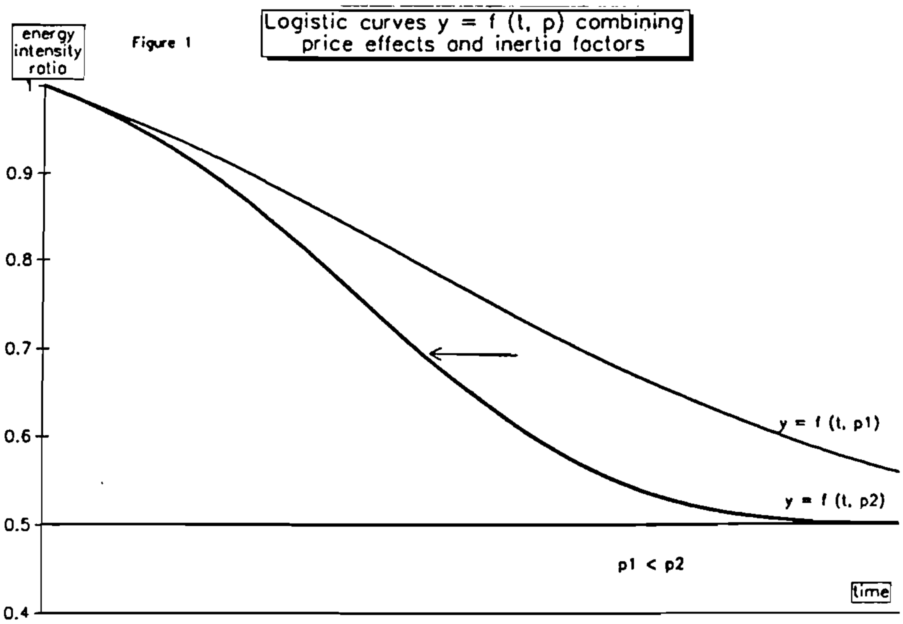

Figure 3. Logistic curves combining price effects and inertia factors.

static macroeconomic equilibrium (absence of public deficit, balance between income and expenditure for all sectors), this equilibrium being the result of non-specified production functions for non-energy sectors (a single composite good in the first version of the model). The macroeconomic context of the scenario is then fully explained by our assumptions on technologies, structural change and demographics. Then the coefficients of the implicit production function can be calculated at the margin by interpreting (with a few *ad hoc* hypotheses) the results of taxation scenarios at constant economic growth as giving the partial derivatives to prices.

Only one additional hypothesis is necessary to solve the equation system and to assess the impact of a carbon tax on the equilibrium of each scenario[8], the impact of higher prices of fossil fuels on the cost of composite good. This in turn depends on the coefficients of the new production function. It is then possible to carry out sensitivity tests of the impact on the macroeconomic equilibrium of a wide range of values for final total productivity: the production cost of the composite good is increased by the total value of the additional energy costs in the case of technical inflexibility, and

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[8] This tax is applied not as a shock disturbing a given equilibrium in 2030, but is applied today in order to switch towards another stabilized growth path.

remains constant in the case of an efficient, long-term response to the price signal.

The modeled economy has three goods :

- a composite good Q (price p_Q value added tax included)
- the energy consumed by production sector, e_e (price p_e)
- the energy consumed as a final demand e_m (households, mostly) (price p_m).

The economy is characterized by four equilibrium equations :

Macroeconomic equilibrium:

$$\text{(I)} \quad Y = C + I + M_e$$

Y: gross domestic product
C: final consumption
I: investments, including investments made by the government
M_e: net energy imports

Production sector budget balance and price of the composite good:

$$\text{(II)} \quad p_q = [E_e + S + \alpha \cdot p_q]/Q = (1+\chi) \cdot (1 + (\Theta - \Theta')$$

E_e: energy purchase; $E_e = e_e \cdot p_e$
S: total labor expenditures (including social security)
χ: exogenous assumption of technical progress
Θ: value added tax in the baseline scenarios
Θ': value added tax in the taxed scenarios

Household budget balance:

$$\text{(III)} \quad C = c.(r.N + R) + r'.N' = C_q + E_m$$

c: propensity to consume
r: (respectively r′): total wages of employed population (respectively unemployed population)
N: (respectively N′): number of employed population (respectively unemployed population)
R: other income of employed people
C_q: expenditures on the composite good
E_m: energy expenditures of the household sector, $E_m = e_m \cdot p_m$

Government budget balance:

$$\text{(IV)} \quad \Theta \cdot C_q + \tau_e \cdot E_e + \tau_m \cdot E_m + \sigma \cdot N \cdot s = \varphi \cdot Y$$

s: cost of labor (wages, social expenditures)
Θ: value-added tax on the composite good
τ_e: (respectively t_m): taxes on energy purchased by enterprises (resp. households) including value added tax, existing energy taxes, and the carbon tax
σ: social share of security expenditures, included in the cost of labor
φ: ratio government budget in GDP

An additional equation is necessary to solve the system

$$(V) \quad dN = (\delta N/\delta Q) \ .dQ + (\delta N/\delta e_m).de_m \ .$$

The algorithm uses the results of the techno-economics module which gives us the parameters de_m and de_e at constant GDP. On the other hand, using the properties of the general equilibrium, we can write:

- $dN/de_e = -(p_e/s(\sigma))$
- $dQ/de_m = -(p_m/p_c) = p'_m/(1 + \chi - d\Theta)$.

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Economic Costs of Reducing CO_2 Emissions: A Study of Modeling Experience in Japan

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1. Introduction

The purpose of this paper is to review and discuss the existing major studies on quantitative macroeconomic impacts of controlling greenhouse gas emissions in Japan. In December 1991, the Center for Global Environmental Research in Tsukuba, Japan, organized a symposium on "Global Environmental Protection and Economic Growth: Evidence from Quantitative Studies in Japan," and invited several leading modelers.[1] The major questions concerning the global warming issue that occupied the minds of the participants were: "What are the likely courses of CO_2 emissions in Japan and in the world?" and "Will there be some policy measures that are able to limit or stabilize the carbon dioxide emissions without imposing too much burden on the economy?" Among the policy measures, interests in the environmental taxes (in particular, carbon taxes) were considerable.

In the following sections, I will discuss the major findings of the ten models: seven studies are based on the Japanese models and three studies on global models. The main features of these models are briefly summarized in the Appendix. In the course of the following discussions, I will also refer to the results of the model comparison workshop at the OECD, and touch upon some important aspects of the carbon taxes that must be subject to closer review before such taxes are actually implemented.

2. The Business-as-Usual Scenario

Most authors expect that CO_2 emissions will continue to grow substantially unless something is done, although many people consider that the rates

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[1] The author is grateful to Dr. Tsuneyuki Morita of the Center for Global Environmental Research for his leadership in organizing the symposium, upon which the present paper is largely based (see Amano, 1992). The author also expresses his thanks to the participants who kindly provided various materials concerning their models. The present paper is financially supported by the Asahi Glass Foundation.

of increase in CO_2 emissions will decline in the future partly because of the decline in GNP growth rates and partly because of the tendency for decoupling (i.e., the existence of wedges between GNP and CO_2 growth rates; see Table 1). There are, however, some variations in the rates of decoupling. The expected average annual growth rate of real GNP in Japan during the period 1990–2000 ranges from 3.3 to 3.9 percent with CO_2 emission rates ranging from 0.8 to 2.7 percent. These ranges become 2.5–3.5 and 0.4–1.5 percent, respectively, in 2000–2010.

Results of a recent OECD simulation with GREEN are also reported in Table 1 for reference. Their results reported for Japan indicate that the average rate of increase in CO_2 emissions will become substantially smaller for the period 2000–2010, turning into a negative value; but there is no clear explanation why this will happen.

3. The Carbon Tax Scenario

Many authors ascertained the effectiveness of economic measures such as carbon taxes to curb CO_2 emissions. There are disagreements, however, concerning the accompanying costs in terms of GNP losses. Most studies report percentage reductions of real GNP/GDP and of CO_2 emissions measured as relative differences from baseline paths and also the levels of carbon tax to attain these results. However, it is not straightforward to make comparison because of the differences in the method of taxation and in time horizons. Therefore, in order to make comparison easier, I computed two ratios: one is the ratio of percentage reductions in real GNP/GDP to those in CO_2 emissions (i.e., percentage GNP/GDP losses caused by one percentage point reduction of CO_2 emissions relative to the baseline), and the other is the ratio of carbon tax levels (measured in \$/TC) to percentage reductions in CO_2 emissions (i.e., the amount of carbon tax required to achieve a one per cent reduction in CO_2 emissions). Table 2 reports the results for the Japanese economy. Similar ratios are calculated for reference in Tables 3 and 4, using the results of OECD GREEN and Manne–Richels' Global 2100 models, respectively,

Comparing these tables, it can be seen that model results reported in Table 2 may be grouped into three. The first group (Goto and Ban) obtained results similar to those in Tables 3 and 4. OECD GREEN and Manne–Richels' Global 2100 models are computable general equilibrium models as the Goto model. These models generally indicate that the GNP losses resulting from price-induced cuts in CO_2 emissions are modest. In developed

Table 1. Average rates of increase in the baseline scenario (%/yr).

Model		2000/ 1990	2010/ 2000	2020/ 2010	2030/ 2020
Yamaji[a]	GNP	3.69			
	CO_2	1.84			
	dif.	1.85			
Ban	GNP	3.53			
	CO_2	2.22			
	dif.	1.31			
Onishi	GNP	3.90			
	CO_2	1.60			
	dif.	2.30			
Shishido[b]	GNP	3.26			
	CO_2	0.76			
	dif.	2.50			
EPA[c]	GDP	3.80	2.70		
	CO_2	2.00	1.50		
	dif.	1.80	1.20		
Ito	GNP	3.80	2.80		
	CO_2	1.77	1.36		
	dif.	2.03	1.44		
Yamazaki	GNP	3.72	3.54		
	CO_2	0.94	0.39		
	dif.	2.78	3.15		
NIKKEI	GNP	3.56	3.28		
	CO_2	1.18	0.89		
	dif.	2.38	2.39		
Mori	GDP	3.61	2.46	2.41	
	CO_2	1.44	0.51	0.43	
	dif.	2.17	1.95	1.98	
Goto	GNP	3.42	3.18	2.92	2.83
	CO_2	2.73	1.53	1.54	1.32
	dif.	0.69	1.65	1.38	1.51
OECD GREEN[d]	GDP	3.70	2.70	2.70	2.20
	CO_2	2.80	-0.40	1.20	1.20
	dif.	0.90	3.10	1.50	1.00

[a] 2005/1988.

[b] Developed Asia-Pacific.

[c] EPA stands for Economic Planning Agency.

[d] Burniaux *et al.*, 1992.

Table 2. Carbon tax and GNP loss ratios, Japan.

Model	Final year	GNP Reduction ratio	Carbon Tax ratio
Goto	2030	0.02	2.7
Ban[a]	2000	0.05	5.6
Mori	2020	0.22	17.0
Yamaji	2005	0.23	18.5
Ito	2010	0.29	16.5
Yamazaki	2010	0.36	15.9
NIKKEI	2010	0.16	51.8
Shishido[a,b]	2000	1.16	55.0

[a] The carbon tax ratio is calculated here on the assumption that the international price of crude oil is $30/bbl in 2000.

[b] Developed Asia-Pacific.

Table 3. Carbon tax and GNP loss ratios, OECD GREEN (2005).[a]

Country/Region	GNP Reduction ratio	Carbon Tax ratio
Former Soviet Union	0.01	0.9
Central & Eastern Europe	0.01	1.0
United States	0.02	2.0
EC	0.02	2.1
Other OECD	0.01	2.0
Rest of the World	0.01	2.6
Japan	0.02	3.1
China	0.03	3.2
India	0.02	3.1
Dynamic Asian Economies	0.03	6.5
Brazil	0.04	6.5
Energy Exporting LDCs	0.07	6.4

[a] Burniaux *et al.*, 1992.

countries, the GNP reduction ratio is around 0.02–0.03. This means that a 20 percent cut in CO_2 emissions, for example, will reduce the level of GNP by 0.4–0.6 percent from the baseline path. If this is achieved within a ten-year period, the growth rate of GNP will be reduced only by 0.04–0.06 percent per annum.

The result of Ban's model is fairly close to those of this group. However, the model is econometric. It was constructed with special attention to estimating price elasticities of demand for energy. Table 5 reports the estimates of income and price elasticities of demand for energy for some models that

Table 4. Carbon tax and GNP loss ratios, Global 2100 (2100)[a].

Country/Region	GNP Reduction ratio	Carbon Tax ratio
USA	0.03	2.4
Other OECD	0.02	2.4
Former USSR	0.06	8.6
China	0.06	2.4
Rest of the World	0.06	2.4

[a] Manne (1992).

Table 5. Long-run income and price elasticities of demand for energy.[a]

Model	Income Elasticity	Price Elasticity
Ban	1.42	-0.97
Goto	1.00	-0.43
Mori	0.76	-0.44
Ito	0.58	-0.49
Yamaji	n.a.	-0.64
NIKKEI	0.71	-0.14

[a] Simple averages.

are available from papers at hand. The elasticities are simple averages for various sectors. The average price elasticity is around -0.4 for other models, but in the Ban model it is close to -1.0.

The second group (Mori, Yamaji, Ito, and Yamazaki) obtained somewhat larger ratios on both counts. Models in this group are based on econometrically estimated forecasting macromodels of demand-determined type, combined with some sort of energy-sector submodels. The time horizon is generally short. The results within this group are fairly similar to each other, and they tend to form a consensus view of the short-run effects of curbing CO_2 emissions, because these models are often used for regular forecasting and what-if simulation exercises in major private institutions.

Finally, the third group (NIKKEI and Shishido) shows substantially higher levels of carbon tax to achieve a one percentage reduction of CO_2 emissions. Although not completely reported in Table 5, these models are characterized by rather small price effects compared to other models.

One common problem encountered in this kind of simulation studies is that estimates of economic losses (in terms of GNP reductions) vary quite widely. As can be seen from the above results, econometric models usually tend to yield larger reductions in output than CGE-type models in which responses to price changes are more fully modeled and adjustments take place relatively more smoothly. An important question remains, however, whether CGE models can make realistic assessments of short to medium-term adjustment costs. Even if CGE models can represent the exact evaluation of possible long-run macroeconomic effects of CO_2 emission abatements, it is likely that there exist some additional short-run losses. If these effects are real, they should be properly taken into account and adequate policy responses of transitory nature need to be devised.

On the other hand, some of the earlier models of the Japanese economy drew quite gloomy pictures for CO_2 abatement policies using models with demand for fossil fuels being quite insensitive to changes in relative energy prices. The EPA model cited in Table 1 reported a simulation result saying that GNP growth rates would have to be reduced by 2 percentage point for the period 1990–2000 and by 1.2 percentage point for the period 2000–2010 in order to keep per capita CO_2 emissions at the 1990 level after 2000 (see Appendix). If we compute a GNP reduction ratio as defined in Table 2 above from this result, we obtain a value of 1.03 for the period 1990–2000 and 0.99 for 2000–2010, which are far larger than those reported for other models in that table. Since CO_2 emissions were reduced in the EPA simulations by directly decreasing production and consumption activities, it is natural that output reductions became substantial. However, it seems quite unrealistic to suppose that responses through relative price changes are actually negligible or very small, and there exists a danger of overstating necessary reductions of economic activities or a danger of over-reliance on subsidies for energy-saving technologies to attain a certain target of emission abatement.

Another problem is related to the availability of other policy measures that can offset undesirable impacts of carbon (or other environmental) taxes. Some authors maintain that the economic costs of a carbon tax can be fully offset by using the revenues to remove severe distortions of pre-existing taxes (see Shackleton *et al.*, 1991). Simulation exercises dealing with carbon taxes usually keep other policies unchanged in order to isolate the effects of original changes. This does not mean, however, that "economic losses" are inevitable. We may conceive of a policy package involving various measures that can neutralize undesirable side-effects of the initial set of measures. We shall come back to this point in Section 5.

4. Energy-Saving Investments and Subsidies

The effects of energy-saving investments and subsidies to encourage introduction of less carbon-intensive technologies have been analyzed by Ito (1990),

Table 6. Investment subsidy and CO_2 emission reductions in 2005[a].

Introduction Cost (1,000 yen/TC)	Amount of subsidy (Tril. yen/Year)	Total CO_2 emission reduction (Mil. TC/Year)
5	0.101	20.2
10	0.366	36.6
20	0.736	36.8
40	1.780	44.5
60	2.652	44.2
80	3.608	45.1
100	5.470	54.7

Source: Matsuhashi *et al.* (1991), Figures 7 and 8.

Yamazaki (1991), and Matsuhashi *et al.* (1991). In the Ito model, a certain proportion of the total private fixed investment is directed toward energy-saving purposes. Since this type of investment does not contribute to create productive capacity, such diversion will lower the potential growth rate of the economy. Energy-saving investments, on the other hand, will directly reduce the energy requirements per unit of production. He estimated that one million yen of energy-saving investment can reduce 2,500 liters of oil or 1.725 tons of carbon. (This is equivalent to 224 tons of carbon emission reduction per one million dollars of investment.) Therefore, if 2 percent of gross fixed investment in the private sector (roughly 2.2 trillion yen in 1990) is diverted to energy-saving purposes, its direct effect can reduce the annual emission of carbon dioxide by 3.8 million tons of carbon or about 1.2 percent of the annual emissions.

A research group at the University of Tokyo (Matsuhashi *et al.*, 1991) pursued a comprehensive approach in evaluating the efficacy of subsidies to encourage the introduction and diffusion of carbon-saving technologies. Based upon a survey on energy/carbon-saving technologies that accompany investment expenditures, they first estimated the potential scale of CO_2 reduction and additional costs required per unit of carbon content of introducing these particular technologies. The results were then fed into a macroeconometric model to derive the relationship between the amount of subsidy and the extent of CO_2 emission reductions. Table 6 summarizes the results.

There are three interesting points. Firstly, the impact per yen is much larger than Ito's estimates. Secondly, fairly large emission reductions can be attained at very low costs. Thirdly, there is a clear tendency for diminishing returns.

Obviously, this is an important area where model-based analyses have not been pursued extensively so far and further studies should be encouraged. At the OECD workshop on global-model comparison studies, the importance of assumptions concerning the "AEEI" (autonomous energy efficiency improvements) has been stressed, but the AEEIs are simply set exogenously in each model and no attempt has so far been made to justify the numbers theoretically or empirically.[2] At the same time, the question of consistency between subsidies for investment or R&D and the Polluter Pays Principle should also be examined. The same is probably true for the question of international technology transfers, although only scanty attention has been paid to it so far. The greater part of energy-saving and clean-energy technologies is proprietary of the private sectors, therefore the areas and extent of required public promotion, together with financial requirements, need further investigations.

5. Recycling of Tax Revenue

Some papers discussed the question of recycling tax revenues. If the aim of carbon taxes is to stabilize CO_2 emission at around the current level or even to reduce it, the size of tax revenues can become substantial and their disposition may have important implications. In order to isolate the incentive effects of emission taxes as far as possible, it would be necessary to maintain revenues neutrality in analyzing their effects. However, the problem is that there are various ways of attaining revenue neutrality. Tax revenues can be used to reduce direct taxes, indirect taxes, social security contributions, or to increase investment tax credit, and so on. That is, attainment of revenue neutrality may have different implications on income distribution, sectoral prices, sectoral employment, etc. Therefore, in order to avoid confusion, the incentive aspects of carbon taxes should be analyzed by assuming, for example, revenue neutrality through reduction of indirect taxes or social security contributions.

Table 7 reports some examples of the effects of tax revenue recycling in terms of GNP reduction ratios defined in Table 2. With tax revenue recycled, CO_2 emission reductions tend to become smaller because of smaller GNP reductions. However, the substitution effects of carbon tax are not much

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[2] In a recently published book, however, Manne and Richels examined their assumptions concerning the AEEI and ESUB (the elasticity of substitution) by means of historical tracking tests (see Manne and Richels, 1992, Chapter 9).

Table 7. Effects of tax revenue recycling: GNP Reduction Ratios.

	Tax Revenue	
Model	Not Recycled	Recycled
Yamaji	0.23	0.19
NIKKEI	0.22	0.16

affected by this change, and the GNP reduction per one percentage point reduction in CO_2 emissions can become smaller.

The above discussion does not imply that carbon taxes should actually be introduced in such a fashion. In countries where non-trivial carbon taxes were introduced in the past, however, they usually accompanied some sort of tax reforms because of a big change in tax revenue. Questions such as the regressiveness of carbon taxes (see, e.g., Poterba, 1991) and different sectoral impacts can then be considered in this context.

6. International Aspects of Carbon Taxes

When we look at the problem from the international perspective, there are a few important channels through which impacts of carbon taxes in one country or a group of countries can affect the international economy at large. An important factor is changes in the world prices of fossil fuels resulting from decreased demand for energy. They can impart at least three different impacts. First, they alter the terms of trade of energy importers and exporters, favoring the former. No model developed in Japan has paid sufficient attention to this problem, but the OECD study shows (see Burniaux *et al.*, 1992) that the terms of trade effects on real incomes can be significant. This means that some compensation schemes might be required inter-regionally for energy exporters, or inter-sectorally in a country for coal producers, for instance.

Secondly, the changes in energy prices may alter the structure of comparative advantages in various countries. If carbon taxes are levied in an internationally uniform fashion, then the resulting problems, if any, are of short-term adjustment character. The optimal international division of labor will not be seriously disturbed by the carbon tax. Rather, it will make the price structures reflecting real social costs more adequate, leading to a more efficient resource allocation. If, however, carbon taxes are introduced only in a subset of countries or with different intensities, then the supply sources of carbon-intensive products may shift from more efficient countries to less efficient countries because the latter adopt less restrictive tax schemes. This kind of trade-distorting effects of energy taxes are already present. Hoeller and Wallin (1991) have shown substantial differences in implicit carbon taxes among OECD countries, and Burniaux *et al.* (1992) revealed much wider differences in relative domestic energy prices in the world economy. Removal of these distortions will certainly improve the efficiency of energy use and carbon emissions. This point should doubtless be subject of careful attention when realistic simulation exercises are to be performed. The OECD GREEN model indicated that existing taxes and subsidies can have significant effects upon the carbon tax structures. The reason is that many industrial countries impose substantial implicit carbon taxes already whereas in some other countries energy is heavily subsidized (Burniaux *et al.*, 1992).

Finally, when only a certain group of countries introduce carbon taxes, the resulting reduction in international energy prices may induce increases in energy demand in non-participating countries. The original reduction in carbon emissions is offset by an increase in the latter group of countries. This effect, combined with the second effect mentioned above, is called "carbon-leakage" by Rutherford (1992). The carbon-leakage rate, therefore, represents the percentage by which the effects of a unilateral cut are offset by increased emissions in other regions. According to Rutherford, the carbon-leakage effect is fairly large, particularly for stricter controls of CO_2 emissions. His model suggests that the marginal leakage rate for unilateral OECD action is nearly 100 percent for cutbacks of rate of emission increase above 3 percent per annum in the period 2000–2100. In the year 2000, the "trade-diversion" and "substitution" components are estimated as roughly equal, both leakage rates being around 30 percent.

In contrast, the latest simulation exercises by GREEN have shown that carbon-leakages of a unilateral stabilization action in OECD countries are quite small with a peak rate at 2.5 percent (Burniaux *et al.*, 1992). On average, over the period 1990–2050, the largest decline in the output of energy-intensive sector is only -2.6 percent (in Japan) and the smallest is -0.4 percent (in the United States). Since these opposing findings are both based on fairly aggregated trade models with only two types of goods (energy-intensive and other goods) being involved, it seems that further, more disaggregated studies are needed.

More recently, Manne and Rutherford (1992) reported somewhat smaller leakage ratios for the unilateral OECD action, ranging from around 10 to 35 percent, which are still higher than those suggested by the GREEN model. Since the carbon-leakage effects are heavily dependent upon what happens in the world oil market, assumptions concerning the behavior of OPEC countries seem to be quite important.

In a recent article, Nicoletti and Oliveira-Martins (1992) also examined the carbon-leakage effects of the EC energy/carbon tax proposal by using the GREEN model. The net leakage effect measured by the ratio between the change in emissions outside the EC and the size of the emissions out in the EC is reported to be around 11 percent by the year 2000 and then to decline to zero toward the middle of the next century.

Their simulation experiments indicated that the following two factors are important in determining the degree of carbon leakages: (a) the degree of trade linkage between countries participating in the unilateral agreement and non-participating countries, and (b) the supply elasticities of fossil fuels. A reason why the GREEN model yielded very small net leakage effects for the unilateral OECD carbon-tax exercise is that trade flows between OECD and non-OECD areas are relatively small.

They also concluded that the degree of carbon leakages may be sensitive to assumptions concerning capital mobility (i.e., possibilities of international relocation of industries), the differentiation of goods in international trade and the behavior of oil prices.

7. Concluding Remarks

A final comment on the method of modeling analysis for mitigating global warming. As we have seen, economic measures to curb GHG emissions will tend to become rather comprehensive in order to avoid undesirable side effects. In order to evaluate possible macroeconomic and sectoral effects of such a policy package, we need to rely upon a detailed model of the domestic economy. On the other hand, the greenhouse effect is global in nature, and the abatement policies should have a global point of view. Problems such as impacts upon international energy prices, international leakage effects, and the creation of international markets for tradable emission permits can only be analyzed by a global model. However, it is not practical to link all detailed country models together to build a global model.

It appears that we should have short to medium-term models of a particular country with sufficient details of functional and sectoral disaggregation, on the one hand, and a global, long-term model with less sectoral disaggregation but a wider geographical coverage of the world economy, on the other hand. Models of these two types could then be used simultaneously to obtain a globally consistent, and locally detailed view of appropriate policy packages to contain global warming.

Appendix: Outline of Economy/CO_2 Interaction Models

In this Appendix, a brief outline of the models and the results of representative simulations are summarized.

Japanese Models

EPA (1991): 1990–2010

A long-term, multi-sectoral planning model of the Economic Planning Agency with 22 sectors. It is called a turnpike model because it is based on the consumption turnpike theory. It is a dynamic optimization model, maximizing the sum of discounted national utility arising from consumption of flow goods and flow services from stocks over the planning horizon under various constraints. Input coefficients for labor, capital and intermediate inputs in the planning period were formed on the basis of hearing inquiries at various sectors.

Stabilization of per capita emissions of CO_2 at the 1990 lever by 2000. Scenario 1: uniform reduction of output. Scenario 2: Scenario 1 with the rate of increase in energy demand in the household sector being halved from 4 percent (past average) to 2 percent per annum. Scenario 3: Scenario 2 with the same rates of energy saving in the industrial sectors as in the period 1975–1986.

	Percentage reduction relative to baseline			
	GNP		CO_2	
Scenario	1990–2000	2000–2010	1990–2000	2000–2010
1	-17.7	-26.8	-17.2	-27.2
2	-13.6	-20.8	-17.2	-27.2
3	0.0	0.0	-17.2	-27.2

Goto (1992): 1990–2040

A dynamic optimization model with a detailed energy sector. Five primary fuels and nine secondary fuels. Nine industries and one residential sector. Annual CO_2 emissions stabilized at 320 MtC (around the 1990 level) after 2000.

	Shadow price of CO_2			GNP losses (Dev. from baseline)	
Year	Yen/TC	$/TC	Year	Tril. yen	%
2000	26,710	205	2000	1.3	0.22
2010	32,500	250	2010	6.1	0.76
2030	18,040	139	2040	14.2	0.99

Yamaji (Nagata et al., 1991): 1988-2005

A large-scale, medium-term econometric forecasting system developed by the Central Research Institute of Electric Power Industry, composed of four sub-systems: World Energy Model, Domestic Multi-Sector Model, Interfuel Competition Model, and Domestic Regional Model.

Carbon tax of 4,000 yen/TC (about $31/TC) introduced in 1990, raised by the same amount every year until 2005 to reach 64,000 yen/TC ($492/TC). The CO_2 emission level in 2005 is to be reduced to the level of 1988. Annual real GNP growth rates are reduced by 0.4 percent when tax revenue is not recycled, and by 0.3 percent when it is recycled via income tax cut.

Ban (1991): 1991-2000

A macroeconometric model based on intertemporal optimization behavior of the energy demand in private sectors such as iron and steel, electric utilities, automobiles, and gasoline. Nuclear power generation and new energy sources are exogenous.

Scenario 1: Carbon taxes to stabilize CO_2 emissions at the 1990 level; 24 percent on oil, 16 percent on LNG, and 30 percent on coke and coal (about $66/TC in 2000) with tax revenue recycled via indirect-tax cut. Scenario 2: Direct regulation; uniform cut in production and consumption (roughly by 5 percent) to reduce emissions as in Scenario 1.

Scenario	Cumulative reduction in real GNP (1985 prices) in 2000	Equivalent reduction in constant average growth rates (% p.a.)
1	28 Tril. yen	0.10
2	41 Tril. yen	0.15

Ito (1992): 1988-2010

A macroeconometric model with a simple energy sector. Modeling the impacts of energy price changes and energy saving investments.

Fossil fuel taxes. Scenario 1: 50 percent on coal, 40 percent on oil, and 30 percent on LNG. Scenario 2: 100 percent on coal, 80 percent on oil, and 60 percent on LNG. Scenario 3: the same as Scenario 1 with additional energy saving policies and foreign aid programs.

	Carbon tax rates ($/TC)		Reductions in GNP growth rates	
Scenario	2000	2010	1990–2000	2000–2010
1	97	138	0.2	0.1
2	200	280	0.4	0.1
3	99	141	0.2	0.1

Mori (1991): 1988–2020

An econometric energy-sector model combined with a simple aggregate-demand block. Six primary energy sources and eight secondary energy sources. Three final demand sectors using thermal/electric energy.

Carbon taxes introduced after 1993 to stabilize annual CO_2 emissions at around the 1990 level. Required carbon tax rates: 17,500 yen/TC ($135/TC) on average for the 1993–2020 period. Maximum rate of GNP reduction during the period is 3.6 percent relative to the baseline (tax revenue being not recycled).

Yamazaki (1991): 1990–2010

A medium-sized macroeconometric model combined with an energy model. Three final energy demand sectors and seven primary energy sources. Energy-saving investments partly explained by energy prices. Increases in energy prices also reduce relative importance of energy-intensive sectors in the economy, thus leading to a decline in the aggregate energy-intensity.

Carbon tax is levied to stabilize CO_2 emissions after 2000 at the 1990 level. One third of energy-saving investments are subsidized by the carbon tax revenue.

	Percentage deviation from baseline		Carbon tax
Year	GNP	CO_2	($/TC)
2000	-5.88	-10.50	132.3
2010	-4.51	-10.95	209.9

Global Models

Onishi (1991): 1991–2000

Detailed global econometric model with 180 countries/regions based on an AI oriented expert system. The model has been used for various other simulation studies of the world economy.

CO_2 emissions stabilization at the 1990 level by 2000. Scenario A: all countries introduce carbon taxes of 10 percent on oil, 12 percent on coal, and 8 percent on natural gas; furthermore, all countries cut back non-housing investments to attain their emission targets. Scenario B: developed countries increase R&D expenditures by 0.5 percent of GDP to reduce CO_2 emissions; these countries also increase ODA by 20 percent compared to the baseline case to help reduce CO_2 emissions in developing countries. Scenario C: most countries introduce at least 5 percent carbon tax on fossil fuels; developed countries increase R&D expenditures by 0.25 percent of GDP to reduce CO_2 emissions; these countries also increase ODA by 10 percent compared to the baseline case to help reduce CO_2 emissions in developing countries.

	Changes in growth rates: 1991–2000 av.					
	GDP			CO_2		
Scenario	A	B	C	A	B	C
World	-2.0	0.1	-0.4	-1.5	-2.2	-2.3
Developed Market Economies	-2.1	0.1	-0.4	-1.4	-2.2	-2.0
Developing Market Economies	-1.6	0.0	-0.3	-1.7	-5.0	-2.1
Planned Economies[a]	-2.0	0.1	-0.7	-1.4	-2.2	-2.5
Japan	-3.2	0.4	-0.6	-1.3	-1.9	-2.1

[a] Including Eastern Europe and former USSR.

Shishido (1991): 1990–2000

A global econometric model with 36 countries/regions, emphasizing sectoral details of production and trade in industrial countries. CO_2 emissions are explained by production and prices.

Fossil fuel taxes introduced only in G7 countries, starting from 10 percent in 1990, raised to 20 percent in 1995, and sustained thereafter.

	Percentage Deviation from the Baseline in 2000	
Region	GDP	CO_2
World	-0.85	-1.35
Developed Market Economies	-1.20	-3.27
Developing Market Economies	-0.36	-0.56
Planned Economies[a]	-0.08	-0.08
Developed Asia-Pacific	-1.15	-0.99

[a] Including Eastern Europe and former USSR.

Nihon Keizai Shimbun/GEF-KANSAI (1991): 1991–2010

A global econometric model with nine countries/regions, each having macroeconomic and energy blocks.

Introduction of carbon taxes to stabilize CO_2 emissions at the 1990 level by 2000. Uniform tax is applied throughout the world with no tax revenue recycled.

	Percentage deviation from baseline				Carbon tax	
	GDP		CO_2		($/TC)	
Region	2000	2010	2000	2010	2000	2010
World	-3.5	-7.4	-17.4	-30.4	546	1,780
Developed Market Economies[a]	-3.2	-5.9	-13.7	-22.3		
Developing Market Economies	-5.2	-8.9	-23.1	-39.3		
Planned Economies[a]	-3.4	-12.4	-17.5	-31.6		
Japan	-1.7	-4.3	-16.8	-26.9		

[a] Including Eastern Europe and former USSR.

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Costs and Benefits of CO_2 Reduction in Russia

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Introduction

Dissolution of the former USSR inflated the results of analysis made last year by a group of Russian experts on a greenhouse gas (GHG) emission inventory, and short- and long-term projections of energy-related GHG emission. The value of these results has been reduced not because of the use of a wrong analysis methodology or for any scientific reasons. The main reason is that we are at present living in a world where several new independent states (NIS) replaced the former USSR. Now we need to revaluate our results for Russia and for other NIS separately. As the borders between former republics were not precisely determined and basic statistical data were available mainly for the whole former USSR, the disaggregation of analysis into values for each independent state presents some difficulties and would definitely require some time to implement. This work has already started in Russia. Due to insufficient financial support for this research, results for Russia may only appear later this year. Nevertheless, some preliminary results already exist. In this paper I will use them, as well as extrapolations of some conclusions on Russia made for the former USSR. Further work definitely would correct these extrapolations, but I do believe that those corrections would be within a reasonable range of the existing extrapolations and will not alter the conclusions presented in this paper.

1. Energy-related GHG Emission in Russia in 1990

CO_2. Based on the preliminary results of Russian energy balance estimates made at the Energy Research Institute and the methodology of the GHG emission inventory developed by the OECD (Bashmakov, 1992), table of CO_2 emissions for Russia in 1990 was estimated (see Table 1). The total amount of CO_2 emissions in Russia is about 650 million t-C or approximately 65%

Table 1. Energy-related CO_2 emissions in Russia in 1990[a], in million tons of C.

	Coal	Other solid fuels	Oil	Gas	Total
Indigenous production			4.53		4.53
Primary energy consumption	202.8	27.5	187.5	237.2	654.36
Electricity generation	34.4	1.1	8.7	28.0	72.1
CHP plants	28.4	2.2	19.3	38.7	86.8
District heating	49.3	0.7	2.2	73.3	145.6
Own use and losses	15.4		12.7	38.9	67.0
Final energy consumption	75.2	18.5	124.6	58.3	276.6
Industry	42.6	9.8	16.4	34.0	102.9
Agriculture	1.8	0.8	15.7	0.6	19.0
Transport			72.0	0.2	72.2
Residential and commercial	30.7	7.8	7.3	14.5	60.4
Non-energy use			13.2	9.0	22.2

[a] Preliminary estimates.
Source: Author.

of the former USSR's emissions and 10% of the global, energy-related CO_2 emissions. Russia occupies second place in the list of major CO_2 emitters in the world.

Processes of energy transformation, production, transportation, and distribution are mainly responsible for the emissions. The contribution of final energy consumption is 42%. Natural gas dominates CO_2 emissions from the use of fuels. This is understandable, keeping in mind that natural gas contributed 46% of fossil fuel consumption in Russia in 1990.

CH_4. The preliminary estimation of methane emissions is equal to 17.8 million tons of CH_4. This is approximately 73% of the emissions of the former USSR in 1990. The major source of methane emissions is the gas supply system (71%), followed by coal production (28.5%).

CO. Total CO emissions equal 29.9 million tons of CO. The major source of these emissions is petroleum consumption by transport.

NO_x. NO_x emissions equal 6.2 million tons of NO_2. Among major contributors are : transport, electricity, and heat generation.

GHG. Total GHG emissions in terms of CO_2 equivalent equal 3,110 million tons (see Table 2). The Russian contribution to the former USSR GHG emissions was 64% in 1990.

Table 2. Energy-related GHG emissions in Russia in 1990[a], in million tons of CO_2.

	Coal	Other solid fuels	Oil	Gas	Total
Indigenous production	106.5		19.7	264.7	391.2
Primary energy consumption	916.6	86.1	893.3	929.3	2718.6
Electricity generation	809.8	4.3	35.2	111.5	289.2
CHP plants	138.1	8.4	75.9	152.1	347.7
District heating	111.3	2.8	88.8	289.8	576.6
Own use and losses	195.1		48.9	151.2	259.1
Final energy consumption	59.0	70.7	644.5	224.7	1246.1
Industry	306.2	37.3	64.16	132.5	409.3
Agriculture	175.4	3.2	60.30	2.4	73.4
Transport	7.4		443.31	1.1	444.4
Residential and commercial	123.4	30.2	28.3	55.8	237.7
Non-energy use			48.5	32.9	81.3

[a]Preliminary estimates.
Source: Author.

Among the major means of reducing CO_2 and other GHG emissions are: energy efficiency improvements; more nuclear and renewable energy in the energy balance; change fossil fuel structure in favor of natural gas; and finally, CO_2 removal. Due to political and economic reasons (Makarov and Bashmakov, 1990), in Russia at present the most promising way to deal with emission reduction is to improve energy efficiency. According to proposals for a new Russian energy program, hydro and nuclear power would develop very slowly up to the year 2005 (Energy Research Institute, 1992). Therefore, energy efficiency will be at the center of the costs and benefits analysis in this paper.

2. Energy Conservation Potential

2.1. Direct technological energy conservation potential: scale and structure

As the former USSR has been exhausting oil, gas, and coal resources, it has simultaneously been accumulating the world's highest energy conservation potential. Any study of energy conservation possibilities has to start with the accumulation and systematization of vast amounts of information on the possibilities for efficient use of energy in various spheres. The most

Table 3. Direct and indirect technological energy conservation potential in the former USSR, in million tce.

	Final energy consumers			Energy complex			GHG emission	
	Direct[a]	Indirect	Total	Direct	Indirect	Total	reduction[b]	Total
Coal	49.6	77.8	127.4	20.5	23.4	43.9	695.5	171.3
OSF		5.6	5.6		1.4	1.4	22.0	7.0
Oil	50.9	54.9	105.8	7.2	20.0	27.2	335.4	133.0
Gas	76.3	96.4	172.8	143.3	44.8	188.1	792.7	360.8
Electr.	45.6	10.3	55.9	10.1	3.4	13.5		69.4
Heat	66.3	5.4	71.6	30.9	2.4	32.9		104.5
Total	288.7	250.4	539.1	211.5	95.4	306.9	1845.6	846.0

[a] Only conservation of secondary energy carriers.

[b] In million tons of CO_2 equivalent.

Source: Author.

recent study for the former USSR, carried out at the Energy Research Institute (Moscow) and sponsored by the Advanced International Studies Unit at Battelle, Pacific North West Laboratory, contains the technical and economic parameters for 120 aggregate measures to improve energy efficiency (Bashmakov and Chupyatov, 1992). This data base, together with more details on savings by energy carriers, was used in this paper.

The aggregated structure of the potential for energy efficiency is presented in Table 3. As far as the author knows, it is the first effort to present energy efficiency potential in such a way. This approach allows us to identify gaps in our knowledge of energy efficiency potential. For instance, several empty cells in Table 4 clearly display a lack of knowledge of energy efficiency improvement opportunities in the electricity and heat generation industries based on coal and petroleum, and in the agricultural sector. At the same time, this approach provides a very clear and systematic picture of the possible contribution of energy conservation to the reduction of energy consumption by sectors and energy carriers.

Only major, identified measures were included in the potential inventory and therefore are included in this table. However, even this relatively restricted vision of the potential provides an opportunity of saving 501 million tons of coal equivalent (tce) of secondary energy or 25.4% of primary energy consumption in the former USSR in 1990. According to Makarov and Chupyatov (1992), Russia's share in this potential is 67–70% or approximately 350 million tce.

Of course, not all this potential is cost effective for all energy processes. The cost efficiency depends to a high degree on energy prices and on such

Table 4. Technological energy efficiency improvement potential in 1990–2005 in the energy balance of the former Soviet Union in 1990[a], in million tce.

	Coal	Other solid fuels	Oil	Gas	Hydro	Nuclear	Electricity	Heat	Total
Indigenous production	425		811	964	28	79			2338
Exports	-23		-217	-215			-5		-370
Imports	9		24	2					-35
Stock changes	-7		-7	-18					-32
Primary energy	70.1	0	58.4	220					500.4
consumption[b]	404	30	611	823	28	79	-5		1971
Electricity				89.9					89.9
generation	-80	-7	-27	-100	-28	-79	137		-185
CHP plants	8.5			23.8					32.3
	-70	-1	-80	-228			73	211	-95
District heating				10					10
	-43	-7	-71	-118				182	-56
Own use	12		7.2	20			10.1	30.1	79.4
and losses	-18		-32	-91			-49	-35	-226
Final energy	49.6		51.2	76.3			45.6	66.3	288.8
consumption	192	16	402	286			155	359	1409
Industry	22.8		6.5	48.1			28.4	36.8	142.6
	92		82	115			94	254	637
Agriculture			3.3	3			0.6	0.4	7.3
	10	3	62	20			16	7	118
Transport			40						40
			156	3			13	2	174
Residential and	26.8		1.4	25.6			16.6	29.1	98.9
commercial	85	13	17	89			33	95	331
Non-energy use	5		85	59					148

[a] Numerator = energy efficiency potential; denominator = energy consumption.

[b] Totals for secondary energy carriers.

Source: Author.

Table 5. Impact of energy prices and internal rate of return on the cost-efficiency of energy conservation measures in the former USSR, in million tce.

	Energy prices[a]				
	IRR = 0.12			IRR = 0.5	Maximum potential
	1990	1991	1992	1992	
Electricity and heat generation	130.9	130.9	132.2	130.9	132.2
Energy sector	40.7	29.3	70.9	40.7	79.3
Industrial sector	134.5	121.5	149.6	134.0	149.6
Residential and commercial	98.7	56.3	99.1	99.1	98.9
Total	404.8	338.0	451.8	404.7	460.1
Percentage of total	88.0	73.0	98.2	88.0	100.0

[a] Under the assumption that these real prices would last until 2005.

Source: Author.

capital budgeting rates as an internal rate of return (IRR). Previously in the former USSR, the normative IRR was equal to 12%. With this IRR and even at 1990 energy prices nearly 90% of the potential is cost effective (see Table 5). However, cost-cutting investments were invisible in the process of central planning, and, as a result, in spite of the cost efficiency of the major part of the potential, very insignificant amounts of fixed investments were directed to the realization of energy efficiency measures.

In new market conditions with high interest rates and a shortage of capital, cost-cutting investments would be made with a shorter expected payback time: probably not more than two years or with IRR = 0.5. For mid-1992 prices, even with IRR = 50%, 88% of the energy efficiency improvement investments are cost effective, and with IRR = 12%, almost 100% of energy efficiency projects could be economically justified. When energy prices approach world prices all measures under consideration and many additional measures would be cost effective.

As can be seen from Table 5, the energy sector and the residential and commercial sector are the most sensitive sectors to IRR and energy price fluctuations. Power and heat generation sectors are the least sensitive. It also means that not all the relatively expensive possibilities for energy conservation were identified in this sector.

Table 6. Intermediate energy consumption by the energy complex in the former USSR in 1990, in million tce.

	Coal	OSF	Oil	Gas	Electr.	Heat
Coal	18.0	0.3			222.3	117.1
Other solid fuels					20.0	1.3
Oil	0.8	0.02	25.6	6.0	86.7	141.6
Gas	1.3		4.0	86.2	215.6	243.1
Electricity	3.0	0.01	10.0	4.4	30.2	1.5
Heat	3.2		16.6	4.0	1.0	10.0
Total energy consumption	404.0	30.0	611.0	823.0	209.5	393.3

Sources: Bashmakov *et al.* (1990); Bashmakov (1991, 1992); Narodnoye Khoziaistvo SSSR (1988, 1989); Sagers and Tretyakova (1988).

2.2. Indirect technological energy conservation potential

Only direct energy conservation potential was shown in Table 4. But there is an additional indirect one. The energy balance for any country could be presented in the following manner:

$$PE = A^{*}PE = FE \quad ,$$

where PE = total energy consumption; FE = final energy consumption; and $A = ||a_{ij}||$, a matrix of coefficients, a_{ij}, where the energy carrier of type i is consumed to produce and deliver one unit of energy carrier of type j.

Data for this matrix are shown in Table 6. This table was produced based on detailed information on energy consumption in the energy production and transformation sector split up according to the processes and fuels used. Energy consumption and losses at various stages of production, transformation, enrichment, transportation (by pipeline), and distribution were included in the list of processes. For simplicity the name "energy complex" is used for all these processes. Thus this complex combines electricity, heat generation, and energy sector activities according to the standard energy balances presentation in the OECD methodology.

The row "coal" in Table 6 shows how much coal was used in 1990 by the energy complex to produce, process, refine, transport, and distribute coal, other solid fuels, oil, natural gas, electricity, and heat. On the other hand, there is a need for petroleum, gas, electricity, and heat to produce coal itself (see column "coal"). This table is a complete analog of a first quadrant in the input–output table. The data for the former USSR are preliminary. More data collection should be carried out to improve the accuracy of the results

Table 7. Direct coefficients of energy consumption by energy complex per unit of total energy consumption, in tce/tce.

	Coal	OSF	Oil	Gas	Electr.	Heat
Coal	0.0289	0.01			0.9814	0.2680
Other solid fuels					0.0955	0.0034
Oil	0.0020	0.0005	0.0419	0.0073	0.4138	0.36
Gas			0.0065	0.089	0.7409	0.544
Electricity	0.0050	0.0003	0.0157	0.0052	0.1224	0.00373
Heat	0.0077		0.0198	0.0047	0.0047	0.0173

Sources: Calculations based on data from Table 6.

presented. Nevertheless, the author believes that possible future corrections would not significantly change the numbers in Table 6, as well as the results achieved in this paper based on this primary information.

The analogy with the input–output table leads to the calculation of matrix A by dividing elements of Table 6 by volumes of total primary energy consumption. There is one problem with computing these coefficients: part of the energy produced is exported. Therefore, energy used to produce, transform, and deliver exported energy is not directly related to primary energy consumption. This problem could be easily solved if energy export were to be considered as a part of the final energy consumption. In this paper, we will not go into so much detail.

The distribution of fuels to produce electricity and heat mirrors the real proportions in the 1990 energy balance of the former USSR under the proposal that all electricity and heat should be produced by using fossil fuels. Table 7 displays direct coefficients.

Knowing these data and the volume of total primary energy consumption by fuel, it is possible to calculate how much of each different energy carrier would be needed by the energy complex to transfer primary energy into secondary carriers to deliver it to the final consumers:

$$\mathrm{EC} = \mathrm{A}^*\mathrm{PE}$$

where EC is the energy consumption of the energy complex.

The next step is a computation of the matrix of so-called "full" or "direct and indirect" coefficients, or, mathematically speaking, the matrix $(\mathrm{E}-\mathrm{A})^{-1}$. Using this matrix, total energy consumption could be presented as a function of final energy consumption:

$$\mathrm{PE} = (\mathrm{E} - \mathrm{A})^{-1} * \mathrm{FE} \ .$$

There are numerous possibilities for increasing energy efficiency in the energy complex of the former USSR. Calculations of the indirect effects of these measures should be viewed differently. The reason for this is that any measure to improve energy efficiency in the energy complex has an impact on the values of direct coefficients or leads to changes in the matrix A(A′). Therefore, correct calculations of the indirect effect should be carried out based on the new matrix:

$$\mathrm{dPE} = (\mathrm{E} - \mathrm{A}')^{-1} * \mathrm{dFE} \ .$$

In this case indirect effects would be lower. Based on the distribution of measures by sector, fuel, and process in the energy complex (see Table 4), matrix A′ was estimated. Based on this new matrix, indirect energy conservation for all technological measures was estimated. The indirect effect of direct energy conservation by final energy consumers is that the energy demand became lower by 49 million tce due to improvements in the energy efficiency of processes in the energy complex. Without correcting matrix A, it would be overestimated.

To supply a final consumer with a unit of coal, 0.11 units of energy would be consumed by the energy complex, and for electricity this ratio is 3.66, including 3.4 units of fossil fuel. This number is far above the normally calculated ratio for the amount of fossil fuel needed to produce a unit of electricity with a given power generation efficiency (2.6:1 for the former USSR). Therefore, because a more systematic approach is used, more complex, more correct, and more significant results were obtained: to supply a unit of electricity to the final consumer not 2.6 but 3.4 units of fossil fuel are needed, and to produce a unit of heat not 1.3 but 1.52 units of fossil fuel are required.

These data show how much energy would be *saved* in the energy complex if a unit of secondary energy is saved by final consumers. This, in turn, means that energy efficiency improvements in the utilization of any secondary energy resource by final consumers are always accompanied by significant additional or indirect energy savings in the energy complex. Normally only calculations of partial indirect effects for electricity and heat are performed.

Electricity is the first item in the list of total (direct plus indirect) energy conservation effects produced by saving a unit of energy, followed, at a significantly lower level, by heat, oil, natural gas, coal, and other solid fuels. A direct reduction in final energy consumption of dFE is, therefore, accompanied by an indirect reduction equal to:

$$dPE = (E - A)^{-1} * dFE \ .$$

Indirect energy savings appear as a result of structural changes in the energy complex induced by technological changes. If the final consumer needs less electricity, all distribution and transportation losses and own electricity use by power plants related to the production and delivery of this unit to the consumer would not appear, as well as all the energy embodied in and needed to produce, transform, and deliver coal, oil, and natural gas to power plants to produce this unit of electricity.

The indirect effect is very significant: generally speaking, any unit of energy saved by improving the energy efficiency of technologies is accompanied by an additional 0.69 units of energy savings [(250.4 + 96.4)/(288.7 + 211.5) = 0.69] produced as a side effect of structural shifts caused by these improvements.

Therefore, any improvement in energy efficiency by final consumers is accompanied by structural shifts in the energy complex and these structural shifts bring an additional energy conservation effect with no extra cost. There is no need to spend any money to get this side effect. It comes automatically. While the private investor benefits from the direct effect of any technological measure, society enjoys the side effects. This side effect calculation could be a basis for sharing the burden of energy efficiency improvements between a private investor and society.

The utilization of this approach could significantly change present estimates of the economic costs of energy conservation, as well as benefits.

2.3. Total technological energy conservation potential

The technological energy conservation potential for the former USSR described above was used to calculate the direct and indirect effects of identified technological measures to improve energy efficiency. The potential is divided into two parts:

- energy efficiency improvements in the energy complex, and
- energy efficiency improvements by final consumers.

Data from Table 3 show that the indirect effect is slightly higher than the direct one and the total effect is twice that of the direct effect. *In other words, the average costs of energy conservation measures for society are only half of those for the final consumer and the benefits are twice as* *large.* Electricity and heat have higher indirect effects in terms of reduction of fossil fuel consumption than usually calculated based exclusively on the notion of efficiency of their generation.

Similar calculations were made on the basis of the most recent input–outout table for the former USSR (Trelm, 1989). The 18-sector input–output table contains 4 energy industries: electric power, oil and gas, coal, and other fuels. All deliveries of energy to consumers are presented in Leontief's tables in monetary units. Therefore, there is no direct correspondence with data we used for the above calculations. These four sectors were aggregated into one energy sector. Then matrices of direct and full coefficients were estimated.

According to these results, the full coefficient for the aggregated energy sector is equal to 1.5. In other words, one unit of energy cost saved by the final consumer produces an additional 0.5 units of energy cost savings due to a reduction of energy consumption in the energy complex.

Remembering that electricity is much more expensive than fossil fuels, and that oil is more expensive than coal and natural gas, the results in terms of physical units should not coincide with the results in terms of costs. Hence, it could be concluded that the results produced by two different methods are very close. This gives the author additional confidence in stating that any unit of energy saved in the process of energy efficiency improvement, on average, is accompanied by an additional, free 0.7 units of energy saved in the energy sector.

This general ratio could be applied when no information on the distribution of energy conservation measures by type of energy carrier is available. In cases where this information does exist, more precise calculations based on matrix A could be done.

Total energy conservation potential in terms of primary energy does not include reduction of secondary energy carriers – electricity and heat – because of double counting. If calculated traditionally (taking into account only the efficiency of electricity and heat generation) it would be equal to 619 million tce. Based on the approach presented in this paper, this potential equals 672 million tce (the first 4 cells in the "total" column of Table 3). Including 3 million tce in the reduction in transport energy consumption caused by reduced energy resources transportation as a result of direct and indirect effects of the implementation of the technological potential, the total primary energy consumption reduction effect of energy efficiency improvements up to the year 2005 equals 675 million tce or 34% of the energy consumption in the former USSR in 1990.

The Russian share of this potential is approximately 70%, or 473 million tce. The GHG emission reduction calculated based on data on direct and indirect coefficients equals 1,845 million tons CO_2. If the Russian share is again 70%, then the GHG reduction potential through energy efficiency in Russia is 1,290 million tons CO_2, or 42% of the 1990 level of emission.

2.4. Structural changes in the economy and energy efficiency improvements

The process of transformation to a market economy could not be successful if the old structure of the economy is preserved. Structural changes are necessary. The economy could be structured in many different ways, and changes in these structures would directly or indirectly affect overall energy efficiency. Only two kinds of impacts from structural changes are investigated here:

- change of final product structure, and
- changes of several basic materials' intensities.

To estimate possible effects of structural changes on energy intensity and energy consumption, a set of calculations based on the 1988 input–output table was implemented. The 1988 input–output table contains four energy industries: electrical power, oil and gas, coal, and other fuels. It creates some difficulties in implementing calculations, because oil and gas are not separated. To transfer results from monetary to physical units, the following procedure was applied: monetary values were divided by physical units taken from the energy balance for 1988 (see Table 4). Average prices were obtained as a result of this procedure. These prices were very close to real prices (see Table 6). This gives the author more confidence in the reliability of the calculation results.

The effects of four different measures were estimated:

1. Reduction of capital investments in 1988 by one third.
2. Complete elimination of losses. (It is, of course, an extreme case, because this item in the input-output table includes terminated construction projects, abandoned dry oil and gas wells, and accidental losses of livestock. These losses are not avoidable completely.)
3. Reduction of military purchases by two-thirds. [In the 1988 input–output table there is an item in the final demand called "other users" which lists deliveries to the military including delivery of arms and weapons. These data have never been published in the former USSR before (Trelm, 1989)].
4. Military research and development, as well as current expenditures on military end products (e.g., ammunition, fuel), is included in public

Table 8. Impacts of structural changes on energy consumption in the former USSR[a], in million tce.

	1	2	3	4	5
Electricity	19.5	21.7	28.4	35.8	40.0
Oil and gas	122.6	137.9	183.8	219.8	243.2
Coal	24.8	27.2	35.1	47.3	58.7
Other fuels	2.4	2.8	3.4	4.5	4.8
Total	169.3	188.2	250.7	307.4	346.7

1 = Reduction of capital investments in 1988 by one-third.
2 = Complete elimination of losses.
3 = Reduction of military purchases by two-thirds.
4 = Reduction of public consumption by 20% (to mirror the reduction of military spending and the reduction of over-consumption by the bureaucratic apparatus).
5 = Reduction by 10% of ferrous and non-ferrous metals and building materials intensities in all branches of the economy as a result of better management and equipment maintenance, and more rational utilization of these materials.

[a] Each column shows the cumulative reduction of energy consumption including previous measures. The 1988 input–output table was used to calculate the reduction of energy production: energy export was held constant, therefore, all reductions were attributed to energy consumption.

Source: Author.

consumption. This component of final demand was reduced by 20% to mirror the reduction in military spending and the reduction in over-consumption by the bureaucratic apparatus.

5. Reduction by 10% of ferrous and non-ferrous metals and building materials intensities in all branches of the economy as a result of better management and equipment maintenance, and more rational utilization of these materials.

One important feature of all these experiments is keeping personal consumption constant. In other words, these structural changes bring about changes in value-added or national income, and other economic indicators, but not in private consumption.

The results are shown in Table 8. There are two major structural changes which could bring significant economic benefits: a reduction in the investment intensity of the economy (169 million tce) and its demilitarization (another 110 million tce). The total reduction due to the implementation of all 5 measures is 340 million tce or 305 million tce in terms of primary energy consumption. This is more than the annual energy consumption in Germany.

The effects of structural changes come at no cost as a side effect of programs to improve the overall efficiency of the economy. Of course, these programs are not free from expenses, but it is very difficult to attribute any of these investments to energy efficiency improvements directly.

If private consumption were to grow, say, by 10% in 1990–2005 with preservation of the existing structure of the economy, the structural energy conservation potential would also be larger than in 1990 by 10% or would be equal to 374 million tce (335 million tce in terms of primary energy).

The total potential for energy efficiency improvements in the former USSR in 2005 includes 675 million tce of technological potential (direct and indirect contributions to primary energy reduction) and 335 million tce of structural potential. Altogether it is 1,020 million tce in the year 2005, or 51% of the 1990 level of the primary energy consumption of the former USSR and 8% of world energy consumption. The Russian share of this potential is 710 million tce, equivalent to 56% of the primary energy consumption in Russia in 1990.

3. Costs of Energy Conservation Programs

The existence of energy conservation potential is a necessary but not sufficient condition for the realization of energy efficiency programs. In a market economy, implementation of these measures should be cost effective. Therefore, the costs of energy conservation programs should be considered and compared with costs of equivalent energy services provided by the increasing energy supply. The cheapest ways to deliver energy services to final consumers should be realized.

Several important points should be mentioned before costs are discussed:

1. Costs could be attributed only to direct energy improvement projects: indirect energy conservation and contributions from structural changes are free.
2. Only net costs should be considered. In other words, the difference between the investment costs of efficient equipment and the regular equipment is attributed to the difference in energy consumption of these two types of equipment. The efficient equipment may cost less than the regular equipment, therefore, negative investment costs are possible.
3. Some technological measures are implemented for reasons not directly related to energy efficiency improvements. For example, the extensive application of continuous steel casting and construction of quality highways are mainly justified by non-energy considerations. These measures could be classified as accompanying measures and have zero cost because investments are not solely prescribed on the basis of energy savings.

4. Some dedicated energy efficiency improvements have additional benefits in terms of higher productivity of other factors. These effects are not included in the considerations.
5. The method of measuring energy conservation should be specified. Results could be monitored in terms of secondary energy or primary energy, including direct only or also indirect effects.
6. Investments in energy efficiency would be made by private and commercial enterprises, and therefore a demand for payback over not more than two years would be expected.
7. The limitations of manufacturing industry in producing more energy-efficient equipment and the limitations of consumers in replacing regular equipment ahead of its lifetime by energy-efficient equipment were already considered in the process of technological potential estimation.

Costs of energy conservation measures are shown in Figure 1. All 120 measures were rated according to the value of investments per unit or primary energy saved (when transition from secondary to primary energy conservation is made only on the basis of electricity- and heat-generation efficiency). If a different method for the estimation of energy consumption reduction from the same variety of measures is applied, the sequence of measures arranged by level of costs, of course, could change.

The curve for total primary energy efficiency mirrors the additional effect from structural changes in the energy sector. As mentioned earlier, this effect occurs automatically and costs nothing. The relationship between specific investments per unit of direct primary energy conservation and total primary energy conservation is shown in Figure 2. Several declines on this curve occur because of the changing ranges of measures: measures with electricity and heat conservation receive a higher ranking. Generally speaking, there is a 16% cost premium compared with the traditional way of cost estimation.

It was shown that the largest potential for improving utilization efficiency exists for natural gas. According to Gandkin and Shamis (1991), in 2005 specific investments to produce and deliver natural gas to the final consumers would cost 300 rubles(1990)/tce or 7,500–9,000 rubles (mid-1992)/tce. More than 92% of the total technological conservation potential is less capital intensive than additional production of natural gas.

If only this part of the potential is considered and results for the former USSR were to be extrapolated for Russia, the following conclusions from the analysis of energy efficiency improvement capital costs could be made:

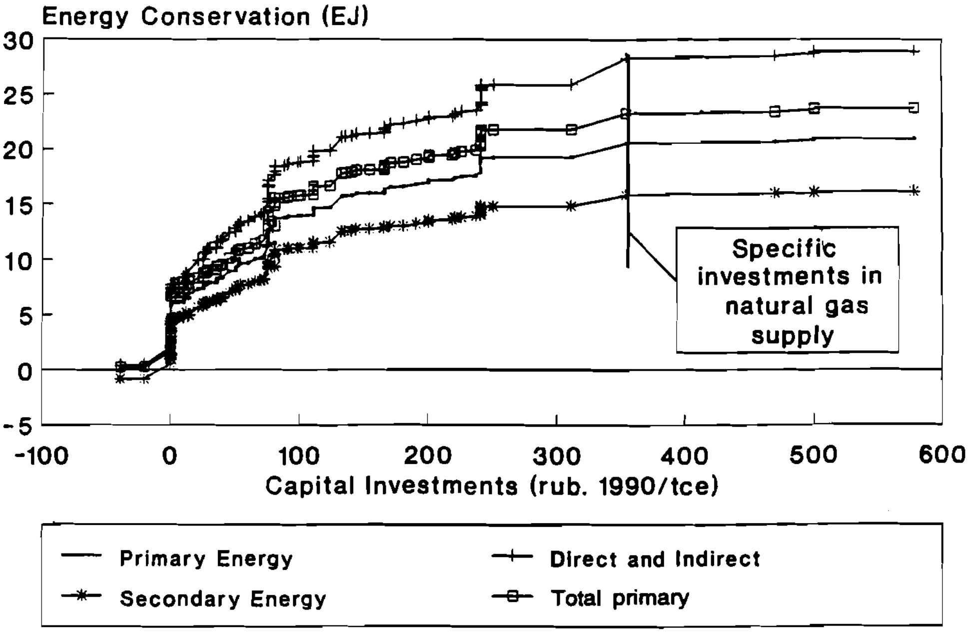

Figure 1. Costs of energy conservation in the former USSR: 1990–2005.

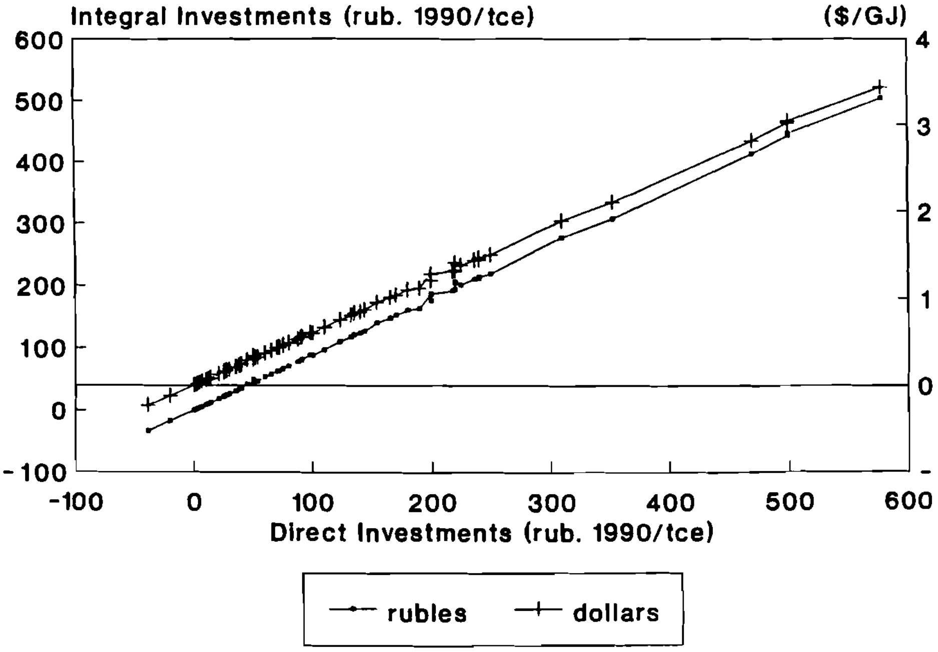

Figure 2. Energy conservation costs, total versus direct.

- 430 million tce/year could be saved up to the year 2005 with specific capital investments less than 7,500–9,000 rubles (1992)/tce/year or $38–45/tce/year (using a 200:1 ruble to dollar exchange rate).
- The total amount of investments needed for the whole potential realization equals 720–860 billion rubles at 1992 prices or $3.6–4.3 billion.
- The average direct investment cost of 1 tce/year of primary energy saved equals 1,830–2,200 (1990) rubles or $9–11 and the corresponding average total costs are 1,600–1,900 rubles and $8–10.
- The energy conservation potential in Russia and the former USSR is not only the largest in the world, but also the cheapest one. Russia is Saudi Arabia in the energy efficiency area. If a 20% discount rate is applied and the average lifetime of energy conservation measures equals 10 years, an average annualized cost of a barrel of oil equivalent saved in Russia is only 40 cents.

With $4 billion, GHG emissions equal to 1,290 of CO_2 equivalent could be mitigated in Russia, that is, at the specific investment cost of $3/t CO_2. It seems very difficult to find any other country with such a large and such a cheap GHG conservation potential and with a relatively well-educated labor force capable of developing and realizing programs to capture this potential.

4. Benefits of Energy Conservation Programs

4.1. Economic benefits from energy conservation

While the costs of energy efficiency improvement projects are attributable only to the direct technological energy conservation measures, benefits are attributable to both direct and indirect effects, as well as to structural change effects. Benefits from the latter are not considered here.

Energy efficiency improvements bring multiple economic benefits:

- reduction of energy bills for consumers;
- reduction of costs to provide the necessary amounts of energy services;
- reduction of pressure on the natural resources base;
- reduction of investments in the energy complex;
- reduction of investments in environmental protection due to a reduction of energy-related pollution;
- growth of the competitiveness of Russian goods and services on the international markets due to the reduction of production costs;
- growth of energy export potential without an increase in energy production;

- liberalization of investment and export revenue resources to increase the volume of consumer goods and services production, as well as residential building construction.

It has already been mentioned that 88% of the technological potential would be cost effective with a new set of energy prices, even within a two-year payback period. Therefore, energy consumers would gain substantially from investments in energy efficiency improvement projects. The total economic effect for consumers calculated as the difference between the costs of energy saved and the annualized costs of energy efficiency improvement measures in 2005 equals 1,050–1,269 billion (1990) rubles/year, or $5.3–6.3 billion/year.

While 430 million tce of primary energy would be saved, construction of 590 million tce of production capacity in the energy complex would be unnecessary. Coal production could be 200 million tons lower compared with the base case, with no effort in the energy efficiency direction, oil production could be 65 million tons lower, and natural gas production 218 billion m^3 lower.

Electricity generation would be 395 billion kWh lower in 2005. With an average utilization of 5,600 hours per year, this means that construction of 75 GW of new power-generation capacity would be unnecessary, which would cost not less than 1,500 billion rubles at 1992 prices.

Investments in the realization of the whole cost-effective technological potential for energy efficiency improvements in Russia would cost 720–860 billion rubles at mid-1992 prices, but would save not less than 5,250 billion rubles of investments in the energy complex in 1990–2005. Annual investments in the energy supply could be twice as low relative to the sum of industrial investments as they were in the late 1980s.

If technological energy conservation potential were to be realized completely by equal increases over the next 15 years, then the cumulative coal, oil, and natural gas consumption in the next 15 years would be correspondingly lower: by 1.6 billion tons, 525 million tons, and 1,750 billion m^3, respectively. More fuel would be available for future generations at a much lower cost.

Another alternative is to maintain the level of energy production and to export unused coal, oil, and gas abroad. The additional volume of fuels available for export would be 200 million tons of coal, 60 million tons of oil, and 200 billion m^3 of natural gas. These volumes are so large that international energy markets would probably be unable to absorb them completely. Therefore, some rational combination of both approaches should be implemented.

4.2. Social benefits

The social benefits of energy conservation are numerous: a higher level of employment; higher standards of living; better working and environmental conditions and therefore better health; and a lower share of the labor force working in dangerous conditions in deep coal mines or in the extremely severe climate conditions of Siberia on oil and gas wells and pipeline construction, etc. Only the first two benefits are considered here in more detail.

Every ruble invested in the production of energy efficiency equipment produces throughout the economy five times more jobs than a ruble invested in electricity generation and seven times more than a ruble invested in the oil and gas industry. Therefore, 720–860 billion rubles invested in energy will create as many jobs as 5,250 billion rubles invested in energy supply.

If some part of the investments released were to go into light industry, the food industry, and residential buildings construction, it would simultaneously create more jobs and increase the production of consumer goods, and as a result increase the level of well-being for the Russian population.

The difference between 720–860 and 5,250 billion rubles of investment equals 40% of the total capital accumulated in residential buildings. In other words, it is energy efficiency which could release the necessary resources to substantially improve present living conditions for the Russian population.

4.3. Environmental benefits of energy efficiency improvements

In the former USSR, economic growth with constant emphasis on production over efficiency led to the transformation of the formerly beautiful country into "toxic wasteland" (*US News and World Report*, 1992). Improvements in energy efficiency provide the cheapest and the most effective way of stopping further environmental degradation.

Reductions in the emission of different air pollutants and greenhouse gases were estimated (see Figure 3). The parameters of emission obtained in the process of collating the greenhouse gas emission inventory were used for direct greenhouse gas emission reduction estimates [CO_2, CO, NO_x, and CH_4 (Bashmakov, 1992)]. The realization of energy efficiency improvements would lead to the reduction of CO_2 emissions by 37%, of CO by 29%, of CH_4 by 37%, and of NO_x by 36%. Approximately a 14% reduction in ash emission and a 28% reduction in SO_2 could be achieved through energy efficiency improvements. Including indirect effects, GHG emission reduction would reach 42%.

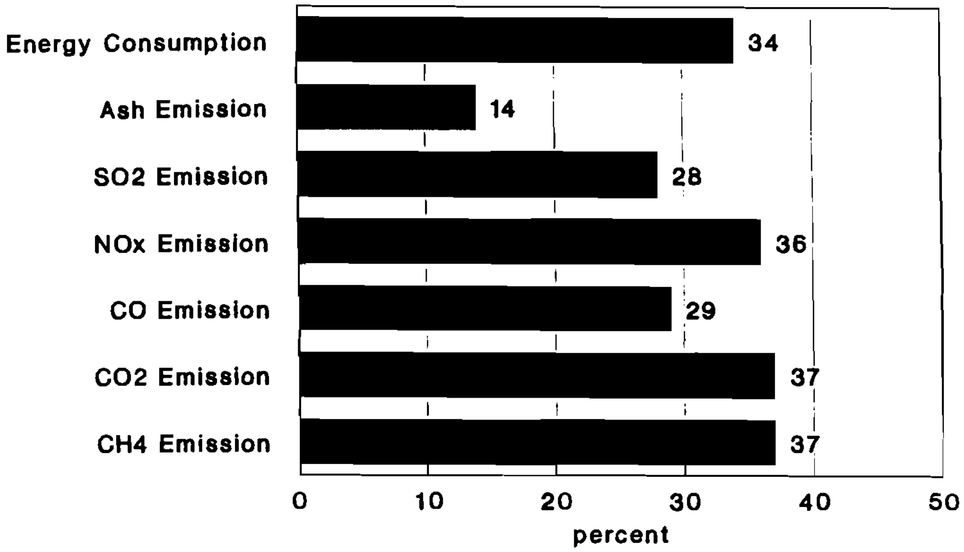

Figure 3. Ecological benefits of energy efficiency improvements; reduction in 2005 relative to 1990 (only due to technological energy conservation).

In addition to the substantial reduction of air pollution, much less land and water would be poisoned by energy supply enterprises, much less damage to wildlife and nature would occur as a result of lower coal, oil, gas, electricity, and heat production and long-distance transportation, and there would be a much lower risk of another Chernobyl-type nuclear disaster if aggressive policies on electricity conservation were to be implemented and unsafe nuclear reactors were allowed to shut down.

Environmental benefits are directly related to economic benefits. According to A. Styrikovich, to reduce SO_2 emissions to permitted levels would cost 1,500 billion (1992) rubles (Energy, Economy, Ecology, 1991). According to the former Soviet Minister of Ecology, N. Vorontsov, every year economic losses from soil, water, and air pollution cost 2,550 billion (1991) rubles (Vorontsov, 1991). Energy efficiency improvements could reduce these economic losses by 20–30% with no special investments. This also means that 720–860 billion rubles of investment in energy efficiency would replace not only 5,250 million rubles in energy supply, but also 1,500–2,000 billion rubles spent in the reduction of the level of pollution. With this effect taken into consideration the score in the competition for investments is 8:1 in favor of energy efficiency.

The Russian share of air pollution is approximately 65–80% (depending on the kind of pollution) of that of the former USSR. The reduction of emissions in terms of percentages is very similar to the former USSR numbers, but the reduction of pollution from oil and gas production and transportation – oil spills, methane leakages, gas flaring, pipeline breaks, and the like – would appear mainly in Russia. It is energy efficiency improvements which will allow Russians to breathe fresh air, drink clean water, and enjoy beautiful nature.

The threat of global warming stresses the responsibility of the Russian energy complex, not only for local environmental degradation but also for global climate change. The importance of environmental interdependence is now recognized around the world. In the process of negotiating international environmental treaties, governments should take actions locally, as well as internationally, to achieve globally desired results in reducing greenhouse gases with minimal global costs. Full implementation of the wide range of technological measures available to improve energy efficiency in Russia alone with very low costs could directly reduce CO_2 emissions by 1,290 million tons in the year 2005. Even if only half of this potential were to be realized it would equal 20% of the 1990 GHG emissions in Russia and would neutralize the trend toward growth of GHG emissions after the recovery of the Russian economy.

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Reconfiguration of the Russian Economy and Energy in Response to Environmental Problems

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1. Introduction

An ongoing growth of fossil fuel consumption in many countries leads to further degradation of the environment and in particular the atmosphere. A reduction in the energy intensity of the economy and a decrease in the fuel share (especially coal) of the energy balance are the most efficient ways of improving the negative tendency.

During the last 20 years, a transition to a post-industrial society started in the USA, Germany, Japan, and some other countries, and fuel consumption per GNP unit decreased on average by 1–2% per year. At least 50% of this reduction was due to structural changes in the economy. In the countries where industrialization is in progress, the energy intensity decreased much more slowly and the effect of the structural factor was not so profound, but it should be enhanced later on (Kononov *et al.*, 1992). However, the processes of structural change and the reduction of the energy intensity of the economy occur more slowly everywhere than the local and global degradation of the environment. Therefore, there is an urgent necessity to introduce constraints on atmospheric pollution or make them more strict. These constraints will affect the future evolution of energy consumption and production, as well as economic development.

The present paper analyzes some direct and indirect energy/environment relations in the conditions formed in the territory of the former USSR. Quantitative manifestations of these relations will naturally be different for individual countries of the Commonwealth of Independent States (CIS), but the qualitative results of the analysis will obviously be common. This is especially true for Russia whose share of GNP in 1990 accounted for 57% and whose resource consumption accounted for 64% in the total resource consumption of the USSR, with an approximately identical economy and energy structure in both countries.

Cost estimates given below correspond to prices in the early 1990s when the real exchange rate between dollars and rubles was about 0.8–1.1.[1]

2. Peculiarities in the Development of the CIS Economy and Their Effect on Air Pollution

The USSR economy in the late 1980s corresponded to the US level in the late 1960s and early 1970s in the main technoeconomic and structural characteristics, i.e., it was at the stage of completion of industrialization. This is evidenced by the GNP structure, in which the share of non-service sectors is higher than in the USA, almost twofold (*The Economy and Life*, 1990):

	USSR (1989)	USA (1987)
GNP	100	100
Industry	32	21
Agriculture	18	2
Construction	10	5
Transport and communication	6	9
Trade	12	16
Services	22	47

In the economic structure of Russia and many other CIS countries energy-intensive and environmentally harmful industries and production prevail. The following figures give an idea of the comparative adverse effect of different industries on the atmosphere from the viewpoint of the emission of greenhouse gases.[2]

	CO_2 emissions per unit of output (%)
Machine building	100
Chemistry	525
Metallurgy	835
Agriculture	295
Construction	145
Transport and communication	855
Trade	50

Due to high inertia and low efficiency, the USSR economic structure changed slowly and had a weak effect on the dynamics of its energy intensity

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[1] These figures were obtained using the available estimations of Soviet GNP in both currencies developed by Soviet and American experts. The same dollar/ruble ratio gives the total cost of Soviet exports and imports.

[2] The estimates are given for the conditions in Russia in 1990 accounting for the fuel and electricity intensity of products and the structure of energy consumption in industries.

(Kononov, 1990a). Consumption of primary energy per GNP unit in 1990 in the USSR was approximately 2.2 times higher than in the USA and 3 times higher than in Western Europe and Japan.

The peculiarities of the economy indicated here predetermine a sufficiently high level of atmospheric pollution. In 1990 stationary plants in the USSR territory released 56 million tons of pollutants in which there were 12 million tons of solid particles, 16 million tons of SO_2, 5 million tons of NO_x, 13 million tons of CO, and 10 million tons of hydrocarbons (*Statistical Annual on the Soviet Economy*, 1991). Emissions from motor cars accounted for about 35% of the total emissions for the country and were only 1.6–1.8 times lower than in the USA, although the number of cars in the USSR is 10 times less.

Harmful gaseous emissions per GNP unit in the USSR and Russia are approximately 2.4–2.7 times higher than in the USA and emissions of CO_2 are 2.3–2.5 times higher. The rates of pollution reduction in the CIS are lower than those in the developed countries.

Progress toward a market economy including an increase in economic efficiency and acceleration of economic restructuring can change this picture. However, history provides no clear precedents for the transformations which are to occur in the CIS. Even with the assumption that this transition will be free from catastrophic disasters, difficulties abound in establishing a "most likely" case.

The possible effects of three variants of the development of energy and the economy in the CIS on atmospheric pollution are considered below.

The first (pessimistic) scenario is characterized by the most durable economic crisis and relatively slow rates of subsequent development of the national economy. The levels of nuclear energy development and oil and gas production in this variant are minimal. According to the second (optimistic) scenario, the economic reforms are more successfully realized and the economic growth rates are almost twice as high as in the first scenario. The third (maximal) scenario suggests active participation of foreign capital with intensive introduction of new technologies, more successful conversion of military industries, and more active and efficient foreign trade. All these factors would provide approximately 3.3% of the mean annual growth rates of the GNP between 1991–2010.

Differences between the scenarios on fuel and energy consumption are much less than for the GNP value. The energy intensity of the economy is inversely proportional to the rates of economic growth and introduction of the economic mechanism. This is explained by the fact that the increased

Table 1. Three scenarios of economic development and energy use.

	Scenarios		
	1 (pessimistic)	2 (optimistic)	3 (maximum)
GNP	125	170	190
Energy/GNP ratio	93	74	70
Primary energy consumption	116	126	133
Production			
Electricity	136	154	160
Oil	84	88	100
Natural gas	142	150	155
Coal	119	127	129
Nuclear	129	185	185
Emissions			
CO_2	102	108	115
NO_x	70	71	73
SO_2	60	64	65

economic growth rates promote the updating of technologies and the development of new production with low energy intensity, and the market mechanisms stimulate energy conservation.

According to calculations, emissions of NO_x, SO_2 and other harmful substances will be reduced in all the scenarios and emissions of greenhouse gases will grow. Emissions of CO_2 by 2010 will exceed the level of 1990 by approximately 2.5% according to the pessimistic scenario, by 8% according to the optimistic scenario and by 15% according to the maximal scenario (Table 1).

3. Macroeconomic Effects of More Strict Environmental Constraints

Large-scale changes in the national environmental protection policy can change the prices of energy and other commodities and influence the development of many sectors of the economy, as well as the capital and labor markets.

In a simplified form these direct and feedback effects of carbon emissions reduction strategies are shown in Figure 1. These strategies may require capital investment in energy conservation or the development of new energy sources, above the base scenarios, which may lead to the additional production of specialized energy equipment, construction and other materials, and the development of an infrastructure. This in turn will require further use of labor, material, and energy resources. The equipment and materials required can be imported, but to increase exports to compensate for this it will be necessary to expand output, requiring additional capital investment and energy.

The cumulative effect of changes in energy development on the consumption of goods and services, prices, and the state of the environment is depicted by the quality of life. The dynamics of this index compared with the Base Case could determine social costs and be used as a criterion of the relative efficiency of the considered strategy. However, the problem of its quantitative estimation has yet to be solved. Therefore, the variation in consumption during the specified period, taking into account certain environmental requirements, is more likely be used as such a criterion.

The feedback effects of energy development alternatives on economic growth rates and energy consumption is non-linear in character and its slope largely depends on the conditions of national economic development, the rates of growth, the balance of investments, economic flexibility, and so forth.

A method for the analysis. Estimation of the possible change of final consumption and other macroeconomic indices require sequential solution of the following problems:

1. Identification of the possible and most efficient methods for reducing CO_2.
2. Determination of the impact of these methods on the development of the energy supply system (ESS) and its capital intensity. In this case one should take into account corresponding changes in the pollution of the environment with ash, sulfur, nitrogen oxides and other harmful components.
3. Determination of the impact of the above changes on the production structure of the national economy and macroeconomic indices.

The first problem is solved by simple comparison of the possible alternatives. Dependence of their comparative efficiency on the scales of application is also taken into account.

The second problem can be solved using the known simulation and optimization models of the ESS that take into account the energy/environment relations.

A simulation system of models, MAKROEN, has been developed in the Siberian Energy Institute for solving the third problem (Kononov, 1990b).

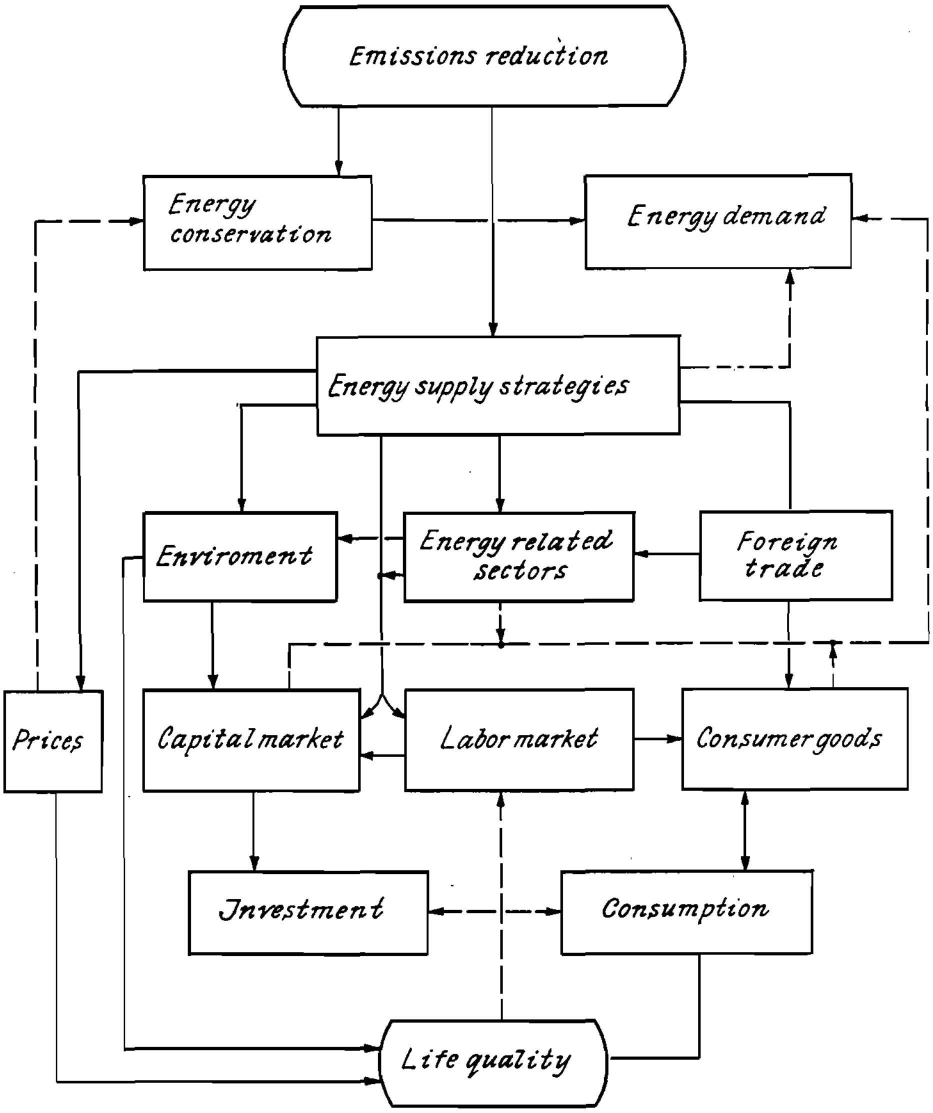

Figure 1. Impact of carbon emissions control strategies on energy production and the social sphere. Key: ←— direct impact; ←- - - indirect (feedback) impact.

Table 2. Characteristics of some CO_2 emission reduction strategies.[a]

	Maximal possible decrease, mill.tons C/year	Net marginal capital cost rubles/t-C
Substitution of gas for coal	40–75	360–580
Replacement of fuel-fired power plants by:		
Hydropower	7–9	480–790
Nuclear power	50–60	200–370
Solar photovoltaic power	2–3	1000–1300
Additional energy conservation:		
Moderate	50–100	100–220
Large	150–200	380–770
Maximal	250–300	1500–2250

[a] In addition to base scenarios.

Its main element is the dynamic macroeconomic model MIDL. It takes into account intersectoral relations and maximizes the private and governmental consumption within the given constraints on the development of individual branches, on the structure of a final product and labor resources.

Capital costs of CO_2 reduction. Emissions of CO_2 can be reduced by four main methods: (1) energy conservation; (2) substitution of coal by gas at the power and boiler plants; (3) substitution of fossil fuel by nuclear energy or renewable energy sources; and (4) cleaning waste gases to remove CO_2.

Table 2 presents the capital intensity of these methods applied in addition to the base scenarios.

The analysis shows that even under the most favorable conditions the installed capacity of hydro- and solar power plants can hardly be increased by 10–13 million kW by the year 2010, and thus cannot reduce CO_2 emission by more than 9–12 million t-C. Rapid development of nuclear energy might have yielded a larger effect at a lesser cost: but even with a positive attitude from the population to nuclear energy hardly more than another 35 million kW can be commissioned.

The case scenarios envisage very high rates of gas industry development. Therefore, gas production by 2010 will increase by more than 100–200 billion m^3. This would allow CO_2 emissions to be reduced by 40–75 million t-C, but would increase the danger of increased emission of another greenhouse gas – methane. According to our estimates, its leakages from the Russian

Table 3. Capital investment to cut CO_2 emission by 20% (billion rubles).

Structure	Scenarios 1	2	3
Direct investment			
Energy conservation	240	372	863
Energy supply	-82	-117	-183
NO_x and SO_2 reduction	-14	-17	-20
Indirect investment			
Energy conservation	36	78	214
Energy supply	-20	-27	-47
Total investment	160	289	827

gas supply system (including wells and distribution networks) exceed 3–4% of total gas production.

Energy conservation is the most large-scale and efficient method of reducing CO_2 emissions, but only to a certain extent.

Each particular condition has its own optimal level of energy conservation. In excess, the additional direct and indirect capital investments in energy conservation measures can overlap the saving of investments in the energy supply system and related branches, as well as in measures to reduce environmental pollution by ash, sulfur, and nitrogen oxides.

The base scenarios already incorporate the implementation of the cheapest methods of energy conservation by the year 2010. Further reduction of CO_2 emissions requires more costly energy conservation measures among which the thermal insulation of buildings and reduction of losses in the heat supply system play an important role. As the scale of energy conservation increases, its cost grows exponentially. At the same time the cheaper fuel is saved. This causes a nonlinear dependence of the total additional capital investments in energy saving, the ESS and related branches on the scale of the required reduction of CO_2 emissions (see Table 3).

Calculations have shown that a 10% reduction in CO_2 emissions by the year 2010 compared with 1990 will require an additional 50 billion rubles to be invested in the national economy in conditions of slow development, and 70–110 billion rubles at higher rates of development. For a 20% reduction in emissions the figures increase 3–8 times and exceed the total capital investments in energy supply and energy conservation envisaged in the base scenarios by 30–60%. In this case considerable capital investments would be required in the near future to extend the production of energy-saving equipment and the required materials.

Adaptation to a deficit of capital investments in the existing economy is realized by changing the production structure, increasing the share of accumulation in the national income, and reducing private and government consumption.

Macroeconomic costs of CO_2 reduction. Negative consequences for the economy and society due to the introduction of constraints on CO_2 emissions grow nonlinearly as these constraints become more strict, as follows from the figures below.

Reduction of CO_2 (mill. tons)	100	200	300
Losses from consumption fund during the period (rubles/t-C)	150–250	400–600	1,300 –1,800

Lower figures correspond to the scenarios with more efficient development of the national economy.

With increased rates of economic development the situation becomes more flexible and can be more easily adapted to the capital investment deficit. However, energy demand and CO_2 emission grow simultaneously. Therefore, it is difficult to realize the requirement to reduce emissions to a certain level (by the same percent compared to 1990) at higher rates of economic growth and this results in serious negative consequences for the society.

Figure 2 shows that a 20% reduction in CO_2 emission can result in a 5% reduction in private and government consumption in the pessimistic scenario, an 8% reduction in the optimistic scenario, and almost a 20% reduction in the maximal scenario.

4. Conclusions

Among different technical measures, energy conservation is the most effective way to bring about a large-scale decrease in carbon and other emissions from fossil fuels. Even this, however, would require large capital investment and might influence the economic welfare of the population.

High rates of economic growth and the successful solution of environmental problems can be achieved only with deep structural shifts in the Russian economy: and the more strict the requirements for environmental quality, the faster the transition to a post-industrial society has to be. This in turn requires acceleration of economic reforms and development of the market mechanisms in Russia.

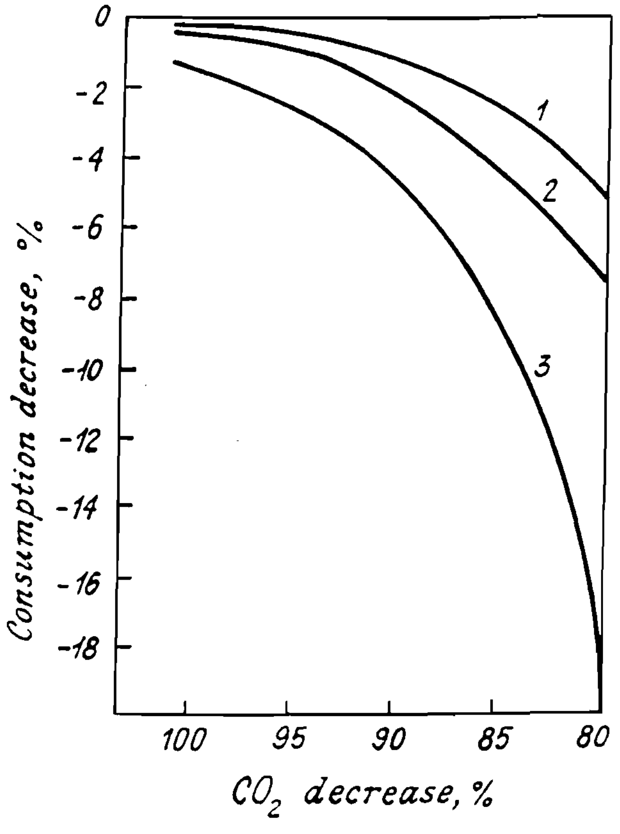

Figure 2. Impact of CO_2 emission limits on final consumption of goods and services. Scenarios 1, 2, and 3 are for GNP growth rates of 1.1%, 2.1%, and 3.3%, respectively.

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Study of China's Energy System for Reducing CO_2 Emission

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Abstract

Energy efficiency improvement and fuel substitution by low CO_2 emission and non-fossil fuel are the major technical strategy for reducing CO_2 emission. This paper introduces the potential for energy efficiency improvement in three energy-intensive sectors on the energy demand side – iron and steel, synthetic ammonia, cement – and possible ways of improving both energy conversion efficiency and energy substitution on the energy supply side. A dynamic optimization model of energy system technology options (ESTOM) is then established to study future energy systems' technology options and make a corresponding macro-economic assessment. Five scenarios of energy system development are studied, and the results show the primary energy composition, electricity composition, CO_2 emission, technology choices of energy conservation, etc., in the target year of 2030. The costs of reducing CO_2 emission in different ways are roughly estimated from the results.

Key words: energy efficiency, energy substitution, energy composition, CO_2 emission, technology options, scenarios, costs.

1. Technological Options for Reducing Energy-related CO_2 Emission in China's Energy System

Under the prerequisite that the future final energy demand is guaranteed, the energy system's major technical strategy for reducing CO_2 emission could cover two aspects. First, improving energy conversion and end-use efficiency, thus reducing losses in energy conversion and processing. Second, adopting a switch in fuel, developing fossil fuels with a low amount of CO_2 emissions (e.g., natural gas) and non-fossil fuel, as well as renewable energy with no CO_2 emission, to replace coal which has a high amount of CO_2 emissions.

1.1. Energy demand side

Final energy demand in the industrial sector accounted for nearly 70% of the total final energy consumption in recent years, and the iron and steel, chemical, building material manufacturing subsectors, etc., are the big energy consumers yielding energy-intensive products such as steel, synthetic ammonia, cement, etc. So technologies which aim to improve energy efficiency in these sectors are of significance for economic development and environmental protection.

Iron and steel

Iron and steel production is the largest energy consumer of all the industrial subsectors. Annual steel production in 1990 amounted to 66 million tons. Integrated energy consumption per ton of steel is 0.84–0.98 toe. China's average energy consumption per ton of steel is 0.27 toe higher than Japan's (in Japan's accounting method), that of China's large iron and steel enterprises is 0.16 toe higher than the Japanese value. The reasons are:

- Low share of fine material in raw material and fuel for iron and steel smelting.
- The majority of the fuel mix is coal.
- High iron/steel ratio in product composition.
- Bad recovery of waste energy.
- Backward management.

If proper measures for improvement were employed in the above factors, the comparable energy consumption per ton of steel would decline by 0.17 toe up to the year 2000, and decline by 0.25 toe up to the year 2030, which is close to the advanced level existing in Japan in the 1980s.

Synthetic ammonia

Chemical engineering is the second largest energy consumer in industry, and ammonia is the major energy-intensive product. The current annual production level is around 20 million tons, 1/4 of which is produced by large firms, the other 3/4 by medium and small ones. The two different kinds of enterprises have different scales as well as different raw materials. Large enterprises use natural gas or oil, whereas medium and small ones mainly use coal as the raw material. Due to the different raw material and processing techniques, the energy consumption per ton of ammonia in medium and small enterprises is 60–70% higher than that of large ones.

In recent years, the energy consumption of ammonia production has been rising slightly rather than falling. The reason lies in the rapid development of local enterprises, in particular, most of them are small ones. Out of all the enterprises, small ones have the biggest energy consumption. Therefore, with the rise of the share of small enterprises, the nation's average energy consumption of ammonia has gone up slightly.

In order to guarantee the food supply of China's increasing, huge population, agricultural production always plays an important role: the demand for chemical fertilizer will keep rising. Limited by the shortage of oil and natural gas, the pattern of using coal as the major raw material for synthetic ammonia will not change substantially. Besides, large numbers of medium and small enterprises will retain their significant share. Therefore, arduous work should be done to decrease the energy consumption of synthetic ammonia production. The main measures could include improving the production techniques of small-sized, synthetic ammonia plants and reinforcing management. In addition, the share of oil and natural gas should be increased as much as possible. The target is to decrease energy consumption by 10%, to 1.3 toe/t by 2000, and by another 10%, to 1.15 toe/t, by 2030.

Cement

China's annual cement production has reached more than 200 million tons. The annual energy consumption is 28 Mtoe, amounting to 0.14 toe/t. One-quarter of the total production is produced by large and medium enterprises, three-quarters is produced by small ones. Over half of the production in large and medium enterprises operates using the wet process, the energy consumption of clinker is 0.15 toe/t. The remaining part is produced using dry or half-dry processes, which are in fact improvements of the wet process. Thus the average energy consumption is 0.13 toe/t, far higher than 0.09 toe/t which represents the real level of the outside-kiln decomposition process – a dry process.

Due to the large amount of production and the high energy consumption, harnessing the energy-saving potential is of great importance in practice. The major measures for this should include increasing the share of production by large enterprises and adopting the advanced dry process. It is expected that the share of production by large enterprises would reach over 40% by 2000, of which 30% is produced by the dry process; and energy consumption declines to 0.12 toe/t. By 2030, the share of production by large enterprises would be over 60%, of which 80% is by the dry process, to enable the energy consumption to decline to 0.09 toe/t and then to reach the world's current advanced level.

1.2. Energy supply side

Improvement of energy conversion efficiency

Power generation. In 1990, China's thermal power generation amounted to 494.5 Twh, which required 136 Mtoe of fuel to be burned. The fuel burned per Kwh was 0.276 Kgoe, which is equivalent to a thermal efficiency of power generation of 31.2%. For China the amount of fuel burned per Kwh is about 70 Kgoe higher than that of the developed countries. In the fuel mix for thermal power generation, coal has a share of about 90%, which amounts to 270 Mt, and accounts for 1/4 of the total coal consumption or 1/5 of the total primary energy consumption. Therefore raising the efficiency of coal-fired power plants could play a significant role in the reduction of CO_2 emissions.

The major reason for China's high coal consumption in power generation is the considerably large share of small-capacity and out-of-date units. The composition of China's generating units, by capacity, in recent years is the following: 23% of units are under 50 MW, 40% of units are 50–200 MW, and only 37% of units are over 200 MW. Small generating units have a much higher coal consumption than large ones. In 1990 China's average coal consumption per Kwh supplied was 299 goe, whereas that of small units was as high as 388 goe.

Measures to reduce the coal consumption of thermal power generation could be summarized as follows:

- Imposing a restriction on the development of steam condensing units and the construction of steam condensing units with a capacity below 25 MW, developing co-generation, and reforming the current medium and small steam condensing units to heat-supply ones.
- Building high-coefficient, large-capacity and super-critical units and updating medium- and low-pressure units and out-of-date units. In the 1990s and beyond, a majority of China's generating units will be 300 MW and 600 MW units, and China will make a great effort to manufacture super-critical units domestically as early as possible. The coal consumption of these units could decline to 224 goe/Kwh, which is equivalent to over 38% heat efficiency of power generation.

- Renovating fans, pumps and other power devices used in thermal power plants so as to reduce the electricity consumption of the plants themselves.
- Developing and adopting more advanced power generating technologies such as pressurized fluidized bed (PFB), coal-gasification combined cycle technologies, etc. It is expected that PFB technologies could be applied on a large scale in China after the year 2000, and the total capacity adopting advanced technologies would equal a share of 2/3 of the total in 2030 which would result in reducing the fuel consumption of thermal power generation to about 210 goe/Kwh on average.

Development of coal gasification. China's energy supply will still be dependent on coal for a long time, and gas production from coal only amounted to 5.2 billion m^3 in 1990, corresponding to a coal input of 3.6 million tons which accounted for 0.4% of the total coal consumption. Hence the development of coal gasification technology, with high efficiency and on a large scale to convert coal into a clean and convenient fuel which may be used in the household and as a raw material in the chemical industry, is not only an important energy supply policy in medium- and long-term economic development but also one of the important policy responses for reducing CO_2 emission.

At present, demonstration plants of available gasification technologies have been put into operation in China, of which the Lurgi process is the typical type of city gas production. In addition, the HTW and KRW processes can substitute oxygen by air in producing industrial fuel gas. The TEXACO, SHELL, HTW processes, etc., can yield fuel gas which is used as feedstock in synthetic ammonia production. When compared with the out-of-date technologies, the efficiency of these advanced technologies could be 20–30% higher, and 25–34% energy conservation would be obtained under the same production scale.

Energy substitution

To promote the use of fossil fuels with less CO_2 emissions as well as non-fossil and renewable fuels with no CO_2 emissions for replacing fuels with high mounts of CO_2 emissions, is a major technical strategy in reducing CO_2 emissions in China's future energy industry.

Oil and natural gas. Compared with coal, oil and natural gas have a much lower amount of CO_2 emissions when burned to generate the same amount of heat. The CO_2 emission of natural gas is about half that of coal. According to the analysis of China's oil potential, the resources base is equal to 78.7 billion tons, but proven oil resources are not well prospected and production has not reached its peak. It is predicted that oil production would reach its peak around the year 2020 with annual production of 200–300 million tons.

At present, exploitation and production of natural gas are very weak, as little work has been done, and it seems that it will not develop rapidly in the near future. The other reason for the low natural gas output is probably that the ratio between oil and natural gas production is 10:1 (in heat equivalent terms), which is much lower than the world average of 1.5:1. Thus, this might show the comparative bright prospects for natural gas production in China. It is expected that natural gas production would increase from 15 billion m^3 in 1990 to 150 billion m^3 in 2030.

Hydropower. There are abundant hydropower resources in China. It is estimated that exploitable hydropower reaches a level as high as 380 GW, believed to be among the largest in the world. At present, only about 9% of the available hydropower is utilized: hydropower accounts for about 20% of the total power supply so far. Why didn't China accelerate the development of abundant hydropower to ease the power supply shortage situation a long time ago? The reasons might be as follows.

First, the distribution of China's hydropower resource is unbalanced. 67.8% of the available hydropower resources are concentrated in the Southwest. The major power load centers are in the eastern coastal areas, but the hydropower resources in these areas only account for 6.8% of the total. At present, many favorably situated power stations near major load centers are under construction. The hydropower resources not exploited are mainly distributed in the southwestern and northwestern areas. After hydropower has been exploited in these areas, electricity has to be transmitted to major industrial and household centers via a 1,200–1,500 km transmission line.

Second, there is a shortage of funds for power investment. In addition to the investment of the hydropower station itself, the costs of resettlement, compensation for loss of the inundated area and funds for the long-distance transmission circuit should also be included in the hydropower investment calculations. Thus, when compared with coal-fired stations, which have a lower investment requirement and shorter construction period, hydropower possesses a low competitive capability under the condition of limited power investment.

It is planned that the total installed capacity of hydropower by the year 2000 would reach 65–80 GW, with annual electricity generation of 240–290 Twh: and 180 GW of hydropower would be exploited by 2015, the hydropower resources in Eastern and Central China would be completely exploited then. The other resources would be adequately developed by the year 2030: a total of 280 GW or so. The remaining 100 GW of hydropower resources available are constrained by the geographic conditions and would be difficult to exploit.

Nuclear power. Nuclear energy is generally acknowledged to be the most realistic form of energy which can substitute fossil fuel on a large scale in the short term. At present, world nuclear power is equal to total installed capacity of 300 GW, and accounts for 17% of total electricity generation. In some countries, nuclear power accounts for more than half of the generation, e.g., it is close to 70% in France. Since the cost keeps rising and the public is greatly concerned about the impact of nuclear radiation on health and the environment, the development of nuclear power has slowed down in the past decade.

At present, the ever-increasing global concern for the threat of global warming and acid rain, as well as the progress in the design of a new generation of nuclear reactors with inherent safety, may lead to a further large-scale development of nuclear power stations.

The main goals of China's nuclear power development by the year 2000 are: grasping the manufacture of nuclear power stations as quickly as possible, and once self-reliant in design and manufacturing, getting prepared for the faster development of nuclear power beyond 2000. Efforts will be made to build nuclear power stations with a total capacity of 6 GW by 2000. According to a preliminary program, the total capacity of nuclear power would reach 40–50 GW by 2030.

Renewable energy. Solar, wind, ocean, geothermal energy, etc., belong to the class of renewable energies which do not release CO_2. Due to the global shortage of oil and natural gas in the next century, more and more emphasis will be put on the development of renewable energy in the world. Owing to the fact that the total renewable energy supply amounted to 0.3 Mtoe a year in the past few years in China, which occupied a very, very small proportion (0.04%) of the total commercial energy supply, and the consideration of financial and technological difficulties in its development, it could be imagined that renewable energy taken as an alternative energy source would not play an important role for a long period in China.

2. Energy System Technology Option Model

2.1. Brief description of the model

In order to evaluate the future energy system's technology options and the rational composition of primary energy, and to make a macro-economic assessment of the funds needed for developing the future energy system and the effect of CO_2 emission reduction, a dynamic optimization model of energy system technology options (ESTOM) was set up. The model goes up to the year 2030, the horizon is from 1990–2030 with a span of 5 years in each period. The main constraints of the model include:

- Constraints of the resources.
- Constraints of energy end-use demand.
- Constraints of the balance between the capacity and production of energy technology processes.
- Constraints of the transfer and replacement of the production capacity of energy technology processes.
- Constraints of the penetration of new energy technologies.
- Constraints of investment.
- Constraints of limitation on CO_2 emission.
- Constraints of the energy import–export balance.

The objective function of the model is the minimization of discounted supply cost of energy systems. The consideration of the energy technology options in the ESTOM model is shown in Figure 1. The energy end-use demand is given in terms of useful energy demand for households, and in terms of various types of final energy demand for the other sectors. In order to further evaluate and compare the development of the energy industry, energy substitution and energy conservation in the energy consumption sectors, to analyze the rational flow of investment and to assess macro-economic performance, some technical process options in the final energy consumption of several major energy-intensive sectors are also introduced, in addition to the consideration of the energy supply system.

The coefficients of energy production, conversion, and end-use shown in Figure 1 are listed in Table 1.

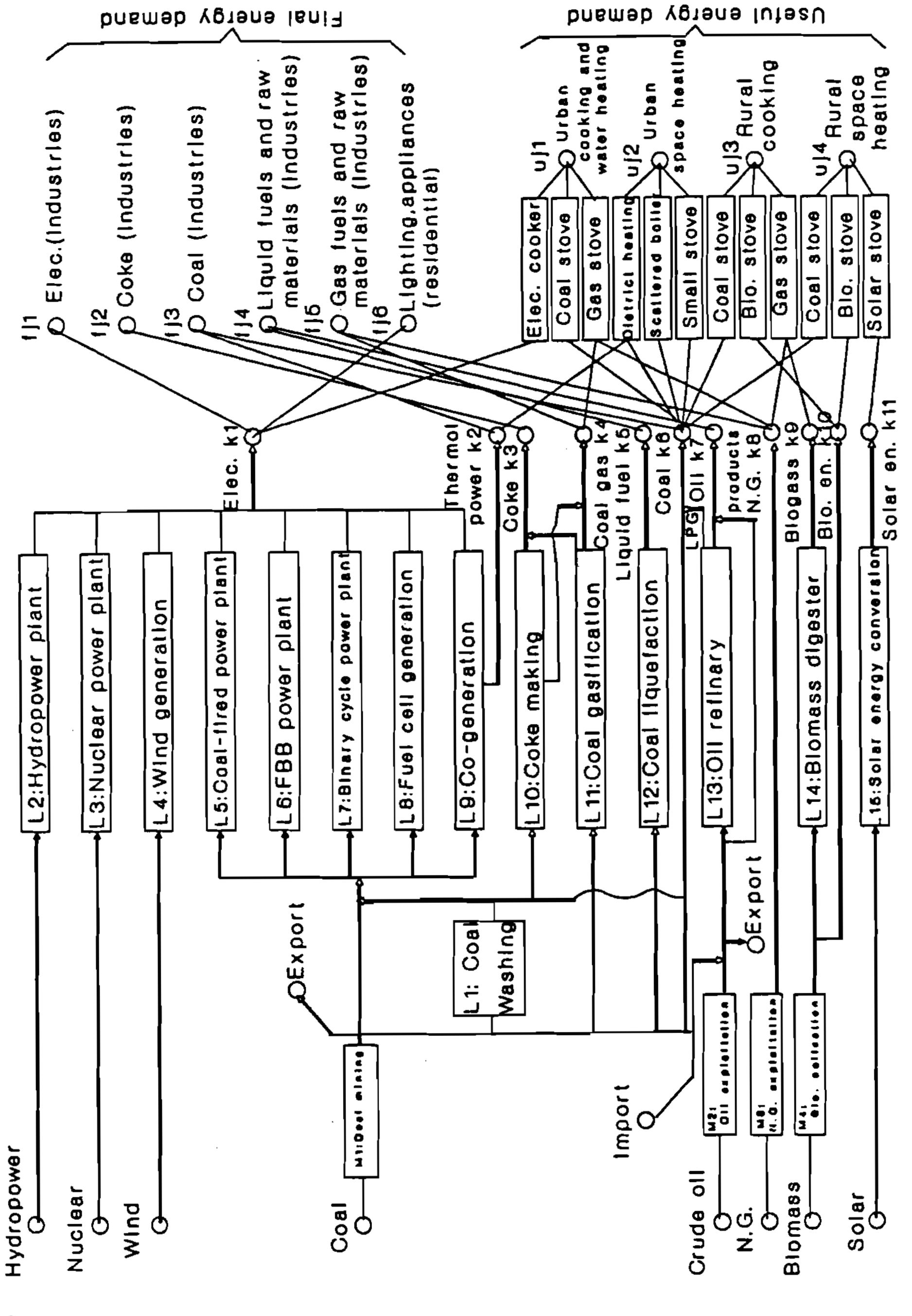

Figure 1. Energy flow network.

Table 1. Parameters of energy production and conversion (Yuan[a]).

Technology options	Specific investment	Variable operation cost[b]
1. Coal mining	180.80/t	53.55/t
2. Oil mining	937.60/t	109.00/t
3. N.G. mining	872.50/km^3	74.50 km^3
4. Trans. of coal (railway)	86.50/t	11.40/t
5. Trans. of oil (pipeline)	94.00/t	15.00/t
6. Trans. of N.G. (pipeline)	109.50/km^3	40.00/km^3
7. Coal washing	50.00/t	30.20/t
8. Coking	350.00/t coke	25.00/t coke
9. Oil refinery	350.00/t	75.00/t
10. Urban coal gas	2300.00/toe	200.00/toe
11. Coal liquefaction	1876.00/t	350.00/t
12. Hydro	4365.00/KWe	0.01/KWh
13. Nuclear	6500.00/KWe[c]	0.036/KWh
14. Wind	6000.00/KWe	0.01/KWh
15. Coal-fired power	1926.00/KWe	0.07/KWh
16. Pressurized fluidized bed	2640.00/KWe	0.01/KWh
17. Combined cycle	2855.00/KWe	0.01/KWh
18. Fuel cell	2000.00/KWe	0.015/KWh
19. Cogeneration	2400.00/KWe	0.009/KWh
20. Trans. and distri. of elec.	480.00/KWe	0.003/KWh
21. Biogas	3830.00/toe	50.00/toe
22. Solar	7715.00/toe	57.00/toe

[a] Investments and costs are expressed in Yuan (Chinese currency) at 1989 constant prices. The exchange rate in 1989 was US$1=Yuan 3.76.

[b] Excluding energy cost in the system.

[c] Including investment in fuel recycling systems.

2.2. Arrangement of scenarios of energy system development

On the basis of the analyses of the above technical energy measures, a number of scenarios are generated, and optimization and comparison are carried out by the ESTOM model, which include:

(a) Efficiencies of the technologies being developed for the future energy systems do not improve and primary energy composition remains unchanged.

(b) Efficiencies of the technologies being developed for the future energy systems rise gradually, but primary energy composition remains unchanged.

(c) Efficiencies of the technologies being developed for the future energy systems rise gradually, and primary energy composition switches toward an increasing share of non-fossil fuels or decreasing share of high-carbon-content fuels.

(d) Intense measures for energy conservation are employed in energy end-use sectors, so that the final energy demand correspondingly declines. Meanwhile, both the efficiency of the future techniques of the energy system and primary energy composition have substantial changes similar to scenario (c).

(e) Compared with scenario (c), CO_2 emission induced by future energy consumption is reduced by 10%.

For all scenarios, there are two options for the future final energy demand. First, if the economy were to grow at a higher rate. Second, if the economy were to grow at a lower rate.

Based on the above scenarios, computations are made for Case 1 and Case 2. The results will offer a series of conclusions, such as the future primary energy composition, technical options adopted in the energy system, CO_2 emissions of fossil fuels, energy import and export, foreign exchange balance, etc., in each of the scenarios, so that the effects of the future reduction of CO_2 emissions can be assessed from the viewpoint of the macro-economy.

2.3. Results and analyses

The lower economic growth scenario is taken here as the basic reference scenario whose results and their brief analyses are given below.

Economic growth and primary energy consumption

The data of economic growth and energy consumption of scenarios (c) and (d) under the premise of a low growth rate are given in Table 2.

Table 2 shows that the future annual rate of decline of energy intensity (energy/GNP) is over 1%, the energy elasticity is around 0.6–0.7. In (d), the energy elasticity during 2000–2030 is only 0.53, and the electricity elasticity is no more than 0.85. In the future energy system, the share of primary energy used for electricity generation will be rising, from the current 25% to around 40% by 2030. The energy intensity would decrease correspondingly, namely, fall by half from 1990 to 2030 (see Figure 2). In 2030, China's energy consumption per capita would be as low as 1,400 Kgoe, which is equal to the current average world level.

Table 2. Economic development and energy consumption (low economic growth option).

Item	Unit	Scenario (c)			Scenario (d)		
		1990	2000	2030	1990	2000	2030
1. Population	million	1143	1290	1450	1143	1290	1450
2. GNP	billion Yuan	1700	3045	8794	1700	3045	8794
3. Per capita GNP[a]	Yuan	1490	2350	6060	1490	2350	6060
4. Primary energy consumption	Mtoe	686	1002	1991	686	984	1752
5. Electricity consumption	TWh	619	1171	3332	619	1171	2905
6. Share of power generation in primary energy consumption	%	25.0	28.5	38.9	25.0	28.5	37.9
7. Energy intensity	Kgoe/Yuan	0.40	0.33	0.23	0.40	0.32	0.20
8. Electricity intensity	KWh/Yuan	0.36	0.38	0.38	0.36	0.38	0.32
9. Per capita energy consumption	Kgoe	600	776	1609	600	763	1208
10. Per capita electricity consumption	KWh	541	907	2297	541	907	2003
11. AAGR[b] of GNP	%		6.00	3.60		6.00	3.60
12. AAGR of energy consumption	%		3.90	2.30		3.70	1.90
13. AAGR of elec. consumption	%		6.60	3.50		6.60	3.10
14. Energy elasticity			0.65	0.63		0.62	0.53
15. Electricity elasticity			1.10	0.99		1.10	0.85

[a] GNP is at 1989 constant prices.

[b] AAGR means annual average growth rate.

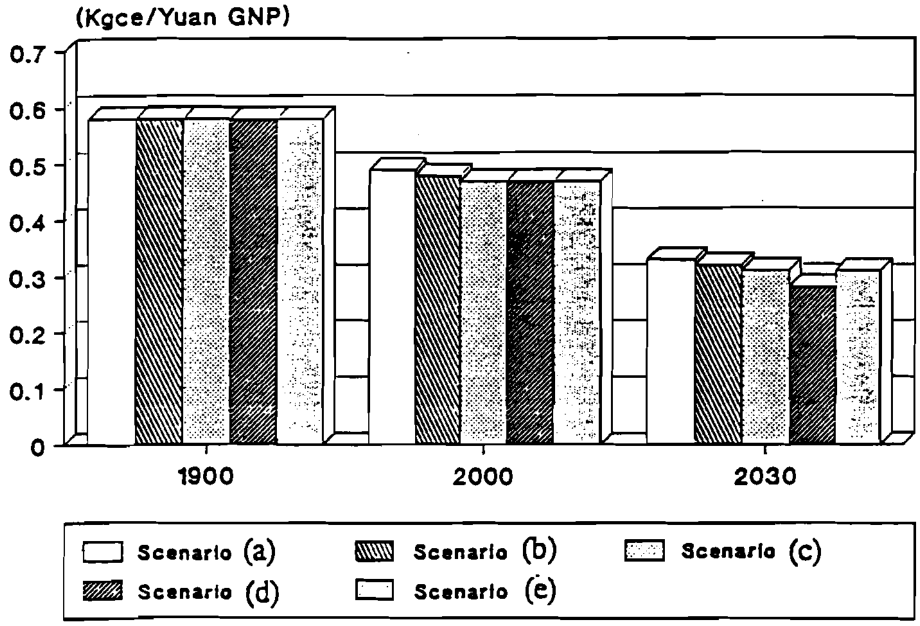

Figure 2. Energy intensity figures for different scenarios.

Table 3. Primary energy composition in 2030 (low economic growth option).

	Scenario (c)		Scenario (d)		Scenario (e)	
	Mtoe	%	Mtoe	%	Mtoe	%
1. Hydropower	234.2	11.8	234.2	13.4	234.2	11.9
2. Nuclear	69.9	3.5	69.9	4.0	268.8	13.7
3. Coal	1230.3	61.8	1032.9	59.0	1006.7	51.2
4. Oil	322.8	16.2	280.8	16.0	322.8	16.4
5. Natural gas	121.0	6.1	121.0	6.9	121.0	6.2
6. Renewable	12.4	0.6	12.4	0.7	12.4	0.6
Total	1990.5	100	1751.3	100	1965.9	100

Primary energy composition

The mix in the primary energy in the future energy system corresponding to scenarios (c), (d) and (e) is shown in Table 3 and Figure 3.

In the light of the characteristics of China's energy resources, China's primary energy composition, a majority of which is coal, will not undergo substantial change. Under the low economic growth premise, coal will form over 60% of the primary energy supply in 2030, but it will still have decreased

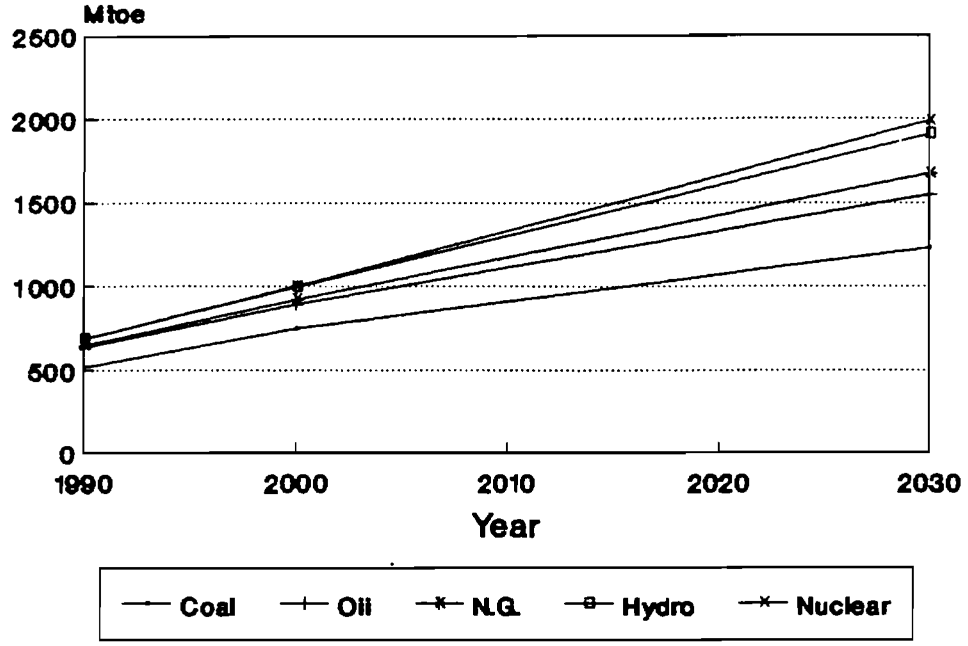

Figure 3. Primary energy composition of scenario (c); low economic growth option.

by more than 10% compared to the present level. The shares of non-fossil fuels, such as hydropower and nuclear power, in the future energy system will increase greatly: in 2030 the share of non-fossil fuels would go up from 5.3% to 15%, the share of natural gas from 2% to more than 6%, compared with those in 1990. A shortage of liquid fuels would become more and more serious in the coming years as the limitations of the oil resources in China were reached. China's oil exports will reduce gradually from their current level of about 25 million tons each year, and China would change from being an oil exporting country to a country with net oil imports around the year 2020. It is estimated that oil imports would be up to 70 million tons yearly in 2030. The oil share of the primary energy consumption will remain at the level of 16%, which is commensurate with the current one. Generally speaking, the change in the Chinese primary energy mix in the future will gradually reduce the CO_2 intensity of energy consumption (CO_2/energy) and contribute ultimately to the mitigation of CO_2 emission.

Table 4. China's electricity composition in 2030 (low economic growth option).

	Scenario (c)	Scenario (d)
1. Power generation (TWh)	3332	2905
2. Composition (%)		
Thermal	60.5	54.6
Hydro	29.4	33.7
Nuclear	8.8	10.1
Wind	1.4	1.5
Total	100	100

Electricity composition

In 1990, the total power generation capacity in China was 135 GW, and power generation was 618 Twh, of which hydropower made up 126 Twh and thermal power 492 Twh, accounting for about 80% of the total generation. Electricity composition in 2030 would consist of multiple components, shown in Table 4.

It can be seen from Table 4 that the share of thermal power will decrease, hydropower increase, and nuclear power emerge from nothing and develop greatly in the next century, i.e., account for about 10% of power in 2030. Wind power and other renewable energy generation would also develop in the next century but their position in the power system would still be weak. Since there will be a shortage of oil and natural gas resources, the development of power stations fueled with oil and natural gas will be restricted by state energy policies. Considering the facts, that the oil shortage will become more and more serious, and the increase in natural gas production will not be able to satisfy the growing demand for gaseous fuels and compensate the demand deficit caused by inadequate oil production, the development of oil-burning or gas-burning power stations will not be a major consideration in the future power system.

CO_2 emission induced by commercial energy consumption

China's primary energy composition, in which coal is the major fuel, will lead to a high CO_2 emission intensity. However, in 2030, the share of coal in China's primary energy composition will decrease, which will result in some decrease in the CO_2 emission intensity of energy consumption (see Table 5 and Figure 4): by around 14% in 2030 compared with 1990.

Table 5. CO_2 emission intensity of commercial energy consumption (low economic growth option).

			2030	
	Unit	1990	Scenario (c)	Scenario (d)
1. Commercial energy cons.	Mtoe	686	1990	1752
2. CO_2 emission	Mt-C	644	1615	1395
3. CO_2 emission of energy cons.	t-C/toe	0.94	0.81	0.80
2. CO_2 emission intensity	kg-C/Yuan	0.38	0.18	0.16

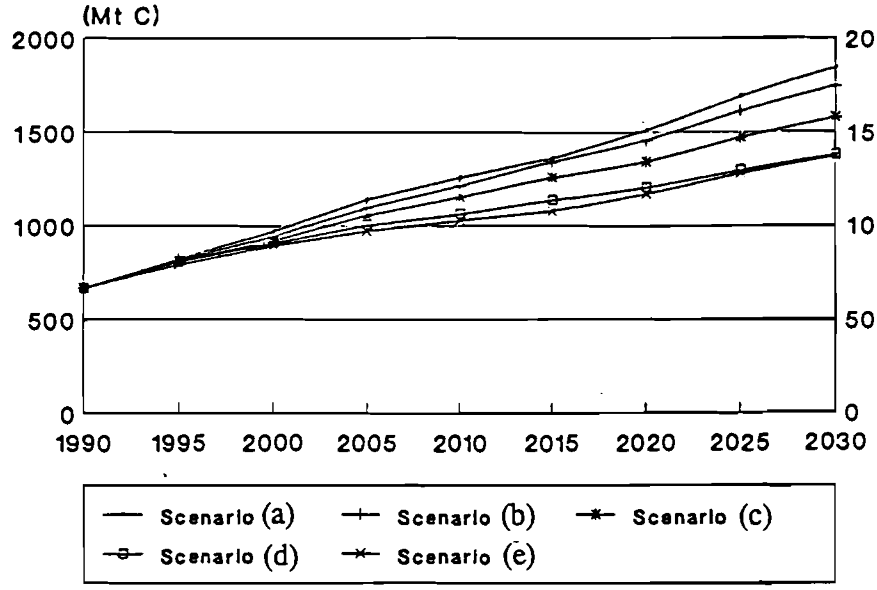

Figure 4. CO_2 emission (low economic growth option).

China's future economy needs to be developed at a rapid rate in order to meet the ever-increasing demand of material and cultural life, so energy consumption and CO_2 emission will increase at a reasonable rate, but the growth rate of the GNP will be higher than that of commercial energy consumption. In addition, since the primary energy composition will change, the growth rate of CO_2 emissions will be lower than that of commercial energy consumption (see Figure 5). The CO_2 emission intensity of the GNP will correspondingly decrease (see Figure 6). Taking scenario (c), for instance, the CO_2 emission intensity of the GNP will decrease from 1.43 kg-C/US$ in 1990 to 0.69 kg-C/US$ in 2030, a decrease of over half.

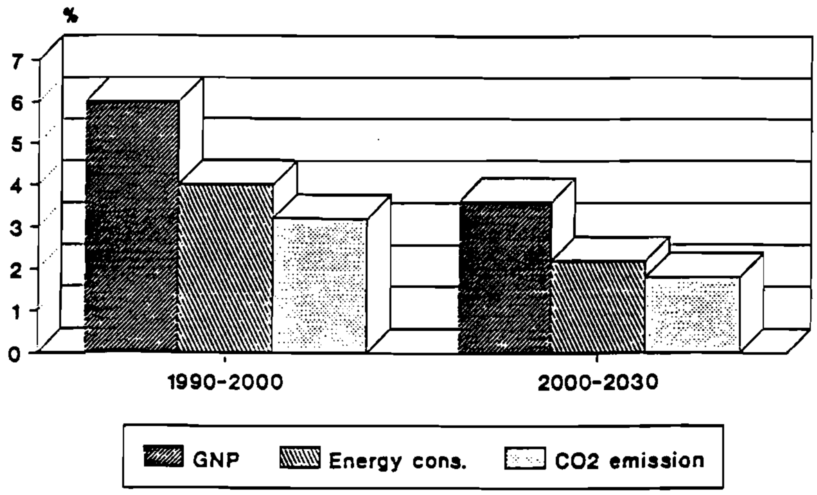

Figure 5. Growth rate of the GNP, energy consumption, and CO_2 emission.

Technology options for the energy system

The technology options for the energy system are shown in Table 6. The table illustrates that advanced power generation technology will be greatly developed in the next century, the development is mainly limited by technical maturity and commercialization. Imported, advanced technology will push up energy conversion efficiency. To meet the same final energy demand, the primary energy consumption of (c) is about 5% less than that of (a). In (e), with coercive measures for reducing CO_2 emission, nuclear energy should be vigorously developed as a substitute for coal: the nuclear power capacity would approach three times that of (c), so the share of non-fossil fuel in the primary energy composition is considerably raised. Due to resource conditions and technical limitations, the shares of hydropower, wind, and solar power would not have changed substantially. In view of China's condition as regards resources and technology, the development of nuclear power will play an important role in the reduction of the CO_2 emission intensity in a large scale and the improvement of the primary energy composition.

Investment in the energy system and macro assessment of mitigating CO_2 emission

Investment in the energy system and CO_2 emission in various scenarios are summarized in Table 7.

Table 6. Technology choices for energy conversion (low economic growth option).

Scenarios	(a)			(b)			(c)			(d)			(e)		
Year	1990	2000	2030	1990	2000	2030	1990	2000	2030	1990	2000	2030	1990	2000	2030
Hydro (GW)	33	66	191	33	66	190	33	66	280	33	66	280	33	66	280
Conventional (GW)	95	147.4	399	95	146.3	338	95	131	221	95	131	145	95	125	116
Nuclear (GW)							0	6	45	0	6	45	0	8	136
Press. fluid. bed (GW)							0	1	30	0	1	30	0	1	30
Combined cycle (GW)							0	0	14	0	0	14	0	0	14
Fuel cell (GW)							0	0	15	0	0	15	0	0	15
Wind (GW)							0	0.2	10	0	0.2	10	0	0.2	10
Cogeneration (GW)	11.7	20	75	11.7	20	75	11.7	20	75	11.7	20	75	11.7	20	75
Coal gasification (Mt)	2.8	4.2	80	2.8	4.2	80	2.8	4.2	80	2.8	4.2	80	2.8	4.2	80
Coal liquefaction (Mt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coke (Mt)	98	150	400	98	150	400	98	150	400	98	150	400	98	150	400
Oil refinery (Mt)	110	180	300	110	180	300	110	180	300	110	180	300	110	180	300
Biogas (Mtce)	0.7	0.85	2	0.7	0.85	2	0.7	0.85	2	0.7	0.85	2	0.7	0.85	2
Solar (Ktce)	25	40	160	25	40	160	25	40	160	25	40	160	25	40	160

Table 7. Investment in the energy system and CO_2 emission (low economic growth option).

	Unit	1990	2000	2030	Total for 40 years[a]
Scenario (a)					
1. Primary energy consumption	Mtoe	686	1026	2110	-
2. CO_2 emission	Mt-C	644	949	1876	47105
3. CO_2 intensity	t-C/toe	0.94	0.93	0.89	-
4. Investment in the energy system	B[b] Yuan	78.3	92.7	204.8	930.3
5. FE[c] demand for energy IM[d] and EX[e]	B Yuan	-20.2	-9.3	31.8	-150.9
Scenario (b)					
1. Primary energy consumption	Mtoe	686	1003	1994	-
2. CO_2 emission	Mt-C	644	937	1782	45567
3. CO_2 intensity	t-C/toe	0.94	0.93	0.89	-
4. Investment in the energy system	B Yuan	78.3	89.9	190.7	900.0
5. FE demand for energy IM and EX	B Yuan	-20.2	-9.2	32.6	-149.8
Scenario (c)					
1. Primary energy consumption	Mtoe	686	1002	1991	-
2. CO_2 emission	Mt-C	644	910	1615	43231
3. CO_2 intensity	t-C/toe	0.94	0.91	0.81	-
4. Investment in the energy system	B Yuan	78.3	99.5	201.1	986.3
5. FE demand for energy IM and EX	B Yuan	-20.2	-89.9	33.8	-148.1
Scenario (d)					
1. Primary energy consumption	Mtoe	686	984	1751	-
2. CO_2 emission	Mt-C	644	896	1395	40188
3. CO_2 intensity	t-C/toe	0.94	0.91	0.80	-
4. Investment in the energy system	B Yuan	78.3	90.4	164.4	935.3
5. FE demand for energy IM and EX	B Yuan	-20.2	-19.2	10.3	-180.6
Scenario (e)					
1. Primary energy consumption	Mtoe	686	987	1966	-
2. CO_2 emission	Mt-C	644	890	1380	39261
3. CO_2 intensity	t-C/toe	0.94	0.90	0.70	-
4. Investment in the energy system	B Yuan	78.3	125.9	236.0	1025.6
5. FE demand for energy IM and EX	B Yuan	-20.2	-3.2	43.7	-125.5

[a] Investment in the energy system is shown in terms of discount value back to the year 1990 at the discount rate of 10%.

[b] B = billion.

[c] FE = foreign exchange.

[d] IM = import.

[e] EX = export.

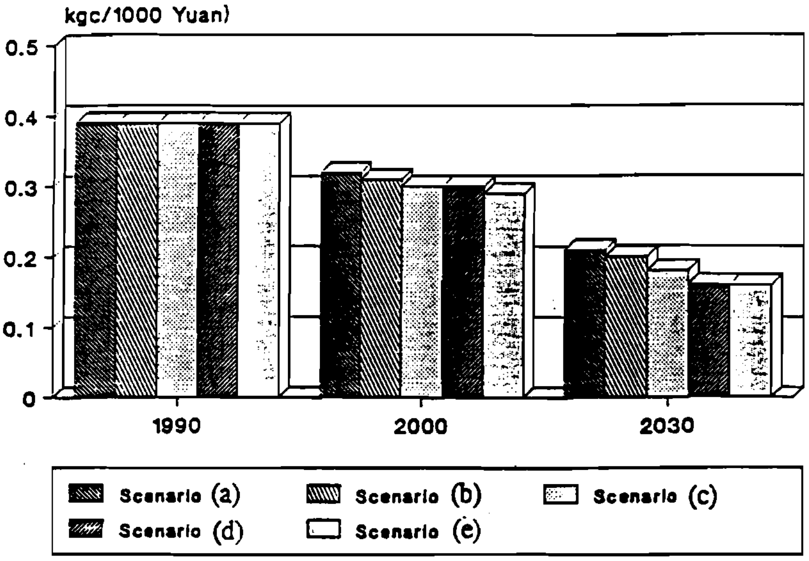

Figure 6. CO_2 emission intensity of the GNP.

Comparing scenarios (a) and (b), both primary energy consumption and CO_2 emissions are less in (b) than (a) due to efficiency improvement, e.g., total CO_2 emissions in 40 years would decrease by 1,538 million tons of carbon, thus total investment in the energy system during the 40-year period would be US$37 billion less in (b) than (a). Efficiency improvements in the energy system result in positive economic benefits of about US$24/t-C for a long-term period based on saving energy and reducing CO_2 emission. In conclusion, great efforts should be made to improve the efficiency of the future energy system.

A fairly obvious reduction in CO_2 emission will be obtained in (c) compared with (a) and (b), e.g., total CO_2 emissions during the 40-year period would decrease by 3,874 Mt-C, i.e., a cut of 8.3% compared with (a), and by 2,336 Mt-C, i.e., a cut of 5.1% compared with (b). However, investment in the energy system in (c) would increase by US$90.4 billion and US$127.7 billion in comparison with (a) and (b) respectively, i.e., an increase of 5.7% and 8.8% respectively, because of the much bigger investment costs for hydro and nuclear power than thermal power.

Conducting analyses on amounts of CO_2 reduction and the extra investment increase, it can be seen that the CO_2 reduction cost in terms of energy substitution would be US$55/t-C when a comparison is made between (b) and (c). However, when a comparison is made between (a) and (c), the CO_2

Table 8. Costs of CO_2 reduction measures.

Measures	Costs of CO_2 reduction (US$/t-C)
(1) Energy efficiency improvement	−37
(2) Energy alternatives	55
(3) Combination of (1) and (2)	24
(4) Acceleration of policies	65

reduction cost would then go down to US$24/t-C in terms of the comprehensive effects of both improvement of the efficiency of the energy system and energy substitution. Compulsory CO_2 emission reduction is considered in (e), based on (c). Since there would be a decrease in the CO_2 emission intensity of energy consumption, total CO_2 emissions of the energy system in 2030 would be cut down by 235 Mt-C in (e compared with (c) under the condition of satisfying the same end-use energy demand. However, total investments in the energy system and expenditure on energy import and export would increase by US$161 billion in 40 years in (e) compared with (c). This means that the specific investment in CO_2 reduction would be US$41/t-C on the basis of (c). It is clear from Table 3 that the major difference in primary energy composition in (e) compared with (c) lies in the replacement of coal by nuclear power: the share of nuclear power in 2030 rises from 3.5% to 13.7%, the share of coal drops from 61.8% to 51.2%.

In scenario (d), the implementation of some enhanced energy conservation policies in end-use energy sectors is considered, but the optimization of the energy system is similar to that in (c). The reduction in end-use energy demand, which is estimated to be 3,000 Mtoe in total, will result in a decrease in primary energy consumption and finally in a reduction in energy supply system investment of US$122 billion (total for 40 years).

In conclusion, the costs of CO_2 reduction in terms of cost analysis of the development of the energy supply system are summarized in Table 8.

3. Major Conclusions

The improvement of the exploitation and conversion efficiency of the energy system in terms of developing new energy technologies will reduce energy consumption and then CO_2 emission, at the same time reducing investment in the development of the energy system from the long-term viewpoint under the condition of satisfying the same end-use energy demand.

China should actively develop and import new energy technologies, such as advanced power generation technologies like pressurized fluidized bed, combined cycle, fuel cells, etc., whose efficiency can reach 40% and where the benefits for the energy system would be distinct after commercialization. However, it is very difficult for developing countries to raise such an enormous amount of funds for spending on new technology development.

Additionally, there is a long way to go in adopting new technologies, for instance, some new power generation technologies could not be put into operation until 2010 at least. Therefore, in order to reduce the global CO_2 emission level, developed countries should transfer advanced technologies to developing countries under the most favorable conditions and provide developing countries with favorable loans to study, develop, and diffuse new technologies to promote renovation of energy industries as well as to achieve the effect of reducing CO_2 emission as early as possible.

Alternative energy resources may be achieved by greatly expanding the capacities of hydropower and nuclear power. These are important measures to alleviate CO_2 emission. Additional investments are required to accelerate energy replacement as specific capital investments are much higher for hydro- and nuclear power than coal power generation. A nuclear industrial system and nuclear power stations are being established step by step in China. The goal of nuclear power development would be that the nuclear share of total power generation would account for 10% beyond the year 2030. China needs to set up an independent industrial system and master advanced technologies. This requires that China obtains assistance and support in terms of either technology or funds from around the world to conduct research and development.

More economic benefits could be achieved if investment funds are distributed for energy conservation in end-use sectors rather than for the development of the energy supply system, i.e., energy conservation in end-use sectors is of direct economic benefit and in accordance with the target of reducing CO_2 emission, and no additional investment is needed for CO_2 reduction. However, it should be pointed out that specific investment in energy conservation will rise constantly as the innovation cost of end-use technologies becomes higher and higher, and it will ultimately exceed that needed for the development of the energy system, then additional investment funds will have to be raised for reducing CO_2 emission by saving energy. In any case, promotion of energy conservation in end-use sectors, treated as either an important measure for CO_2 emission reduction or an option for easing the energy supply shortage in China, will be a key policy measure over a long period of time.

Review of Costs to Developing Economies

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1. Introduction

The costs of CO_2 mitigation for the developing countries present a set of complexities in analysis which differ in several ways from those related to the developed countries. This happens largely because several developing countries are still in the initial stages of establishing their economic infrastructure. This reality brings in an element of opportunity cost in terms of foregone possibilities for economic development which are generally not significant in the case of developed economic systems. Thus, for example, even if the mitigation strategies are funded on concessional terms (as is envisaged under the Framework Convention for Climate Change), the amortization and interest payments could impose a considerable burden on the developing economies.

One could carry this observation further by stating that given a reasonably long time horizon, the cost of several mitigation measures which appears to be low in the short run could actually turn out to be large in magnitude over a long time horizon. Conceptually, it can be seen that if a particular action results in reduction of CO_2 emissions at low direct cost, but over a period of time slows down the removal of poverty, then this could lead to large positive costs in the long run, for the following reasons:

1. Poverty and population growth have a strong and positive correlation.
2. Deforestation for fuel and fodder is also exacerbated by high levels of poverty.
3. With limited modern infrastructure, a developing country may not have the benefits of joint products to the extent that a developed country might have, as say in the case of reduced air pollution from public transport.

Undoubtedly, the metropolitan areas of the developing world are far more polluted in several cases than cities in the developed world but, despite rapid growth, the metropolitan populations in the third world are still a very small percentage of the non-urban populations in these countries. Hence, we cannot make sweeping generalizations about the benefits of reduced pollution, as one might be able to do in the case of developed countries. Besides, the costs of pollution, even for comparable physical levels, differ markedly between low income countries and richer societies. The absence of well developed data systems only exacerbates the problem of obtaining good estimates and neat conclusions.

In assessing CO_2 mitigation costs, there is a need, therefore, for developing methodologies that are comprehensive and reliable. There is a danger that with the growing global interest in quick numbers and pressure from several funding organizations to arrive at cost estimates for ranking opportunities, several misleading and inaccurate estimates of costs may be produced to serve the very limited purpose of global negotiations and financial transfers. However, such methodologies cannot be developed overnight, and would probably follow an evolutionary process. It is within this view that the Asian Energy Institute (AEI) has developed the order-of-magnitude estimates of costs for a number of member Asian countries and Brazil.

2. The AEI Study on Abatement Costs

It is generally predicted that several countries in Asia are likely to experience higher rates of economic growth than other major regions of the world, well into the next century. Largely on this account, it is also believed that CO_2 emissions in Asia will increase at a faster rate than in any other region in the world. Further, it has been contended that Brazil emits a large quantity of CO_2 attributable to deforestation. It is, therefore, important not only to study the sources and activities that produce these emissions, but also to evaluate potential solutions by which these could be minimized in cost-effective ways in the future.

The overall aim of the AEI study was to identify and evaluate existing and emerging technologies to limit CO_2 emissions for different sectors in the participating countries. These technologies, which may be implemented by the year 2000, were broadly classified as follows:

1. Improvements in energy efficiency and energy conservation.
2. A shift to lower carbon fuels such as natural gas and greater use of renewable resources such as hydro, solar, and wind.
3. Afforestation to sequester atmospheric carbon.

The broad plan of the study for each participating country was as follows:

The feasible technologies were first identified. Then the potential for adoption of each technology by the year 2000, and the related costs and CO_2

abatements made possible over the lifetime of the technology, were analyzed. A country-specific approach was adopted keeping in mind the overall growth and other policy concerns of each country. The concept of "cost" varied across the different country studies which are, therefore, not comparable in this particular aspect. The detailed results for the Bangladesh, Brazil, China, and India country studies are presented in the Appendix.

A cross country comparison reveals that in all of the countries included in the study the industrial sector consumes a major share of the total energy supply. Therefore, improvements in energy efficiencies in this sector could lead to significant savings in CO_2 emissions. Obviously, the particular measures adopted differ across countries. For example, in India improved housekeeping, installation of energy efficient equipment and better instrumentation may well result in saving 88 million tonnes of carbon (Mt-C) at an investment of $ 3.5 billion. In Brazil, the package for the industrial sector includes better choice of electric motors (in terms of their size), appropriate design of the internal distribution of electric network, installation of small size transformers in parallel with the large ones, and correction of load factor, requiring an investment of $ 1 billion and saving 4.8 Mt-C.

The electricity sector presents considerable opportunities for emission reduction in all of the countries studied. There is, for example, a large scope for reducing transmission and distribution losses which range from 22% in India to 40% in Bangladesh. Thus, if these losses were reduced to 16% by the year 2000 in India, an investment of $ 7.2 billion would yield a reduction of 210 Mt-C (assuming that the entire reduction in CO_2 emissions is attributed to reduced power generation by coal-based thermal plants). In China, an increase in the shares of pressured fluidized bed boilers and combined cycle plants (oil-based) which are more energy efficient than the conventional plants can together save 14.7 Mt-C at a total investment of $ 372 billion.

A wide menu of options to limit CO_2 emissions is available in the transport sector. In Brazil, transport plays a key role in minimizing carbon emissions. Currently, this sector accounts for 32% of the total carbon emissions. Fuel substitution, highway improvements, efficient diesel engines, and improvements in vehicle efficiencies are the main options available. The highway improvement program will cost as much as $ 2,954/t-c. In Bangladesh, the best way to conserve energy in the transport sector is through improved road maintenance as it is easily implemented. This would require an investment of $ 110 million and may save 1.2 Mt-C. Similarly, in India, enhanced mass urban transport (by increasing bus fleet and introducing metro rail systems) and increased rail freight movement could reduce significantly the energy consumption in the transport sector. The total investment of $ 48 billion will save 279 Mt-C.

In the residential sector, the strategy for CO_2 abatement comprises improvements in the energy efficiency of both cooking and lighting devices. Improvements in cooking devices range from improved firewood *chulha* in India, to coal saving stoves in China, *unnata chulhas* (based on woody biomass) in Bangladesh. There are large differences arising in abatement potentials across countries due to the difference in the fuel used. Thus, *unnata chulhas* in Bangladesh save only 2 Mt-C, whereas in China the improved coal stoves can save as much as 305 Mt-C. With respect to improvements in lighting devices in Brazil, by the year 2000, a stock of residential lamps that comprises 50% improved incandescents, 30% fluorescents and 20% compact fluorescents will save 2.33 Mt-C at a specific cost of $ 545/t-c. On the other hand, in India, replacing 50% of the incandescents by fluorescents and 50% of the incandescents by compact fluorescents, by the year 2000, could save 72.9 Mt-C at a total investment cost of $ 3.5 billion. The specific costs are $ 12/t-c and $ 86/t-c, respectively.

Sequestration of carbon through afforestation can be an effective strategy to limit CO_2 emissions. In fact, in India, afforesting one-third of the land mass by the year 2000 could save as much as 1,540 Mt-C. The specific cost would be $ 27/t-c. It is interesting that specific investment cost for afforestation are quite comparable for India, China and Bangladesh. In China, afforesting 16–17% of the land area (48–63 million hectares) would imply a specific cost of $ 26.3/t-c while in Bangladesh the specific cost is $ 19.2/t-c for afforesting 2.64 million hectares. However, in all three countries it is felt that afforestation programs require careful planning and management to be successful.

3. Conclusions

Two points need to be emphasized in establishing the significance of this study:

1. While the countries of Asia and Brazil have not been the major contributors to the increased atmospheric concentrations of GHGs in the past, their share is likely to increase relative to other regions in the future. Also, certain regions of Asia would perhaps be the most vulnerable to the adverse effects of climate change. For example, the Maldives and other coastal areas of South Asia with respect to sea level rise; parts of Brazil, China, and India with respect to impacts on agriculture; and

all the major river basins and deltas of Asia with respect to changes in precipitation patterns.

2. In any global effort to limit the emissions of GHGs and measures to reduce their concentration in the atmosphere, policymakers and leaders of public opinion can perhaps best be persuaded by analysis and research by credible institutions located in the concerned countries themselves, rather than relying on the work of scholars who may have little first-hand knowledge of conditions and policy concerns of the respective countries.

At the same time, a word of caution needs to be added. The estimates of the AEI study are by no means sacrosanct. They only represent a first cut estimate. Each of the options considered needs to be studied carefully with special attention given to the practical aspects of their implementation because, in the final analysis, that is the real solution to the problem at hand.

Appendix

Table 1. Specific cost of technologies for limiting CO_2 emission in Bangladesh.

Technologies	Carbon saved/fixed (MT)	Investment required ($M)	Specific cost ($/T)
Electricity sector			
T & D Loss	2.4	82.2	34.3
Industry sector			
Housekeeping + operation and Management	1.4	10.78	7.7
Combustion control	0.96	12.09	12.59
Simple retrofit	0.07	1.1	15.77
Process improvement	0.43	14.93	34.73
Cogeneration	0.55	92.809	168.74
Transport sector			
Road maintenance	1.18	110.0	93.0
Residential (rural)			
Unnata chulha	2.3	10.6	4.7
Unnata koopi	0.04	1.06	26.5
Afforestation	65.4	1255	19.2

Table 2. Strategies for abating CO_2 emission (up to the year 2000) in China.

	Potential (new added)	Total cost (in US$)	Lifetime (years)	Cumulative CO_2 reduction during lifetime (million T-C)	Specific cost of CO_2 reduction (US$/T-C)	Specific cost of CO_2 reduction (US$/T-C)
1. Coal-saving stove	64 MH	1.5/H	10	305	0.3	9
2. Retrofit of existing boilers	0.2 million	5,700	10	160	5	19
3. Pressured fluidized bed	1.5 GW	150/KW	30	9.5	12	19
4. Retrofit of existing kilns	46 thousand	65,000	8	92.5	19	35
5. Hydropower	40 GW	1,010/KW	50	1,900	20	18.4
6. Nuclear power	6 GW	1,185/KW	30	284	24	15
7. Solar heaters	1.9 M m^2	115/m^2	15	8	25	21
8. Afforestation	34 Mha.	370/ha.		690	30	26.3
9. Combining cycle	1.0 GW	290/KW	30	5.2	30	37
10. Wind generation	48 MW	1,270/KW	20	1.5	42	39
11. Solar P.V.	9.3 MW	815/KW	20	1.5	49	45
12. Urban gasification	49 MH	475/H.	30	360	50	42.3
13. Solar cooker	60,000	50	10	0.05	68	64

Notes:

1. US$ is at 1990 prices.
2. MN means million households.
3. Total cost includes investment cost, and operation & maintenance and fuel cost which have been discounted to the start of the year at the 10% of social discount rate.
4. Specific cost of CO_2 reduction in the fifth column covers the costs of capital investment, operation & maintenance, and fuels, but that in the sixth column only involves capital investment cost.

Table 3. Potential and cost of various CO_2 emission reduction options in India.

	Potential for reduction in CO_2 emissions over life (Mt-C)	Investment cost (billion US$)	Specific cost of CO_2 reduction (US$/t-C)
1. Increase in energy utilization efficiency			
1.1. Electricity Sector			
Electricity generation			
- Coal washing	192.25	0.58	3
- Replacement of coal TPS by gas combined cycle TPS	82.5	1.68	20
Transmission and distribution			
- Reduction in transmission and distribution losses	210	7.21	34
1.2. Industrial sector			
Improved housekeeping	28	0.38	14
Installation of energy-efficient equipment and better instrumentation and control	35	1.15	33
Upgrading industrial technology	25	1.92	77
1.3. Transport sector			
Enhanced urban public transport			
- Increasing bus fleet	9.35	0.83	88
- Metro rail systems	122.4	14.86	121
Enhanced rail freight movement	147	32.43	221
1.4. Agricultural Sector			
Pumpset rectification	50.6	5.1	101
1.5. Domestic sector			
Improved firewood *chulha*	6	0.08	14
Improved lighting			
- Replacement by tube fluorescent	37.2	0.44	12
- Replacement by compact fluorescent	35.7	3.06	86

Table 3. Continued.

	Potential for reduction in CO_2 emissions over life (Mt-C)	Investment cost (billion US$)	Specific cost of CO_2 reduction (US$/t-C)
2. Deployment of renewable energy technologies			
2.1. Biogas plants	18.40	6.41	348
Solar thermal systems	96	1.83	19
2.2. Electricity from other renewables			
Biomass	128.9	4.8	37
Wind	43.0	4.5	105
Small hydro	51.6	2.4	47
Sewage sludge	1.4	0.075	54
Distillery effluent	4.0	0.03	7
Municipal solid waste	4.6	0.32	70
PV pumps	1.1	0.09	82
Windpumps	0.3	0.055	182
Solar energy	5.73	3.60	628
3. Afforestation	1,540	42.04	27

Policy Instruments for CO_2 Mitigation: The Case of Brazil

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1. Introduction

The emphasis of the paper is on carbon dioxide (CO_2) emissions, the principal greenhouse gas (GHG), of which Brazil is a major contributor at a global level. It is widely recognized that the country's overwhelmingly large source of CO_2 emissions is from clearing of the forest land for other uses. Quantitative estimates of this source are issues of active debate so that precision is impossible. Despite the preponderance of deforestation in CO_2 emissions, this paper also considers fossil fuel emissions and the possibilities for its reduction. Some broad elements of a policy to decelerate deforestation, accelerate afforestation and to estimate the costs will be outlined as well as the potential critical connections with energy policy.

2. Quantification of Anthropogenic CO_2 Emission

2.1. CO_2 energy emission sources

In 1990, the total energy consumption in Brazil reached 183.7 million tons of oil equivalent (toe). Table 1 shows that 37% of Brazil's primary energy comes from fossil fuels, 26% from biomass fuels, and 37% from hydroelectricity. Notable aspects of this matrix are the preponderant role of hydro in electricity generation (94.4%), the relative large amount of biomass that is used at an industrial scale (alcohol, charcoal and wood – see Table 2), and the small penetration of natural gas. Energy system has resulted in the emission of approximately 51.6 million tons of carbon (tc) as CO_2[1] from the combustion of fossil fuels in 1990 (Table 3).

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[1] In this paper we are only considering carbon (C) emission due to CO_2 production. C equivalent emission due to other greenhouse gases are not quoted.

Table 1. Energy supply and consumption in Brazil, 1990 (in million tons of oil equivalent).

	Coal	Natural gas	Petro-leum	Subtotal fossil	Biomass	Hydro	Nuclear	Total fuel and other Primary[a]	Electricity
Gross internal supply	9.21	3.75	55.06	68.02	47.33	67.75	0.58	183.68	n.a.
Electricity generation	1.15	0	1.15	2.30	0.72	67.75	0.58	71.35	71.74
Other energy sector[b]	0.82	1.16	1.93	3.91	13.78	...	...	17.69	10.88
Non-energy use	0.06	0.59	8.94	9.59	0.33	...	...	9.92	0
Final energy demand	7.18	2.00	43.04	52.22	32.50	...	...	84.72	60.86
Residential	0	0.16	5.19	5.35	8.49	...	...	13.84	13.85
Commercial/services	0	0.07	0.65	0.72	0.18	...	...	0.90	12.09
Agriculture	0	0	3.16	3.16	2.15	...	...	5.31	1.83
Transport	0.01	0	26.77	26.78	5.65	...	...	32.43	0.34
Industry	7.17	1.76	7.28	16.21	15.92	...	...	32.13	32.85

[a] Gross internal supply and electricity generation include all energy consumption, thereafter electricity is excluded. The actual inputs for electricity generation are included in this column since these are different than the coefficient of 0.29 toe used in the last column – there is a slight discrepancy.

[b] Includes transformation and other losses and energy use (e.g., in refineries).

General notes: Data for fuel include derivatives of the primary energy source (e.g., coke from coal, alcohol from sugarcane). Electricity (last column) is calculated assuming that 1 MWh = 0.29 toe.

Sources: Boletin do Balanço Energético Nacional, 1991.

Table 2. Biomass supply and consumption, 1990 (in million toe).

	Wood for charcoal	Other wood	Sugarcane	Other[a] biomass	Total
Gross internal supply	12.31	15.14	18.14	1.74	47.33
Electricity generation	0	0.12	0.23[b]	0.37	0.72
Other energy sector[c]	6.43	0	7.41[b]	0.06	13.78
Non-energy use	0	0	0.33[d]	0	0.33
Final energy demand	5.88[e]	15.14	10.17	1.31	32.50
Residential	0.63	7.86	0	0	8.49
Commercial/services	0.06	0.12	0	0	0.18
Agriculture	0.01	2.14	0	0	2.15
Transport	0	0	5.65[d]	0	5.65
Industry	5.19	4.90	4.52[b]	1.31	15.92

[a] Basically pulp mill liquor.

[b] Sugarcane bagasse.

[c] Includes transformation losses and fuel use; specifically losses in producing charcoal from wood and alcohol from cane.

[d] Alcohol.

[e] Charcoal.

Source: Boletin do Balanço Energético Nacional, 1991.

Table 3. CO_2 emissions from energy consumption (million tons of carbon).

	Fossil fuels[a]		Biomass[a,b]	Total	
Gross internal supply	51.64	(59.77)[c]	11.44	63.08	(71.21)[c]
Electricity generation	2.24		0	2.24	
Other energy sector	3.29		3.31[d]	6.60	
Non-energy use		(8.13)[e]	0		(8.13)[e]
Final energy demand	46.11		8.13	54.24	
Residential	4.48		1.94	6.42	
Commercial/services	0.60		0.05	0.65	
Agriculture	2.72		0.44	3.16	
Transport	23.03		0	23.03	
Industrial	15.21		5.70	20.91	

[a] The conversion factors are: fuel oil, 72.6 tons of CO_2/10E12J; natural gas, 50.6 tons of CO_2/10E12J; coal, 100 tons of CO_2/10E12J; hydroelectricity, 0 ton of CO_2; fuelwood, 83.9 tons of CO_2/10E12J.

[b] Sugarcane and "other biomass" are assumed to have no CO_2 emissions. For wood it is assumed that deforestation results from 20% of residential, commercial and agricultural use; 60% of industrial use, and 50% of charcoal use. These shares are somewhat arbitrary as discussed in the text.

[c] Includes non-energy CO_2 equivalent in parenthesis [see (e) below].

[d] All due to conversion of fuelwood to charcoal.

[e] CO_2 equivalent of fossil fuel used, if burnt (see text).

For simplification at this stage of work, hydroelectricity is assumed to have zero CO_2 emissions.[2] Similarly, sugarcane supply (alcohol and bagasse) and "other renewables" (pulp industry liquors) are assumed to result in zero CO_2 emissions as shown in Table 3.

The emissions resulting from using wood are more problematic and vary widely. Most of the wood used in the residential and agricultural sectors do not exceed natural regeneration. In this way Brazil's fuelwood results in net CO_2 emissions. Industrial fuelwood use is more concentrated and leads to deforestation when supply depends on natural forest, as is often the case in Brazil. Again, information is scarce. It has been assumed that 60% of industrial fuelwood contributes to CO_2 emissions.

The conversion of wood to charcoal (the largest use of fuelwood) and its impact on deforestation is highly controversial. Only one-third of charcoal is supplied from planted forest and the rest being from clearing natural forest (mostly drier forests of the cerrado). Since land is cleared for grazing and agriculture, it is arbitrarily assumed that three-fourths of the charcoal from natural forest contributes to deforestation. Overall, 50% of fuelwood for charcoal (one-third of planted forest) is assumed not to result in CO_2 net emissions. Thus, it is roughly estimated that 40% of total fuelwood use results in CO_2 emissions of 11.4 Mtc or 22% of that resulting from fossil-fuel energy use. In practice, fuelwood is still far from being a fully renewable resource. At the same time, it can be seen that the contribution of fuelwood to deforestation is small – only 3–4% of a total of about 300 Mtc from deforestation. In 1990, the total energy emissions of CO_2 are thus estimated to be about 63 Mtc (71 Mtc if non-energy use of fossil fuels is valued at its combustion equivalent). This is roughly 470 kg of carbon per capita.

2.2. Deforestation and CO_2 emission

By far, the largest source of anthropogenic carbon dioxide emission in Brazil (mainly in Amazonia) is the result of deforestation. The carbon stock of seasonal and rainforest vegetation in Amazonia is estimated to range from 140 to 200 tc/ha, of pasture 10 tc/ha, and of cropland 5 tc/ha. The forest carbon stock may be adjusted by new information on below-ground biomass of vegetation. Changing landuse also reduces the carbon content of soil although less drastically. For example, in pastures, it may be about 10% or 10 tc/ha (Houghton *et al.*, 1991). Thus, assuming a deforestation rate in

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[2] An estimate for the US is 3 tc/GWh (USDOE, 1990) but any extrapolation for Brazil, especially for reservoir filling, would be arbitrary. A complicating factor is the release of methane from reservoir (Moreira and Poole, 1992).

Amazonia of 1.8 million hectares per year, the gross CO_2 emissions would be 250–360 Mtc (although not all appears immediately in the atmosphere). Emissions from deforestation in other regions of Brazil should be added to this, however, the estimates are not readily available. These will be substantially smaller but are not insignificant. At the same time, processes which accumulate carbon occur, for example, regrowth of natural vegetation on abandoned land or forest plantations. The rate of natural regrowth can vary by a factor of 20 in humid tropical areas depending on the local landuse situation (Nepstad *et al.*, 1990). The scale of countervailing sequestration is poorly understood. Despite these uncertainties, it is clear that emissions from deforestation dwarf those of fossil fuel use (60 Mtc) as well as from biomass use for energy (about 11 Mtc). The latter is consistent with the observation that fuelwood use is not a major factor in overall deforestation, although it may be significant in some regions (e.g., charcoal from cerrado; mangrove). The primary direct cause is the clearing for pasture and cropland, with logging often opening up the occupation process.

2.3. Energy policy and landuse trend synergism

The relationship between landuse trends and energy policy has not been fully explored in Brazil. Some points of interaction exist, of which the most important are the following:

- Fuelwood for industry and charcoal. This is the most important direct energy-related source of deforestation. The key issue is whether a decisive move to put these uses on a sustainable basis is justified or whether they should be phased out;
- Hydroelectric development in Amazonia. The relative priority, rate of development and ultimate potential may all be influenced by a strategy to minimize deforestation. The major concerns are infrastructure and migration occasioned by hydro. Some projects may provoke deforestation while others help to decrease it, for example, on the Tocantins river (Moreira *et al.*, 1990). This effect is likely to be larger than differences in direct CO_2 emissions from electricity which results from alternative scenarios of hydro/thermal generations and is always considered in planning electricity supply.
- Availability of electric power for isolated communities. In Amazonia, above all, power shortage is a constraint in economic development which may favor more extensive resource exploitation (Poole *et al.*, 1990).
- Fuel subsidies, especially for diesel, in Amazonia (Reis, 1991).

The common denominator of CO_2 emissions reinforces the need to consider energy, landuse and regional development altogether.

3. CO_2 Mitigation Strategy

3.1. Energy conservation

Energy conservation was first introduced in the electricity sector as an important tool for reducing the strong demand on new hydroelectric plant construction which increased five-and-a-half times of the total installed capacity during 1970 and 1990. The initiative began at the University of São Paulo as early as 1980 and at Companhia Energetica de São Paulo in 1984. The aspect of CO_2 emission was not seriously considered even as a side effect since 95% of electricity produced is from hydro. In 1985, the interest in electricity conservation motivated the federal government to create a national program, PROCEL. Its activities along with the high involvement of some academic institutions caused the issue of CO_2 avoidance to be easily incorporated as another argument for energy conservation (Geller and Moreira, 1991).

As observed from the profile of electricity production in Brazil (see Table 1), it is out of the question to practise conservation mainly as an instrument to decelerate the installation of new energy supply facilities rather than as an instrument to reduce CO_2 production. New energy supplies must be provided in the near future to fulfill the necessity of the growing population but, more than that, to provide more comfort to the present population. In the case of electricity, the astronomical cost of new hydro projects along with the present high cost of money are strong arguments for significant changes in the traditional hydroelectric approach.

More recently, the increase in natural gas supply is being considered as a better economic solution for electricity production. National and imported coal, presently responsible for less than 2% of the national electricity supply, has a chance of becoming a more important source of electricity generation. Within this framework, electricity conservation can also become a tool to avoid explosive growth of CO_2 emission in the long term. The concept of energy conservation for other sources of energy is relatively new and has gained importance only in the last five years since global warming has become a major concern. Fossil fuels are used mainly in industrial, transportation and household sectors. Recently, an organization similar to PROCEL was created at the federal government level. This entity, CONPET, has a major responsibility to improve energy uses from oil and natural gas. Obviously,

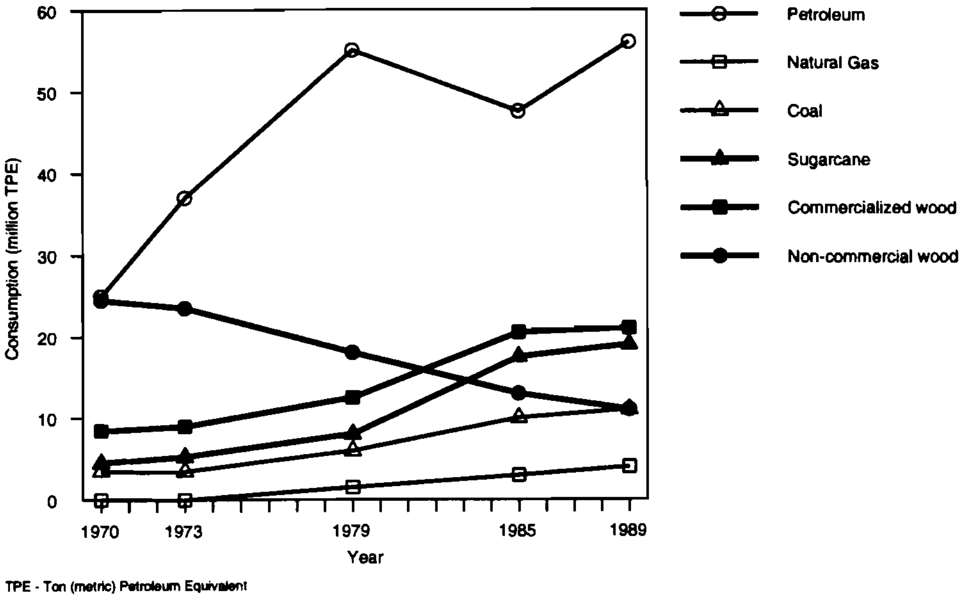

Figure 1. Consumption of primary fuels.

the well-designed policies in this area will have a greater impact on CO_2 mitigation than the efforts of PROCEL.

3.2. Renewable energy supply

Traditionally, Brazil and other countries in Latin America have invested heavily in hydroelectricity because of the following reasons:

1. Availability of water resources compared with other regions of the globe (Table 4).
2. Low investment cost for exploiting the best water resources opportunities.
3. Policies defined by Multilateral Development Banks (MDB) which prioritize large projects due to convenience in administration and the guarantee that investment will be fully used since operational costs are minimal.

Biomass is also an important source of fuel for the country. Contrary to the general trend in the world – relative participatory reduction in the energy matrix as countries develop – this has not been observed in Brazil due to high commercial use of biomass (mainly, charcoal, ethanol sugarcane bagasse, and pulp residues). Figure 1 illustrates the decline in non-commercial uses being off-set by the increase in commercial uses.

Table 4. Annual world water balance.

	Surface area	Precipitation		Evaporation		Runoff[a]	
	(10^6 km^2)	(mm)	(10^3 km^3)	(mm)	(10^3 km^3)	(mm)	(10^3 km^3)
Europe	10.5	790	8.3	507	5.3	283	3.0
Europe	43.5	740	32.2	416	18.1	324	14.1
Africa	30.1	740	22.3	587	17.7	153	4.6
N. America	24.2	756	18.3	418	10.1	339	8.2
S. America	17.8	1,600	28.4	910	16.2	685	12.2
Australia and Oceania	8.9	791	7.1	511	4.6	280	2.5
Antarctica	14.0	165	2.3	0	0	165	2.3
Total land area	149.0	800	119.0[b]	485	72.0	315	47.0[b]
Pacific ocean	178.7	1,460	260.0	1,510	269.7	-83	-14.8
Atlantic ocean	91.7	1,010	92.7	1,360	124.4	-226	-20.8
Indian ocean	76.2	1,320	100.4	1,420	108.0	-81	-6.1
Arctic ocean	14.7	361	5.3	220	8.2	-335	-5.2
Total ocean area	361.0[b]	1,270	458.0[b]	1,400	505.0[b]	-130	-47.0[b]
Globe	510.0	1,130	577.0	1,130	577.0	0	0

[a] Outflow of water from continents into ocean.
[b] Small differences are due to roundoff.
Source: Atlas (1977).

The global environment advantages in using hydro and biomass have been considered in market promotion only in the last five years. Even then, the advantages are not fully recognized since greenhouse gas emissions from inundated biomass rich areas exist, and one-third of the total commercial biomass used is delivered from native forests (see Section 2.1). Also, local environment aggressions are reported due to ethanol production and water dam construction. Nevertheless, the global benign effects of these energy sources are well recognized. CO_2 production and the localized problems were also reduced mainly in the ethanol producing industries.

3.3. Forest preservation

Deforestation releases CO_2 in the atmosphere because trees and forest soils hold 20–50 times more carbon than the crop or pasture system which typically replaces forests when they are cut (Houghton, 1991). Estimates of carbon emission due to deforestation in the tropics are highly uncertain due to three main factors: rates of forest loss and clearing versus degradation, carbon stocks in various types of forest and soils, and the fate of deforested land, especially whether forests are cleared permanently or for shifting cultivation in which short periods of cropping alternate with long fallow intervals during which the forest regrows.

In Brazil, concern with regard to forest preservation is focused on the closed forest of the Amazon. Past policies favored the exploitation of the Amazon for pasture and cropland. Logging and hunger for land by small farmers are also responsible for the usage of the forest area.

Reduction in financial and fiscal incentives for commercial activities, decrease in the country's economic activity, enforcement of existing legislation, and strong publicity in the importance of green areas preservation have decreased the rate of deforestation in the Amazon. Measurements by satellite have shown an average annual deforestation rate of 1.8 Mha in the last 2 years. Such efforts are expensive and require fundamental policy changes at every level from international and national to the individual. Macroeconomic modeling suggests that for every 1% reduction in deforestation, the gross domestic product (GDP) in the Amazon State would have to fall roughly 1.7% (Reis, 1991). While pessimistic in this sense, the model suggests a first approximation of CO_2 abatement cost at the margin which is roughly US$4/tc according to the model's author. This low cost (equivalent to a tax of 0.50/barrel of oil) is probably an upper limit since the model assumes historical relationships.

3.4. Creation of CO_2 sinks

The possibility of using fertile land and abundant water together with tropical temperatures to grow artificial forests to enable to store CO_2 is continuously under analysis (Marland, 1988; Myers, 1989; Noordwijk, 1989; Trexler *et al.*, 1989). It is unquestionable that advanced forestry, science, and good management can make afforestation growth rates mentioned in the above references look conservative. In Brazil, eucalyptus plantations produce over 30 t/ha/year, with records over 70 tons (Hall and Rosillo-Calle 1990). In

1989, a project known as FLORAN was presented with an objective of reforesting and afforesting a total of 20 Mha with a mix of native and exogenous wood tree species (Ab'saber *et al.*, 1989).

4. Energy Conservation Policies

Developing countries need energy services to raise productivity and to improve the standard of living. But the traditional way of meeting these energy needs, by increasing energy supplies with little attention to the efficiency of energy use, raises serious financial, institutional and environmental problems. The magnitude of these problems underlines the need for improving efficiency with which energy is currently used and produced in developing countries. While the advantages of energy saving technologies are usually recognized, the common perception is that its widespread adoption will not occur because of high initial cost which is an important consideration for poor, heavily indebted countries. Studies show, however, that when the capital requirements of both supply and end-use technologies are combined on a system-wide basis, highly efficient technologies reduce overall capital costs (Geller, 1990a; Goldemberg *et al.*, 1988). The higher capital costs of the energy-efficient end-use equipment are offset by lower investment required for electricity generation.

The rapid adoption of these technologies is, however, being retarded by a variety of technical, institutional, economic and financial barriers that occur throughout the entire technology transfer and diffusion process.

Technical:	Many improved technologies, although well established in industrial countries, may not be well adapted to conditions in developing countries. People in developing countries may not be aware of new technologies or have access to the training necessary to make effective use of new technologies.
Institutional:	Both public and private developers are organized to fund large-scale conventional energy supply expansion rather than demand-side energy efficiency projects. Rules and practices in the critically important electric power sector do not often weigh efficiency and renewable energy equally with conventional large-scale supply options in providing energy services.

Economic and financial:	Energy prices are frequently subsidized in developing countries and therefore provide neither the economic incentives for energy-efficient equipment nor adequate revenues for system expansion. Particularly in poor countries, consumers may not have access to the capital needed for high initial costs of energy-efficient equipment (even though these technologies reduce costs to the user over the product's lifetime and lower overall capital costs for the nation).

4.1. Technical policies

(a) Publicity Campaigns

Probably, the most widespread publicity campaign for energy conservation was carried out mainly through television by the incandescent light bulb manufacturers. Sponsored by Philips and General Electric, the campaign was launched to introduce an incandescent bulb that was 10% more energy efficient. The motive for the private interest is not at all clear, but it can be attributed to the interest of the government to conserve energy in addition to commercial concern regarding the existence of official price control regulations. The campaign called the attention of the public to the importance of conserving energy and was also implemented by the federal government during 1988, designated as the Year of Energy Conservation.

- At the state level, a campaign was carried out by the state of São Paulo with the help of the state utilities. The campaign was based in popular fairs and designed to attract the people by presenting efficient products and technologies, and extensive use of computer softwares that could evaluate the cost/benefits of a particular technology.
- PROCEL spent over half of its budget for the period 1986–1989 on education, promotion, and information dissemination (ELETROBRAS, 1990).
- Other utilities and energy agencies also funded information and education programs.
- Universities introduced graduate courses in energy planning with emphasis on energy conservation. The first one which started as early as 1982 was at the Federal University of Rio de Janeiro, followed by the University of Campinas in 1987, and the University of São Paulo in 1989. These courses were attended by a variety of students, a significant number of which were professionals working in utilities and oil industries.

- Seminars and workshops sponsored by the federal government, the National Congress, public utilities, and private enterprises are frequently held. Two major events (held biannually) are the Congresso Brasileiro de Energia and Congresso Brasileiro de Conservaçao de Energia.

Manuals and other educational materials in energy conservation have been produced for all consumer groups (Agencia, 1990). Data banks with information on energy conservation are available for all users with remote access to computer modem (Agencia, 1990). Studies and publications have been stimulated by sponsoring organizations, giving premium to the best ones. The most well known were the Pirelli premium in Energy Conservation and the Energy Conservation context of Secretaria de Ciencia e Tecnologia. Some daily newspapers have often carried out information on energy conservation and its achievements, and technical journals have advertised products based on its energy efficiency.

Organizations created by the federal government have played an important role in disseminating information. The Executive Group for Rational Production and Use of Energy (GERE), an inter-ministerial organization quite active in 1990–1991, created a special program to disseminate information to all public institutions. The internal commission for energy conservation (CICE) was officially installed in all public institutions with a demand for electricity and/or oil derivatives above a minimum level (Moreira and Iturra, 1992). The members of the commission (consisting of 5 or more) were instructed through workshops and direct mail about available technologies and more efficient products which could be useful should expansions or retrofittings occur in their organizations. They should also be responsible for the energy bill and to initiate actions of better management in favor of energy consumption reduction. In early 1992, CICE has attracted more than 700 members (Moreira and Iturra, 1992). The results of its activities are still not properly documented with the exception of one that was carried out on government buildings situated at the Esplanada dos Ministerios in Brasilia. At this site, 1.2 million dollars in electricity saving was achieved in one year, owing to better management (Moreira and Iturra, 1992).

Another important achievement of GERE was the creation of CONPET in 1991, an official program similar to PROCEL, only it addressed the issues on oil and natural gas conservation. The objective of the program was to improve the flow of information within the employees of the oil industry and its major clients and users in the same way as PROCEL has done with electricity.

(b) Energy Audits

Energy audits have become a popular tool for increasing the interest in energy conservation. The auditing was performed by some state utilities in an independent way but the main program was carried out under the auspices of PROCEL which sponsored and stimulated the auditing of small and medium-sized industrial and commercial buildings so as to identify no-cost and low-cost electricity conservation measures. Local utilities and their contractors promote and conduct the audits. During 1987–1989, PROCEL directly sponsored about 2,400 audits and CEMIG nearly a similar number. In most industries, the audits have identified the measures that could cut electricity use by an estimated 8–15% (Geller, 1990b). The evaluation showed that some industries have immediately taken action which yielded about 30% of the total savings potential (Lattore *et al.*, 1990).

(c) Labels and Guidelines

Appliance labeling programs have been used to upgrade the stock of appliances by influencing manufacturers and providing consistent, comparative information to consumers. Although few consumers use the labels in their purchasing decision, the program was considered incremental and cost effective in improving the efficiency of appliances by introducing competition among manufacturers.

In 1990, PROCEL proposed a series of efficiency regulations for new appliances, lamps, ballast and motors. The proposals were presented to manufacturers as voluntary protocols rather than mandatory requirements. Both the appliance and lighting industries have signed protocols with PROCEL which call for technical cooperation as well as for efficiency improvement where possible, but without specific efficiency goals. Presently, all one-door refrigerators, wall-mounted air conditioners, and instant electric showers used for bathing purposes carry an efficiency label. Recently, a joint effort of one large refrigerator manufacturer and a public utility at São Paulo has developed and introduced one-door refrigerators (270 l capacity) with energy consumption of 31 kWh/month and two-door refrigerators with energy consumption of 74 kWh/month. These figures should be compared with the average consumption of replaced refrigerators, 43.6 and 98.0 kWh/month, respectively (Vodianitskaia and Schmid, 1992).

GERE has been very active in trying to sign protocols with the automotive industry to introduce efficiency labeling. However, the effort has not been successful due to the present economic difficulties being experienced by car manufacturers.

4.2. Institutional policies

Regulations and standards for energy conservation are still not operational in Brazil. Standards are efficiency levels established by governments for appliances, buildings or passenger cars. These are usually mandatory. Regulations refer to controlling or directing conservation actions through government rules or restriction.

GERE has recently started to work in regulations. Its objective is to satisfy most of the federal government's electricity-intensive equipment and vehicles by using minimum energy requirement. CICE was recognized as a good instrument to follow-up such procedures. One example of this action is being carried on a mammoth scale in a country-wide educational project with the purpose of constructing 3,000 new schools. For such buildings the illumination project requires minimum energy efficiency standards (PROMON, 1991).

A draft bill for Congress dealing with minimum compulsory standards for residential and commercial appliances has been subject to discussion for almost two years. Presently, a few private entrepreneurs and new NGO organizations such as the Instituto Nacional de Eficiencia Energetica (INEE) and International Energy Initiatives (IEI) has been supporting programs similar to the GREEN LIGHT project in the USA with an objective of using environmental protection actions as a tool to improve efficient energy use. Other efforts are being conducted by private enterprises to install Energy Saving Companies (ESCO).

Electricity tariffs are set by the federal government and are the same throughout Brazil. High-voltage industrial customers and low-consumption residential customers (the largest fraction of households) have received highly subsidized electricity in recent years (Geller, 1990a). For example, in 1989, high-voltage industrial consumers typically paid below $0.03/kWh and low-consumption residential consumers (less than 300 kWh/per month) typically paid under $0.05/kWh. During the last two years, the federal government has increased the cost of electricity mainly due to financial crisis experienced by the electric utilities. The present average cost of electricity is shown in Table 5.

In the medium term, tariffs are expected to increase even further to reduce pressures from MDB and to generate money for utilities in order to

Table 5. Example of electricity costs in Brazil, August 1992.

Category	Utilization factor (%)[a]	Tariff (US$/MWh)	Tax (US$/MWh)		Final Cost (US$/MWh)
High voltage Users 230 kV and above	80	30.00	State Federal	6.61 11.50	48.11
Industries 88 kV and above	70	34.65	State Federal	7.60 11.50	53.75
Small industries Commerce	50	60.63	State Federal	13.30 11.50	85.43
Residential 300 kWh/month		79.20	State	15.70	94.90
Residential 600 kWh/month		97.70	State	24.10	116.80

[a] Assumption was made for tariff evaluation since it is composed of a power cost (kW) and energy cost (kWh). It is assumed that a certain percent of the year the users will be in operation. Also it is assumed that the utilization factor is the same during dry and rain seasons.

sustain a minimum supply expansion program. This effect should bring more room for energy-efficient technologies.

4.3. Financial and economic policies

With an encouragement from PROCEL, the National Development Bank started two financing programs for conservation projects by industrial, commercial and public sector enterprises. These two programs, PROEN (1986–1989) and PROEN AUTOMATICO (1989–1990), were poorly used by privately owned enterprises because of insufficient promotion of the programs and low electricity prices during the period. Therefore they were discontinued. Efforts are now underway by non-governmental organizations (NGOs), such as INEE and KLABIN foundation, to reopen the programs under the appeal of high electricity prices and concern for environmental preservation. Loans charge low interest rates (approx. 10%/year) and cover 70 to 80% of the total investment and a loan term of five years. The existence of such a program is an important condition for promoting energy conservation measures that are quite often cost-effective but unable to provide return in a short period of time compared to commercial loans with an annual interest rate on loans as high as 35%.

Another possible way of implementing energy efficiency is through the operation of ESCO enterprises which could be supported partially by low cost external money. Compared with the Brazilian market, the interest rates in developed countries are much lower and good opportunities are open to outside investors. An obvious way is the utilization of MDB to finance projects and/or for the Global Environmental Facility (GEF) to grant them. Unfortunately, the MDB has high operational cost to administer low value projects that are typical in the area of energy conservation. One attempt made in 1989, and a total volume of US$30 million was tied to a major amount which would be addressed to electricity supply. Difficulties in satisfying tariffs levels required by MDB impeded the disbursement for energy supply projects and consequently the minor amount. The loan was cancelled at the beginning of 1992.

GEF is totally open to cost-effective projects in the area of energy conservation and can provide grants to cover a portion of the total investment. Since ESCO companies are still in its initial stage of operation, and the financial situation is unlikely to motivate private investors, there has not been any attempt to prepare a proposal for consideration by GEF.

5. Renewable Energy Supply

Renewable energy sources are being pursued as cleaner options to those derived from fossil fuels. In Brazil, hydroelectricity and biomass energy are the most favorable. In the area of hydroelectricity, competence for the construction and administration of medium and large projects are available. Some hydroplants are under construction but the present surplus of supply of nearly 3,000 MW of electricity, in a market of 25,000 MW, is obviously an impediment for new initiatives. Simultaneously, the high cost of money (with interest rates of above 10%/year) limits the cost-effectiveness of such investments especially when the best sites are already explored as in the case of Brazil. The temptation is to shift from an almost pure hydro system to the construction of thermoelectric plants which would be less expensive on a per capita basis and installable in a time frame shorter than the conventional hydro (Larson and Williams, 1988). Thermoelectric plants under consideration would use high viscosity oil, natural gas and biomass as sources of energy and operate with steam or gas turbines.

Biomass is being considered as an excellent option for tropical countries with significant land availability. Ethanol production from sugarcane is very successful, with an annual production of 14 million m^3. Unfortunately, low oil prices have stagnated ethanol production since 1988. There is an interest now in this sector to use sugarcane bagasse, a residue of ethanol and sugar mills, as a source of extra electricity generation in these units.

5.1. Technical policies

Information on renewable sources of energy is spreading fast as a result of graduate courses at universities, environment legislation being issued, government and privately sponsored seminars and workshops, and increase in circulation of technical books and journals. A consortium of public and private enterprises supported a project for using biomass as a source of energy (BRASCEP, 1991), and part of the total investment is being covered by a grant from the GEF. The use of the advanced technology (conversion of wood in gases which will be burned in gas turbine combustors) demonstrates that technical competence is available.

5.2. Institutional policies

The government has set several institutional policies to foster ethanol use. All of the policies were introduced a long time ago when CO_2 issues were not so popular (Geller and Moreira, 1991). Procurement, price regulation and preference for low cost loans are still in use today. In early 1990 when the federal government was reviewing its position with respect to alcohol use as a fuel, the issues of Global Warming and Social Fringe Benefits were included to justify its use (Secretaria, 1990). Thus, in an indirect way, it can be claimed that institutional policies for CO_2 mitigation, at least for one particular renewable energy source, exist.

At the state level, a compromise between the government of São Paulo and sugar/ethanol producers was agreed in early 1992. The measure stated that electricity would be acquired by the utilities at the marginal generation cost when residues of the mills would be used as a primary fuel (São Paulo Governo, 1992). Thus, the market space is preserved by institutional action. Tied to the same interest, Eletrobras – holding of public electric utilities – has decided to guarantee special tariffs for electricity produced from the demonstration unit above the market price, and this was partially sponsored by the GEF project. This decision recognizes the necessity to promote demonstration projects for modern technologies.

The use of ethanol and its impact regarding CO_2 production has benefited from institutional measures prepared for other purposes. Carbon monoxide (CO) is the major concern regarding air quality in big cities. The use of 78% gasoline and 22% ethanol blended to power 60% of all automobiles in Brazil has been guaranteed at least in the city of São Paulo to avoid excessive CO engine exhaust release when ethanol fraction is less than the specification, to which proper engine tune-up was performed. Other state legislation, imposed by the Secretary of Environment, exists which requires the maintenance of 22% content of ethanol (Decree 1553, State of Parana, published on August 19, 1992). Since ethanol shortage and opposing interests from the oil industry have always retarded ethanol use, such measures have avoided market reduction with the frame benefit of adding near zero CO_2 emission to the atmosphere.

Deregulation of fuel prices is being considered by the federal government. The issues were discussed with the ethanol producers at the beginning of 1990. The major conclusion was that a significant number of sugar/ethanol mills located in the State of São Paulo should be able to compete with gasoline in a free market. Competition will be possible provided that no further investments would be made in the mills' production expansion. Since only the producers from the State of São Paulo (with exception of a few regions) would be able to survive, the action would destroy the Alcohol Program in the country because nobody would buy an automobile which could run exclusively in one particular state. Thus, deregulation, if introduced, should be partial, preserving some economic advantage for ethanol against gasoline.

5.3. Financial and economic policies

Ethanol use as an automotive fuel has not been economically feasible. Subsidies were always used as a way to guarantee commercial competition. The volume of subsidies has changed over time. They are much less today than during the 1975–1985 period. Subsidies will also be provided for the demonstration unit of electricity generation through biomass gasification. Low interest rates on capital to finance private enterprises are available from the Federal Development Bank. Such loans treat energy and renewable energy on the same level as other investments and are able to cover up to 60% of the total cost. As mentioned in Section 4.3, a special loan program already existed for energy and negotiations are currently underway to re-establish it.

6. Forest Preservation

6.1. Technical policies

As discussed in Section 2.1, biomass is used as a significant source of energy and as a raw material for charcoal, the pulp and paper industries. End-use efficiency of biomass is very poor for most of its energy use. Cooking with wood requires 0.6 ton of wood per capita per year compared to cooking with liquefied petroleum gas (LPG) that requires an amount of energy equivalent to 0.15 tons of wood per capita per year (Goldemberg *et al.*, 1988). Improvements in stove efficiency are well known and fuel switching is even more recommended.

The charcoal industry is much more aggressive to forests than cooking. Charcoal is widely used for the production of pig iron and steel. The overall amount of energy used per ton of pig iron and steel is larger than coal-based steel. Technical improvements are required to increase the conversion rate of wood in charcoal and to reduce the amount of charcoal consumed for each ton of steel. Biomass consumption can be reduced by 30% with low cost technologies (Moreira and Poole, 1991). More modern technologies are available for the production of charcoal but there is a lack of information about them.

The pulp and paper industry uses raw material from man-made eucalyptus forests and competes in the international market to export a significant part of its production. A policy for technological improvement related to energy consumption in the processing phase is necessary to compete in the market.

Change in land-use trends is a major source of deforestation. Technological policies to avoid the problem range from more productive agricultural exploitation to confined cattle ranching. Again, the alternatives are well known but more intensive marketing of these approaches must be carried out.

6.2. Institutional policies

The vast biological diversity and extensive area of Brazil are factors which cause difficulties in the preparation of a National Forestry Policy. Analysis on forest legislation shows that the main document dealing with targets and objectives of such subjects is the Forestry Code which was issued as Bill Number 4771 in 1965. This document has, unfortunately, set rules and regulations for land occupation as the only way of protecting natural forests. Such an approach emanated from the issue of native soil occupation which was a major concern at that time. The Code has set economic mechanisms to stimulate afforestation and reforestation, but only the fiscal incentives were completely adapted and used. This particular mechanism induced reforestation on 6 million hectares within a 20-year time span with an investment of US$5 billion.

During the last few years, the mechanism was abolished. Simultaneously, an increased awareness on the importance of environmental preservation motivated a build-up of legislation requiring compulsory reforestation from rural and industrial entrepreneurs who used biomass as raw material for their economic activities. One possible legislation was Bill Number 0242 of 1988 which required all commercial organizations using forest products as raw material to have man-made forests satisfy their needs completely.

Another potential legislation is a bill, still being discussed in Congress, which defines forest policies for the Amazon Region with the following goals:

1. Preservation of Amazon ecosystem
2. Sustainable use of natural resources
3. Integration of the Amazon in the country
4. Protection to the indigenous population
5. National security

To achieve the goals the following actions should be implemented:

1. Build complete ecologic and economic zoning;
2. Discipline and regulate the process of human occupation and land property areas;
3. Define government property areas;
4. Define Indian reserves;
5. Create and implement in native preserved areas (as defined in item 1) the appropriate exploration activities;
6. Set rules and regulations for rational exploitation of fauna and flora;
7. Intensify research on fauna and flora and on the preparation of qualified human resources; and
8. Promote environmental preservation through better education.

6.3. Financial and economic policies

The Brazilian Forestry Code, in effect since 1965, was designed to use several financial and economic tools to enhance forestry activities. Unfortunately, most of them as credit, interest rate and appropriate financing term were never the object of regulations; tax exemption on man-made forest products was cancelled; tax exemption on land property covered by forest which was established on the code was cancelled and treated on the same basis as agricultural land; income-tax exemption from profits due to man-made forest exploitation was vetoed and the total deduction on the income tax from investment required for the establishment of man-made forest was substantially modified as time went by. Fiscal incentives for reforestation have been the only financial policy for forest development. The results from this program were already discussed in Section 6.2.

Regarding new tree plantation due to commercial forest exploitation, a Fund for Compulsory Forest Replantation was formed. With the funds collected, a reforestation program was implemented (REPEMIR). This program was promoted in few states and was an important incentive mechanism for entrepreneurs to plant new forests.

7. CO_2 Sinks

Since carbon-free energy sources (e.g., safe nuclear, solar, renewable biomass, and wind) are future technologies that may take decades before making significant global contribution to energy supply and may not be useful for all countries, carbon scrubbing is a very important priority. The advantage of removing CO_2 from a large, concentrated source such as the flue gas of a power plant compared to direct removal from the atmosphere is obvious. CO_2 is nearly 500 times more concentrated in flue gases compared to its dilution in the ambient atmosphere.

At least three different scrubbing technologies for CO_2 removal exists: cryogenic distillation of CO_2 from flue gases, separation by membrane, and chemical absorption. The cost estimates of the various options range from US\$25 to US\$45 per ton of CO_2 removed (Hendriks *et al.*, 1991). Unfortunately, the amount of carbon generated by scrubbing alone would be gigantic. For example, a single automobile produces its own weight in carbon per year. Thus, the best solution would be its use as raw material for plastics and construction materials, but this possibility is still far from being operational.

Another method of CO_2 sequestration is the use of biomass. Photosynthesis by plants is the only viable technology for absorbing carbon from the atmosphere. Thus it is not surprising that energy experts see massive afforestation as an opportunity for removing large amounts of CO_2 emitted. Many difficulties are anticipated for the success of such technology, but the cost of CO_2 sequestration seems quite reasonable. An evaluation of the FLORAN project – a mega-reforestation world effort where the Brazilian participation will require tree plantation over 20.1 million ha in a period of 30 years – will absorb 7.7 tc/ha/year with the final result of 5×10E9 tc absorbed as CO_2, representing 4.3% of the excess of atmospheric carbon above the pre-industrial index of 273 ppm (Ab'saber 1989). Since the typical reforestation costs in Brazil are estimated by FLORAN as US $400–1000/ha, the total investment will be US$15 billion or US$3/tc absorbed with zero interest rate. At a more realistic interest rate of 3%/year (the historical average cost of money in developed countries), the cost would be US$7.3/tc.

7.1. Technical policies

Improved forest management will yield sizeable payoffs. Man-made forests for the pulp and paper industry have achieved high yields (see Section 3.4). Replication of successful innovations and best practices are probably more important than new research. Decentralized approaches are needed, including support from the local people. In the area of innovation, there is a space for improved crop and tree genotypes, and for specific agro-ecological conditions where large productivity gains are possible (e.g., in the case of sugarcane crops in Brazil, productivity gain of 4% per year was achieved in a decade of research with annual investments under US$30 million) (COPERSUCAR, 1989).

The strengthening of land-related institutions and training is needed in the country. Forest departments still have low status compared with agriculture. Also, information dissemination on the importance of CO_2 sinks would circulate more rapidly if there was a carbon tax.

7.2. Institutional policies

Emission taxes or charges (i.e., to tax emissions or raw material inputs, e.g., carbon proportional to emissions) is a possible way to enhance man-made forest growth. Money generated from tax collection could be used in reforestation. Limiting the total quantity of emissions and allocation of the rights to emit carbon dioxide in accordance with some principle of equity, and permitting to buy and sell for money is another interesting policy. Emission taxes or the creation of tradable rights to emit would have a similar and direct effect on the price of carbonaceous fuels. The outcome could be positive for reforestation since this could be understood as a way of offsetting CO_2 emissions. Such policies are difficult to implement since they require a global agreement (or involvement of most developed countries).

Once mega-reforestation starts it will be necessary to guarantee the preservation of the areas. This can be achieved through appropriate legislation and continuous surveillance. Forests are very often planted for reasons other than for its use as raw material and energy source. Soil protection, reduction in erosion and consequently water dam siltation have motivated investments in tree growth. Institutional measures that set limits on the amount of sediments carried by water in strategic rivers used for electricity generation would stimulate man-made forests. Such limits should be set in accordance with the local value of energy.

Another way to promote reforestation for CO_2 abatement is the rationale of the "long view" of the damage done. But the long view is inconsistent with the economic approach to discounting. Conventional benefit-cost approaches would regard \$1 of future damage as being less important that \$1 of damage now because of the phenomenon of discounting. The problem is that discounting discriminates against future generations.

As cited by Pearce (1991) there are two options for accommodating the distant nature of the effects of global warming and other environmental costs. The first requires that some intergenerational criterion of sustainability be imposed, leaving the "conventional" discount rate unmodified. The second involves seeking some quantitative adjustment to the conventional discount rate.

7.3. Economic and financial policies

Much of deforestation and land degradation is simply due to lack of investments and interest by central governments and planners. The amount of money involved is huge as was roughly quoted for implementing project FLORAN. The unique possibility is the establishment of international sources of financing and grants. One obvious way to collect the necessary fund is to charge the mitigation costs for CO_2 abatement to the cost of energy produced from fossil fuels. This seems a natural consequence of what is being practised today in most energy supply projects. New dams for hydropower production, for example, must incorporate in its cost a variety of expenditures required to finance actions to reduce the social impact of people displacement, the biological impact due to extermination of native species, and all other risks associated with the project. This practice is a requirement either from the government of a country or from the financing organization (MDB). In a similar way, fossil uses should incorporate in their costs the amount of money required to finance CO_2 sequestration at a global level.

8. Conclusion

A historical review of policies used and implemented in Brazil with direct and indirect effects on CO_2 mitigation was presented. In some cases, desirable policies and arguments in their favor were discussed.

Efficient energy end-use is probably the easiest option to achieve the goal since most of the required new technologies are cost-effective and provide short payback time to users and society. Renewable energy sources, mainly biomass, is the natural option to curb CO_2 emission when more energy is added to the supply system.

Deforestation and afforestation are much more complex issues when it comes to economic analysis. Capital investment is required to avoid deforestation, to create new job opportunities, and to make the necessary research. Better life conditions must be offered to the poor in order to curtail using natural forest as a source of survival.

Financial support from developed countries is necessary in the form of low cost loans for efficient energy end-use and new energy based on renewable sources. Grants from external organizations must be addressed to the country to overcome the economically infeasible question of deforestation avoidance and afforestation. Only under these circumstances will policies already in use as well as others being proposed in this paper be effective.

CO_2 emission is a global problem and has to be solved with global money. Brazil and some other developing countries have already made significant economic efforts to reduce global warming through massive investments in hydroelectricity and ethanol. Such options are costlier than the traditional ones and represent participation of the Brazilians in solving the global problem. Continuation of such efforts or significant action in other areas are beyond the country's economic capability.

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Methodologies for National GHG Abatement Costing Studies

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1. Introduction

In parallel with the negotiation process leading to the Framework Convention on Climate Change (UN, 1992), there has been widespread activity on assessing the costs associated with the possible effects of climate change and the possible ways of avoiding or reducing them. This has involved the application of various types of models representing global, regional, and national aspects, and focusing on time scales from the short to long term. The use of a wide variety of model types with divergent results and conclusions has emphasized the urgent need for comparable cost estimates and standardization of methods and assumptions. This is complicated by the intimate interrelation between global and national economic development, and by the very different national settings.

The UNEP costing study was started in December 1991 (UNEP, 1992a) with the aim of developing comparable national GHG costing studies for developed and developing countries. In the first phase the participating countries were Zimbabwe, India, the Netherlands, and Denmark. These have now been joined by Brazil, Venezuela, Egypt, Senegal, and Thailand for the second phase of the project. The first phase was primarily a review of already conducted global and national GHG costing studies, while the second phase comprises a joint methodological and empirical effort, using common guidelines and economic assumptions for the national studies in participating countries (UNEP, 1992b).

This paper focuses on the methodological background for defining compatible economic assumptions for national abatement costing studies. The discussion is specifically related to the "agreed incremental cost" concept as stated in the Climate Convention (UN, 1992) and to the problems associated with constructing suitable national reference and abatement scenarios. Finally, the methodological discussion is related to modeling experiences in the UNEP country studies of Zimbabwe, India, the Netherlands, and Denmark.

2. Relation to the Climate Convention

The Framework Convention on Climate Change (UN, 1992) which was signed at the UNCED meeting in Rio de Janeiro in June 1992 lays considerable emphasis on issues of cost. The precautionary approach is accepted, subject to the caveat that measures adopted should be "cost effective". This is not defined, but clearly questions relating to the economic cost of limiting emissions (as well as the benefits of doing so) will be crucial to the future policy debate. Furthermore, the convention focuses upon "incremental cost" in relation to the transfer of financial resources for GHG abatement in the developing countries. "Incremental cost" is not defined in detail in the climate convention, but can be understood both in relation to project implementation and to more general economics of total abatement strategies.

There are a number of potential definitions of "cost" and "incremental cost". Some studies underway are attempting to clarify appropriate definitions for use in relation to the convention (King and Munasinghe, 1992; London Economics, 1992). There are also extensive debates on the quantification of benefits to be gained from limiting emissions (Nordhaus, 1991; Cline, 1992).

Avoided climate effects will provide both global and national benefits. Economic theory indicates that an efficient global GHG reduction policy should fulfill the condition that the marginal global benefit of GHG reduction is equal to the marginal cost of the reduction. The benefits of avoided climate effects, seen from a national point of view, cannot be expected to be the same as the global benefits. Countries which gain a relatively small benefit from global GHG reduction could therefore argue that they need some kind of "compensation" in order to live up to globally specified emission reduction targets. This is particularly important because of the widespread view in developing countries that the "responsibility" for current atmospheric GHG concentrations is that of the developed countries.

In view of the considerable uncertainties inherent in climate impact assessment, the present UNEP project does not include the estimation of the benefits of reduced climate change. This means that benefits of avoided climate impacts cannot be used as a metric for the "results or gains" of a GHG abatement strategy. Instead, a GHG emission reduction target compared with baseline emission in a given year can be defined as the goal. The aim is then to assess GHG abatement costs in the countries involved for an interval of reduction targets, covering small reductions as well as relatively far-reaching reductions.

The use of discounting factors for GHG emissions has recently been advocated in discussions on the comparison of abatement projects implemented at different times and with different emission patterns over time. Such a transformation could also include a weighting of different greenhouse gases according to their atmospheric life times. A positive discounting factor would give short-term reductions higher value than long-term reductions. The use of discounting assumes a specific exponential form for the time-dependent "benefits" associated with GHG reduction, which may be an over-simplification of the time dependence problem. It is, moreover, very important to distinguish between time dependence related to global and national emission–reduction targets. The time dependence of emission reductions must be determined at the global level where all types of GHG emissions and national contributions are taken into consideration, and this cannot enter directly into partial national analyses. A more appropriate procedure would be to carry out country specific abatement cost assessments for a range of reduction targets and GHGs and for different time steps, and afterwards use this information as input to global cost–efficiency studies.

3. Joint Benefits of GHG Abatement

GHG abatement can lead to a number of economic and environmental effects other than climate impact and this complicates the assessment of GHG abatement costs. These effects may include employment, balance-of-trade and equity effects, and reduced environmental impacts like local air pollution, acidification, water pollution, and solid waste. These related benefits must be defined and measured according to a specific national goal function.

A strict definition of incremental costs would imply that international funding for GHG abatement in any country should be reduced to account for any related benefits which that country would receive. Local benefits would be assumed to be in the national economic interest and should therefore be achieved by local means, and this could present severe problems in relation to developing countries. The definition of incremental cost is thus an extremely difficult and potentially controversial problem which is likely to involve competing interests between different groups, and conflicts between different economic and environmental issues.

Following economic theory, the benefits of a given action must be measured according to the preferences of the agents who are affected by the action. In practice these preferences can be difficult or even impossible to reveal, especially for non-traded goods, such as environmental effects. A further complication is that agents who are negatively or positively affected by an environmental externality caused by GHG abatement, will have an interest in "overvaluing" or "undervaluing" the importance of the effect, respectively, either because they expect to gain an economic compensation, or because they do not expect to pay the bill for reducing the externality (the so-called "free-rider" problem).

This can be exemplified by the problems associated with measuring the costs and benefits of a GHG abatement option like the construction of large hydropower plants. Several external effects are associated with such an investment, including direct economic loss to the agricultural and other production sectors, loss of recreational and optional values, and health impact. The higher these values are measured to be, the higher the incremental cost will appear.

It is not possible to solve these valuation problems in any simple way, either by internationally agreed assumptions or by national research and judgment. However, it may be instructive to go as far as possible in the physical and economic estimation of costs and benefits associated with specific options and abatement policies, and to discuss the importance and weight of the different parameters as seen from the national and international points of view. It is essential that this information is submitted for open and detailed scrutiny so as to allow critical investigation by international experts on implicit valuation attributes.

4. Defining Scenarios

The determination of abatement cost involves the comparison of an abatement scenario with a "non-abatement" reference situation. The definition of the scenario for the reference case, however, may present considerable difficulties. This is particularly evident in developing countries where economic and technological development may be expected to fluctuate and continue to be dependent on external funding to a greater or lesser degree for some time into the future. Reference scenarios for many developing countries cannot therefore be derived on the normal "business as usual" basis.

Reference scenarios for developing countries should assume no particular GHG abatement. This means, for example, that there should be no bias against the use of fossil fuels, at least for GHG abatement reasons. The reference scenario should assume a continued development of the energy system along similar lines to the past decade. It must be assumed, however, that modern efficient technology is installed, as capacity is replaced or extended.

It may be particularly appropriate to include two reference scenarios: an optimistic future, in which developmental goals are fulfilled according to official plans and the required resources are available, and a more pessimistic future in which funding is heavily constrained, and planned industrial and social development is not achieved as rapidly as hoped.

The GHG abatement scenarios should assume a bias against fossil fuel use, particularly coal, toward higher efficiency than the reference, increased use of renewable energy, including large and small hydropower, and concentration on the use of sustainable biomass resources for the production of modern fuels.

As with the cost and benefit measurement referred to above, there is a "bias problem" associated with the definition of the reference scenario. Full and detailed information on the reference scenario must be presented, and this information should be discussed in relation to any relevant official forecast made by national authorities or international organizations.

National scenarios must be constructed on the basis of consistent global scenarios describing economic growth and fuel price projections, and some indication of technological development. Recently developed scenarios provide convenient common reference points (WEC, 1992; IPCC, 1992). The precise relation between global and regional scenarios and national scenarios is difficult to define in general, and therefore it is left to the judgment of the national teams in the UNEP project to decide on how the exogenous global scenario assumptions influence national growth patterns and energy system development, etc.

The abatement costs in each country are, in principle, dependent on the actions of every other country, through the effect on fuel prices, industrial competitiveness, trade, etc. This makes it difficult to define national reference and abatement scenarios in a consistent way relative to the global situation. It can generally be concluded from a broad review of GHG costing studies (UNEP, 1992a) that the effect of a 50% reduction in projected global CO_2 emissions from fossil fuels on average global GDP is likely to be small, amounting at most to a few percent compared to baseline in 2020 or 2030. Therefore, it seems appropriate to assume the same average global GDP growth rates in the reference and abatement scenarios.

Fuel prices, on the other hand, must be expected to change as countries introduce significant abatement measures, leading to depressed demand for fossil fuels. The extent and timing of such reaction will be the result of the concerted abatement efforts in many countries, rather than one country alone. This can be solved pragmatically by defining two global fuel price scenarios, consistent with current thinking, to be used as the exogenous background for the country studies.

Partial national abatement studies assume implicitly that the abatement cost in each country is assessed within a static global environment in which the abatement actions of the remaining countries are predetermined. The alternative to this would be a full simultaneous optimization where all countries and abatement options are represented. Such an analysis would inevitably be at a more aggregated level.

The global fuel price assumptions can be incorporated in the national abatement analysis in three distinct ways as described below.

First, the national reference scenario and an abatement scenario can be constructed on the basis of the global reference fuel price scenario. This combination can be interpreted as representing abatement in one country, in a world in which fuel prices have not yet been affected by a substantial worldwide abatement effort.

Secondly, both the national reference and abatement scenarios can be based on global fuel prices affected by considerable worldwide abatement. This represents the case of a country undertaking abatement in a world in which compliance with a far-reaching agreement on global GHG limitations is already a reality and therefore has affected international fuel prices.

Thirdly, the national reference scenario can be based on the global reference fuel prices, while the national abatement scenario assumes the global abatement-affected fuel prices. This corresponds to the theoretical case in which one calculates the cost incurred in one country of simultaneous global compliance with a climate agreement from a starting point of no abatement at all. This cost can be interpreted as the economic loss to the country which follows from a binding global climate convention which may embody varying benefits for different countries. The result is an important indicator of the country-specific interest in the establishment of such an agreement. On the other hand, when an agreement is in fact established and being implemented, globally affected fuel prices will eventually be a reality for the countries, irrespective of whether they undertake abatement. Therefore, a cost assessment using different global fuel prices in the national reference and abatement scenario will not be an appropriate indicator for the necessary compensation to equalize national and global benefits of GHG limitation.

In conclusion, it seems that the most consistent and informative way of using global fuel price scenarios in partial national studies is to calculate cost differences pairwise between national reference and abatement, keeping global fuel prices constant, either at the reference level or at the global level.

5. Construction of Abatement Cost Curves

One of the most important results of a national GHG abatement analysis is the construction of an abatement cost curve, which shows the relationship between emission reduction targets and associated costs. Ideally, such a curve should cover a wide range where both small GHG reductions and larger reductions are represented. Thus a GHG reduction cost curve must, by nature, be an aggregate of many different technical and structural changes and this needs to be treated in a detailed integrated system model.

GHG reduction in the energy system can be achieved through changes at many stages, involving a wide variety of different energy technologies. Fully cost-efficient abatement should consider all available abatement options on an equal footing, at end-use, conversion, and production stages. A cost-efficiency analysis of GHG abatement in the energy system must therefore be able to compare all these different options in an integrated procedure.

One important background concept for GHG reduction cost curves is the Least Cost Utility Planning approach developed in the USA during the 1970s and 1980s. The method was originally designed to treat electricity savings and electricity supply technologies together. Thus electricity saving appliances (such as new refrigerators or low-energy light bulbs) could be considered in the planning process alongside new power plants and other supply-side developments. Since either type of technology achieved the societal goal of satisfying an energy service requirement, a true "least cost" solution was feasible. The method was developed in opposition to the dominating planning method, still used in many countries, which neglected potential energy savings and planned new supply capacity on the basis that the utility could or would not influence future demand.

An important part of the Least Cost utility approach is that both electricity "demand technologies" and "supply technologies" are measured by the same economic, technical, and environmental parameters. This means that all demand technologies such as refrigerators, low-energy light bulbs, electricity efficient industrial processes, etc., are assigned energy efficiency and emission factors. These attributes are defined in relation to the reference power system behind the analysis and have in some studies been directly translated into an abatement cost curve (Lovins and Lovins, 1991).

Such a procedure can be satisfactory for the lower part of the cost curve where each abatement option can be recognized as representing a marginal adjustment of the total energy system. If, however, more fundamental, non-marginal, structural changes of the supply system, such as fuel substitution and the introduction of combined heat and power (CHP) systems, are considered, then the economic and GHG emission "values" for the demand technologies are not unique and cannot be determined independently of the supply system. Any investment alone can influence the total economy and GHG intensity of the energy system. Technologies must therefore be assigned different economic and GHG emission "values" depending on the system in which they take part.

Different types of existing energy system models can be used to estimate such an advanced cost curve. Energy system optimization models as well as integrated energy system simulation models are relevant (UNEP, 1992b). The idea of both these types of models is to determine any point on the cost curve as the least cost solution for a total energy system compared with a reference system, where in principle all demand and supply system parameters can vary.

The procedure in constructing a cost curve using an integrated energy system simulation model will include the following main elements:

1. Ranking of possible technological options on a partial basis related to a reference case calculated with an energy system model
2. Introduction of different "baskets" of GHG reduction technology options (chosen with starting point in step 1) calculating a large number of scenarios for possible GHG reductions and related costs.
3. Choice of the lowest costs for a given reduction of GHG, thus establishing an envelope curve for the annual GHG emissions reduced and the annual costs related.

A probable result of such an analysis is that a given GHG emission target can be fulfilled with several energy system solutions which on the whole are economically equivalent. Such energy system solutions may, however, be quite different technically, for example, with regard to the dominant power-generation technology, or the weighting of investments in demand or supply technologies. It must be expected that the technical variety among the economically "comparable" energy system solutions will expand with increasing GHG reduction targets. This is, in itself, an important conclusion, which introduces the possibility of other parallel criteria for project judgment such as complementary environmental effects or specific national economic interests.

According to this method, a GHG reduction cost curve must be considered as a kind of theoretical relationship between GHG emissions and energy system costs. It is not possible to identify a unique technical energy solution at all points on the curve, but the procedure aims at showing the magnitude of the cost of GHG reductions throughout the range. At the same time, the curve shows some energy system solutions which are economically relevant for the fulfillment of a given GHG reduction target.

In order to investigate the time dependence of abatement strategies, the potential development pathways for a few selected energy system solutions (abatement strategies) on the cost curve can be examined in more detail. The first part of the cost curve should represent the partial cost and emission-reduction values of the most valuable projects. The next part of the curve should subsequently include the next most valuable projects and should be calculated on the assumption that the technologies in the first part are implemented, and so on for the rest of the curve. The purpose of making such a detailed time-dependent analysis is to determine the robustness of a presumably efficient energy system in relation to irreversibility and uncertainties.

Although some elements of the problem have been treated in different energy model studies, the cost curve concept is not fully developed yet. Studies must be extended to investigate system integration aspects in more detail. It is especially important to make the cost curve concept dynamic with respect to technical constraints, and to analyze time dependence in the costing of abatement options.

Priority should also be given to attempts to integrate macroeconomic impact assessments into the cost curves constructed by energy system models. The most important links which could be included are macroeconomic forecasts of energy demand and factor price effects originating from relatively large abatement efforts. On the other hand, investment requirements associated with implementing a given energy system solution should be coupled to a macroeconomic investment function. An example of such an integration is the MARKAL-MACRO model (Manne and Wene, 1991).

6. Modeling Experience in Country Case Studies

The country case studies of Zimbabwe, India, the Netherlands, and Denmark in the first phase of the UNEP project have identified some very important practical problems in abatement scenario construction and cost assessment. For Zimbabwe and India, appropriate emission forecasts, and energy and economic system data are not presently available and must be built up as part of the abatement costing study. For the Netherlands and Denmark, a great deal of useful data and models exist and efforts are already well underway to link technical-economic and macroeconomic models and to analyze regulation schemes in detail. A brief summary of the methodological elements in the country studies is given below.

Zimbabwe. The Department of Energy along with a local consultancy, Southern Centre for Energy and Environment, are conducting the country study in cooperation with a Danish project team (Maya *et al.*, 1992). The main activity in the project is to establish an emission data base and an energy system model, where energy system and biomass emissions can be treated in a consistent way. This will be related to the official economic plan of the Zimbabwe government. This plan is not generated by a formal macroeconomic model, and therefore it will only be possible to investigate the energy system–economic system link qualitatively in the country study.

The market plays a minor role for the energy sector in Zimbabwe at present. For example, the coal mines are heavily subsidized due to national economic interests. For this reason, economic regulation mechanisms are less appropriate for encouraging GHG limitation in the current situation. Important national, social, and economic interests are embodied in the existing regulation system for the energy system and the economy as a whole, and GHG emission reductions are not given a particularly high priority. In view of the scarcity of financial resources in Zimbabwe, the implementation of GHG abatement options is heavily dependent on international agreements and transfers.

India. A country study is being carried out by Tata Energy Research Institute (TERI, 1992).

Relatively detailed emission and energy system data are available for India and these have been used for constructing an abatement cost curve by ranking "up-front" investments. In the next step, this analysis will provide input to a more comprehensive energy optimization model.

Macroeconomic forecasting is difficult to carry out for the Indian economy because the market generally plays a minor role, although a wide ranging liberalization is now taking place. At the same time, there is a large informal sector which is not covered by official economic statistics. For this reason, the project team has chosen to analyze the macroeconomic effects of abatement strategies in a Computable General Equilibrium Model using shadow prices for scarce natural and economic resources.

GHG abatement is recognized as only one among several important national goals for economic policy, employment, equity, and environmental effects. Similarly, capital scarcity and relations to international aid organizations are important restrictions for the implementation of GHG abatement.

The Netherlands. The country case study is carried out as a cooperation between a technical-economic expert team at ECN and a macroeconomic team from the Free University of Amsterdam (van der Burg *et al.*, 1992).

Several technical-economic and macroeconomic studies of GHG abatement costs have been carried out, but they are not comparable because of inconsistent assumptions. The most advanced energy system studies have been made using an LP optimization model (MARKAL), deriving one optimal abatement strategy for a given reduction target over a time period. This solution cannot be directly related to a more specific GHG reduction path. Neither can it provide the detailed sectoral investment and consumption information which is needed if a macroeconomic model is to be coupled to the analysis.

Implementation issues and related costs are not treated in the technical-economic models and therefore it has been difficult to use the results together with macroeconomic results where economic regulation, such as GHG taxes, are considered. At the same time the abatement cost estimates made by macroeconomic models seem to have been very dependent on tax recycling schemes and related investments.

Denmark. The Danish case study is being carried out by a technical-economic project team at Risø National Laboratory (Morthorst and Grohnheit, 1992).

A wide ranging planning activity was carried out in conjunction with the Danish Energy 2000 action plan. Part of this involved the construction of a purpose-built energy system simulation model. This technical-economic model contains a very detailed data base for electricity and heating savings for households, service sector and, industry coupled to end-use technologies. The forecasts for energy demand and technological development were only partly coupled to macroeconomic analysis. In the current activity, new scenario calculations are being made, involving direct coupling of the official macroeconomic model of the Danish Ministry of Finance to the technical-economic model.

Previous Danish GHG abatement costing studies have concluded that a number of "no-regret" options exist, and consequently, that CO_2 emission reductions compared to 1990 emissions can be made relatively cheap over the next twenty years. In order to validate these results, a parallel research activity is studying different means of regulation and the political, organizational, and social barriers to energy savings.

7. Conclusion

The Convention on Climate Change will enter into force ninety days after it has been ratified by at least fifty countries. In the period leading up to ratification, a number of points and concepts in the convention will have to be clarified and expanded upon so that signatory countries have a clear understanding of what the obligations involve. One important area for such clarification is that of costing, in particular the obligations of each country for reporting of the cost of limiting GHG emissions. The ongoing UNEP study referred to in this paper aims to contribute through the formulation and refinement of guidelines, including the execution of national studies in selected countries by local teams.

A central notion in the UNEP activity is the building of local expertise and familiarity with the concepts of GHG abatement costing in the countries concerned. The small core of countries involved in the first phase of the project is now being expanded with the addition of Brazil, Egypt, Senegal, Thailand, Venezuela, and possibly others. Thus the study will cover a wide range of geographical, economic, and developmental settings, allowing the proposed methodological guidelines to be discussed and tested in a broad forum.

It is unlikely that the difficulties inherent in the concepts such as "agreed incremental cost" and the definition of reference and abatement scenarios will be solved completely by undisputed "scientific" means. The difficulties should rather be treated pragmatically through broad discussion, and definitions sought which can meet with consensus and which best reflect the aims of the convention. National abatement analysis should therefore be carried out as a collaborative effort between national technical and economic experts, and public authorities, and thereafter laid open to international scientific discussion and investigation.

The costing methodologies and models are bound to vary from country to country depending on local traditions and availability of data. Nevertheless, general consensus on some basic concepts, such as the definition of the baseline scenario and the construction of cost curves, is likely to contribute to a better understanding and acceptance of the procedures within the Climate Convention. We believe that the UNEP study represents and important step in this direction.

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Postscript

Mitigation and Adaptation for Climate Change: Answers and Questions

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Abstract

This paper states knowns and unknowns about efforts to curtail greenhouse gas emissions (mitigation) and lessen the harm of climate change (adaptation). The knowns about mitigation are that decarbonization and efficiency of the energy system are advancing steadily; some mitigation will be cheap; strict curtailing of emissions might cost 2 percent of gross domestic product (GDP); gradual control steps are better; and doubling of atmospheric concentration is not inevitable. Knowns about adaptation are that vulnerability to climate is lessening; climate change might cost 0–2 percent of GDP; analysts should assume adaptation rather than dumb farmers; and analyses of mitigation and adaptation need integration. Questions are how energy prices affect emissions; whether it is preferable to regulate emission prices or quantities; the shape of the damage function from climate change; ways to improve long-term predictions of socio-technical systems; how much policies intended to affect emissions matter; and the opportunity costs of focus on the climate issue. In conclusion, prosperity and technical progress may make both mitigation and adaptation affordable and avert the climatic danger.

1. Introduction

Greenhouse warming vexes us because destruction threatens on one side if we do nothing to curtail emissions but bankruptcy threatens on the other if we do much. Can the growing evidence that both adapting to the climate change and curtailing the emissions will be affordable resolve the dilemma and still our vexation?

This dangerous question animated the Workshop on Costs, Impacts, and Possible Benefits of CO_2 Mitigation held in September 1992 in Laxenburg, Austria, under the auspices of the International Institute for Applied Systems Analysis (IIASA) and the Intergovernmental Panel on Climate Change

(IPCC). This essay draws on the papers and discussions at the Workshop first to state the answers which the Workshop and related recent research allow and then to ask the questions the answers provoke. "Mitigation" is the curtailing of emissions. "Adaptation" is the lessening of the harm or the increasing of the benefits of climate change.

2. Answers About Mitigation

Decarbonization and efficiency of the energy system are advancing steadily.

Decarbonization is the progressive lightening of the amount of carbon used to produce a given amount of energy, as the energy system favors molecules that favor hydrogen over carbon (Figure 1). Twenty years of energy analyses, largely by Arnulf Grübler, Cesare Marchetti, and Nebojša Nakićenović at IIASA, were needed to reveal and establish firmly this most fundamental of all trends in the energy system, which has held for 150 years (Figure 2). Appreciation of decarbonization is recent (Ausubel, 1991a).

Decarbonization began long before organized research and development in energy and has continued with its growth. The long-term rate of decarbonization is about 0.3 percent per year. Many ways to continue down the curve have been documented (Nakićenović, 1992).

During the 1970s and the 1980s the countries that reduced their carbon emissions were for the most part countries that expanded nuclear energy (Figure 3). The 150-year history suggests an ever-changing evolutionary envelope of opportunities.

The history of the efficiency of the energy system is similarly encouraging. Though each country follows its own path, dependent on specifics of geography, capital stock, and other factors, the direction is decisively efficient (Figure 4). In the United States, as an example, on average it has taken about one percent less energy to produce a good or service each year since 1800. Thus, it takes less carbon to produce not only a unit of energy but a unit of gross domestic product (GDP) (Figure 5).

Some mitigation will be cheap.

Many estimate that a reduction in carbon dioxide emissions of 20 percent below what they would otherwise be comes at low or no cost (Weyant, this volume; National Academy of Sciences, 1992; Pearman, 1992). Estimates range between 10–40 percent, depending on approach and assumptions. It will not be difficult to achieve lower rates of emissions, hewing to the courses

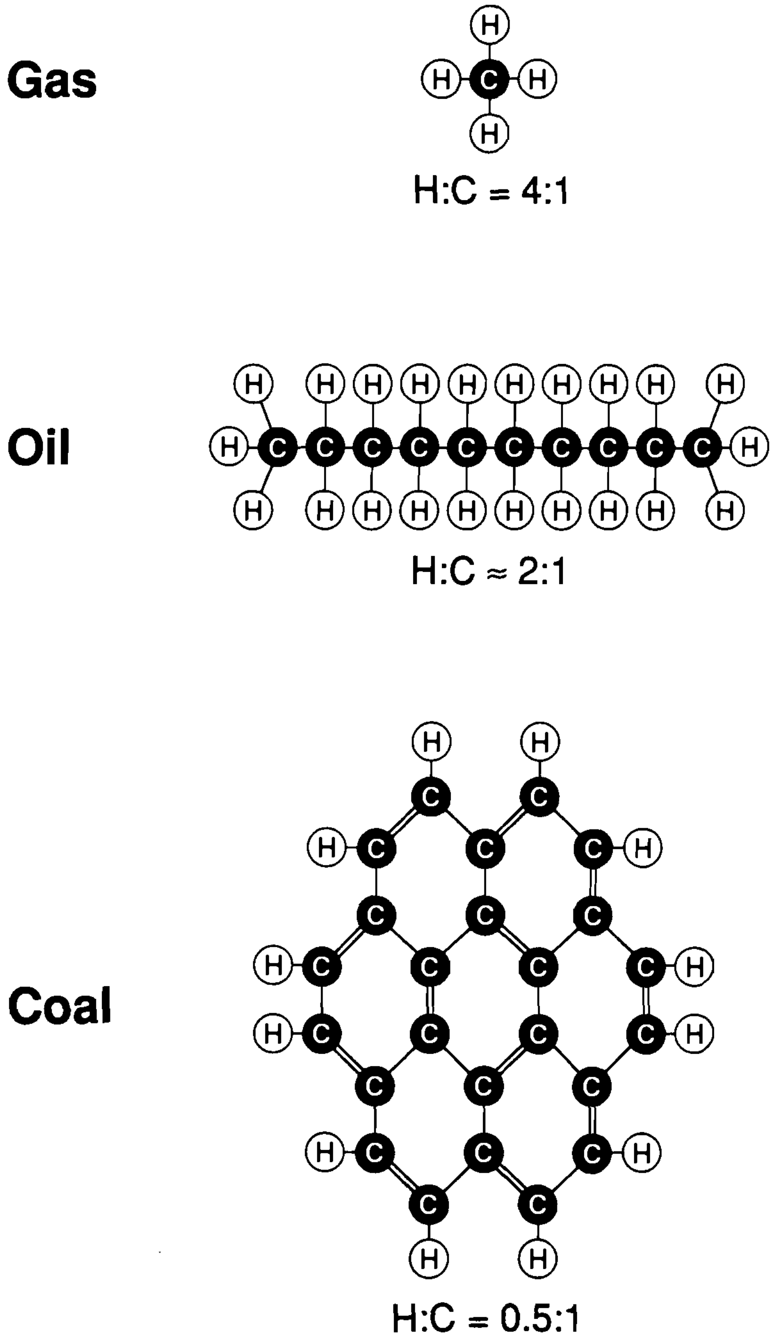

Figure 1. The atomic structure of typical molecules of coal, oil and gas, and ratio of hydrogen to carbon atoms.

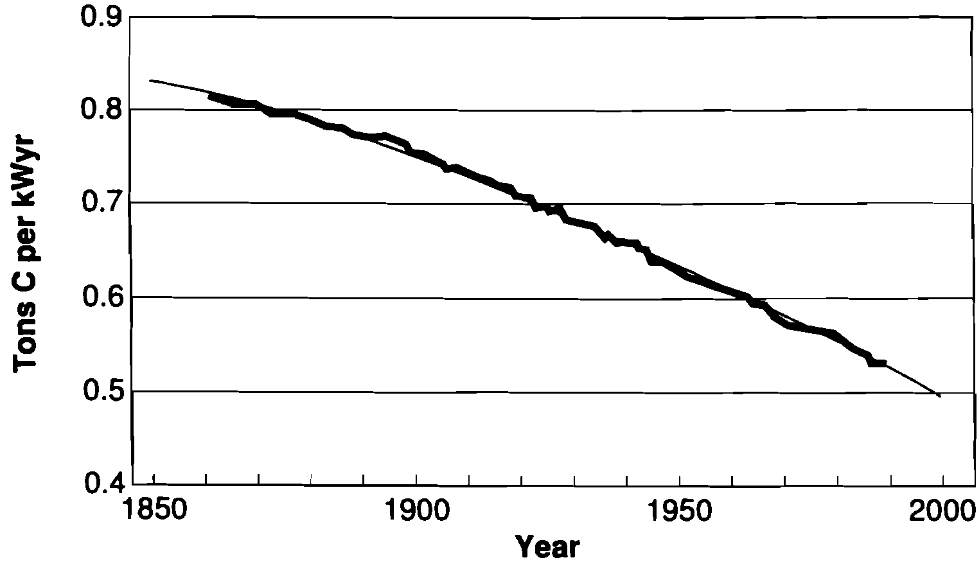

Figure 2. Decarbonization or the changing carbon intensity of primary energy for the world. Carbon intensity is calculated as the ratio of the sum of the carbon content of all fuels to the sum of the energy content of all primary energy sources. Carbon emission in tons carbon per kilowatt year are: wood, 0.84; coal, 0.73; oil, 0.55; and gas, 0.44. Courtesy A. Grübler and N. Nakićenović.

of both decarbonization and efficiency, even in China (Jiankun *et al.*, this volume). Pieces of ripe fruit are hanging low, waiting to be picked. Some argue that low hanging fruit will continue to ripen with each decade.

Strictly curtailing emissions might cost two percent.

What if society chooses to go beyond the favorable "dynamics-as-usual" of the energy system? After all, population and economic growth can dominate efficiency gains and decarbonization, resulting in absolute emission growth. Studies of Brazil, Japan, Russia, the European Community, and developing countries, and a survey of models suggest that the price of strictly curtailing greenhouse gases might be 2 percent of gross domestic product (see respectively, Moreira, Amano, Bashmakov, Koopman *et al.*, Pachauri and Khanna, and Dean, this volume). Globally, 2 percent of gross world product might stabilize emissions at present levels. Some confidence in the estimate comes from the lack of contradiction in the results of diverse models. The models

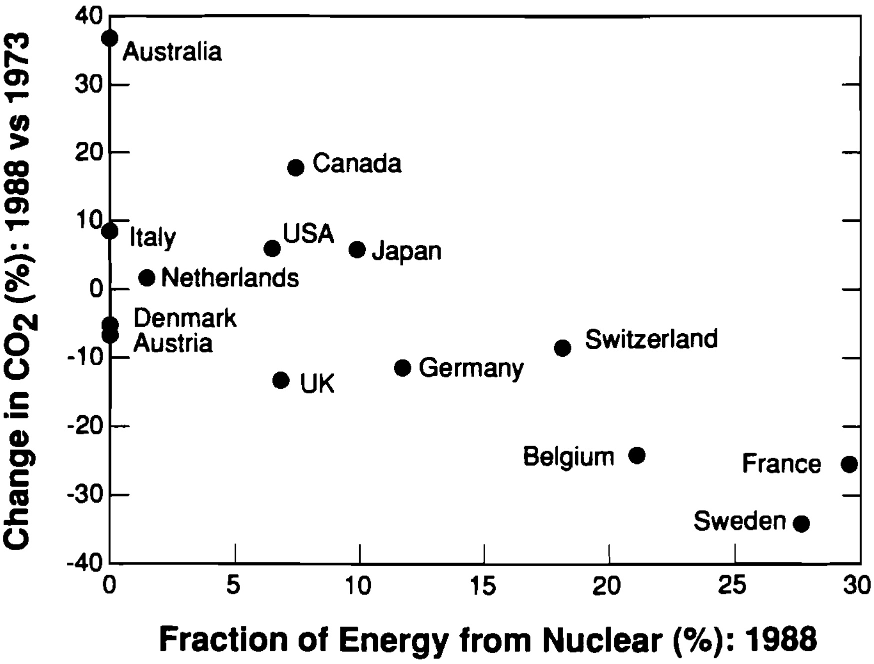

Figure 3. Decrease in CO_2 from 1973–1988 for major OECD countries from nuclear power. Source: After Bodansky, 1991; data from OECD, 1990.

may be more reliable than a few years ago. Coefficients are estimated with more and better data. Superior algorithms calculate the results.

Gradual control steps are better.

Gradual use of policy instruments to control emissions is preferable to abrupt moves. Quantifiable benefits exist for acquiring new information about costs that can influence policy design (Kolstad, Peck and Teisberg (a), this volume). An economically efficient path is more likely if policies evolve through regular rounds of review and negotiation.

Doubling of concentration is not inevitable.

Studies of the greenhouse effect conventionally analyze the climate when atmospheric concentrations of greenhouse gases are twice the pre-industrial level, or 600 ppm, usually estimated to occur about 2070 AD. The good news from studies of mitigation is that the canonical doubling of concentration

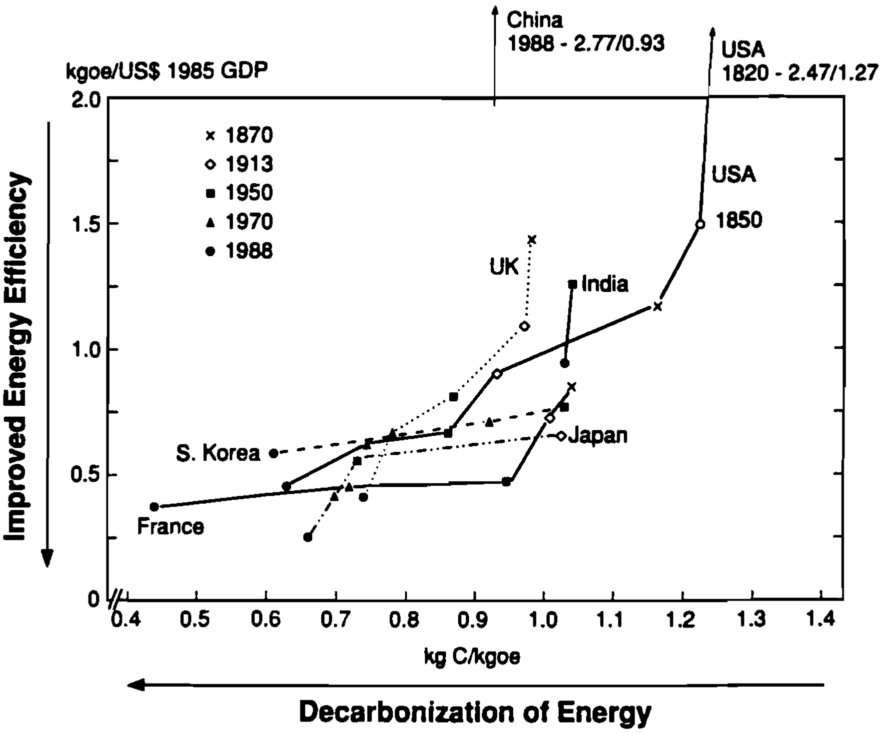

Figure 4. Trajectories of energy efficiency and decarbonization for selected countries. Courtesy A. Grübler and N. Nakićenović.

can be avoided. Cresting around 500 ppm is feasible, if we stay on course to wring most of the carbon out of the energy system over the next 100 years.

This conclusion is important for adaptation studies, because most adaptation studies have been pegged to at least a 600 ppm world, which may well be more distant than 2070 or never come. Doubling is founded on technological and political stagnation. Interestingly, a scenario in which decarbonization was reversed and efficiency almost freezes was labelled by the IPCC (1989, p. 341) "business-as-usual" and served as the reference case for most IPCC adaptation studies.

3. Answers About Adaptation

Vulnerability to climate is lessening.

A range of social and technological developments have lessened human vulnerability to the natural environment, including climate (Ausubel, 1991b).

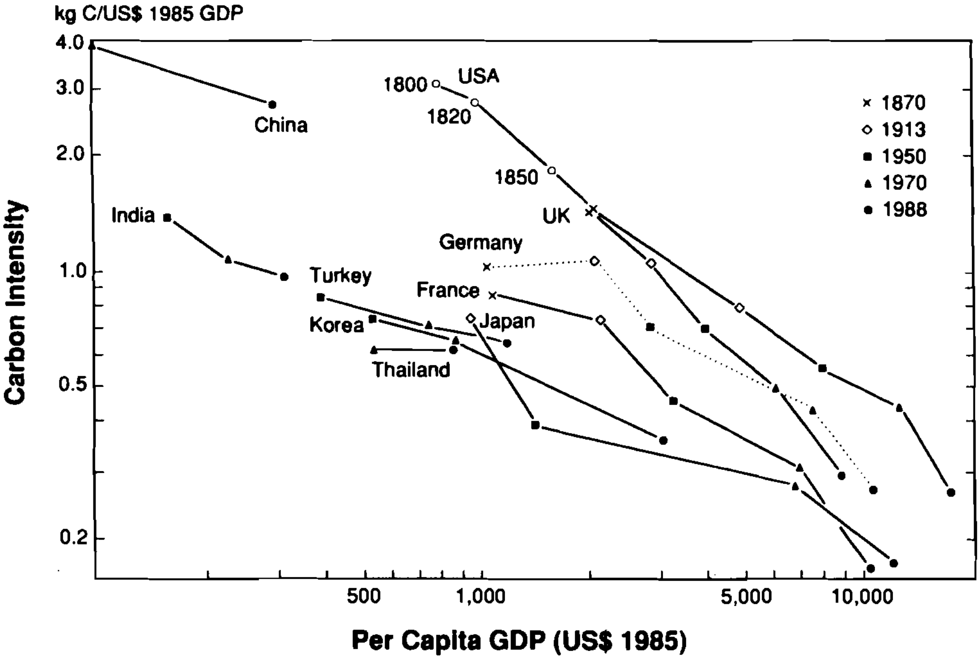

Figure 5. Diminishing carbon intensity of GDP for selected nations. Analysis includes fuelwood and other renewable sources of energy. Source: Nakićenović, 1992.

The lessening trend is widely repeated throughout the world, explained by industrialization, better built structures, telecommunications, and institutional innovations, in short, development.

Compare yourself to your grandparents and great grandparents. Climate surely mattered more for our ancestors who crossed perilous seas in windblown boats, struggled with horses and wagons through the mud when it rained, prayed for a shining harvest moon, and dried fruits and canned vegetables to tide them over the long winter.

Numerous facts confirm the lessening. For example, the tornado death rate has decreased sharply in the United States in this century (Figure 6). With indoor malls for shopping and domed stadiums for athletic events, climate matters less.

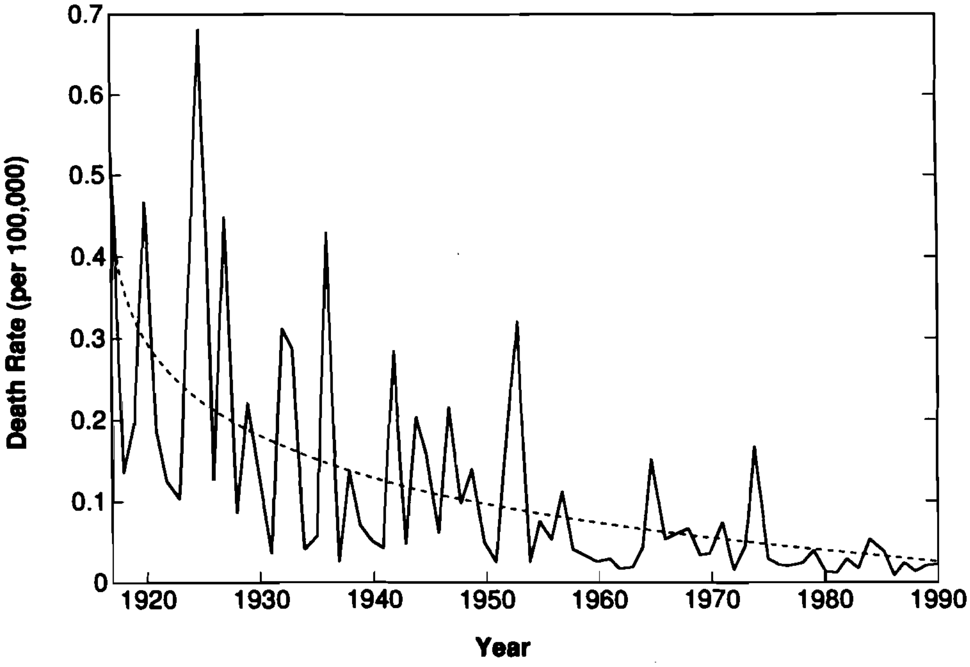

Figure 6. Tornado death rate: Actual (solid line) and fitted trend (dashed line) for the United States, 1917–1990. Source: National Safety Council, 1992.

Is the trend valid globally and for developing countries? Nordhaus (personal communication) addressed this question by analyzing the changing shares of population and output associated with agriculture. Indices of agriculture, the prime activity exposed to climate, are probably the best measures of vulnerability to climate. In 1987 agriculture provided about 15 percent of total world output. As Figure 7 shows, a small fraction of world output is currently produced in economies that are heavily dependent on agriculture. In 2050 only about 5 percent of global output may be agriculture.

This measure elevates goods rather than people. Though the developed nations may account for 80 percent of current gross world product, only one billion people dwell in these less vulnerable economies, while over 4 billion struggle in the developing world. Though most of the developing countries hope to develop substantially by 2050, some certainly will fall short.

The proportion of population (by nation) gaining income from agriculture shows that people vulnerable to climate change are more plentiful than

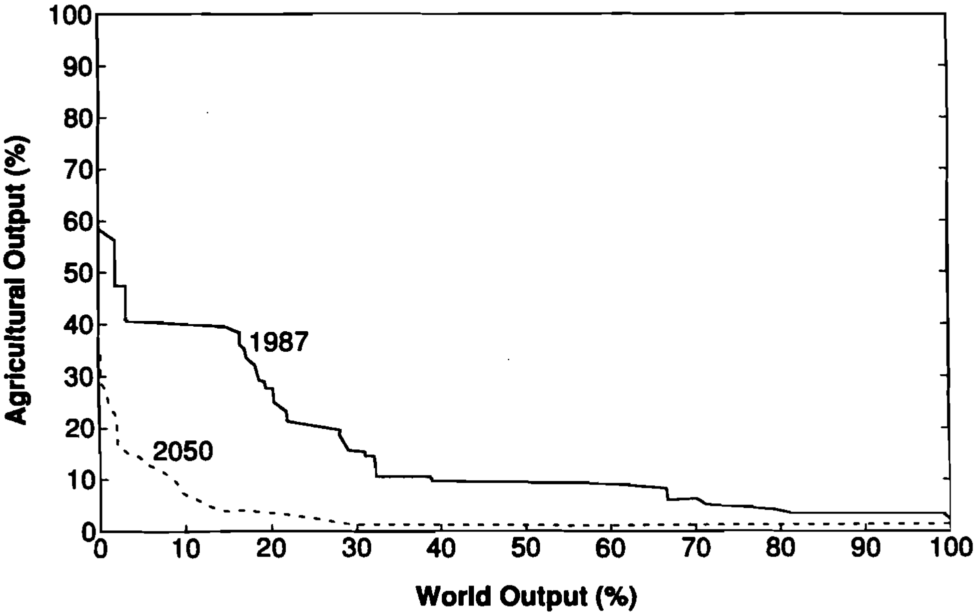

Figure 7. Distribution of the share of economic activity in agriculture arrayed by the fraction of world output (sum of gross national products) for 1987 (solid line) and projected for 2050 (dashed line). The area under the line, representing in total the share of world output in agriculture, is a measure of vulnerability. For any given segment of gross world output, the closer to the horizontal axis, the lower the vulnerability. To project the situation in a new climate, GDP in 2050 for each country is estimated by extending average growth rates 1965–1987 to 2050, with some downward adjustments for countries such as Japan and Korea that have had high growth rates unlikely to be sustained for six more decades. Then the relationship between per capita GDP and the share of the economy in agriculture that existed in 1987 for the cross-section of countries is applied. Source: After William Nordhaus, New Haven, Connecticut, USA, personal communication.

output (Figure 8). In the industrialized countries, the vulnerable are few. But, 60 percent of the world's population still earns 40 percent or more of its income in agriculture. Yet, the trend again is toward a lessening of vulnerability to climate. By 2050 the share of world population heavily reliant on agriculture is projected to halve, though the absolute number would remain about the same.

Hazard is a largely human construct. As the American engineer Norman Augustine (1987) observed, trailer parks cause tornadoes. Typhoons

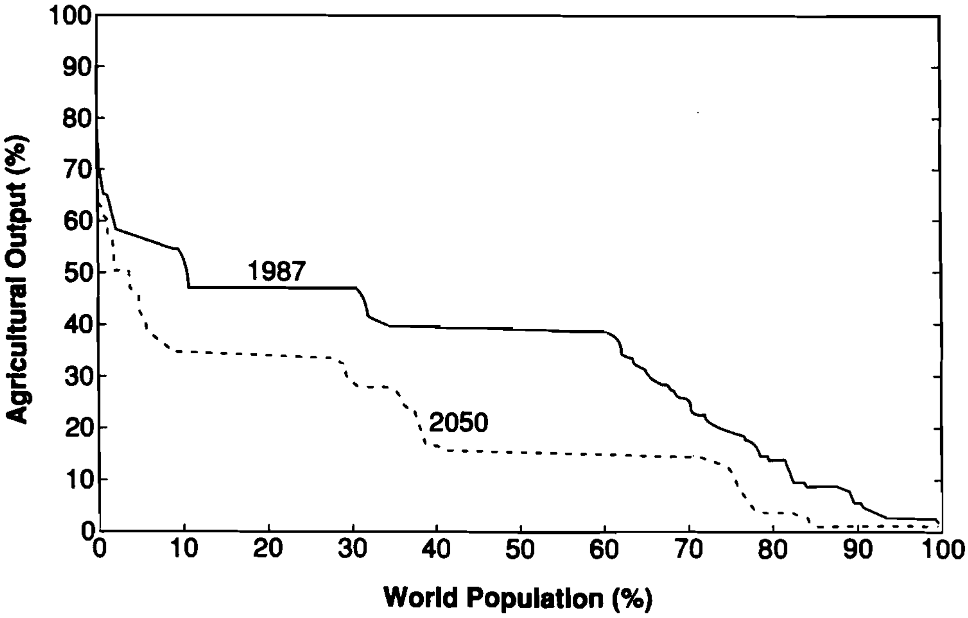

Figure 8. Distribution of the share of economic activity in agriculture arrayed by the fraction of world population (sum of national populations) for 1987 (solid line) and projected for 2050 (dashed line). Source: After William Nordhaus, New Haven, Connecticut, USA, personal communication.

matter when an empty low-lying coastal island in the Bay of Bengal gains 100,000 residents. Hurricanes pass without legacy unless buildings are badly constructed and sited, as many were in southern Florida. Grain reserves, crop insurance, and futures markets decrease the disaster of drought.

Climate change might cost 0-2 percent.

Studies suggest that the cost to gross world product of the climate change accompanying a CO_2 doubling might be between about 0.25–2.0 percent (Fankhauser, Scheraga *et al.*, this volume). The amount is logical. If agriculture is heading toward 5 percent of world product in a 600 ppm world, loss of 20 percent of farm output would take 1 percent. Losing even the 20 percent of farming output and 1 percent of total output is unlikely as well as intolerable. Nevertheless, this 1 percent plus another 1 percent from other problems, such as rising seas, does add to a loss within the range mentioned.

If estimates of costs of climate change are biased to date, the bias is likely to excess costs because most studies incorporate little or no adaptive behavior, as discussed below. Reassuringly, a novel, independent way of assessing the economic worth of climate through land values, which already reflect adaptation, produces preliminary results that also point to small numbers (Mendelsohn *et al.*, this volume).

Though the small numbers may reassure the person on the street, they can upset people who have invested their time in climate change or want to avoid all risks.

One reason is that the small impact numbers cause a political problem for budgets of science and environmentalism. High estimates of the cost of impacts have been used to justify large expenditures for research projects, particularly for satellite programs, and drastic surgery on the energy system.

The small numbers also cause discomfort when compared to other relevant numbers. When used in a cost-benefit analysis, the conclusion might be that no social response is warranted, if avoiding the problem costs 2 percent and incurring the problem costs only 1 percent. Costs could outweigh benefits (McKibbin and Wilcoxen, this volume).

Four serious defenses are mounted against the small percentages.

One is that in absolute terms the numbers are large. 1 percent of today's gross world product is about $200 billion. 2 percent of gross domestic product is about what industrialized nations, including the private and public sectors, now spend on environmental quality in total. The numbers may be hard to discern in statistical tables but not in the political process.

A second defense is that the distribution of costs will exacerbate problems well above what the magnitude suggests. In short, the poor will suffer more (Scheraga *et al.*, this volume), and they will add heat to warming.

A third defense is that further research on impacts and adaptation may reveal added costs. People search for neglected considerations or flaws in the analyses.

Threats to health hold hopes of high costs. What about deaths from hot weather? In the United States in 1989 of 95,000 killed in accidents, 201 died of the heat and 94 in storms (Table 1). Cold took five times as many as heat. From that perspective global warming does not appear a direct hazard to public health. The conjecture that greenhouse warmth will aid the emergence of alarming new viruses can form a fallback position.

More compelling is the scarce understanding of consequences for ecosystems and other non-marketed goods (Jansen, this volume). Results from one experiment with an artificially constructed tropical ecosystem suggest that increased CO_2 fertilization can promote losses of soil carbon and the

Table 1. Deaths due to injury, United States, 1989.

All Accidental Deaths		95,028
of which:		
Transport	50,436	
Falls	12,151	
Poison	6,524	
Fire	4,716	
Drowning	4,015	
Medical	2,850	
Excessive cold	1,015	
Excessive heat	201	
Storms & floods	94	

Source: National Safety Council, 1992.

release of mineral nutrients similar to the effects when sugar is added to soils (Koerner and Arnone, 1992). Yet, natural vegetation near gas vents which create a chronically CO_2-enriched atmosphere suggests that plants have acclimated without trauma (Miglietta and Raschi, 1993). We are in speculation. By changing the climate, the context for nature and conservation shifts. The consequences could be large. Assessment is hard, especially in monetary terms.

The fourth defense is that actions must be evaluated not only for expected net costs (or benefits), but also for the levels of uncertainty surrounding them. Here the "Precautionary Principle" for environmental management comes into play. The Precautionary Principle is a legal term found in a growing number of international environmental agreements (Cameron and Abouchar, 1991). The declarations of the Second World Climate Conference and the UN Conference on Environment and Development cite it. Basically it requires that proof of no harm exist before an activity is allowed.[1]

The Precautionary Principle may be understood as the appropriate treatment of uncertainty. To a considerable extent it equates with risk aversion. The Precautionary Principle should significantly influence decision making where there are abrupt thresholds in loss functions or possibilities of very large or infinite damages.

When asked the question "Would you prefer a certain million dollars or a gamble with an expected value of a million dollars?", most respondents will prefer the certain million. If the level of uncertainty surrounding the benefits is high, this fact is extremely important in the formation of strategy. Such

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[1] In the extreme, the Precautionary Principle equates with "guilty until proven innocent," or, in Robert Frosch's words, the injunction, "Don't do anything for the first time."

uncertainty is a reason the insurance business is profitable. It also accounts for the popularity of casinos, where, however, most people play for small stakes.

The Precautionary Principle is a warning to take into account risk aversion in making decisions under uncertainty. Making the Principle operational for global warming is difficult because decision-makers disagree about the probability and size of potential losses. Within economics, this disagreement is usually displayed in divergences over the appropriate discount rate.

Environmentalists resort to the possibility of climatic calamity as a trump card (Cline, Grubb, this volume). Should, therefore, the central estimates or best guesses about costs and benefits of mitigation and adaptation be ignored in favor of contingencies based on outlying possibilities?

The specter of doom *always* hangs. The Old Testament of The Bible records the prophet Jeremiah in 612 B.C.: "I looked upon the earth and lo it was waste and void, and to the heavens and they had no light. I looked on the mountains and lo they were quaking, and all the hills moved to and fro. I looked and lo there was no man and all the birds of the air had fled. I looked and lo the fruitful land was a desert and the cities were laid in ruins." (Jer 4:23-26)

The climate issue deals with deep human fears, the oldest human fears. It evokes the list of Kates (1992): Are we too many, will there be enough, is there too much, will humankind, any kind, survive?

The debate over climate is the latest occasion for these concerns, and we want to hedge against catastrophe. Whether the probability of climatic catastrophe is 1–1000, 1–100, or 1–2 is unknown and perhaps unknowable. A survey of 19 experts suggests the mean probability of extremely unfavorable impacts for a 3°C warming over a century is about 1–20 (Nordhaus, personal communication). Additional research in the natural sciences may not help reduce the number of possible worlds but increase it.

Our ancient fears will never go away. Jeremiah preached for forty years, and during that time, as far as we are aware, nature was not unusually harsh. Political catastrophes befell the Jewish people, including the Babylonian exile. Concern, like energy and matter, is conserved, and catastrophe always could happen. The climate issue ultimately reduces not to what is known but to fear of the unknown.

In short, ±1 percent may well remain the reference estimate for cost of climate change, with arguments raging about the shape of the distribution in which this is a good guess.

Assume adaptation, not dumb farmers.

Most studies of the impact of climate change assume that the climate shifts over the next decades and other matters such as technology, trade, and diet change little or not at all. The impact of climate is usually calculated as the difference in production between today's output and that in a different climate superimposed on today's farm or city. Because today's activities are adapted to today's climate, the estimated impacts of climate change are usually losses.

Scaling up or multiplying studies made for small areas to cover larger ones tends to create a further negative bias. Compensating possibilities for trade, migration, and emergence of new activities to benefit from new conditions are neglected.

The Adaptation Panel of the National Academy of Sciences (1992) study on global warming definitively ends the reliance in climate impact studies on "dumb farmer" scenarios in which people, like turkeys, stare up at the rain with open mouths until they drown. After the massive political and media attention to climate during recent years, many people who need to know that climate is likely to change over the next decades and century are now aware of it. Even without the media attention, people are alert to changes in their environment. We should study the responses of smart farmers, smart businessmen, and smart householders, as well as dumb ones.

Climate change should not be superimposed on the world as it is, but on the world as it may be. The Missouri-Iowa-Nebraska-Kansas (MINK) study offers an advanced approach to considering impacts and adaptation (Rosenberg and Crosson, 1991). The effort to foresee climate 30 years hence is matched by effort to foresee other changes in the region over the same period.

Importantly, adaptation does not require waiting. Much adaptation is anticipatory. Like its counterpart mitigation, adaptation often takes the form of investment.

A prime example of adaptation is weather forecasting. The weather forecast precedes the storm, so behavior can adjust. Adaptation need not rely on one climate scenario but can prepare for a variety of conditions: dryer, wetter, hotter, stormier, more variable.

In fact, fitting human life better to a warm environment is a necessity. About 75 percent of today's population of 5.3 billion live in what are now developing countries, which are largely hot countries. By 2020 the world's population is expected to exceed 8.2 billion, and 85 percent of that will be in the countries now categorized as developing. Growth rates are highest where annual average temperature is above 20°C. Regardless of climate change, a growing share of the world's population will dwell in high temperatures in the next century. Changes in the percent of the world's population living in different climate zones will be influenced much more by population growth than by changes in climate, for several decades at least.

Global warming is a reality for the human population even if our emissions stop today. More efficient, pleasing, and less environmentally damaging ways to live in hot areas can help billions of people regardless of climatic shifts associated with greenhouse gases.[2]

The vulnerability of societies to environmental hazards can certainly be further lessened, especially in developing countries. We need to identify the actions which can reduce vulnerability and avoid the behaviors which increase it. These are the central tasks of adaptation and justify the importance of adaptation research.

Integrate analyses of mitigation and adaptation.

Almost always analysts set mitigation and adaptation in opposition or consider them unrelated alternatives. Setting mitigation and adaptation against one another may enliven the debate, but it makes the debate academic as well as unsound.

The production that creates emissions creates the income that pays for both mitigation and adaptation. Rising incomes have provided countries, regions, and individuals the means for overcoming a sequence of environmental problems. The World Bank (1992) has proposed a provocative set of relationships between income and pollution (Figure 9). The Bank finds that increasing per capita income is applied early to provide water supply and urban sanitation. As income rises further, problems with local air quality continue to worsen, but these also crest and are solved by prosperity.

In contrast, the Bank concludes that the production of carbon dioxide and garbage have yet to show signs of abating with increase in per capita wealth. The analysis of Nakićenović (1992) suggests the Bank's picture of carbon dioxide emissions is not complete and possibly wrong. Per capita carbon dioxide emissions must be viewed as a function of both technology

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[2] It is curious that this "natural" warming is ignored. The preference for addressing "man-made" additions to the environment also appears in regulation of carcinogens and radiation. If the goal is to reduce risks to human health and safety, high payoffs may well come from reducing exposure to natural carcinogens and radiation. In the case of climate change, adapting to actually existing climate variation may be more rewarding than planning for sea level rise.

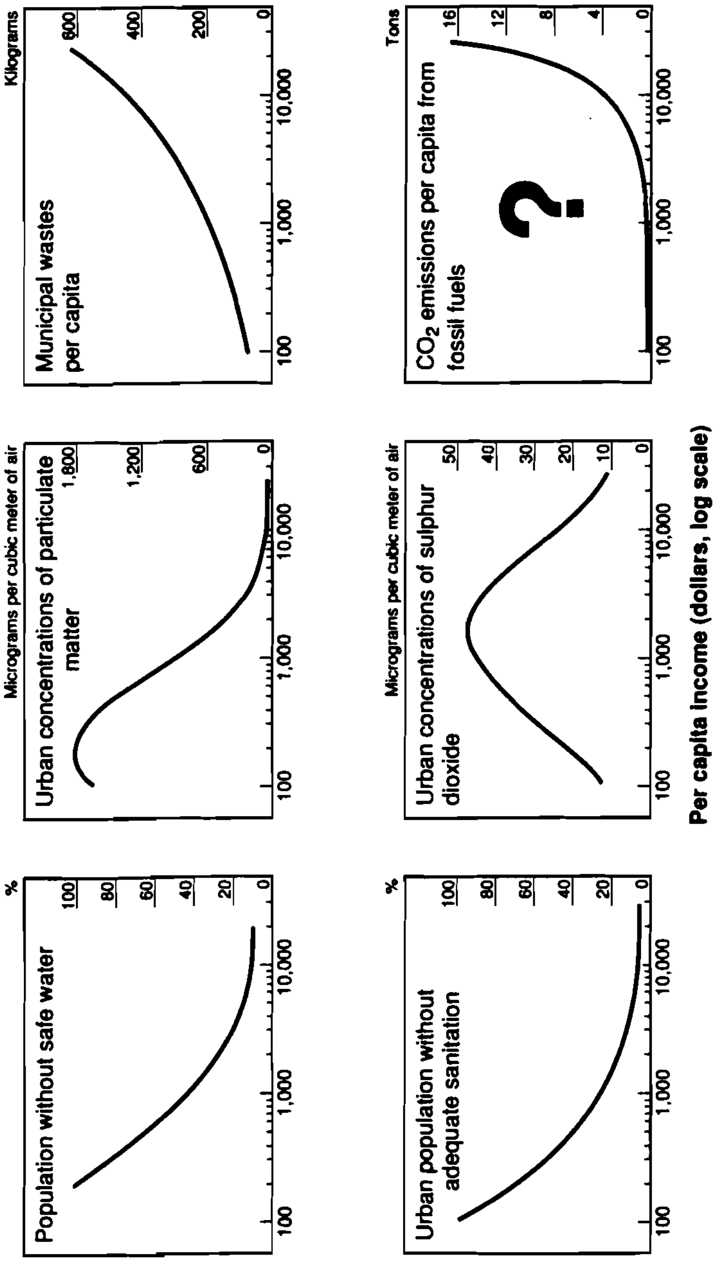

Figure 9. Relationship between environmental problems and income growth, based on cross-country regression analysis for data from 1980s. Approaches based on time series for individual countries may yield a different pattern for carbon dioxide emissions. Source: After World Bank, 1992.

and income and may well be at or near saturation in many industrialized nations.

To illustrate the influence of income, consider the scenario prepared by the U.S. Environmental Protection Agency to study impacts of unimpeded growth in the emissions of greenhouse gases (Lashof and Tirpak, 1989). Annual global income in the year 2100 reaches $35,600 per capita, about 8 times the present level. The economic activity producing such incomes can surely emit much gas. It also permits purchase of water desalinating plants, dikes, and umbrellas, as well as energy-efficient and low-carbon devices. Moreover, technologies for energy efficiency can aid both mitigation and adaptation. A well-engineered residence or office can reduce both emissions and vulnerability to weather and climate.

Nearly all studies to date have failed to address thoughtfully the question of the resources that may become available for adaptation or how wealth itself may enhance the preference for clean energy. The resources available for adaptation are largely the same ones as for mitigation. It is curious to propose that societies will be rich in looking at energy alternatives and poor in considering approaches to provision of water and food.

The common sets of resources that should be considered in analyzing mitigation and adaptation are social as well as financial and technical. Certain mitigation strategies may require a cooperative social order or new lifestyles, within a nation or internationally. Assumptions about social order and structure also have implications for the capacity to adapt.

Conversely, the knowledge haunts us that, if development fails, many problems will be more serious for nations than climate change.

Explicit treatment of the rate of technical change is particularly important for an improved, consistent set of analyses of mitigation and adaptation. With respect to mitigation, it is fashionable to assume rapid progress in energy technologies, particularly for energy efficiency. Yet, comparable assumptions are scorned with regard to plant genetics, protection of human health, and supplies of freshwater. If the worldwide research and development enterprise is successful in energy over the next 50 years, work in materials, information, telecommunications, and other fields important for adaptation is unlikely to trail behind. The same cluster of technologies will determine practice in the future with respect to emissions and adaptation, just as the electric motor is found in both power plants and household appliances today.

Adaptation and mitigation must be analyzed within a consistent, dynamic framework. This needs to be reflected in the organization of academic research, within national studies, and in the activities of the IPCC.

At a national level, exemplary progress is found in the study of the Council for Agricultural Science and Technology (1992), based on the well-posed question: "For a warmer planet with more people, more trade, and more CO_2 in the air, can U.S. farming and industry prepare within a few decades to sustain more production while emitting less and stashing away more greenhouse gases?"

At a global level, the first dynamic, integrated model of climate change and the economy now functions (Nordhaus, 1992a; 1992b). Enough information about adaptation and mitigation exists to calculate an optimal investment in curtailing CO_2 emissions. The calculation has been made and cannot be ignored.

Though the broad understanding of mitigation and adaptation has advanced rapidly, vexing questions remain, some technical and some fundamental.

4. Technical Questions

How do energy prices affect emissions?

The questions of how and when prices matter are baneful for energy economists. Powerful short-run effects have been demonstrated by the oil price flares of the 1970s. Studies comparing energy use in countries where consumers face different prices argue for strong relationships as well. But major questions remain about transferability of experience from one setting to another and about long-run behavior (Hourcade, this volume). Long-run price elasticities in the energy sector are not well-understood.

A problem is that energy prices do not want to change. Crude oil prices, one of the most telling index prices for energy, have been strikingly constant since about 1915 except for the few flares (Santini, 1990). Neither resource depletion nor market manipulation by producers or consumers has had a sustained effect. A strong invisible hand does indeed appear to be at work. This hand may not help those who see high prices as the best route to low emissions.

Of course, prices paid at the gas pump may vary greatly even if those at the wellhead do not. Filling a tank costs much more in Rome than in Riyadh. Better understanding of end-use behavior is critical to the success of policies that rely on taxing energy or changing its price to reflect full social costs. It is impressive that even the price flares which were sustained for 5–10 years, while they brought recessions and temporarily depressed emissions for heavy energy users, left the configuration of the energy system intact. In energy, the price of repression may be affordable for a few years but the price of revolution out of reach.

In fact, most of the emissions "saved" or avoided globally since the early 1970s are not attributable to actual price rises. Rather they are caused by growth of nuclear energy (now saving about 1/2 Gt C/yr over the probable alternatives); global economic slow-down which has lessened energy demand by 10–20 percent of what it otherwise would be; and "autonomous" efficiency gains proceeding at 1–2 percent year. Of course, expectations about prices, as well as actual prices, may have played a role.

More insight would be helpful as a new round of aggressive play with energy taxes begins. It would hardly be surprising if high energy prices (disguised as taxes) fall quickly after a few years. Transport, housing, food, and other sectors resist alteration in the share of the social budget which they receive.

One price puzzle is how innovative technologies become economically superior to those they replace. At the time of introduction, the fresh competitors are often decidedly inferior by standard bottom-line calculations. A combination of continuing technical improvements, productivity change in related industries, economies of scale in production, and the growth of related networks for provision of goods and services work to their advantage. Also, richer consumers change tastes.

In brief, as much as prices may pinch, they are not sufficient alone to explain quantities.

An important asymmetry has also appeared in the price debate. Scarcely anyone thinks now about the virtues of cheap energy, a popular theme in the 1950s, 1960s, and early 1970s. Should all the benefits of low energy prices be forgotten because of environmental issues?

Is it preferable to regulate emission prices or quantities?

In a classic paper, Weitzman (1974) pointed out that under conditions of perfect information prices and quantities are equivalent control instruments. With perfect information a market-based system is superfluous, because a center could specify the efficient output (quantity) for every producer. Information is imperfect, and several studies conclude that an approach based on prices (including taxes) may be economically several times as efficient as regulation of quantities.

But, where marginal costs are uncertain, an error in the quantity of outputs (including pollution) may occur. The reduction that would be achieved, for example, in greenhouse gas emissions by a given price or tax for carbon is not known in advance. If the impacts of climate change on society are highly nonlinear, as the proponents of Precautionary behavior uphold, then even small quantity errors may be intolerable. Reliance on taxes then becomes risky.

A system of marketable permits could achieve a specified reduction while equalizing marginal costs (Okada and Yamaji, this volume). A market for emissions trading requires high quality data about baseline emissions, information about the characteristics of site operations, sound models of consequences, and means for emitters to identify and contact one another. Some have expressed optimism about creation of a worldwide greenhouse gas permit market (United Nations Conference on Trade and Development, 1992). Others, less sanguine, argue that the market will take decades to form and trading will be thin. Experience with the Clean Air Act in the United States suggests that pollution markets are still experimental and may need twenty or thirty years to bustle.

Will institutional and other considerations allow market formation and operation quick enough to respond to the fears that are driving social action? Idealized discussion is often shocked by the harsh tests of practice. Whatever the analytic community will propose will be distorted by politics and institutions. The resulting laws and regulations will also have some perverse effects.

Moreover, in most countries green taxes will prove unpopular like other taxes. People hate taxes. Public skepticism is warranted that governments will make carbon taxes revenue-neutral. Tax collectors have been shot and killed all over the biosphere. Green camouflage may not provide protection if the arm inside it reaches deep into many pockets. Thus, carbon taxes will likely have a largely symbolic value, at least in the United States (Schelling, 1992).

Uniform approaches for carbon or energy taxes, sometimes proposed for all of the European Community or all of the industrialized nations, also worry. Countries have historically taken different paths toward the destination of low carbon and high efficiency (Figure 4). Moving down either axis reduces emissions. Each country is on a particular historical path and faces specific technological and other choices. Diverse instruments thus apply (Jorgenson and Wilcoxen, this volume). Uniform policies may fail to appreciate the heterogeneity and specificity of individual countries. On the other hand, international trade may confound diverse national strategies (Manne and Rutherford, this volume).

As theoretically appealing as market-based strategies are, serious study of quantity approaches needs to be sustained. We should not put all our eggs into the market basket. We ought to examine carefully the experiences in Britain, Japan, and Poland with proposals to shut down or vastly reduce their coal industries. What would abandonment of coal involve globally and for key nations such as China? It may be as feasible as global taxes, and, with transfer payments and retraining, reliable and even economical.

What is the shape of the damage function from climate change?

The search is underway for the shape of the climatic damage function, which relates loss of gross domestic or world product to climate change over time. Rather than tamely linear, its form could be quadratic or cubic, changing abruptly (Peck, this volume).

The question can never be fully resolved. Climate change will not be experienced apart from the general tangle of the one economic history of the Earth. Experiments to verify the shape of the function over decades are hard to envision. But, several approaches are possible. One is to estimate cumulative expenditure on adaptation which would otherwise not be made. Analogies with other chronic problems and surveys of expert opinion may also be suggestive.

5. Fundamental Questions

Can we improve long-term predictions of socio-technical systems?

Long-term means more than 20 years. Global climate modeling and carbon cycle modeling are supported generously around the world. Comparable support for study of the socio- technical dimensions of the climate problem is due. New computational tools set off a wave of futures studies in the 1970s. Few new approaches have been tried since the early 1980s. An ambitious, fresh worldwide research program for long-term analysis of socio-technical systems is needed.

A new generation of socioeconomic and socio-technical models involves ways to chart not only future development, but to understand long-run economic history as well. Reconstruction of long times series of data about economic performance and the diffusion of technologies is needed, going back as far as possible, and at least a hundred years. Such series exist for only the United States, Sweden, United Kingdom, and a handful of other countries. For most of the world, especially developing countries, quantitative economic history has yet to be written. With imaginative use of sources, the record can be built with which to calibrate models and predict more confidently.

A vexing problem is the inability of almost all current models to reproduce the historical decarbonization trend and the changing historical market shares of primary energy sources.

Areas for improvements in analytic tools are recognized. One is technical change and the issue of "autonomous energy efficiency improvement." What exactly does autonomous mean? To what extent is it price-induced? To what extent can it be made endogenous through incorporating more realistic treatment of R&D in models? What about the view that technology advances in certain directions and is not fine-tuned to changing demand and cost conditions? Better ways to understand and show uncertainty ranges and forecast errors are needed. Advances in the generic study of complex systems may provide a fresh analytic vocabulary.

Empirical data on how people budget their time and where flexibility lies are required to separate probable scenarios from wishful thinking. Clas-Otto Wene pointed ironically in the Workshop to the poor match between "the top-up and the bottom-down models." Time budgets and the budgets for expenditures in various social sectors are among the checks to achieve consistency at the various levels of analysis.

The set of world regions to use for analysis is in question. The political geography that underlay the global studies of the 1970s and the 1980s has fractured. Today's division of developing and developed countries is already blurred and surely will not apply in 2050 or 2070. When we do not know East from West and North from South, it is time to begin again.

Many models are still inappropriately constrained by availability of energy resources. Updated geological knowledge shows oil and natural gas resources will be plentiful through the 21st century (WEC, 1992).

Imaginative thinking is needed about the far future of energy, food, transport, and other human wants. The needs go well beyond economic modeling, but long-term economic modeling may provide a framework to raise many of the right questions.

How much do policies intended to affect emissions matter?

Recall the analyses of the factors modifying population growth. Billions of dollars are spent each year under the rubric of family planning. Reviews of the literature (Lapham and Maudlin, 1987) show that the slowing of births has been largely the result of factors incidental to other social and economic changes underway, changes primarily associated with development. Perhaps 15–20 percent of the change is attributable to intentional population programs. Some scientists report lower efficacy.

Deliberate policies to affect greenhouse gas emissions may also account for only 15–20 percent of the change in emissions that will take place. More thought is needed about the factors that will account for the other 80+ percent. These include growth of general productivity as well as population (Birdsall, 1992). According to Ogawa's (1991) analysis of the factors that contributed to global growth in CO_2 emissions 1973–1987, the net annual +1.75 percent increase owed to population increase (+1.74), GDP per capita increase (+0.99), energy/GDP ratio decline (efficiency gains) (-0.59), and CO_2/energy ratio decline (decarbonization) (-0.39).

What are the opportunity costs of focus on the climate issue?

The 2 percent that a stringent regime might cost is equal to the average current total national expenditure of industrialized nations on environmental quality. If society wants to double its green budget, should the full amount be allocated to the climate issue? Alternatively, is the world focusing its environmental investments on the most serious problems? Largely due to bad water, 800 million people have hookworm, and 750 million children a year suffer from diarrhea, of whom 4 million die. The list of risks in the human environment remains long. Will commitment to strict greenhouse gas control leave money for other important issues? Opportunity costs must be considered.

The fundamental question is "What are rational allocations of funds for environment around the globe?" The UN Conference on Environment and Development produced no priorities, only rosters of problems and renewed competition among issue entrepreneurs seeking to micro-optimize. New institutional means are required for international consultations on the agenda for environmental research and development worldwide (Carnegie Commission, 1992).

In considering mitigation and adaptation for climate change, "tie-ins" and "no regrets" strategies are much mentioned. How much other profit will accompany the greenhouse gas emission reductions to help justify the sums expended? Large collateral benefits are promised for investments in energy efficiency, water use efficiency, and coastal zone management. The economics of these investments needs to be rigorously evaluated. Recognizing that solving one environmental problem may help solve others, we must not forget the hard, unfinished environmental problems such as water quality, waste disposal, and degraded lands that climate-oriented policies are unlikely to alleviate. Tradeoffs will remain.

6. Climate Change Amidst Global Change: Fin-de-Siècle Then and Now

Let us close with a thought experiment about the climate question as it might have arisen in the 1890s. Toward the end of the last century the Swedish geochemist Svante Arrhenius (1896) published his classic article projecting a warming as high as 5°C for doubling of CO_2. Suppose this came to the attention of the leading governments ....

The Swedes contacted the British, French, and Germans, who were deeply concerned. An enormous, populous, coal-burning nation loomed on the far shore of the ocean. Called the United States, it was building railroads, steel mills, and power plants at a furious rate. Its population had soared from 5 to 80 million in the 19th century. Emissions would surely rise rapidly.

To prepare memoranda for governmental use, the European Panel on Climate Change (EPCC) was created. The rest of the world did not count scientifically. The British assumed the chairmanship. They selected for the role the world's foremost expert on economic growth, Alfred Marshall, author of *Principles of Economics* (1890). Marshall had excelled in his advisory capacity with the Royal Commission on the Depression of Trade and Industry in 1886.

Marshall assembled leading experts from diverse fields. From France came Henri Poincaré, to assess the mathematics; Antoine Becquerel, to consider energy; and Gabriel Tardé, specialist on the diffusion of innovations. From Norway came oceanographer Fridtjof Nansen, from Russia fluid dynamicist Alexander Lyapunov, from Austria-Hungary the geologist Eduard Suess, and from Italy sociologist Vilfredo Pareto. Marshall added fellow Englishmen in physics, William Thompson (Lord Kelvin) and John Strutt (Lord Rayleigh), and statistics (Francis Galton). Germany contributed engineer Karl Benz, climatologist Vladimir Köppen, and zoologist Ernst Haeckel, inventor of "ecology."

The EPCC considered energy and emissions. About 65 percent of world energy came from coal and about 30 percent from wood and hay. The geological community asserted energy was not a question: coal was king. Oil was a novelty that would soon be depleted. Coal consumption was 500 million tons in 1890 and emissions 340 million tons. The growth rate of emissions 1850–1890 had been 4.7 percent.

The "business-as-usual" forecast was troubling. If the rate of emission growth and airborne fraction were maintained, the atmospheric concentration of CO_2 would rise from the 290 ppm recorded currently at the observatories to double that level by the year 2000.

Poincaré was alarmed about chaotic behavior of the climate system, Nansen worried that the ice caps would melt, and Suess pointed out that such changes had not occurred for millions of years. Köppen and Haeckel feared that vegetation would be mismatched with the new atmosphere and the intricate web of life destroyed. Anxious letters kept arriving from water expert John Wesley Powell, head of the United States Geological Survey. In short, catastrophic and irreversible developments were underway.

Marshall himself was sensitive to the fact that England imported many of its food staples from poor, unstable regions such as Ireland and the Ukraine. "Corn laws" to protect domestic farmers and prevent dependence on foreign food supplies had caused massive political crises earlier in the 19th century. Gross domestic product per capita in Western Europe in 1890 had reached $1,000 per capita and gross world product $1.4 trillion ($1985). Who would responsibly jeopardize this achievement?

But, Lord Rayleigh was unsatisfied with the energy balance in Arrhenius' model, and Lyapunov was concerned about the stability of the equations and missing feedbacks. Galton questioned the reliability of the data and insisted on the need to show the confidence with which conclusions were stated. Becquerel and Benz asserted that innovations in energy and transport were sure to come. Tardé and Pareto insisted societies would adapt; the social and economic transformation of European societies in the 19th century was surely more rapid than what added sunshine would bring. And, after all, Europeans were competing madly to colonize tropical territories.

Marshall set out to define a compromise. An eager consumer of statistics, Marshall noted that economic growth since the start of the industrial revolution had averaged about 3 percent. If emissions rose at this rate, which assumed advances in efficiency and fuels, then concentrations would reach about 355 ppm a hundred years later. The atmosphere would warm by at least 0.6°C, and possibly as much as 2°C, depending on the climate's sensitivity. Earth would still be the hottest it had been for 1,000 years. This seemed a reasonable case to consider.

As an economist, Marshall sought to reckon how much income the world should forego to stay at 290 ppm. To answer, he wondered what would be the gross world product in 1990 if Earth warmed and if it retained the climate of 1890. Working with an actuary, Marshall laboriously calculated what the next 100 years might bring. Assuming the established rate of long-term growth continued, the result was that between 1890 and 1990 world product would grow from \$1.4 trillion to \$20 trillion, and income per capita from \$1,000 to \$10,000 dollars in Western Europe.

Marshall was astonished. Both adaptation and mitigation would be affordable. In fact, the 0.6°C warming would be lost in the noise of such massive change. Provided there was genuine development, neither would emissions rise at a reckless rate, nor would climate threaten human survival.

Marshall circulated a draft report with his prognosis for global change. Almost the entire panel was disbelieving. Lord Kelvin's copy came back with derisive marginal annotations about prospects for technical progress: "Heavier than air flying machines are impossible" and "Radio has no future." Marshall was suddenly called to work on urgent near-term issues of unemployment. Tensions between the European powers worsened. The report of the EPCC was forgotten.

Marshall, of course, was right.

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Appendix

INTERNATIONAL WORKSHOP ON COSTS, IMPACTS, AND POSSIBLE BENEFITS OF CO_2 MITIGATION

28–30 September 1992

IIASA, Laxenburg, Austria

PROGRAM

Monday, 28 September 1992

08:30 **Registration**
09:00 Welcome, P. de Jánosi, Director, IIASA
09:10 Opening Remarks by:
  W. Nordhaus, Yale University
  Y. Kaya, University of Tokyo
  B. Bolin, Chairman, IPCC
09:40 Introductory Address, Akira Yajima, Vice-President, CRIEPI
09:55 Workshop Background and Overview, N. Nakićenović, IIASA

SESSION I: ECONOMICS OF CLIMATE CHANGE

Chairperson: D. Jorgenson
Invited Paper:

- The Economics of Greenhouse Warming: What Are the Issues (W. Nordhaus)

Contributors: M. Grubb, J. Ausubel, T. Schelling, N. Nakićenović
10:30 Paper Presentation
11:00 Presentations by Contributors
12:20 General Discussion

SESSION II: IMPACTS

Chairperson: B. Bolin
Invited Papers:

- Assessment of Climate Change Impacts (J. Scheraga)
- Reconfiguration of the Russian Economy and Energy in Response to Environmental Problems (Y. Kononov/I. Bashmakov)
- The Impact of Climate Change on Agriculture: The Ricardian Approach (R. Mendelsohn/W. Nordhaus)

Contributors: S. Fankhauser, G. Fischer, H. Jansen, S. Peck
14:30 Paper Presentations
16:00 Presentations by Contributors
17:20 General Discussion

Tuesday, 29 September 1992

SESSION III: COSTS

Chairperson: W. Cline
Invited Papers:

- Review of Costs to Developing Economies (R.K. Pachauri)
- EMF 12: Global Climate Change: Impacts of Greenhouse Gas Control Strategies, An Executive Summary (J. Weyant)
- Carbon Coalitions: The Cost and Effectiveness of Energy Agreements to Alter Trajectories of Atmospheric Carbon Dioxide Emissions (J. Edmonds)

Contributors: A. Amano/M. Kainuma, A. Dean
09:00 Paper Presentations
11:00 Presentations by Contributors
11:45 General Discussion

SESSION IV: POLICY INSTRUMENTS

Chairperson: K. Yokobori
Invited Papers:

- Greenhouse Policy After Rio: Economics, Science, and Politics (W. Cline)
- The E.C. Proposal for Combining Carbon & Energy Taxes: The Implications for Future CO_2 Emissions (R. Richels)

Contributors: M. Al-Sabban, Y. Jia, M. Levine, M. Mors
14:00 Paper Presentations
15:30 Presentations by Contributors
16:30 General Discussion

NEW SESSION BY POPULAR DEMAND: DISCOUNTING

Chairperson: T. Schelling
Contributors: W. Cline, A. Manne, W. Nordhaus
17:00 Brief Presentations and Discussion

Wednesday, 30 September 1992

SESSION V: MODELLING

Chairperson: W. Nordhaus
Panelists:

- Reducing U.S. Carbon Dioxide Emissions: An Assessment of Different Instruments (D. Jorgenson)
- Top-down–Bottom-up: A Systems Engineer's View (C.-O. Wene)
- A Simulation Study on Tradable CO_2 Emission Permits (K. Okada/K. Yamaji)
- International Trade in Oil, Gas and Carbon Emission Rights: An Intertemporal Equilibrium Model (A. Manne)
- Modeling Long Run Scenarios: Methodological Lessons from a Prospective Study on a Low CO_2 Intensive Country (C. Hourcade)
- Looking vs Leaping: The Timing of CO_2 Control in the Face of Uncertainty and Learning (C. Kolstad)
- G-Cubed: A Dynamic General Equilibrium Growth Model of the Global Economy (W. McKibbin)

09:00 Paper Presentations by Panelists
10:30 Discussion
11:00 Paper Presentations by Panelists
12:15 Discussion
12:40 Summary of Key Isssues (J. Ausubel)
13:00 Adjournment

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