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Note to the reader from the UNU

Future Global Change and Modelling is an ongoing programme that aims to have the United Nations University serve as a forum on the megatrend of global change and structural transformation. This programme is a response to the need to evaluate recent changes in the perception and structure of the world's politics, economics, demography, technology, ecology, and ethics. Practitioners of futures research have, over the past few decades, developed an array of systematic and powerful methodologies in an effort to understand the range and probabilities of future global scenarios. The UNU brings together this international community of scholars to undertake futures studies of global change and incorporate a wide range of variables and methodologies to increase both the early warning and longer-term planning capacities of the UN system and policy makers in general.

This book is based on the first of a series of UNU conferences on Future Global Change and Modelling held in Tokyo in October 1991. Scholars and representatives from various UN agencies and leading research institutions from 17 countries discussed immediate and long-term world problems with simulation analysis by various model systems. Subsequent UNU conferences held under this programme include Arms Reduction: Economic Implications in the Post-Cold War Era, and Global Environment, Energy, and Economic Development.

Modelling global change

Edited by Lawrence R. Klein and Fu-chen Lo

3rd Party Paper

Details on SGM model

United Nations University Press

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sterile and did not go further to exploit the potential of the simple, but differentiated enough model. Thus, for example, it might be interesting to analyse the effects of various asymmetric policies, in which various countries would face different target levels, or the potential use of compensation schemes to induce less developed countries to introduce abatement measures. For it is highly probable that concerted international measures will be hindered by the pressing needs for development and economic restructuring of the less or medium developed countries, who on the other hand are emitting a significant amount of greenhouse gases leading to global consequences.

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9

Modelling future greenhouse gas emissions: The second generation model description

J.A. Edmonds, H.M. Pitcher, D. Barns, R. Baron, and M.A. Wise

Introduction

The analysis of greenhouse gas emissions has made enormous progress during the course of the past decade.[1] Analysis has progressed from the use of simple time-trend extrapolations to the analysis of emissions of several greenhouse gases with parallel but independent behavioural and optimization models of energy, manufacturing, agriculture, and land-use systems. But our ability to examine potential future scenarios of greenhouse gas emissions is limited because modelling tools adequate to the task of integrating analyses of technologies and human activities on a global scale with regional detail, including energy production and consumption, agriculture, manufacture, capital formation, and land-use, along with the interdependencies between these categories, do not yet exist.

The first generation of models were specialty models which focused on a particular aspect of the emissions problem without regard to how that activity interacted with other human and natural activities. The Edmonds-Reilly model (ERM) (Edmonds and Reilly 1985), for example, is a global energy model in which the production of commercial biomass has no interaction with the agriculture sector or land-use in general. The Global 2100, Manne and Richels (1990a,b,c,d,

1991) is a computable general equilibrium model, but is limited in its applicability beyond energy-related issues. Other computable general equilibrium models such as Jorgenson and Wilcoxen (1990a,b) focus exclusively on national issues. Other modelling systems such as the Atmospheric Stabilization Framework (ASF) (Lashof and Tirpak 1989), utilize a system of models that provide global coverage of all emissions generating human activities, but do not provide a consistent analysis system in which the interaction between human activities can be analysed. The number of models in use to analyse greenhouse gas emissions reductions is large and growing, including for example: Nordhaus and Yohe (1983); Fossil2, AES (1986, 1991); GREEN, Burniaux et al. (1991), OECD (1991); CETA, Peck and Teisberg (1991); GEMINI, Scheraga et al. (1991); and IMAGE, Rotman et al. (1989).

The current state of understanding of the natural science of the global environmental change issue indicates that a variety of gases are associated with potential changes in the radiative composition of the atmosphere. These gases include: CO_2, CH_4, CO, N_2O, NO_x, SO_2, VOCs, chlorofluorocarbons (CFCs) and CFC substitutes. These gases are released in the process of a wide variety of human activities including: fossil fuel production, transfer and oxidation, land-use change, silvaculture, the application of some fertilizers to crops, the husbandry of ruminant livestock, the cultivation of wetland rice, and specific manufacturing processes such as cement manufacture, nylon manufacture, and chemical manufacture. Moreover, though local air chemistry plays an important role with regard to very short-lived[2] gases, it is the sum of all releases and absorptions of all gases by all human activities that governs the short-term[3] rate of change of the atmospheric composition of radiatively important gases, and the earth's atmospheric radiation profile. In addition, the human activities that govern emissions are interdependent. That is actions that are taken in one segment of the economy affect other segments of the economy. These interactions are likely to become extremely important if policies are undertaken to reduce potential future emissions. For example, carbon taxes raise great quantities of revenue. While the disposition of tax revenue can generally be assumed to be unimportant to the scale of macroeconomic activity, this is certainly not the case with carbon taxes (Bradley et al. 1991; Brinner et al. 1991; and Scheraga et al. 1991). Other potential policy actions such as tree planting to enhance the carbon sink and/or the extensive development of potential biomass resources to replace fossil fuel energy

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sources, can have substantial impacts on land-use, Marland (1988), Kinsman and Marland (1989), Sedjo and Solomon (1989), Moulton and Richards (1990), Adams et al. (1991), Bradley et al. (1991), and Barfield et al. (1991). Finally, it is essential that the relationship between technology, institutions, economics, and human activity be explicitly represented.

No currently existing model is capable of assessing the global emissions from all human activities and the major direct and indirect consequences of potential policies to reduce emissions. Future analysis requires a more sophisticated suite of models. The new suite of models must include both a global integrating model and compatible regional/national models. These new models must be capable of analysing the emissions of all greenhouse gases from all sources, including both those of natural and human origin, and provide an analysis of the interplay between the variety of human and natural activities responsible for greenhouse gas emissions.

The purpose of this paper is to describe the design of a model, currently under development, which is capable of addressing greenhouse gas emissions and the potential consequences of alternative policy options. We refer to this model as the *second generation model* (SGM).

Paradigms for the SGM

The development of SGMs will benefit greatly from the application of three simple principles: problem orientation, minimum modelling, and parametric modelling. The overriding design principle is that the model should be *problem oriented*. That is, the design of the model should be derived from an analysis of the underlying problem. Model design cannot begin with the set of available models and then try to make the problem fit existing model characteristics. For greenhouse gases, the issues to be addressed are: What are global emissions of greenhouse gases likely to be over the course of the next five to 100 years by region and human activity? What effect will the exercise of policy instruments to control emissions have and what will they cost? What effect will new technologies have on emissions?

Beginning with the problem and working to the design of the model allows the implementation of the second design principle, *minimum modelling*. Minimum modelling means that the model contains all of the information pertinent to answer the research question, but no extraneous information. If chemical manufacture of CFCs is an important activity in determining the rate and timing of climate change it should be included. Moreover, the model should be *parametric*. That is, the model should utilize a database in which all parameters are open to examination and change by the user. In addition, the model should be an *open model*. The purpose of the model is not to provide a one-pass forecast of the future. Where complex human activities subject to public policy action are involved, the future is fundamentally unpredictable. The purpose of a formal model is to provide a consistent, reproducible framework in which to examine possible scenarios. It is important that model results be reproducible and that the model be open to public scrutiny, and criticism, and that all of the parameters be available for inspection and alteration by model users. Finally, given the complexity of the model, it is important to use a *sequential model development* process, beginning with a simple model and adding additional important behaviours in a sequential fashion.

In applying the above cited principles, it is necessary to begin by outlining the pertinent dimensions of the greenhouse gas emissions phenomenon. The critical features associated with the emissions of radiatively important gases are as follows:

1. The issue is *global*, emissions from all sources in all regions of the world determine total atmospheric change;
2. the greenhouse results from the emission of *multiple gases* including: CO_2, CH_4, CO, N_2O, NO_x, SO_2, VOCs, CFCs, and CFC substitutes;
3. emissions result from *multiple human activities* including: agriculture (including forestry), energy production and consumption, transportation, manufacture, services, and land-use;
4. emissions depend upon *multiple resources and technologies* including: managed and unmanaged ecosystems, capital stocks, and labour;
5. emissions depend on *international trade patterns*, and possibly, migration patterns;
6. factors 3, 4, and 5 depend upon *institutional arrangements*;
7. policy analysis requires both mid-term (five-year) and long-term (100-year) *time horizons*.

The second generation model

In light of the above discussion we have undertaken the design of the SGM incorporating the above-listed criteria into the model architecture. The model is global in scope, with five-year time steps and a horizon of 2100. All the major sources of greenhouse gases, as well as SO_2 will be modelled. The economic model is a member of the class referred to as computable general equilibrium models. It contains sectoral detail on households, government, agriculture, energy, and other products activities. Capital stocks are kept by vintage, with economic retirement and retrofit options available. Depletable and renewable resources are tracked in addition to land-use. Economic decision makers include households, government, and producers. The model is regionally disaggregated, with key countries represented individually. Trade between the regions occurs in energy, agriculture, and other products.

Model overview

At base the SGM is a very simple model. Figure 1 depicts the basic structure and flows of goods and services within the SGM version 0.0. At the core of the model are three productive sectors: agriculture, energy, and other products. These, as we will discuss, are disaggregated into 10 sectors in SGM version 0.0. The greatest disaggregation, eight sectors, is found in the energy sector. The central focus on energy reflects the central role energy issues play in determining the future release of radiatively important gases into the atmosphere. Agriculture is similarly handled separately due to the importance of agriculture and land-use issues in determining emissions. All other production is aggregated into a single sector, other products, in SGM version 0.0.

The three productive sectors use three primary factors of production: land, labour, and capital, in combination with produced factors: energy, agriculture, and other products, to produce final output. Note that two aspects of land-use are considered: surface land resources, and sub-surface resources, for example, energy resources.

The household sector is assumed to own land, labour, and private capital. The demographic character of the society is determined within this sector. Household supplies of land and labour are determined on the basis of the price of these factors, which in turn determine, with distributed corporate profits, taxes, and subsidies, the income of the household sector. Household savings are also determined in this sector and vary with the interest rate. This sector also determines the mix of final products to consume.

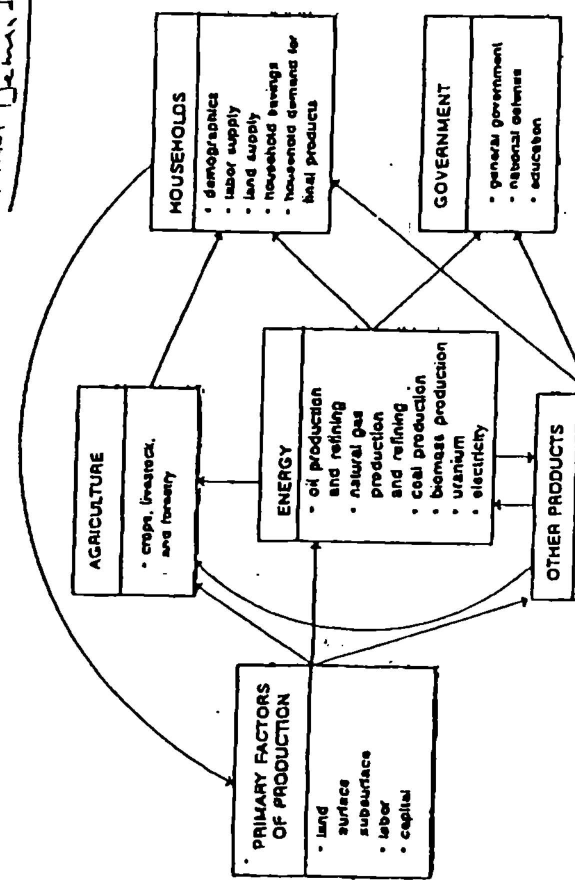


Fig. 1 The flow of goods and services in SGM version 0.0

Finally, the government sector obtains tax revenues from other parts of the economy which are either augmented by borrowing (or reduced by government savings). These revenues go to produce three government services: general government, national defence, and education.

The SGM version 0.0 is a self-consistent dynamic model of the relationship between these six general human activities.

Emissions coefficients are applied to each sector's associated subsector and technology activity rates to derive sectoral, regional, and global emissions of radiatively important gases.

Model development strategy

To reflect the current understanding of anthropogenic sources and sinks for radiatively important gases, and to anticipate the potential for new sources, the model has been designed with a generic structure. This structure allows for a flexible number of production activities, consumption activities, and markets. The implementation of this model utilizes the sequential model development principle. That is, the initial model version will be much simpler than the intended final version. Two model versions are currently identified; SGM version 0.0 and SGM version 1.0. SGM version 0.0 is intended to provide a proof in principle for the modelling system. SGM version 1.0 is intended to provide the first full implementation of the SGM system. SGM version 1.0 will be distributed to the public and have a complete documentation set including: theoretical model description, database description, software description, and user's guide.

For both SGM version 0.0 and SGM version 1.0, the energy production, transformation, and consumption activities will utilize databases developed in support of the ERM, Edmonds and Reilly (1985), Edmonds et al. (1986), Edmonds and Barns (1990; 1991). In addition to the energy structure of the ERM, two producing sectors, agriculture and other products have been added for SGM version 0.0. For SGM version 1.0, the number of sectors will be increased to include expanded government, transportation, other products, and agricultural activities. Final demand sectors for investment, government, and households have been developed. Model development is anticipated to proceed beyond SGM version 1.0, but such model designs lie beyond the present planning horizon.

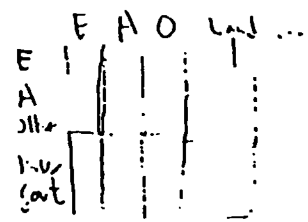
Overview of the SGM structure

Any dynamic model has two problems that it must address. It must describe where the system is at any moment in time and it must describe the process by which it evolves. The SGM is a behavioural model. That is, it attempts to describe how economic systems behave. It is not an optimizing model. The differences between these two approaches are not as great empirically as one might expect.[4] Nevertheless, we have taken the behavioural approach to developing the SGM for two reasons. First, several extremely interesting questions can be addressed in a non-optimizing, imperfect foresight analysis framework. For example, the importance of alternative expectation formation hypotheses can be tested. That is, there is no reason to believe that energy sector decision makers have perfect foresight. In fact, the immediately preceding quarter century of energy history would support the alternative hypothesis, that is that energy decision makers have very imperfect foresight about key future energy parameters such as price. In addition, the behavioural models are computationally simpler in that present behaviour is assumed to be independent of actual future events and decisions. This is of course the domain in which actual decision makers operate. However, the model and its assumed behaviour does depend on anticipated future events and decisions.[5]

Sectors, subsectors, technologies, markets, and accounting

At any moment in time a set of relationships between economic actors can be summarized in a set of accounts that are referred to as an input-output framework. *It is important to emphasize that the SGM is not a traditional static input-output model.* The use of input-output accounting identities to describe economic interrelationships at a point in time does not mean that the SGM simply uses a set of static input-output coefficients that are assumed to remain fixed for an indefinite period in the future to determine production levels and demands. Rather, the simultaneous determination of these input-output coefficients in conjunction with a consistent set of prices is the principal problem facing a computable general equilibrium model like the SGM.

An input-output table shows the relationship between the production, distribution, and use of goods and services in an economy. A row-column entry shows the quantity of a good or service associated



with a row by the sector designated by the column. If a good or service is produced in the economy, it will have both a row and column associated with it. Some sectors, for example, households, investment, and government, may be assumed to consume new final goods and services, but to provide no net output for the rest of the economy. Some factors of production, for example, land, labour, and capital, may be utilized for production in a given period, but are not produced using current flows of goods and services.

GNP accounting: The accounting framework for the SGM relies on simple economic relationships. For example, we can define GNP for any region (note we drop the regional subscript to simplify the notation) as the price-weighted sum of net production of all products,

$$\mathrm{GNP} = \sum_{i=1}^{N} P_i\left(X_i - \sum_{j=1}^{N} A_{i,j}\right) = \sum_{i=1}^{N} P_i(C_i + G_i + I_i + \mathrm{EX}_i - \mathrm{IM}_i), \tag{1}$$

where GNP is the Gross National Product; X_i is the gross domestic production of product i; A_{ij} is the domestic use of product i in the production of product j; P_i is the price of product i; N is the number of product; C_i is the domestic consumption by households of product i; G_i is the domestic consumption by government of product i; I_i is the domestic investment uses of product i; EX_i is the gross exports of product i; and IM_i is the gross imports of product i, which in turn is equal to the disposition of net output among final demand sectors. Alternatively, the GNP can be expressed as the sum of payments to the factors of production,

$$\mathrm{GNP} = \sum_{i=1}^{N}\left(P_iX_i - \sum_{j=1}^{N} P_jA_{j,i}\right) = \sum_{i=1}^{N}\left(\mathrm{TXibt}_i + \pi_i + \sum_{j=N+1}^{N+M} P_jA_{j,i}\right), \tag{2}$$

where TXibt_i is the indirect business taxes; π_i is the profits including net interest and capital consumption allowances; and M is the number of primary factors of production (e.g. labour and land).

The fundamental problem that the model must address is finding a set of prices that are consistent with demands by producers and consumers for goods, services, and primary factors of production. The major behavioural components of the model describe the relationship between prices, production, and consumption of goods and services.

Defining sectors, subsectors, technologies, and markets: For the purposes of SGM documentation we have chosen to use several terms in a specific manner.

Sectors
Sectors represent human activities that produce or consume goods and services. There are two types of sectors, producing sectors and final demand sectors;

Producing sectors
Producing sectors combine factors of production, including the products of other producing sectors and primary factors of production, to produce net output. For example, agriculture, energy, and other products are sectors in SGM version 0.0;

Final demand sectors
Final demand sectors provide final demands for final goods and services, and include households, government, investment, and net exports in SGM version 0.0;

Markets/factor inputs
Markets and factor inputs are intimately related in the SGM. A market exists in the SGM whenever production and consumption decisions are determined separately in the model. Each traded good is also potentially a factor of production, although a product may or may not be used in the production process in the implemented model. For example there may be no net demand for agricultural products by any producing sectors. Nevertheless, there will always exist a row entry in the SGM input-output accounting structure even if the element entered there is zero. Markets define the primary level of aggregation in the model. That is, all subsectors and technologies (see descriptions below) in a sector/market produce a single homogeneous commodity. Markets are defined for each producing sector plus for each primary factor of production, for example, agriculture, energy, and other products plus labour and land in SGM version 0.0;

Subsectors
A subsector exists in the SGM whenever two human activities produce the same output. All subsectors within a sector face the same

price for outputs, but would be expected to have different production functions, for example the production of electricity using oil, gas, coal, hydroelectric power, nuclear power, or solar power. Subsectors may be defined for both producing sectors and final-demand sectors;

Technologies
For some human activities an additional level of disaggregation is useful. Whereas, the number of subsectors for an individual sector in a specific region would not be expected to change from analysis to analysis, there will be times in which multiple, non-mutually exclusive, technology options should be considered. These options have the same output price as the subsectors and sector, but would have individual production functions.

SGM sectors, subsectors, technologies, and markets
For SGM version 0.0 sectors, subsectors, and markets have been identified and are listed in table 1. The technology level of the model has not been separately identified here as there is only one technology for each subsector in version 0.0.

Economic sectors

There are eight energy sectors and two non-energy production sectors in SGM version 0.0. Data for the energy sectors is largely drawn from the ERM model, Edmonds and Reilly (1985) and Edmonds et al. (1986) as updated for Edmonds and Barns (1991). The non-energy sector of the economy will be the primary focus of efforts between SGM version 0.0 and SGM version 1.0. Table 2 shows the additional sectors to be added to SGM version 0.0 to create SGM version 1.0. Producing sectors can be roughly categorized as being either agricultural, energy, or other-products related. The level of disaggregation in each area is driven by the need to understand factors affecting potential future emissions of greenhouse gases and the potential consequences of policy actions to reduce potential future greenhouse gas emissions.

Agriculture
The agriculture sector produces food, fibre, and forest products. In version 0.0, there will be only a single aggregate agricultural commodity. In version 1.0 there will be nine outputs, disaggregated primarily on the basis of greenhouse gas emissions. The three sectors

Table 1 SGM sectors, subsectors, and markets model version 0.0

Sector No.	Market No.	Sector	Subsector No.	Subsector name
1	1	Agriculture	1	Agriculture
2	2	Crude oil production	1–10	Crude oil production by grade. Each resource grade is modelled as a subsector.
3	3	Oil refining	1	Conventional oil refining
			2	Coal liquefaction
			3	Biomass liquefaction
4	4	Natural gas production	1–10	Natural gas production by grade. Each resource grade is modelled as a subsector.
5	5	Natural gas transformation	1	Conventional gas
			2	Coal gasification
			3	Biomass gasification
6	6	Coal production	1–10	Coal production by grade. Each resource grade is modelled as a subsector.
7	7	Biomass production	1	Traditional biomass
			2	Biomass waste
			3	Biomass farms
8	8	Uranium production and refinement	1–10	Uranium production and processing by grade. Each resource grade is modelled as a subsector.
9	9	Electric power generation	1	Oil
			2	Gas
			3	Coal
			4	Biomass
			5	Nuclear
			6	Solar/fusion
			7	Hydro
10	10	Other production	1	Other production
11	n.a.	Households[a]	1	Consumer demand
			2	Demographics
			3	Land supply
			4	Labour supply
			5	Savings
12	n.a.	Government	1	General government
			2	Education
			3	National defence
n.a.	11	Labour	n.a.	n.a.
n.a.	12	Land	n.a.	n.a.
n.a.	13	Savings/investment	n.a.	n.a.

a. Listed household subsectors represent major decisions made within the household sector rather than subsector as used in the other sectors. See section 'Households' below for further details.

Table 2 Sectors and subsectors added to SGM version 0.0 to create SGM version 1.0

Sector SGM version 0.0	Sectors SGM version 1.0	Subsectors
Agriculture		Rice
	Other grains	Other grains
	Ruminant livestock	Ruminant livestock
	Other livestock	Other livestock
	Other food	Other food
	Fibre	Fibre
	Forests	Forests
	Pulp and paper	Pulp and paper
	Wood and wood products	Wood and wood products
	Processed foods	Processed foods
Other production	Manufacturing	Materials intensive
		Other manufacturing
	Passenger transport	Rail
		Air
		Bus
		Other[a]
	Freight transport	Rail
		Air
		Truck
		Other
	Services	Health and other services

a. Passenger automobile in household sector.

closely associated with greenhouse gas emissions are rice (principally CH_4), ruminant livestock (principally CH_4), and forestry (principally CO_2). All sectors are associated with N_2O emissions through the application of fertilizer. Significant quantities of greenhouse gases are also associated with traditional agricultural technology, in particular the practice of slash and burn. The principal inputs in version 0.0 will be land, labour, and energy. In version 1.0 these will be expanded to include fertilizer and materials and land will potentially be disaggregated into multiple categories in accordance with soil types and climate.

Energy

There will be eight energy sectors in the model. Each of these will have subsectors as detailed in table 1 to allow the competing methods for producing the product in question to be accurately modelled.

Two types of energy technologies will be identified, those associated with depletable resources and those associated with renewable resources. All energy technologies will be associated with a resource constraint. A distinction will be made between reserves and resources. Reserves are those resources where two types of energy have been identified and whose location is known and which are known to be producible under present and anticipated economic conditions. Reserves are depleted over time as they are produced. Total reserves are augmented by additions from the resource base. The additions to reserves are determined by grade structure of resources and technologies available to extract them. Renewable resources are handled in a manner similar to depletable resources except that the capacity to produce persists beyond the point of production. Solar energy is an example of a renewable energy resource. A renewable resource may be degraded by production, however. Agriculture, for example, may deplete soils unless investments are made to maintain soil quality.

Other products

In version 0.0, the other products sector will include everything which is neither agriculture nor energy. In version 1.0, the other products sector will be broken down into manufacturing, passenger and freight transportation, and health and other services. There is the possibility of further splitting manufacturing into materials and other manufacturing. Inputs will be capital, labour, and energy in version 0.0 with materials being added in SGM version 1.0. The principal sectors are further disaggregated into subsectors on the basis of their importance to the greenhouse issue, either because they are major energy users, or because they are direct emitters or sinks for a greenhouse gas.

Regions

SGM version 0.0 has 11 regions while SGM version 1.0 will have 20 regions as shown in table 3.

Policy options

Because of the pervasive nature of activities that generate greenhouse gases, a wide variety of policy options needs to be included in the model. Making provision to model these options has had a significant impact on the structure of the model. In addition to the usual tax and regulatory options, provisions have been made in the SGM structure to model such strategies as carbon sequestration by reforestation and afforestation, and biomass energy production, and mandated technologies and practices. The SGM is also designed to explore the consequences of changes in real government expenditure patterns/or complementary reductions in non-greenhouse taxes.

Table 3 Regions in SGM model versions 0.0 and 1.0

SGM version 0.0	SGM version 1.0
1. USA	1. USA
2. Canada	2. Canada
3. Western Europe	3. European Community
4. Japan	4. Other Western Europe
5. Australia/New Zealand	5. Japan
6. Eastern Europe and Russia	6. Australia/New Zealand
7. China and other planned Asia	7. Eastern Europe
8. Mid East	8. Russia
9. Africa	9. China
10. S. & E. Asia	10. Centrally planned Asia
11. Latin America	11. Mexico
	12. Brazil
	13. Other Latin America
	14. Indonesia
	15. India
	16. Philippines
	17. South Korea
	18. Other S. & E. Asia
	19. Middle East
	20. Africa

Theoretical structure of the model

The SGM employs a generic production-cost structure to facilitate the continued development of the model with a minimum of code changes and a flexible modelling response to the wide variety of potential analyses that may be required. The core of the model is the description of production activities. These activities are described by a generic production-cost relationship. This relationship utilizes the theory of duality to describe production functions alternately in physical or financial terms.

sector → subsector → technology

The generic production/cost relationship

The generic production/cost (GPC) relationship uses information about prices, technology, and previous investments to compute levels of production and consumption of commodities as well as demands for investment in new capital stock. Productive activities are described by functional relationships in the SGM which are referred to hereafter as technologies. The term technology is used here to cover a broad array of activities including everything from the production of iron and steel to the production of rice. Technologies, as described earlier, are the fundamental unit of disaggregation in the model. Each sector contains at least one subsector and each subsector contains at least one technology. For SGM version 0.0, there is only one sector, market, subsector, and technology for the production of agricultural output. For the production of electricity, there are seven subsectors each of which can potentially utilize multiple technology options. The SGM keeps all of its information on productive capacity at the technology level of detail.

The SGM uses a vintaged description of technologies. This has a number of important implications. First, it means that history matters. When a technology is installed it remains in existence and can be operated until its retirement. New technologies affect productivity primarily at the margin. They can only affect historical decisions if they are so attractive (unattractive) that they force prices down to the point where existing technologies are retired early (undergo life extension). Another important implication is that once installed, capital stock is not malleable. It cannot be shifted around from one sector of the economy to another. In fact, once installed, capital costs no longer matter. In other words, once the technology is installed the decision to operate or idle a technology depends solely on the ability of the technology to recover its current operating expenses plus taxes and less subsidies.

A technology is described by an array of characteristics including:

1. production function parameters;
2. emissions coefficients;
3. capital investment parameters;
4. installation parameters (e.g. date of first availability, date of removal from the list of options, nominal lifetime, length of installation period); and
5. vintage.

A technology option can be described by the information contained in parameter sets 1, 2, 3, and 4. Once installed, the operating characteristics of a technology can be described by parameter sets 1, 2, and 6.

Within the GPC relationship, the producing sectors all follow the same general structure. There are, of course, some characteristics that are specific to a sector or apply only to a subset of sectors. However, the basic model structure is sufficiently general to accommodate the production/cost and operating characteristics of the various producing sectors in its parameter set.

The sectors represent the highest level of aggregation of production characteristics in the GPC. Within the GPC framework, these production sectors are disaggregated into one or more production/cost subsectors. All sectors, subsectors, and technologies produce a common output and face a common external market price for produced output. The GPC structure allocates investment to technologies based on prior investment history and relative profitability using a logit market-share allocation scheme.

As an example of this sector-subsector hierarchy, consider an electricity production sector with subsectors for coal, oil, natural gas, biomass, nuclear, and hydroelectric power. These subsectors all produce electricity, and they all receive the same price for the electricity they generate. These subsectors do, however, have quite different operating and input requirements for producing electricity, which will in turn affect their relative profitabilities. The allocation of investment among these subsectors in the GPC will reflect these differences in profitability.

Each technology is represented by a vintage-dated, constant elasticity of substitution (CES) production/cost function (one for each vintage of capital stock in operation). For each technology, technological change through time can be captured in the model through the CES production function parameter set. In SGM version 0.0 both an initial set and a terminal set of CES coefficients or parameters is specified for each producing subsector. For any future vintage, the CES coefficients used are a time-dependent interpolation between the initial and terminal values. Different technological change scenarios can thus be modelled in each subsector by varying the terminal coefficient values and the time required to reach these terminal values. *

The general execution path for the GPC is to (1) determine desired levels of investment in new capacity, (2) operate the new capacity, (3) retrofit existing capital stocks, and (4) operate or retire existing capital stocks.

The CES production/cost-function

The CES production function can be written,

$$Xs = \alpha_0 \left(\sum_{i=1}^{N} \alpha_i X_i^{\rho} \right)^{1/\rho}, \tag{3}$$

where Xs is the gross output of the process; X_i is the use of input factor i; α_0 is the scale coefficient; α_i is the individual factor coefficients; and ρ is the elasticity of substitution parameter.

Profit maximization implies that,

$$P_i = P_0 \frac{\partial Xs}{\partial X_i}, \qquad i = 1, \ldots N - M, \tag{4}$$

where P_i is the price of ith input; P_0 is the price of output; $N - M$ is the number of variable factors; and M is the number of fixed factors.[7]

Profits can be written as,

$$\pi = P_0 Xs - \sum_{i=1}^{N-M} P_i X_i. \tag{5}$$

By judicious application of algebra, and equation (4), profits can be expressed as a function of price and the quantities of M non-variable factors of production via,

$$\pi = \alpha_0 P_0 \left[1 - (P_0 \alpha_0)^{\mu} \left(\sum_{i=1}^{N-M} \alpha_i^{(\mu/\rho)} P_i^{-\mu} \right) \right]^{-1/\rho} \left(\sum_{i=N-M+1}^{N} \alpha_i X_i^{\rho} \right)^{1/\rho}, \tag{6}$$

where

$$\mu = \frac{\rho}{1 - \rho}. \tag{7}$$

It is well known that the partial derivative of this expression with respect to the price of the ith input is the negative of the total factor demand, that is

$$\frac{\partial \pi}{\partial P_i} = -X_i. \tag{8}$$

The demand for the ith factor input to the production process can therefore be calculated directly as,

$$X_i = \left(\alpha_0 P_0 \frac{\alpha_i}{P_i} \right)^{\mu/\rho} \left(\frac{Y}{Z} \right)^{1-\rho}, \qquad i = 1, \ldots N - M, \tag{9}$$

where

$$Y = \sum_{i=N-M+1}^{N} \alpha_i X_i^{\rho}, \tag{10}$$

and

$$Z = 1 - (\alpha_0 P_0)^{\mu} \left(\sum_{i=1}^{N-M} \alpha_i^{\mu/\rho} P_i^{-\mu} \right). \tag{11}$$

The above equations can be used to model both operational decision making and investment determination.

Expected future profits from the operation of a technology which employs

$$x_k = (X_{N-M+1}, \ldots, X_N)$$

fixed factors over the course of T years of operation is simply,

$$\pi_e(t_0) = \sum_{t=1}^{T} \left(\frac{\pi(x_k, t)}{1 + \text{dis}} \right)^t, \tag{12}$$

where $\pi(x_k, t)$ is the profit rate consistent with expected future prices in future period t and dis is the discount rate.

Investment and operating decisions

Once a technology has been installed, operation is determined by the set of factor prices for variable factors of production, and the quantity of the fixed factor employed. The determination of factor demands is therefore a relatively simple matter. Investment decisions however are not so simple. These are determined both by the present set of factor prices and the set of expected future factor prices extending out over the expected lifetime of the investment. In the SGM, there are two types of investments, investments in new capacity and investments in existing capacity, in the form of retrofit and renovation (life extension) investments. The existence of retrofit and renovation (life extension) investment alternatives means that present operations are never simple, and that the technology chosen for an addition to new capacity may be substantially altered before its ultimate retirement. The analysis of investment alternatives requires a mechanism for the determination of expectations regarding future prices and taxes.

Future price and tax rate expectations

In each sector, investments are allocated among subsectors on the basis of their relative *expected* profitabilities. Therefore, investment decisions for each subsector require expected profit rate calculations, which require expected prices and taxes for all inputs. For an open economy the purchase price of the good produced by the ith sector in region "1" is given by:

$$P_{i,l} = \alpha_{i,l}[P_i(1 + \delta_{i,l}\mathrm{Tr}_i)\mathrm{txa}_{i,l} + \mathrm{txb}_{i,l}], \tag{13}$$

where $\alpha_{i,l}$ is an adjustment factor to reflect markups and intraregional transport costs; Tr_i is the import transportation costs for the ith good; $\delta_{i,l}$ is a logic driven parameter whose value is 0 if the region is a net exporter, and 1 otherwise, $\mathrm{txa}_{i,l}$ is the proportional tax on the ith product in region 1; and $\mathrm{txb}_{i,l}$ is the additive tax on the ith product in region 1.

Obviously, the price received by the producer of the jth good is simply,

$$P_{i,l} = P_i(1 + \delta_{i,l}\mathrm{Tr}_i). \tag{14}$$

The direct computation of $\pi_e(t_0)$ is cumbersome. An approximation of this value can be obtained by substituting a set of present discounted prices directly into the profit function. This yields an exact solution when $\rho = 1$ (see equation [7]). The present discounted price for product j (either an input or an output), Pe_j, is calculated by,

$$Pe_{j,l}(T) = \sum_{t=1}^{T_{exp}} P_{j,l}(t_0) \cdot \left(\frac{1 + r_j}{1 + \mathrm{dis}}\right)^t. \tag{15}$$

where T_{exp} is the nominal life of the investment; r_j is the rate of expected price change; and dis_j is the discount rate for that subsector.

As noted above, the nominal life of the investment is a parameter of the technology. This parameter value may be different from the maximum potential life of the technology. The tax rate tx is an exogenous variable. Both the rate of expected price change r_j and the discount rate dis are behavioural variables. Expectations of future price and tax rate expectations are assumed to be formed in one of two ways. Either they are given exogenously, and assumed known, or they are formed on the basis of prior experience. This yields four alternative formation assumptions for future prices and taxes of inputs and outputs which can be created by combining assumptions 1, 2, 3, and 4 from the following matrix:

	Formed on the assumption that previous B periods rate of change will continue indefinitely	Given exogenously
Prices	1	3
Taxes	2	4

Note that whenever price or tax expectations are formed on the basis of prior experience, the period of prior experience, B, must also be specified. For $B = 0$, present prices or taxes are assumed to remain constant indefinitely. Furthermore, it is possible to run the model in an iterative sequence to develop a perfect foresight set of exogenously specified set of prices. This would be accomplished by specifying prior solution prices as the set of expected future prices and iterating until stability is reached.

We feel that the ability to model behaviour in which price expectations are formed on the basis of imperfect foresight is important. The period of time between 1970 and the present is marked by decision-making on the basis of flawed foresight in energy markets.

Furthermore, the effectiveness of tax and regulatory policies may in fact depend on the expectations formed with regard to long-term commitment.

The relationship between the discount and interest rates

The discount rate and the real interest rate need not be the same. A great deal of behavioural literature suggests that these rates may in fact be significantly different from each other, Lind (1983), Meier and Whittier (1983), Hausman (1979), and Gately (1980). To reflect this phenomenon, the discount rate, dis, will be linked to the interest rate calculated in the model, interest, by a constant factor of addition, fac_r. The sector-specific discount rate for retrofit investments, will therefore be given by,

$$\text{dis}_r = \text{interest} + fac_r. \tag{16}$$

The add-on factor for retrofit investments need not be the same as the add-on factor for new investments.

The expected future profit rate for a capacity increasing technology

The expected profit rate relative to the capital cost, K, denoted as π_e, is given by,

$$\pi_e = \frac{NR_e}{K} \tag{17}$$

and

$$\frac{NR_e}{K} = \alpha_0 Pe_0 \left[1 - (Pe_0\alpha_0)^{\rho/(1-\rho)} \left(\sum_{i=1}^{N-M} \alpha_i^{1/(1-\rho)} Pe_i^{-(\rho/(1-\rho))} \right) \right]^{(1-\rho)/\rho}$$

$$\times \left(\sum_{i=N-M+1}^{N} \alpha_i x_i^{\rho} \right)^{1/\rho} (1 - tx). \tag{18}$$

where NRe is the expected net revenue, tx is the profits tax rate, there are M fixed factors, and the other $N - M$ factors are variable factors.

In version 0.0, there is only one fixed factor and the fixed factor term reduces to $\alpha_n^{(1/\rho)}$.

When investments in new capacity occur over more than one period

For most investments the decision to invest and the initiation of operation can be assumed to occur within a single five-year time step. This is not always the case. For example, the construction of nuclear electric power plants may require more than five years from start of construction to first production. Forestry similarly requires more than five years between the time of initial investment and the time of harvest. Each of these circumstances requires a somewhat different approach.

Extended construction time

When the construction time for an addition to capacity extends over $T_{construct}$ periods then there is an evaluation of the investment in each of these periods under the assumption that the fraction of total investment required in each period is equal. That is, if the total investment in the new capacity is taken to be K, and the construction time is $T_{construct}$, then in each period an investment of

$$K_t = K/T_{construct}$$

is assumed to be made. If the investment is expected to be profitable in the first period, then construction begins. The present discounted value of the investment requirement is then,

$$K_{e,t} = \left(\frac{K}{T_{construct}}\right) \sum_{tc=1}^{(T_{construct}-t)} \left(\frac{1}{1+\text{dis}}\right)^{tc} \qquad t = 1, \ldots T_{construct}, \tag{19}$$

where, t is the investment period in which the investment decision is being made, $t = 1, \ldots T_{construct}$; and tc is an index of periods of investment remaining, $t = 1, \ldots, T_{construct}$. Note that as each period of construction passes, the expected profit rate will rise, other things being equal, because previous period investments become sunk costs.

Expected net revenues from operation of the investment must also be discounted by a factor,

$$\sum_{tt=1}^{(T_{construct}-1)} \left(\frac{1}{1+\text{dis}}\right)^{tt} \qquad t = 1,\ldots,T_{construct}. \tag{20}$$

The growth-harvest decision

The growth-harvest decision problem does not occur in SGM version 0.0, as all agricultural activities are aggregate. In SGM version 1.0, a forestry sector will be disaggregated and this problem will occur. In this case an investment occurs in period t_0, but no revenue is received until $T_{harvest}$. But $T_{harvest}$ is not predetermined. For growth-harvest production functions the production function given by equation (3) and

$$a_0 = \alpha(C_t, C_{t-1}, \text{Atmos}_t, \text{Atmos}_{t-1}, t - t_0), \tag{21}$$

where α is now a function of a vector of climate and atmospheric state variables, and the amount of time that has elapsed between the initial investment, t_0, and the present period t. C_t is a vector of climate variables such as for example, temperature, precipitation, soil moisture, and evapotranspiration, for $t = t, t-1$; and Atmos_t is a vector of atmospheric state variables such as for example the concentration of atmospheric CO_2, for $t = t, t-1$.

The expected profit rate for an investment in a growth-harvest activity is determined by equations (18) and (21) using the expected price vector for the potential harvest $T_{harvest}$ periods in the future[8] and discounted by the value,

$$\text{discountfactor} = \sum_{t=1}^{T_{harvest}} \left(\frac{1}{1+\text{dis}}\right)^{t}. \tag{22}$$

The value of π_e can be computed for any two potential harvest periods, $T_{harvest_0}$ and $T_{harvest_0} + 1$, denoted respectively $\pi_e(T_{harvest})$ and $\pi_e(T_{harvest} + 1)$. The maximum potential value for π_e can be estimated by beginning with $T_{harvest} = 1$, and increasing the value of $T_{harvest}$ whenever,

$$\pi_e(T_{harvest} + 1) \geq \pi_e(T_{harvest}).$$

Investments with a maximum value for $\pi_e > 0$ are included in the pool of sector specific competing investments.

Resource constrained technologies

Many economic activities take place against a background of resource constraints. This is of particular interest in the field of energy economics, but is in no way limited to the energy sector. For example, the resource base for conventional oil is ultimately finite, and cumulative production from that resource base may potentially approximate the total resource over the period of analysis. Fossil fuels are an example of a depletable resource. Renewable resources, such as solar, wind, tidal, and ocean thermal energy conversion also exist. For renewable resources the resource is available in each period independent of consumption during the previous period. We will define depletable and renewable resources as follows:

- *Depletable resources*: A depletable resource is one in which the consumption of the resource in one period affects potential consumption in the next period.
- *Renewable resources*: A renewable resource is one in which the consumption of the resource in one period does not affect potential consumption of the resource in the next period.

Describing the relationship between resources and production is important for such activities.

Depletable resources

For depletable resources the total resource available for consumption over all periods is the sum of the resource available in each grade of *NG* grades,

$$R_i = \sum_{g=1}^{NG} R_{i,g}, \tag{23}$$

where R_i is the total amount of resource of type i which could be potentially recovered under any possible conditions; and $R_{i,g}$ is the total amount resource of type i, found in concentration c_g or higher up to c_{g-1} under any possible conditions. The resource base can be partitioned into discovered and undiscovered resources. Discovered resources are made up of extracted resources, RE, and reserves, RV. Undiscovered resources are denoted as RU. Thus,

$$R_i = RE_i + RU_i + RV_i, \tag{24}$$

$$R_{i,g} = RE_{i,g} + RU_{i,g} + RV_{i,g}. \tag{25}$$

In the model each sector that produces a depletable resource has a different subsector for each grade of the resource. For a given technology, the grade of the resource is reflected in the value of $\alpha_{ii} = \alpha_{ii,g}$ in the production function. Desired extraction from each resource grade is determined by the expected rate of profitability. The production function implicitly includes the cost of converting undiscovered resources into reserves. Production occurs out of reserves as determined by profit maximization subject to the constraint imposed by total investment in each vintage's productive capacity. The production activity occurs only from reserves, and shifts resources from the reserve category to the extracted category.

Because of the multiplicity of resource grades and the existence of substitutes, there is no guarantee that the price of a depletable resource will rise at a rate equal to the rate of interest, the 'hotelling' result.

Competition among capacity increasing investments within a sector

As discussed earlier, the sector is the highest level of aggregation in the model. Subsectors are assumed to produce an essentially homogeneous product within the sector. For example, in SGM version 1.0 it is expected that there will be four different types of freight transport: rail, air, truck, and other. Each will produce a common unit of output, tonne kilometres of freight transport. Obviously, this assumption violates physical reality. Nevertheless, it is intended to capture the essence of the system. For each subsector, there also exists an additional level of disaggregation, which we refer to as the technology level. Technologies compete within the confines of an individual subsector, and in turn determine the overall profitability of the subsector. A logit function is used to determine the share of total sectoral investment each technology obtains. That share is given by:

$$S_{i,\text{tech}} = \frac{(\pi^{\sigma}_{i,\text{tech}}/N_{\text{tech},N_{ss}})}{\sum_{j=1}^{NO}(\pi^{\sigma}_{j,\text{tech}}/N_{\text{tech}_j}N_{ss})}, \tag{26}$$

where $\pi_{j,\text{tech}}$ is a metric of the characteristic upon which competition is based for technology, tech, in subsector i, N_{ss} is the number of subsectors, N_{tech_i} is the number of technologies competing in subsector i, σ is a sensitivity parameter, and

$$NO = \sum_{i=1}^{N_{ss}} N_{\text{tech}_i}. \tag{27}$$

The logit function is homogeneous of degree zero. That is, any scaler change in the values of all $\pi_{i,\text{tech}}$ leaves the values of all $s_{i,\text{tech}}$ unchanged. For values of σ equal to zero, $s_i = 1/(N_{ss}N_{\text{tech}_i})$. If greater values of $\pi_{i,\text{tech}}$ enhance market share, then the value of σ is taken to be non-negative. (If greater values of $\pi_{i,\text{tech}}$ diminish market share, then the value of σ is taken to be negative.) As the value of σ approaches ∞, $s_{i,\text{tech}}$ approaches one for the largest value of $\pi_{i,\text{tech}}$.

In this model, we will use the logit function to determine the share of a sector's total investment spending that is allocated to each subsector, that is to say each competing technology option. The independent variables then are the profit rate values of π obtained earlier. In general the value of σ will be set to reflect existing market sensitivity.

Aggregate sector investment in new capacity

Aggregate regional sector investment levels are determined by using an accelerator from the previous periods total investment. Specifically,

$$K_{\text{tot}_{t+1}} = K_{\text{tot}_t} \cdot \text{baserate}_{t+1} \cdot f[\exp(\pi_{t+1})], \tag{28}$$

where K_{tot} is the total new investment in sector i, in period $t+1$; baserate is the base rate of growth of investment; and $f(\exp(\pi))$ is a function of the expected profit rate, $\exp(\pi)$.

We do not prejudice the determination of either baserate or the function $f(\exp(\pi))$. For present model development we use,

$$\text{baserate}_{t+1} = \frac{K_{\text{tot}_t}}{K_{\text{tot}_{t-1}}}. \tag{29}$$

The expected rate of profit is taken to be the average expected profit rate which is given by,

$$\exp(\pi_{t+1}) = \bar{\pi}_{t+1} = \left(\sum_{i=1}^{NO} \pi^{\sigma}_{i,t+1}\right)^{1/\sigma}, \tag{30}$$

where $\pi_{i,t}$ is the profit rate for the *i*th technology (taken over all subsectors), in period *t*. This derivation is given in Clarke (1991). For SGM version 0.0 we use,

$$f[\exp(\pi_{i,t})] = \left(\frac{\exp(\pi_{i,t})}{\bar{\pi}_t}\right)^{\alpha}, \tag{31}$$

where α is a sensitivity parameter.

Retrofit and renovation investment decisions and the operation of existing technology vintages

For existing technologies, or technologies with capacity already in place, there are four possible outcomes in any period:

1. *Operate* without change,
2. *Retrofit* and operate,
3. *Idle* the capacity, but do not retire,
4. *Retire* the technology.

The determination of operating mode depends upon the behavioural assumptions. Given the five-year time step in the model, it has been decided to eliminate option 3. In other words, producers will either operate a vintage in the current period or retire that vintage.

For market economies profit maximization is the behavioural paradigm. For investment decisions this means that *NR* is maximized. That is, existing technologies will continue to be operated as long as current operating costs can be covered, unless otherwise prevented from doing so. They will add retrofit technologies either if they are required or if they add to profitability. The behaviour of command economies is similar, except that (1) substantial subsidies, in both the cost of input factors and direct subsidies to total operating costs; and (2) allocation schemes where administered prices do not clear markets are an important determinant of economic behaviour.

Retrofit technologies

Retrofit technologies are the principal complicating factor in the analysis of existing technology operations. The level of operation of the technology is assumed to be identical to the parent technology. The additional capital cost, relative to the original capital cost, is a technology parameter. The presence or lack of presence of retrofit options does not affect the base production or cost functions.

New retrofit options can be incorporated into the operating structure of the technology if they either are required or are determined to be profitable. If retrofit technologies are not required, then it must be determined if the base technology will continue to be operated. If the base technology can cover current costs, it will continue to be operated, even if its present discounted expected future revenues are negative. If it cannot cover present operating costs, then the technology will be retired unless some retrofit package can produce a present discounted expected future profit.

Under some circumstances the present technology may cease to be an option because a retrofit technology must be applied. In such cases the technology will be retired unless some retrofit package can produce a present discounted expected future profit just as if the base technology had been unprofitable in the current period.

To evaluate retrofit technologies we make the following calculations. Consider an existing technology of vintage *V*, installed in period *V*, with nominal lifetime *T*, in existence in period *t*. To determine the profitability of retrofit options for that technology, we begin by computing,

$$Pe_j = P_j(t)\cdot\sum_{t=1}^{T-t}\left(\frac{1+r_j}{1+\text{dis}}\right)^{t}\cdot[1+tx(t)], \qquad j = 1,\ldots,N. \tag{32}$$

Note that a set of expected future prices for retrofit technologies may be different from the set of expected future prices for the base technology due to different discount rates for the two activities. That is, some firms may have a higher discount rate for retrofit technologies than for new base load investments.

Because each retrofit technology can affect the original technology is a wide variety of ways, the total technology, that is including both the base technology and a package of retrofit options, is given by a separate CES production function whose net additional capital cost is some fraction of the original capital investment, and whose lifetime is the expected lifetime remaining on the original technology.

The general formulation for profit with a fixed factor CES production function, as given by equation (6), is used to compute a value of π_{retrofit} for each technology with a retrofit option. Note that for retrofit = 0, the expected future profit for the base technology is given. If any retrofit technology has a positive present discounted expected profit higher than the base technology, then the retrofit technology package with the highest expected future profit rate is selected. If expected profits are negative no retrofit technology is adopted, and if either the base technology is unable to cover present operating costs, or is no longer available due to mandated retrofit actions, then the technology is retired.

Renovation
Renovation is a special case of the general investment/retrofit problem. At the end of T_{exp} years of service the technology must either be retired or renovated. Renovation takes the form of a one-time capital investment, that occurs in the T_{exp}th year of service. In effect, however, the retrofit option can be thought of as competing with other new investment opportunities with the production function coefficients of the original technology, a capital cost of K_{extend}, and T_{extend} years of expected life. The profit rate is computed using equation (15) and expected future prices based on an expected technology life of T_{extend} years. Of course, more than one life-extension technology option is possible. In the case where multiple options are available, the technology with the highest expected profit rate is chosen.

The present operating profitability, *NR*, is still computed from equation (6). The operation, retirement and retrofit logic diagram is given below:

	$NR > 0$	$NR < 0$
$\pi > 0$	Operate and Retrofit	Retire
$\pi < 0$	Retire	Retire

That is, the technology will be retired unless it both can make money in the immediate period and is expected to add to the wealth of the sector over its expected lifetime.

Greenhouse gas emissions

As discussed earlier, the greenhouse issue is complicated by the fact that a wide array of gases are associated with the effect. We make no attempt to discuss either the nature or the extent of the effect various

gases have on the radiative balance of the earth/atmosphere energy balance, but simply note that the following suite of gases will be considered.

- CO_2 emissions from fossile fuel and biomass combustion processes.
- VOC emissions resulting from energy production processes, selected manufacturing processes, some combustion processes (mainly of petroleum based fuel in internal combustion engines), and from selected natural processes.
- CFC emissions from losses from refrigeration and air-conditioning equipment, foam blowing, aerosol propellants, cleaning solvents, and fire extinguishers.
- CH_4 emissions which emanate from the production and distribution of natural gas, mining of coal, from the raising of ruminant animals, the growing of rice, from sanitary landfills, and from combustion processes (principally biomass burning).
- CO emissions, most of which emanate from incomplete combustion of carbon-based fuels, principally in the transportation sector.
- N_2O emissions from combustion processes, fertilizer use, and selected natural sources.
- NO_x emissions from combustion processes – especially from electrical power generation and in internal combustion engines.
- SO_2 emissions and consequent sulphate transformations so that albedo changes can be monitored.

Greenhouse gas emissions coefficients will be included with each technology description. Emissions will be assumed to be proportional to either the scale of input utilization or output of the technology.

Emissions can be calculated simply as,

$$E_{m,1} = \sum_{i=1}^{NS} \sum_{ss=1}^{NSS(i,1)} \sum_{tech=1}^{N_{tech}(i,ss,1)} \sum_{v=V_0}^{t} \sum_{j=1}^{NI} (e_{m,i,ss,tech,j} X_{i,ss,tech,j,1,v} + f_{m,i,ss,tech,j} Xs_{i,ss}), \quad (33)$$

where, $e_{m,i,ss,tech,j}$ is the technology specific emission coefficient for emission *m*, in sector *i*, subsector *ss*, using technology tech, with input *j*; $X_{i,ss,tech,j,1,v}$ is the input demand for factor *j* by sector *i*, subsector *ss*, using technology tech, of vintage *v*, in region 1; $f_{m,i,ss,tech,j}$ is the technology specific emission coefficient for emission *m*, in sector *i*, subsector *ss*, using technology tech, producing output *j*; and

$Xs_{i,ss,tech,j,1,v}$ is the output of good j by sector i, subsector ss, using technology tech, of vintage v, in region 1.

When emissions are released costlessly into the atmosphere they have no effect on either the cost of production or the optimum demand for investment goods. Releases need not be costless. Like other inputs and outputs from the technology, emissions may be priced. Emissions coefficients have been related to individual technologies. This is because the determinants of emissions can be relatively complex. This is even the case for emissions as simple as fossil fuel combustion carbon emissions. In general the release of carbon to the atmosphere is considered to be proportional to the energy content of the specific fuel by a fixed ratio and therefore largely independent of the technology in which the fossil fuel form is combusted. This need not be the case. Emissions capture technologies exist, and the rate of release of carbon to be atmosphere per unit of fossil fuel energy combusted may therefore vary by technology.

On the presumption that emissions can be measured and therefore costs can be associated with them, emissions fees would affect the cost of production. The effect of fees will be reflected in a modification to equations (13) and (14). For consumers of the jth product in the ith sector the cost would become,

$$P_{i,ss,tech,j,1} = a_{i,1} P_i (1 + \delta_{i,1} Tr_i) txa_{i,1} + txb_{i,1} + \sum_{m=1}^{EM} e_{m,i,ss,tech,j}\, tx_{m,i,ss,tech,1} \tag{34}$$

where $P_{i,ss,tech,j,1}$ = the price of good j consumed in sector i, subsector ss, using technology tech, in region 1. For producers, the income from the sale of the jth product produced in sector i is,

$$P_{i,ss,tech,j,1} = P_i (1 + \delta_{i,1} Tr_i) - \sum_{m=1}^{EM} f_{m,i,ss,tech,j}\, tx_{m,i,ss,tech,j,1}. \tag{35}$$

Final demand sectors

In addition to the sectors that produce goods and services, there are three final demand sectors, households, government, and foreign. As is the case with the directly productive sectors, final demand sectors have demands for goods and services and can produce goods and services. We begin with the government sector, not because the analysis of the behaviour of the government sector is simpler than that of the household, but rather because our modelling approach to this sector is simpler than that of the household sector.

Government

Expenditures by the budget of the government sector must satisfy the following identity:

$$TX_{tot} - S_{gov} = TR_{gov} + \sum_{i=1}^{N} P_i X_{i,gov}, \tag{36}$$

where TX_{tot} is the total of all net tax revenues, where subsidies are measured S_{gov} is the net government savings, or for negative values equals net government borrowing, and TR_{gov} = is transfer payments by the government.

In SGM version 0.0, S_{gov} is assumed to be zero. In SGM Version 1.0 this assumption will be relaxed.

In SGM version 0.0 transfer payments are assumed to be a function of demographics,

$$TR_{gov} = \beta_0 \mathrm{POP}_{tot}^{\beta_{tot}} \left(\frac{\mathrm{POP}_{15-} + \mathrm{POP}_{65+}}{\mathrm{POP}_{tot}} \right)^{\beta_a} \left(\frac{\mathrm{POP}_{25\%,Y}}{\mathrm{POP}_{tot}} \right)^{\beta_b} \left(\frac{Y_{personal}}{\mathrm{POP}_{tot}} \right)^{\beta_c}. \tag{37}$$

where POP_{tot} is the total population; POP_{15-} is the population under age 15; POP_{65+} is the population over age 65; $\mathrm{POP}_{25\%,Y}$ is the population whose personal income is 25% or less than the mean; $Y_{personal}$ is the personal income; and β_i is the appropriate empirically determined coefficients.

The government is modelled as producing services. In SGM version 0.0 there are three services produced. In SGM version 1.0 this will be expanded to five. These are given in table 4.

The demand for goods and services by the government sector is modelled as a constrained optimization problem. Government max-

Table 4 SGM government subsectors version 0.0 and version 1.0

SGM version 0.0	SGM version 1.0
General, National Defence, Education	General, National Defence, Education, Infrastructure, R&D

imizes a utility function, presumed to be CES in SGM version 0.0, defined over the three subsectors (general government, national defence, and education), and subject to the net income given by equation (36). This can be represented as,

$$G = \left(\sum_{ss=1}^{NGS} \delta_{ss} G_{ss}^{\mu}\right)^{1/\mu}, \tag{38}$$

where G is the government utility, an unobservable variable; G_{ss} is the production of government service ss; δ_{ss} is a scale parameter; μ is an elasticity parameter; and NGS is the number of services produced by the government.

Government services are assumed to be produced with fixed input–output coefficients. Thus the cost of an additional unit of government service, type ss, can be computed as simply,

$$P_{g,ss} = \sum_{l=1}^{N} a_{l,g,ss} P_l, \tag{39}$$

where $P_{g,ss}$ is the cost of the next unit of government service ss, that is P_l is the price of input l in the production process; and $a_{l,g,ss}$ is the amount of input l required to produce government service from government subsector ss.

Because the cost of producing the next unit of government service is constant for any set P_l,[9] the determination of government demands for goods and services is greatly simplified. This problem can be stated as one of maximizing utility subject to a budget constraint, equation (36), maximize $G(G_1, \ldots, G_{NGS})$, subject to

$$TX_{tot} - S_{gov} - \sum_{ss=1}^{NGS} P_{g,ss} G_{ss} = 0. \tag{40}$$

This problem has a simple solution,

$$G_{ss} = (TX_{tot} - S_{gov} - TR_{gov})\beta_{ss} P_{g,ss}^{\gamma-1} \left(\sum_{ss=1}^{NGS} \beta_{ss} P_{g,ss}^{\gamma}\right)^{-1}, \tag{41}$$

where $\beta_{ss} = \delta_l^{-1/(\mu-1)}$ and $\gamma = \mu/(\mu-1)$.[10]

Households

A great number of decisions are carried out in the household sector. These include the following:
1. Demographics
2. Labour supply
3. Land supply
4. Household savings
5. Household demand for final products

In SGM version 0.0 the determination of the demographic characteristics of each region's population, and its supplies of labour, land, and savings are handled sequentially. Only the composition of demand for final goods and services is handled in a holistic utility maximization framework. Because the demographic characteristics of a region's population are an important determinant of other household behaviour we discuss this element of the model first. We then consider labour, land, and savings supplies. These factors determine disposable personal income allocated to consumption. Finally, we describe the determination of final demand for goods and services.

Demographics
The demographic component of the household sector determines population in a region by employing assumptions with regard to three characteristics: survival rates, fertility rates, and migration rates. For any period, t, total population is given by,

$$\mathrm{POP}_{tot_t} = \sum_{age=1}^{NAGE} \mathrm{POP}_{age,males} + \mathrm{POP}_{age,females}, \tag{42}$$

where $\mathrm{POP}_{age,males}$ is the males in age group age; $\mathrm{POP}_{age,females}$ is the females in age group age; and $NAGE$ is the number of age groups defined.

For the youngest age group, age = 1,

$$POP_{age=1,gender,t} = \sum_{age=2}^{NAGE} g_{age,gender} f_{age,t} POP_{age,female,t}, \quad gender = male, female, \qquad (43)$$

where $POP_{age=1,gender,t}$ is the population in the youngest age group, age = 1, by gender, in period t; $f_{age,t}$ is the fertility rate for females in age group, age, in period t; and $g_{age,gender}$ is the fraction of births by gender, with $g_{age,1} + g_{age,2} = 1$, and for other age groups, population is determined by survival via,

$$POP_{age,gender,t} = SV_{age,gender,t} POP_{age-1,gender,t-1} + POPmig_{age,gender,t}, \quad age = 2, \ldots, NAGE. \qquad (44)$$

where $sv_{age,gender,t}$ is the survival rate by gender from age group age to age + 1; $POPmig_{age=1,gender,t}$ is the net immigration of population into the region in age group, age = 1.

At this point, fertility rates, survival rates, and migration rates are determined exogenously, with the exception that net migration summed over all regions is always zero for each age and gender.

Labour supply
The supply of labour is determined by the working age population, rate of labour force participation, and the wage rate.

$$X_{labour} = \sum_{male}^{female} \sum_{age=1}^{NAGE} \alpha_{age,gender} POP_{age,gender} [P_{labour}(1 - txa_{labour}) - txb_{labour}]^{\beta_{age,gender}}, \qquad (45)$$

where P_{labour} is the wage rate for labour; $\alpha_{age,gender}$ is a scale coefficient for the supply of labour, by age and gender; $\beta_{age,gender}$ is the price elasticity of supply of labour by age and gender, and txa, txb are proportional and additive tax rates, respectively.

Land supply
In version 0.0, land supply is total land area in the region. All land services are sold on the domestic market. Households supply land on the basis of the rental rate via

$$X_{land} = LAND_{tot} \alpha_{land} [1 - \exp(\beta_{land} P_{land})], \qquad (46)$$

where $LAND_{tot}$ is the total surface area potentially available for allocation; α_{land} is the maximum potential share of land supplied to the market; β_{land} is a land supply price responsiveness coefficient; and P_{land} is the rental rate on a unit of land.

In SGM version 1.0, the land supply sector will become much richer. One of the potentially most important determinations is the representation of the character of land, and its potential supply and use, and the potential changes to land character as it is affected by human activity. To be most useful, the model of land must be capable of explaining both the present allocation and use of land, how that allocation and use changes with time, and the consequences of land-use for greenhouse gas emissions. Furthermore, the characterization must also be capable of providing a framework for assessing the consequences of potential changes in atmosphere and climate, and of changes in sea level. Several alternative specifications are being considered. A description of land use in SGM version 1.0 will be the subject of future model development reports.

Personal income
Personal income can be computed from the information already developed via the equation,

$$\begin{aligned} Y = {} & X_{labour\ supply}[P_{labour}(1 - txa_{labour}) - txb_{labour}] \\ & + X_{land\ supply}[P_{land}(1 - txa_{land}) - txb_{land}] \\ & + \pi_{tot}(1 - tx_\pi - s_z) + TR_{gov} \end{aligned} \qquad (47)$$

where Y is the disposable personal income; π_{tot} is the total net profits from the operation of all enterprises; tx_π is the profits tax rate; s_z is the rate of retained corporate earnings; and txy = income tax rate.

Savings supply
SGM version 0.0 represents savings as a function of present income and the interest rate,

$$S_{hh} = \alpha_{hhsave} Y \{1 - \exp[\beta_{hhsave}(\text{interest} + fac_{hh})]\} \qquad (48)$$

where S_{hh} is the total supply of savings by households; α_{hhsave} is the maximum potential household savings rate; β_{hhsave} is the price sensitivity of households to the available interest rate; and fac_{hh} is an adjustment factor linking the market interest rate to the interest rate available to households.

While it is usual for a general equilibrium model to maximize a utility function to determine household behaviour, version 0.0 does not do this. The development of a more sophisticated description of aggregate household behaviour is a development task.

Household demand for final products

Own demands for factor inputs labour and land are computed separately from demands for other goods and services.

The own demand for land is a function of the number of households,

$$\mathrm{NHH} = \left(\sum_{age=1}^{NAGE} \mathrm{POP}_{age}\right) \Big/ \alpha_{hh}, \tag{49}$$

where NHH is the number of households; and α_{hh} is the average number of people per household.

Therefore,

$$X_{land,hh} = \mathrm{NHH}\, \alpha_{land,hh} P_{land}^{\beta_{land,hh}}, \tag{50}$$

where $\alpha_{land,hh}$ is the household land intensity factor; and $\beta_{land,hh}$ is the price elasticity of demand by households for land.

The household demand for labour is a function of the price of labour,

$$X_{labour,hh} = X_{labour} \alpha_{labour,hh} P_{land}^{\beta_{labour,hh}}, \tag{51}$$

where $\alpha_{labour,hh}$ is the household labour demand intensity factor; and $\beta_{labour,hh}$ is the price elasticity of demand by households for labour.

The total value of consumption can then be calculated by difference

$$Y_c = Y - S_{hh} - X_{land,hh} P_{land} - X_{labour,hh} P_{labour}. \tag{52}$$

Consumption of any final product can then be computed using price and income elasticities and an income expenditure normalization via,

$$xd_{i,hh} = \alpha_{i,hh} P^{\beta_{i,hh}} Y_c^{\gamma_{i,hh}} \left(\frac{1}{\lambda}\right), \tag{53}$$

where $Xd_{i,hh}$ is the demand for good i by the household sector; $\alpha_{i,hh}$ is the household demand intensity factor for good i; $\beta_{i,hh}$ is the price elasticity of demand by households for good i; and $\gamma_{i,hh}$ is the income elasticity of demand by households for good i, and

$$\lambda = \sum_{i=1}^{NS} \alpha_{i,hh} P_i^{\beta_{i,hh}+1} Y_c^{\gamma_{i,hh}-1}. \tag{54}$$

Each consumption good, which in version 0.0 is identical to a produced commodity in the GPC, is assumed to have an income and a price elasticity of demand.

In version 1.0, the plan is to embed the household decision making process in a cohesive intertemporal decision-making process which includes consumption, savings, and education. Education is important because, at least in the United States, it is the most important determinant of life-cycle labour-force participation. In addition, the subsector structure in the model will be used to expand the number of demographic groups. The number of such groups has not yet been determined but will reflect significant differences with respect to savings and education decisions. In version 1.0 consumption categories will probably be different from production categories, implying the need for a translation matrix from consumption to production commodities. Computationally more versatile forms for the labour and land supplies will also be explored.

General equilibrium

As noted earlier, markets are defined for each of the 10 producing sectors in SGM version 0.0 plus one for each of the three primary factors of production: land, labour, and capital.[11] There are at least 13 markets for the model to clear even when only a single region is being considered. When multiple regions are being considered simultaneously, the number of markets will expand. Land and labour markets are considered to be closed. This increases the number of markets from 13 to $11 + 2NL$, where NL is the number of regions. If capital markets are closed this number increases to $10 + 3NL$.[12] In addition, the model user can open or close any market in any

Table 5 An example of trading relationship table

Commodity	Region 1	2	3	4	5	6	7	8	9	10	11
1. Agri.	1	1	1	1	1	1	1	1	1	1	1
2. Crude oil	1	1	1	1	1	1	1	1	1	1	1
3. Oil ref.	1	1	1	1	1	1	1	1	1	1	1
4. Nat. gas	1	1	2	1	2	1	1	1	1	1	1
5. Nat. gas tr	1	1	1	1	1	1	1	1	1	1	1
6. Coal prod.	1	1	1	1	1	1	1	1	1	1	1
7. Biomass	1	1	1	1	1	1	1	1	1	1	1
8. Uranium	1	1	1	1	1	1	1	1	1	1	1
9. Elec.	1	1	2	3	0	2	3	0	0	0	0
10. Other	1	1	1	1	1	1	1	1	1	1	1
11. Labour	0	0	0	0	0	0	0	0	0	0	0
12. Land	0	0	0	0	0	0	0	0	0	0	0
13. Sav/inv	0	0	0	0	0	0	0	0	0	0	0

region relative to the rest of the world, and thus create trading groups. This is indicated through a variable, Mktlink defined over regions and commodities, where if for one of the 13 commodities and 11 regions,

Mktlink = 0 indicates that region L is permanently closed to trade in commodity IN. For example, all regions are closed to trade in land in the above matrix;

Mktlink > 0 indicates that the region trades with all other regions with similar Mktlink values for that commodity.[13]

An example of a trading relationship table is given in table 5.

The number of markets will also vary during the execution of the model. This occurs because transportation costs involved in international trade are non-trivial. It is easily possible to encounter a case in which a region would desire to export a good if the region is treated as an importing region and domestic producers are assumed to be able to obtain the world price of the commodity plus the cost of transportation. On the other hand, if the region is treated as an exporting region, in which domestic producers can obtain only the world price of the commodity, the quantity of the product demanded by the region increases and the quantity supplied decreases to the point where the region would desire to import the good. Under such

circumstances, the model will treat that region/commodity combination as if it were temporarily closed.[14]

For each region/commodity combination, an excess demand can be calculated by

$$e_{i,j} = \sum_{s=1}^{Ns} \sum_{ss=1}^{Nss_{i,s}} \sum_{tech=1}^{Ntech_{i,ss,s}} (xd_{i,s,ss,tech,j} - xs_{i,s,ss,tech,j}), \quad i = 1, \ldots N. \qquad (55)$$

where $e_{i,j}$ = excess demand for commodity i in region j.

Consider for a moment the simplest case in which all commodities are traded internationally. For any period, equilibrium exists when a set of prices, $P = (P_1, \ldots P_N)$ can be found for which

$$\sum_{j=1}^{NL} e_{i,j} = 0, \qquad i = 1, \ldots, N. \qquad (56)$$

This set of prices is not unique. Walras's law,

$$\sum_{i=1}^{N} \sum_{j=1}^{NL} e_{i,j} P_i = 0, \qquad (57)$$

which holds as an identity, and guarantees that if an equilibrium set of prices exists, that any positive scalar multiple of those prices is also an equilibrium set of prices. Any commodity can be chosen as a numeraire and its price determined arbitrarily, set for example to one. The number of independent market prices is always one less than the number of markets.

Similarly, since the unit of measure chosen for commodities is also arbitrary, units can be chosen such that all equilibrium prices are unity in one period.

Solving the SGM

The BRM first generation model, used a Newton search procedure in an elasticity metric. Elasticities were computed numerically by perturbing each market price slightly and re-evaluating the model. This required Nmkt+1 evaluations for each search step. It also created a $Nmkt^2$ matrix of partial derivatives, which needed to be inverted. With 42 independent markets, this procedure requires a matrix of

1,764 elements to be inverted. The ERM also incorporated a variety of procedures to be invoked in the event that no change in a disequilibrium set of prices could be identified, through the Newton search approach, which reduced the metric of disequilibrium, the sum of squared excess demands.

Increasing the number of markets to 42 in SGM version 0.0 increases the complexity of the problem of finding numerical solutions to the model. The SGM will employ an even more diverse set of solution algorithm alternatives than the ERM. The most important addition to the set of search techniques is the Gauss-Seidel procedure. This solution algorithm begins with an initial price vector, and then updates each element of the price vector individually.[13]

Concluding remarks

This paper describes a new model under development, a second generation model of global energy and other human activities and greenhouse gas emissions. The model addresses the problem of the relationship between human activities in a wide array of domains, and their effect on the emissions of radiatively important gases, and the potential consequences of changes in the atmospheric composition and climate on those human activities. To address the extremely broad scope implied by these objectives, we have begun the development of a global, computable general equilibrium model, which provides insights not possible with linked independent market equilibrium models. It is also designed to address a specific problem. Its level of complexity and disaggregation reflects the character of that problem. Energy is the single most important human activity affecting greenhouse gas emission. It therefore receives the greatest attention in the model. Agriculture and land-use are the next most important issues and receive greater attention than, for example, their value-added contribution to GNP would indicate they warrant. Other sectors of the economy are modelled in relatively aggregate detail.

The model will be exercised for both regional/national economies independently of the world economy, and as a world model. Projects to model the United States, Chinese, and former Soviet Union are underway in partnership with sister institutions in China and Russia. These projects are anticipated to produce results during 1992. This work in turn will help inform the development of the SGM global model. Progress on these endeavours will be the subject of future reports.

Notes

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2. Gases with characteristic e-folding or average molecular lifetime values of less than 10 years.
3. Century time scales.
4. For example, control runs using the ERM and GLOBAL 2100 models yield remarkably similar results when standard assumptions are employed in both models. This is despite the fact that the ERM is a behavioural model and GLOBAL 2100 is a dynamic optimizing model.
5. It is always possible to recast a model such as the SGM within the dynamic optimization with perfect foresight paradigm.
6. Compared to competing technologies.
7. Note that the price received by the producers, P_{ij}, is equal to the f.o.b. price. The prices paid by producers are equal to the f.o.b. price plus taxes and markups.
8. Note that in this case the period-specific expected price vector replaces the present discounted price vector given by equation (14).
9. Note that this property is characteristic of any production function which is homogeneous of degree one, such as for example the CES, and not simply the Leontief specification.
10. To see this note that first-order conditions require that

$$G_{ij} = \lambda^{1/(\rho-1)} G \beta_{ij} P^{r}_{j,ij}$$

where λ is a Lagrangian multiplier. For convenience define,

$$Y = TX_{jv} - S_{jv} - TR_{jv},$$

and note that

$$Y = \sum_{m=1}^{NGJ} G_{ij} P_{j,m}.$$

Substitute (1) into (2) to yield,

$$\lambda^{1/(\rho-1)} G = Y \left(\sum_{m=1}^{NGJ} \beta_{ij} P^{r}_{j,ij} \right)^{-1}.$$

Resubstituting (3) into (1) gives the final result.

11. Recall that the capital market is a market for savings and investment. It does not allocate existing capital stocks. Those are quasi fixed as a vintaged capital stock.
12. The relaxation of the assumption that capital markets are closed requires the creation of an investment vehicle. This could be accomplished by the creation of an international bond. This bond would imply a future return flow of resources in exchange for savings. Net interest payments would be added to GNP and household disposable income, assuming households hold the bonds.
13. Note that while model logic will not be affected, there should always be at least two regions involved in a trading group for each commodity. The value of the Mktlink variable gives a reference region whose f.o.b. price of commodity *IN* determines the f.o.b. price for that commodity in all other regions in the trading group. For example, in the matrix above, all

regions, except China, use the f.o.b. price of agricultural products in the United States (region 1) as a common reference f.o.b. price.

The value used in Mktlink should *always* use the lowest region index number of any member of the trading group. For example when regions 3 and 6 form an electricity trading group, both members use the number 3 for their Mktlink values.

We note that a region cannot be open to trade in only one commodity.

14. When a region is temporarily treated as if it were closed to trade in a particular commodity, the value of Mktlink is set to the negative of the reference group number.

15. This procedure has an expected solution rate of between 5Nmkt and 10Nmkt model evaluations. It is thus computationally very efficient. The order in which the Gauss-Seidel algorithm operates may be important. For example, we may wish to solve the world market, then iterate to the regional labour and land markets, and then return to the world market. Some thought needs to be given to getting appropriate output and tracking the solution process with an eye to improving its efficiency.

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Comments on chapter 9

1. Nebojša Nakićenović

The design and implementation of the "second generation" model for analysis of future greenhouse gas emissions is indeed a formidable task. Edmonds et al. (1992) set the goals of such a model well beyond the state of the art by specifying that it should be "capable of analysing the emissions of all greenhouse gases from all sources, including both those of natural and human origin, to provide an analysis of the interplay between the variety of human and natural activities responsible for greenhouse gas emission." Clearly, such models currently do not exist that are capable of "assessing emissions from all human activities and major direct and indirect consequences of potential policies to reduce emission." There are many models that already address some specific parts of the problem, e.g., carbon dioxide emissions associated with energy use or models that cover all anthropogenic sources of emissions and resulting atmospheric concentrations (e.g. EPA's Atmospheric Stabilization Framework, Lashof and Tirpak 1989). They are, of course, still very far from the comprehensive approach suggested by Edmonds et al. Hence, the development of the second generation model of the type proposed by

Edmonds et al. is certainly a most welcome effort, although a very ambitious one.

Undeniably, much could be learned by the modelling community from the exercise proposed by Edmonds et al. In particular, the efforts suggested to endogenize demographic and technological changes merit particular praise and attention. However, within a policy context there is also the issue of how such a model can help reduce the uncertainties inherent in modelling global change. Alternatively how can the modelling exercise make more transparent and explicit the uncertainties stemming either from our insufficient understanding of natural and social phenomena or their inadequate abstraction (modelling)? Therefore, a word of caution may be in order. The policy dimension of global warming must confront simultaneously the problems of extreme uncertainty, both in the causes and consequences of global warming, and in the future contexts within which policies related to global warming will operate. Thus, there is a need for great flexibility in policy measures since the socio-economic and technological contexts within which any global change policy is situated will clearly vary and alter. We are confronting policy choices related to a global environmental issue whose effects will be measured in decades and centuries. To illustrate the difficulty of this task, imagine confronting similar issues a century before, say in 1892. At that time, electricity did not have a significant role, the motor car had just been invented, the aeroplane was unknown except as a concept, and nuclear weapons were unthinkable due to the lack of basic physics, while major urban problems were particulates from coal and dung from horses. Thus, it should be clear that it is unlikely we will forecast the future evolution of energy systems, technologies, or its social contexts over the next 100 years any more accurately today than if we had performed the same exercise a century ago. Yet, modelling and assessment of strategies for mitigation of climate change require a very long-term view, one which extends far beyond normal planning horizons.

In view of the large and still unresolved scientific uncertainty surrounding greenhouse gas emissions, their sources and sinks, the consequences such as adverse and irreversible climate change and possible response strategies, the development of the second generation model of the parametric type proposed by Edmonds et al. is a very useful effort since it will allow the testing of different hypotheses concerning future energy and greenhouse gas emissions.

In this short commentary we will discuss a few of the salient characteristics of such a model that appear to be required if it is to fulfil the expectations of its authors, but we will not raise the specific technical questions that would need to be resolved before the model can actually be built. The technical questions include, for example, the problem of integrating the global warming potential of emission and concentration of multiple greenhouse gases, or how to account for historical and current N_2O emissions from human activities and natural sources, or how to reconstruct the capital vintage structure for economies in transition and developing countries. These questions are far from being resolved but are the subject of a number of research activities and international efforts from which the proposed modelling exercise could benefit. Let us assume that these uncertainties and unknowns can be resolved by a parametric modelling approach.

We now return to the discussion of important model characteristics which (in order to be brief) we will limit to four issues: (1) population dynamics, (2) endogenization of technology, (3) socio-cultural aspects and (4) provision of energy services. They are important because they are all linked to the requirement of adopting a very long time horizon for model applications, which extends to the end of the next century. The authors are to be complimented for taking the long-term and global view. Models that focus on time-scales of two to three decades can be based on many static assumptions due to the relative stability of demographic trends, social and cultural relations, and the technology base over such periods. Conversely, extension of the time horizon well into the next century means that many of these long-term processes will become fluid and can no longer be treated as constants or "slow variables."

1. Population dynamics

In a century global population could stabilize but during the next few decades it will certainly continue to grow at rates fairly close to the current 1.7 per cent per year. In fact, the momentum behind global population growth is indeed very large. Even if we assume an abrupt change in fertility throughout the world down to or even below the replacement levels of about 2.2 children per woman, as it now prevails in most of the West European countries (and will thus result in a significant population decline), the global population would continue to grow for a few decades as illustrated in figure 1. Thus, the demographic transition is an important issue if a long time horizon is

World: Total Population in Million

	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025
Low Variant	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
High Variant	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Medium Variant	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

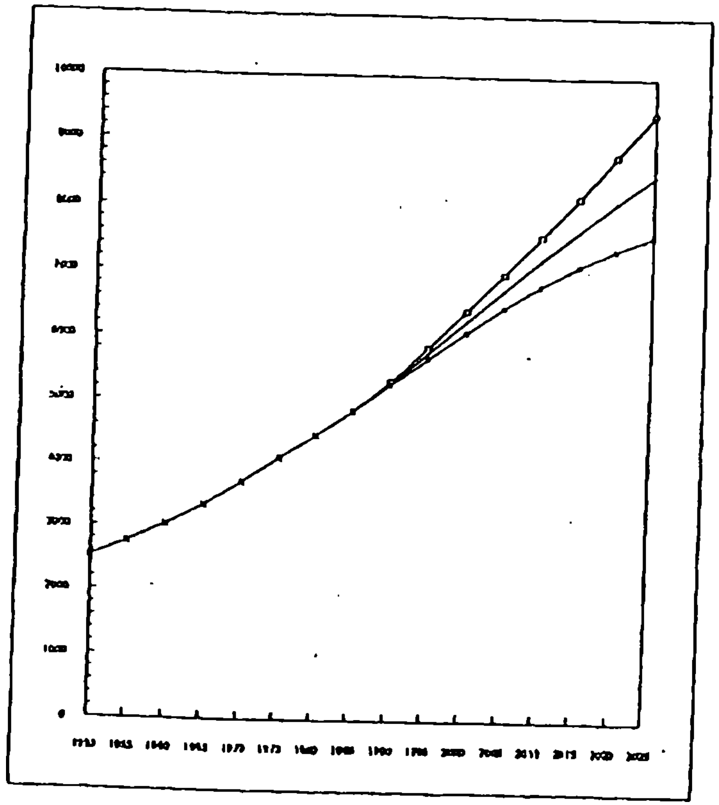

Fig. 1 World population growth, 1950 to the present and three alternative projections to the year 2025 (*UN World Population Prospects* 1990). In the case of the high variant the population is expected almost to double during the next 35 years. Despite the declining growth rates from now on, the high variant still leads to an increasing absolute population increase. By the year 2020 population increase is still about 40, 80, and 130 million per year in low, medium, and high variant respectively compared to about 100 million increase per year today (Source: Hellig 1992).

adopted. It is of paramount importance whether the global population will reach 10 billion or grow beyond. What is almost certain is that it can be expected to double during the next 100 years.

The objective to "endogenize" population growth in the next model version is to be welcomed. The actual problem is how to implement the link between development and population: is the demographic transition a'prerequisite for rapid development or the other way around? How to account for the diverse experiences among countries and regions with respect to the demographic transition? A critical impasse is how to model these theoretically poorly understood linkages at the global and regional level. For the time being Edmonds et al. plan to include assumptions concerning survival, fertility, and migration rates for individual regions over the time horizon. However, increasing the number of exogenously assumed driving variables does not necessarily lead towards a better understanding of the complex issues between development and demographics. It might, therefore, be simpler and also more transparent to assume different population-growth scenarios exogenously as done by the United Nations population forecasts that are the standard reference in this field (UN 1990). Personally I see little merit in making numerous assumptions in a model without explicitly describing the linkages between the variables. The approach leaves a false impression of certainty and accuracy that does not actually exist. This critically affects particularly the treatment of migration in the proposed model. Clearly, emissions will depend on trade and migration patterns but the problem is that there is no obvious way to model international migration, especially the large movements of people that might be caused by the adverse effects of climate change. Low population growth rates and high levels of affluence in some parts of the world can also be expected to attract additional migration and, this again is a possible linkage between development and population issues.

II. Endogenization of technology

One of the important shortcomings of many energy models is that resource scarcity is one of the central driving forces of future energy development. Once the cheap and clean sources of energy are exhausted, the models "dig deeper" into dirtier and costlier options. This is close to the Malthusian concept of limited resources and has by and large been historically falsified for most factor inputs including energy, minerals, or land. It turns out that in the long run technological change leads to production of more with less rather than of less with more. And yet technological change is still a static concept entirely absent in most models. Fossil energy resources remain static, potentials for technological improvements are ignored, etc. Yet alone since the energy crises of the 1970s the discoveries of additional fossil energy reserves have outpaced their consumption. The resource base continues to increase. Table 1 shows that the known global fossil energy resources are equivalent to about 3,000 gigatons of carbon! The carbon content of the atmosphere is in comparison small with about 760 gigatons of carbon. If the current concerns regarding prospects of global warming are confirmed in the future, it is probable that most of this carbon will remain in the ground. The point here is that technological progress and development are exogenous parameters: as soon as some of these externalities are endogenized, decarbonization strategies will be economically more attractive and less costly than "dirtier" options. In retrospect, we no longer consider technologies that are hazardous to human health as "cheaper" options, but rather as non-options. Therefore, the model needs a "dynamic base" rather than the planned static concept of depletable and degradable resources.

The adoption of a capital vintage approach to endogenizing technological change by Edmonds et al. represents a significant improvement and will undoubtedly produce most valuable insights, as demonstrated by similar models for analysing economic structural change. The capital vintage approach can help to model technological change by the introduction of learning and economies-of-scale effects into new additions to the capital stock and the resource base. Nevertheless, the assumption of static resources (even if total potentially recoverable resources are subdivided into reserves and undiscovered resources) over a period of 100 years is indeed a very restrictive constraint that will, no doubt, almost "automatically" lead to high carbon emissions (since cheap and low carbon options are exhausted and renewables and nuclear limited by other "constraints"). For instance, only 10 years ago the existence of methane clathrates was largely unknown. Will they be included as a potential resource base in the model and how is the resource base going to change with the availability of new technologies?

Table 1 Fossil energy consumption, reserves and resources (Gt C)

	Coal	Oil	Gas	Total
1860–1987	114.9	58.2	24.5	197.6
1987	2.5	2.4	1.0	5.9
Reserves	391.6	92.1	58.5	542.2
Resources	2289	622	>115	3026
Additional occurrences	>3500	>1000	>700	>5200

Note: Accounting for historical, present, and potential future carbon emissions from fossil fuel use in gigatons carbon. Historical (1860–1987) and present (1987) carbon emissions from fossil fuel use by source and carbon content in identified, economically recoverable fossil fuel reserves, resources (identified quantities with uncertain prospects of economic recoverability), and additional occurrences (additional quantities inferred from geological information but with speculative technical and economic potential). Compared to historical fossil fuel use, the remaining resources in the ground represent a (perhaps even far too large) "carbon endowment" which is more than a factor 10 as large as the total carbon pool in the atmosphere of around 760 Gt C (corresponding to a present CO_2 concentration rate of about 350 ppm) (Grübler and Nakićenović 1991).

During the next century many new energy systems can also be expected to be introduced that may help avoid the astronomical levels of greenhouse emissions envisaged in many business-as-usual scenarios (e.g., see IPCC 1990). Figure 2 illustrates that even at historical diffusion rates new energy systems can be expected to reach high market shares during the next century. Such systems may include completely new technologies such as carbon removal and deposition (e.g. into the deep ocean) but they will most certainly be also based on improvements and refinements of current technologies such as the electric or hydrogen car (Nakićenović 1992; Nakićenović and John 1991). But even these more evolutionary options will need enabling systems and technologies such as new batteries and fuel cells. The diffusion of whole families of new technologies needs to be modelled both within the energy system and other sectors of the economy. It is not clear how this will be handled in the second generation model, although it is clearly crucial for the understanding of the mitigation and adoption potential offered by new, less carbon-intensive and carbon-free technologies.

III. Socio-cultural aspects

Socio-cultural determinants of future greenhouse gas emissions are also important at all scales but become especially difficult to model when the time horizon is extended to 100 years in the future. Is there cultural convergence over such long periods, especially if the world actually becomes "smaller" through more interaction, global com-

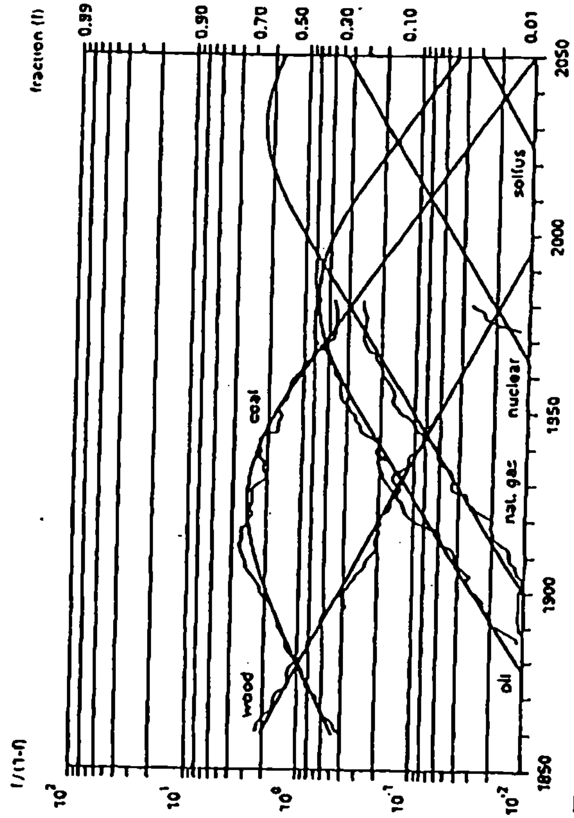

Fig. 2 World primary energy substitution. Shares of primary energy sources in global consumption. Smooth lines represent model calculations, and jagged lines are historical data. "Nat. gas" is natural gas; "solfus" is a term employed to describe a major new energy technology, for example solar or fusion (Marchetti and Nakićenović 1979; Nakićenović 1990). It shows that the diffusion of new sources of energy is a very long process lasting many decades. Replacement of other infrastructures such as that of transport systems is also a long process.

munication, and mobility? At the other extreme, a divergence could be assumed with more heterogeneity and diversity in the world. In fact, this was the historical experience during the last century as illustrated in figure 3 for carbon intensity of value added. In contrast, many of the development strategies and scenario trajectories imply a common global path, e.g., universal adoption of technologies and their transfer despite diverse institutional and regional characteristics, and irrespective of the actual appropriateness of these systems in a given case. The second generation model can be expected to help identify some of the linkages among these issues, but the real problem occurs with the treatment of these social and cultural determinants. For the time being, socio-cultural variables have defined quantifications in most global models and at best have been included as residual values (e.g., derived from general production function approaches). Even if these variables cannot be modelled in the sense of formal abstractions from causality relations, it will be important to make explicit assumptions and scenarios in the model concerning socio-cultural development. This is a potential advantage of a parametric approach.

As another example, is it really reasonable to assume a general equilibrium approach and market-clearing mechanism for analysing the long-term future, when market-clearing mechanism imperfections and regulatory mechanisms are a prevailing characteristic of the world economy rather than an exception? Transfer of "sensitive" technologies is explicitly blocked, diffusion and adoption of technologies can be blocked by local cultures or regulations, and so on. The examples are so plentiful that it is difficult to construct a list of competitive international markets. There are, of course, many methodological reasons for adopting a general equilibrium approach, but the question is whether too much is assumed away by that approach in a model that otherwise includes so much detail. In more aggregate models this might indeed be a very viable and appropriate simplification but in a complex model such as the one proposed it is not clear how to balance detail in some areas against simplistic assumptions in others. In any case, this approach makes the analysis of major and revolutionary changes impossible. Adjustment paths to a low-emissions future is by design at best gradual and excludes socio-cultural diversity. All regions are assumed to have market-based economies and rational, utility maximizing agents (envisaged for version 1.0).

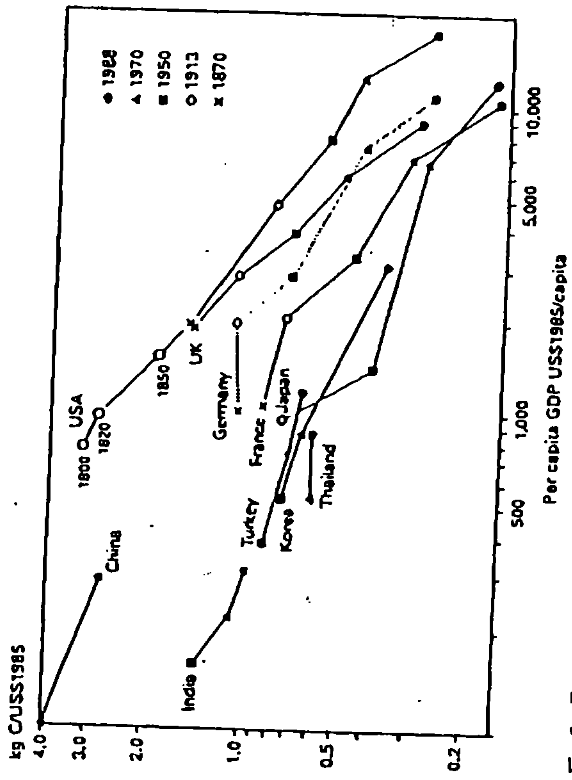

Fig. 3 Energy CO_2 emissions intensity per constant GDP in kg per constant 1985 US$ versus per capita GDP in constant 1985 US$. Energy data include also non-commercial sources such as fuelwood. In general, carbon intensity of economic activities improves as a function of differences between countries for similar per capita GDP levels. It shows that developed countries had higher specific emissions per unit GDP during early development phases that are comparable to current emission intensities of GDP in developing countries (Source: Grübler and Fujii 1991).

IV. Provision of energy services

Rationality of agents is in general a very sticky subject when it comes to describing actual energy consumption and end-use behaviours. Conservation and efficiency lag behind what appears to be rational. Often efficiency improvements are offset by increased energy services. For example, new cars are on average more efficient than the old ones in Germany, but they consume more fuel because they are larger, faster, more powerful, comfortable, and safer. Demand for more comfort at home has also increased due to older age structure, smaller family size, and larger dwellings per household, leading again to higher energy services. Figure 4 shows that longer life expectancy and shorter working time have over the last 100 years reversed the share of life spent at work compared to leisure activities from about 80 per cent to about 20 per cent today. This results in more travel, leisure activities, and time spent at home. All of these phenomena are also linked to economic structural changes, productivity increases, and evolving socio-cultural patterns. The problem arises when changes in the end use are observed at the macro-level and explained only by price mechanisms (e.g., elasticities) rather than by changes in human behaviour and social patterns. In those cases fallacies can occur. For example, the price of motor fuel increases but consumers purchase cars that consume more fuel even though they may be more efficient. Perhaps many of these considerations are marginal on a 100-year time-scale. The salient question for personal mobility in the world is rather whether car ownership will diffuse throughout the world to the degree it has in the industrialized countries. Today there are over 400 million cars in the world. Whether this number doubles or increases tenfold during the next decades will have a larger effect than any model variations in the price elasticity of motor fuels. Another example given in figure 5 shows that most of the cars are owned by the male population in Germany, while only a few, mostly young, women own automobiles. Should the ownership rates converge in the future this could almost double the fleet size.

These examples illustrate that the long-time horizon almost inherently demands an interdisciplinary approach in evaluating greenhouse-gas emission mitigation and response strategies. Economic mechanisms alone will not do nor will engineering perspectives. The complex fabric of many dimensions has to be integrated into more holistic approaches for analysing alternative development paths, those that lead to high emissions and those that are responsive to

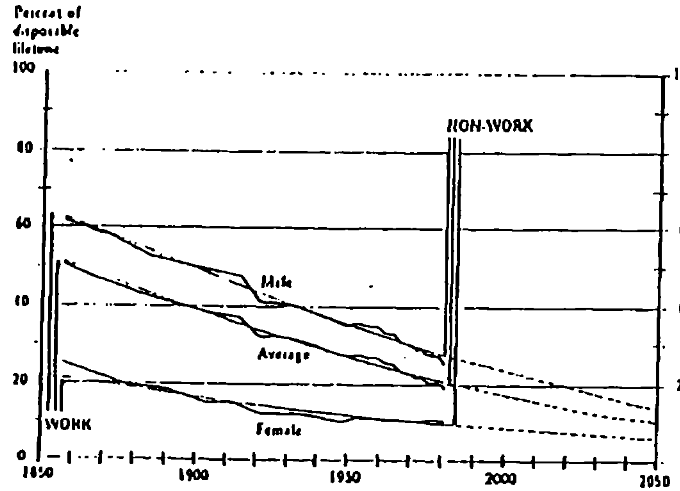

Fig. 4 Fraction of disposable lifetime spent at work and non-work of female, male, and average working population, UK 1856–1981. Figures are derived by comparing life hours of work to total disposable, active non-work hours for adults. Disposable hours are calculated by subtracting 10 years for childhood and first elementary education and also required "physiological" time, e.g., time required for sleep, eating, and personal hygiene, assumed on average to amount to 10 hours per day. For the average working population in the United Kingdom, working hours decreased from about 124,000 to 69,000 hours between 1856 and 1981, while at the same time disposable lifetime hours increased from 292,000 to 378,000 hours. Thus, non-working hours increased from about 118,000 to 287,000 hours over a lifetime. On average over 60 per cent of the disposable lifetime of male adults was spent working in 1856, this percentage has fallen to less than 20 per cent at present (Source: Ausubel and Grübler 1990).

climate change. Perhaps creative scenario writing would even further enhance the value of models such as the one proposed by Edmonds et al.

The ultimate question is what is the appropriate model scale (e.g., number of sectors, equations, variables) that is required to capture some of these characteristics? It is clearly undesirable to have a high degree of complexity in treating problems that are poorly understood such as the effect of global warming on international migration patterns. It is better instead to treat with higher accuracy those things that are well known such as the effect of urbanization, mobility, or

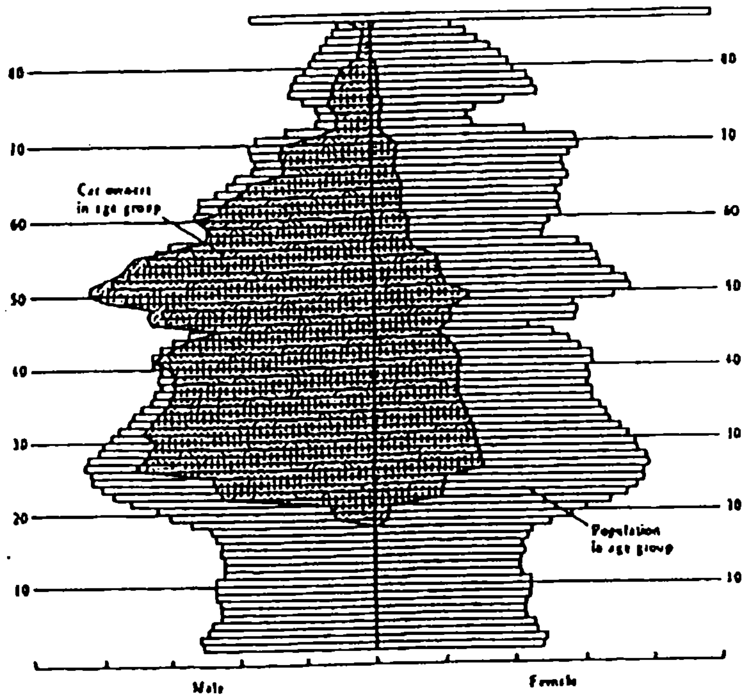

Fig. 5 Demographics of car ownership in Germany (only former FRG territory) in 1989 revealing significant intergenerational and gender differences in car ownership. Combined with demographic projections scenarios of future car ownership are developed at IIASA based on different scenarios of lifestyle changes of successive cohorts entering driving age. Conversely the ownership (or non-ownership) patterns of older generations are assumed to remain relatively stable, consistent with historical experience (Source: Büttner and Grübler 1991).

geography and climate on energy end-use patterns. It is a disbenefit to know the magnitude of the global warming potential of multiple gases if carbon dioxide effects and emissions are known with great accuracy while direct and indirect effects of methane and its emissions are very uncertain. In this case, it would be better to know the atmospheric concentrations of these two gases individually. The second generation model can help and improve the analysis of many of these issues provided it is "scaled" appropriately to answer the posed questions – to use the words of Edmonds et al., it should be problem-oriented and involve minimum modelling. I hope that they will succeed. The proof of the pudding will come in eating it – in this case we will have to be patient and wait for the first model implementation and results. In any case, the authors must be complimented on their ambitious and courageous undertaking.

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2. Kirit S. Parikh

At the outset, let me say that this is an extremely ambitious effort. It is even more ambitious than the one upon which we embarked at the International Institute for Applied Systems Analysis (IIASA) in 1976

in its Food and Agriculture Programme (FAP). We built what we called a Basic Linked System (BLS) of National Food and Agricultural Policy Models.[1] The national models are applied general equilibrium models with a general equilibrium linkage. The system has some 34 models, 20 referring to specific countries or groups of countries having a common agricultural policy and 14 models representing countries of the rest of the world from different regions, grouped according to the similarity of their likely behaviour on the international market. The models distinguish 10 different commodities at the international level (more domestically), of which nine were agricultural commodities and the tenth was a non-agricultural sector to close the system. The parameters of the models were empirically estimated from time-series data. Empirical estimation as opposed to benchmarking was considered essential if the model system were to describe the world with some measure of confidence. It took some 200 person years of effort. The first demonstration version of the model was ready in 1980. A usable one became available in 1984.

However, that was in 1976. Today, it is 1991 and the progress that has been made over these years in computers, algorithms, communication networks, data availability, and the experience obtained with general equilibrium modelling, should make the proposed effort of Edmonds et al. succeed within a reasonable length of time. Without the *Kitty Hawk* of the Wright brothers, 707s would not have come about when they did. With our and similar efforts on building-applied general equilibrium-based linked systems, such an ambitious effort could now be conceived and launched.

My comments on the paper are grouped under different headings. First, I would comment on its approach, then on its scope, limitations, and problem-orientation. These will be followed by some suggestions.

The approach

The approach is a bottom-up approach and the model provides enormous details. With any model that you use, the users always demand more details than what is incorporated into the model. I can confirm that from my personal experience. The model of India that we developed as a part of the IIASA Basic Linked System was one of the more detailed models of the system. I have been using this model for policy analysis and I often find that questions are asked that the model cannot answer without incorporating more details or greater articulation. All the time we keep on updating and modifying the model to address new policy issues as they come up. I am, therefore, sympathetic to the level of detail that is being sought to be incorporated into this model.

There is yet another reason for having a detailed model. A model provides scenarios and these scenarios provide consistent descriptions of a set of variables. These variables can be divided into endogenous and exogenous variables. While a model's solution provides consistency among the endogenous variables, it is not always recognized that consistency among the exogenous variables in specifying a scenario is a difficult and critical task. It does therefore help in specifying for a scenario a set of consistent values for exogenous variables, if their number is minimized. On the other hand this means that the number of parameters to be estimated becomes large. One may also note that when one is exploring long-term strategic alternatives, even empirically estimated parameters cannot be taken to be stable. Even then, the question of descriptiveness of the model cannot be dispensed with: a model scenario is an "if ... then" proposition and the "if" ought to describe the world that we live in if the "then" is to have any relevance.

A simpler CGE model, say of the Manne and Richels, or the Edmonds and Reilly type, provides a starting point for broadly defining some strategic alternatives. However, these models are already available. One should really try to build on them. Moreover, a more detailed model is indeed needed to provide guidance for policy formulations, for international agreements, or to facilitate international negotiations. For these purposes, a model is needed that tells us who gains and who pays under alternative policies and this is where I find some problems with the model.

Problem-orientation, scope, and limitations

I find the model to be what I call a "growth and greenhouse" model and not a "development and environment" model. Its emphasis is largely on loss in economic growth and on the trade-off between economic growth and greenhouse gas emissions. What is required however, is a model that treats both development and environment in a broader perspective. Questions of income distribution, questions of local versus global effects of environmental policy, questions of lifestyles of different groups of people, and questions of consumption patterns and development are very critical and not addressed by the model.

For example, the developing countries do not feel responsible for the current greenhouse problem. Their emissions of CO_2 are less than 30 per cent of the total greenhouse gas emissions in the world, even though they constitute nearly 80 per cent of the world's population. Many of these countries face severe environmental stress in their urban areas due to air pollution, poor sanitation, congestion in slums, use of dirty fuels in poorly ventilated kitchens, and crowded settlements. These environmental issues affect the welfare of their populations in a much more direct way than the consequences of the greenhouse effect. These countries, therefore, rightly feel that they should tackle these local environmental problems before they spend any resources for global environmental problems that in any case they themselves have not created. But, to explore such trade-offs, one needs to incorporate into the model the details of income distribution across different groups in rural and urban areas as mentioned earlier.

To do policy analysis with a model means to compare alternative situations. Some form of comparison of welfare in alternative situations is inescapable. The Edmonds et al. model does not stipulate an integrable demand system without which welfare comparisons would be extremely difficult to make. A consistent integrable demand system is quite essential for such a model. Here, I may also point out that to estimate a consistent demand system that remains meaningful over long periods and large changes in income levels is difficult. Recently, I had occasion to project food demand for the year 2050. When I used elasticities, or a simple linear expenditure system to project these, I got absurd results. The calorie intake implied in these projections was sometimes as high as 10,000 Kcal per day. This is clearly not a feasible intake level. One needs to find an alternative demand system. Here, what we did in the IIASA model is worth noting. We had estimated a separate demand function for each commodity as a function of income and own price. We had also estimated a separate relationship between per capita calorie intake and per capita income. This relationship was asymptotic of what one might consider the physiological limit. For a given target price vector and income level, we estimate an initial vector of demand using each of these individual demand functions. Then we find a vector point that is close to this vector and is such that it satisfies the adding up property as well as meets the aggregate calorie intake constraint. Around the new vector point we then construct a linear expenditure system. Such a procedure was repeated at each time period in IIASA's BLS models. The resulting system can be considered as a local approximation to an underlying utility function and can be shown to be consistent. Such a procedure gave sensible projections for 2050, which were also much more robust to changes in income levels. While the calorie constraint was a logical constraint to impose when dealing with food demand as we were doing in the BLS, it is not adequate for the proposed model, which has many other non-agricultural commodities. It may be necessary to impose some other natural constraint. Perhaps one could impose a constraint on the time required for alternative consumption activities and on the total time available to consume the various commodities. Such a constraint might make the demand system behave sensibly.

It is important that a model does provide insights into trade-offs between alternative development paths, between consumption patterns, between production structures, and across time. Even a long-term model must address some short-term policy issues and the issues of resulting transition costs. If a model does not provide any guidance on what we do now, the model is in some sense useless.

Some points of detail

There are some points of detail which need to be mentioned. First, it is vital to maintain common units for trade of commodities among countries. This is a critical problem and requires much care and data-grubbing work. From the description of the model, I am not sure how these problems are to be handled and how units are going to be kept consistent across different countries.

Secondly, an observation is made in the paper that capital stock data can be "relatively easy to observe." This is not so, as capital stock data are notoriously difficult to obtain. Estimates of total factor productivity growth in Indian industries based on the same data source by two different researchers arrive at two completely contrary results; one saying that factor productivity in India has grown, the other saying that it has not. The difference can be largely ascribed to the way capital stock data are put together from information on the time-series of investment at current prices by assuming certain rates of real depreciation. Unfortunately, the depreciation rates are not observed and a seemingly small change in the rate of depreciation whether it is 3 or 4 per cent per year can make a difference as to whether total factor productivity grew or not.

Thirdly, the model seems to assume that governments do not own land. However, governments can and do own land and substantial

amounts of it in many countries. Thus, questions of deforestation and land markets cannot be adequately dealt with without bringing in government behaviour in the land market. Neither do I see fishery mentioned anywhere, and consequences for oceans seem to be left out of the model, hopefully only for the moment.

Some suggestions

I would like to make a couple of suggestions. It seems to me that the agricultural sector model of IIASA's BLS would provide a very good starting point for this modelling work and the authors might explore the possibility of using this model for the agricultural sector. In addition, the algorithm development for IIASA's system has proved over the years to be robust and efficient even when dealing with policy regimes with quotas. They might also explore the possibility of using the algorithm that was developed by Michiel Keyzer[1] using the Kantarovich lemma.

Finally, I would like to emphasize that in using the model, one should keep in mind that no model can address the important question of welfare distribution and responsibilities. We have to keep this earth functioning and we must think in terms of a mechanism, a system that is fair and feasible. I suggest that we think in terms of using market-friendly approaches towards maintaining the global commons at the desired level by giving tradable emission quotas to different countries. Initial allocation of these should be consistent with the carrying capacity of the earth and should be done fairly. I suggest that the allocation based on population would be a fair way. In order not to encourage people to increase their populations, we may keep the allocations to the populations of a past year, say 1990. I hope this model would give us insights into alternative ways of preserving the global commons, of enhancing local environment, and of improving the quality of life for all persons on earth. I congratulate the modellers on their ambitious project and wish them luck.

Notes

1. Fisher, G., K. Frohberg, M.A. Keyzer, and K.S. Parikh. 1988. *Linked National Models: A Tool for International Food Policy Analysis*. Boston, Mass.: Kluwer Academic Publishers and International Institute for Applied Systems Analysis.
2. Keyzer, M.A. 1983. Computation of Fixed Points by Applied Continuation Techniques to the Kantorovich Lemma. Working Paper SOW-83-02. Amsterdam: Centre for World Food Studies.

3. Yuangzheng Luo

Many of the points taken up in the paper are of interest to me and I have yet to digest them. I cannot agree more with the view expressed in that paper that in the process of designing, a new model should be problem-oriented. We should not lapse into the practice of making the problem fit the model. That would be repeating the mistake of the fool in the Chinese fable who chopped off part of his feet so that they could fit the shoes.

In their reconstruction and economic development after World War II, Europe and Japan did not pay due attention to the issue of environmental pollution. Thus it went unheeded until the 1960s when it became an explosive issue. How to control environmental pollution and maintain the ecological balance became a great concern of the United Nations and governments around the world. To this end the United Nations set up the Environmental Council under the Economic and Social Council (ECOSOC). China began to take part in the Council's work in the 1970s. The developed countries have designed a number of models on environmental pollution in addition to formulating relevant policies and legislation. These have proven through practice to be effective in bringing environmental pollution under control step by step. However, from the global perspective, the problem of environmental pollution has not been solved. The global environmental issue has been aggravated as a result of the accelerated transfer by the industrialized countries since the 1980s of highly polluting and energy-guzzling labour-intensive industries to the developing countries and also as a result of the industrial development of the developing countries themselves. Moreover, the emission of greenhouse gases and the depletion of the ozone layer led to global environmental warming. People are becoming increasingly concerned about such global environmental issues. The developing countries have come to see that prevention is better than "cure." But it must be pointed out that the industrialized countries should bear the main responsibility for global environmental pollution and the degradation of the environment. While they seek to protect the environment in their own countries, the industrialized countries must transfer environmentally sound technologies to the developing countries, increase aid to them for environmental protection, and put an end to the transfer to developing countries of industries that pollute the environment.

Great strides have been made in environmental protection since

the 1960s when the problem of pollution began to catch the attention of industrialists, policy makers, and the general public. In many countries, effective measures have been taken and laws passed to keep the air and the rivers and lakes clean. Today, more and more attention is focused on the greenhouse effect. I am confident that with a common understanding of the gravity of the problem and through concerted efforts, better technologies will be developed to reduce emissions of greenhouse gases from industrial plants, vehicles, and home appliances and wiser policies adopted to control such emissions.

As a developing country, China is equally concerned about the greenhouse effect and about environmental protection. In its pursuit of a reformist policy and its opening up to the outside world, China has, in the past decade or so, made notable progress in controlling environmental pollution and preserving the ecological balance. China is fully aware of the importance of striking a proper balance between achieving economic and social progress and maintaining a sound ecological system between industrialization and environmental protection. We are ready to learn from other countries whatever is useful to us in preserving our environment. However, due to financial and technological constraints, we cannot apply the same standards of environmental protection that the developed countries use.

You may be interested to learn about China's energy picture. In 1990 China's total energy consumption amounted to 980 million tons of standard coal. The breakdown is as follows: coal, 75.6 per cent; crude oil, 17 per cent; natural gas, 2.1 per cent; and hydropower, 5.3 per cent.

You can see from these figures that coal plays a predominant role in China's energy consumption. There was a time in the 1970s and early 1980s when Chinese factories switched from coal burning to oil burning. But before long, China learnt that it could not afford to do this, since exploration of oil requires far greater capital input than the mining of coal. So we switched back to coal burning. While we continue to rely heavily on coal for energy consumption, we plan to make use of nuclear power and tap China's rich hydroelectric resources on a much larger scale. To this end, a nuclear power station is under construction at Da Ya Wan in Southern China and plans are under way for the building of more hydropower stations. Although economic development remains China's overriding concern, increasing attention is being given to environmental protection. In this regard, there is a great deal for China to learn from the advanced

JA

Review Draft – Comments Welcome

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Return to 1990:
The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

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October 1997

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Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

3rd Party Article

Details on SGM model

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ABSTRACT

The Second Generation Model (SGM) is employed to examine four hypothetical agreements to reduce emissions in Annex I nations (OECD nations plus most of the nations of Eastern Europe and the former Soviet Union) to levels in the neighborhood of those which existed in 1990, with obligations taking effect in the year 2010. We estimate the cost to the United States of complying with such agreements under three distinct conditions: no trading of emissions rights, trading of emissions rights only among Annex I nations, and a fully global trading regime.

We find that the cost of returning to 1990 emissions levels in the United States in the absence of trading opportunities is approximately $108 per metric ton carbon in 2010. The total cost in that year is approximately 0.2 percent of GDP. Emissions reductions are accomplished via energy conservation across a broad range of residential, commercial, industrial and transportation activities and by replacing coal fired power stations with natural gas facilities.

International trade in emissions permits lowers the cost of achieving any mitigation objective by equalizing the marginal cost of carbon mitigation among countries. This is sometimes referred to as "where" flexibility. "Where" flexibility allows least expensive emissions reductions to be undertaken first, regardless of where they occur among trade participants.

For the four mitigation scenarios in this study, economic costs to the United States remain below 1% of GDP through at least the year 2020. This was the case even in the scenarios where the United States met its mitigation targets without international trading of carbon permits.

Return to 1990
The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

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Son H. Kim
Christopher N. MacCracken
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More than 160 nations have signed the Framework Convention on Climate Change (FCCC). That agreement required Annex I nations, [1] the developed nations of the world plus economies of the Former Soviet Union and Eastern Europe, to undertake measures to return emissions to 1990 levels or below in the year 2000. The parties to the FCCC met in Berlin in the Spring of 1995 and determined that additional measures were required to implement the ultimate objective of the FCCC, "*to stabilize the concentration of greenhouse gases in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system.*"

Subsequent to the Berlin discussions, nations of the world have begun to consider measures that would set quantifiable emissions limitation requirements in the post-2000 period for Annex I nations. Various measures have been considered. The purpose of this paper is to explore the economic consequences of efficient policy instruments—carbon taxes or tradable emissions permits—which might be employed to achieve a variety of targets in the post-2000 time frame. [2] Using the Second Generation Model (SGM), we estimate the costs to the United States of complying with of four Annex I mitigation scenarios under three permit trading regimes. Specifically, we examine the carbon taxes required for emissions mitigation and provide measures of the costs of mitigation.

We begin by describing the variety of policy options to be considered and our general approach to modeling those policies. We then review some of the necessary assumptions for this exercise, as well as the structure and calibration of the SGM. Finally, we discuss the results of our analysis, including time paths of emissions and measures of cost.

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[1] Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, European Economic Community, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States.

[2] In the United States, efforts were undertaken by the Interagency Analytical Team (IAT), and results were summarized in United States Government (1997). The Second Generation Modeling team was one of three modeling teams that participated in the evaluation of potential emission mitigation measures under discussion. Note that the results presented in this paper differ from SGM results presented under the auspices of the IAT. The IAT effort assumed higher rates of technical change induced by a response to policy implementation. This study does not make the same assumptions.

APPROACH

The SGM was used to simulate the impact of mitigation policies on the United States economy. The SGM is a computable general equilibrium economic model that projects economic activity, energy consumption, and carbon emissions for the United States and 11 other world regions. A more complete description of the SGM follows in the next section.

Four scenarios were constructed that reduce carbon dioxide emissions in Annex I countries by 2010. The four policies, designated 'M_', are listed below. Figure 1 shows United States emissions paths for the four scenarios and the reference case in million metric tons of carbon (MMTC). The reference case is a business-as-usual scenario, or what we project will happen in the absence of a mitigation policy. In each mitigation scenario, allowable emissions are reduced linearly from the reference level in 2000 to the emissions target in 2010.

M1990 — Emissions from Annex I regions must be no greater than 1990 emissions levels beginning in the year 2010.

M1990+10% — Emissions from Annex I regions must be no greater than 10% above 1990 emissions levels, beginning in the year 2010.

M1990-10% — Emissions from Annex I regions must be no greater than 10% below 1990 emissions levels, beginning in the year 2010.

M1995 — Emissions from Annex I regions must be no greater than 1995 emissions levels beginning in the year 2010.

[Figure 1. Carbon Dioxide Emissions Scenarios for the United States]

The four emissions mitigation scenarios each define a set of emissions rights for the Annex I regions. In a mitigation scenario, regions must possess permits, or rights to emit, for every million metric ton of domestic carbon dioxide emissions. Three emissions permit trading regimes were modeled under each mitigation policy: independent emissions mitigation, Annex I joint mitigation, and Annex I mitigation with global permit trading. The 12 SGM regions listed in Table 1 provide the necessary global coverage to simulate these trading systems. Carbon taxes were used to constrain emissions for each of the policy-trade combinations.

Table 1. Regions in the SGM

Annex I	Non-Annex I
United States	China
Canada	India
Western Europe	Mexico
Japan	South Korea
Australia	Rest of World[3]

[3] The Rest of World includes Latin America, Africa, and other Asian countries.

Former Soviet Union	
Eastern Europe	

In the independent mitigation case, each Annex I region must individually meet its required emissions targets without any trading of permits across regions. A time series of carbon taxes is determined for each region to reduce emissions to be equal to its allocated emissions rights.

With Annex I joint mitigation, a common carbon tax is applied to all Annex I regions to meet the overall Annex I emissions target. However, regions are allowed to trade permits amongst themselves so long as the total constraint is met in each time period. Regions may only emit more carbon than their allocated emissions rights allow if another Annex I region is willing to sell a corresponding number of its permits, thereby forcing the seller region to reduce its domestic emissions beyond the required target.

In the global trading case, emissions rights are allocated to Annex I regions at the same levels as in the Annex I trading case. Under global trading, however, the Annex I regions are allowed to purchase permits from each other and from non-Annex I regions so long as the global emissions constraint is met. The global constraint in each period is composed of the Annex I constraint and the sum of the non-Annex I regions' reference level emissions in that period. The SGM is used to determine a global carbon tax just large enough to meet the global emissions target.

In none of the above scenarios and trading combinations are non-Annex I regions forced to constrain their emissions below reference levels. No mitigation targets or emissions trajectories are imposed on those regions. Under the global permit trading regime, non-Annex I regions participate in the market for carbon permits only when it is to their economic benefit to do so. These regions are allocated permits equal to their projected reference emissions, so they are only required to reduce their emissions by an amount equal to the number of permits they wish to sell.

Eastern Europe and Former Soviet Union Permit Allocations

While carbon dioxide emissions in most regions are anticipated to continually increase over time beyond 1990 levels, this is not true for the Eastern Europe and Former Soviet Union regions. Emissions in these regions have declined since 1990. Their reference case emissions trajectories reflect this decline from 1990 to 1995 and then increase slowly from 1995 onward. The downturn in emissions poses a special problem when allocating emissions rights. Two approaches to permit allocations for the regions have been discussed in recent months. The first allocates permits based on the stated policy scenario (e.g., M1990 allocates permits based on 1990 emissions level) so that permits are allocated to them in the same way as they are to other Annex I regions. Because of the decline in emissions in those regions from 1990 to 1995, however, this approach results in emissions permits being granted to Eastern Europe and the Former Soviet Union in the policy years that are greater than their reference level emissions. These 'paper credits' are equal to the difference between the lower post-1990 emissions and the policy-level (i.e., 1990) emissions. For example, the Former Soviet Union's reference emissions level in 2010 is 836 TgC, significantly lower than its 1990 emissions of 1050 TgC. If granted permits equal to its 1990 emissions, it would receive 214 TgC worth of permits more in 2010 than its projected emissions, giving it 214 TgC worth of permits to sell without incurring any emissions reductions of its own.

The second approach to allocating permits to Eastern Europe and the Former Soviet Union is to grant permits equal to reference level emissions in each period until the projected path is constrained by the policy. For example, in the M1990 case, the Former Soviet Union would be granted permits equal to its projected reference emissions through 2020 because emissions in the policy years never recover to 1990 levels.

For the purpose of this exercise, we chose to emphasize the latter approach in allocating emissions to Eastern Europe and the Former Soviet Union. This reference allocation scheme ensures that the stated Annex I emissions targets are achieved in both the independent mitigation and permit trading scenarios. Because a final decision on the permit allocation method has yet to be made, however, we have also included a discussion of the impacts of the mitigation policies utilizing the first approach.

MODEL OVERVIEW

The SGM is designed specifically to address issues associated with global change. The model is designed to perform the following types of analysis:

1. Provide estimates of future time paths of environmentally important emissions associated with economic activity.

2. Provide estimates of the economic cost of actions to reduce greenhouse gas emissions.

Sectors

The SGM has nine producing sectors and twelve inputs to production. The inputs are land, labor, capital, and the nine produced goods. Economic detail is maintained in the energy supply and transformation sectors that are important for greenhouse gas emissions projections, but aggregated elsewhere into one large "everything else" sector.

Five different fuels are used for producing electricity, resulting in five subsectors for the electric generating sector. A separate economic production function, of the constant elasticity of substitution (CES) functional form, is used for each sector or subsector. Capital investment decisions depend on an assumed lifetime of capital for each sector or subsector. Capital lifetimes range from 15 years in the oil, gas, and coal production sectors to 70 years for hydroelectric power. The relative size of each production sector and subsector is shown in Table 2.

Table 2. Producing Sectors in the SGM

	Producing Sector	Gross Output in 1985 (millions of 1985 $)	
1	Agriculture	468,618	
2	Everything Else	5,086,486	
3	Oil Production	64,171	
4	Gas Production	45,804	
5	Coal Production	20,006	
6	Uranium Processing	2,195	
7	Electricity Generation	165,800	
	a. oil		10,959
	b. gas		34,152
	c. coal		85,930
	d. nuclear		21,370
	e. hydro		13,389
8	Petroleum Refining	145,015	
9	Gas Transmission and Distribution	105,330	

Market Clearing

In the SGM, markets are said to *clear*. In other words, the SGM solves for the set of prices for all markets (or sectors) in the modeled economy so that demands and supplies of each market are in equilibrium. The set of prices in which the equilibrium holds is called the *market-clearing* price set. In an equilibrium model like the SGM, markets are linked to other markets through the market-clearing process. For example, a change in the demand for coal will have an effect on not just the price of coal, but also the prices of oil, gas, and, at least indirectly, the prices of all markets in the economy.

Carbon permit prices and taxes are also solved by the SGM as part of the market equilibrium. Specifically, the SGM finds the carbon price such that the amount of carbon emitted is just equal to the carbon constraint of the region or group of regions under a carbon emissions limitation constraint.

Carbon Taxes and Revenue Recycling

The SGM uses a carbon tax within each region to provide an economic incentive for the economy to substitute away from carbon. Revenues obtained from the carbon tax can be very large, and how the revenues are recycled, or redistributed to the economy, makes a difference in the final economic cost. For this exercise, we assume that all carbon tax revenues are recycled back to consumers through a lump-sum government transfer.

For the cases where emissions rights are traded between countries, each SGM region is allocated an initial number of carbon emissions permits based on the stated mitigation policy (e.g., 1990 emissions levels for the M1990 scenario). Carbon permits can then be traded between countries at a price that clears the global market in these permits.

Modes of Operation

All of the SGM regions were initially developed as single-region models with a base year of 1985. Each regional model operates in five-year time steps generally through 2030, 2050, or 2100. Most of the single-region models were developed in collaboration with experts from that country. It is possible to run all of the regions individually or simultaneously in a global model with international trade. The three modes of operation for the SGM are:

1. Single Region
2. Global with Partial Market Clearing
3. Global with Full Market Clearing

Single-region operation. For each SGM region, all produced goods are classified as being tradable, nontradable, or traded at a fixed quantity. When SGM regions are operated independently, a fixed world price is assumed for certain tradable goods; regions may import or export as much of that good as desired at that fixed world price, subject to an overall balance of payments constraint. For all nontradable goods, the quantity of trade is fixed in advance. The following assignments are used when the United States model is operated independently:

Numeraire Sector:	everything else (price always equals 1)
Fixed World Price:	crude oil
Fixed Trade Quantities:	agriculture, coal, nuclear fuel, refined petroleum, electricity
Nontradables:	distributed gas, land, labor

For each region, the large 'everything else' sector is the numeraire, with its price fixed at 1 for all time periods. The prices of the other sectors in the economy are reported relative to this fixed value. The 'everything else' good is a tradable good for all regions. An exogenous balance-of-payments constraint is specified in advance for each region. Most regions are assumed to move linearly from a historical trade balance in 1985 to balanced trade by 2005.

Given a trial set of prices, the SGM computes supply and demand for all producing sectors and primary factors of production. Markets for the nontradables and goods traded at fixed quantities are brought into equilibrium by searching for a set of prices that equate supply and demand. Prices are adjusted until supply and demand are within 0.01% of each other.

Global model with partial market clearing. The global version of the SGM is used when there is at least one market that must clear globally. For the scenarios described in this paper, that market is tradable carbon emission permits. The model searches for a global carbon tax, which can be interpreted as a world carbon permit price, that clears the market for permits.

Each region is initially allocated a number of carbon permits and may trade those permits at the world permit price. Some regions will be sellers of permits and some will be buyers. After trading permits, all regions must hold permits equal to the domestic level of carbon emissions.

All regions are still subject to a period-by-period balance of payments constraint. The model does not allow borrowing to pay for carbon emissions permits. Imports of permits must be paid for with exports of some other good.

Global model with full market clearing. There are no longer any markets with a fixed world price. A set of world prices is found that clears all world markets. Also, world markets can be created for goods that were traded in fixed quantities in the single-region model.

All of the scenarios described in this paper were run in the second mode, global with partial market clearing. This mode was chosen for two reasons. The first is that we chose to adopt a fixed time path of world oil prices for SGM model runs that were completed for the United States Government during the spring of 1997. This meant that the world oil market would not be allowed to clear in the model. The second reason is that model results are often easier to interpret when some variables in the model remain predetermined over time.

Data Requirements

Three types of data are used to construct and calibrate each region of the SGM:

1. Economic and Demographic Data
2. Energy Balances
3. Technology Descriptions

Economic data include input-output tables and supplemental information from the national income accounts. Population projections were obtained from the World Bank. Energy balance tables were obtained either from the International Energy Agency or from government agencies within a region.

Input-output tables describe, in value terms, the flow of goods between industries and consumers in an economy. However, a model concerned with quantities of carbon emissions must also be concerned with quantities of energy. An input-output table alone is not sufficient to determine the quantities of oil, gas, coal, electricity, and refined petroleum that are produced and consumed. Supplemental information on energy quantities is required to map currency units from an input-output table to energy units needed to calculate levels of carbon emissions. We combine economic input-output tables with energy balance tables to create a hybrid input-output table with units of joules for energy products and real dollars for all other products. Miller and Blair (1985) provide a general description of, and the motivation for using, hybrid input-output tables.

Individual energy technologies are characterized by the annualized cost of providing an energy service. Data needed to determine the annualized cost include capital cost, equipment lifetime, annual fuel requirements, the interest rate, and other annual maintenance and operating costs.

REFERENCE CASE AND CALIBRATION

The cost of reducing greenhouse gas emissions is dependent on the reference case. The higher the growth rate of emissions in the reference case, the greater the cost of returning to 1990 emissions. Therefore, much effort is expended to create an acceptable reference case before running any of the mitigation scenarios.

Results for this study are reported for the years 1990 through 2020. The United States reference case was closely calibrated to the Annual Energy Outlook 1997 (AEO97). Since AEO97 projects only up to the year 2015, projections beyond 2015 are SGM model results and are not calibrated to any other established projections. Projections of carbon emissions, population, gross domestic product (GDP), energy consumption, and electricity generation for the United States are described below.

For the other global regions, economic and energy consumption growth rates were roughly calibrated to regional projections from the World Energy Outlook 1996 (WEO96). For the Eastern Europe and Former Soviet Union regions, projected energy consumption levels were adjusted downward from the WEO96 projection to reflect recent events. Population projections for all regions with the exception of the United States were set exogenously based on the World Population Projections 1994-1995, published by the World Bank. The United States population projection was set according to AEO97 projections. As mentioned earlier, the international crude oil price trajectory was also taken from the AEO97. Prices for all other fuels and goods in the model were determined endogenously.

The general calibration procedure was to first match GDP growth by adjusting parameters that control total factor productivity in the 'everything else' sector. Then energy consumption by fuel was calibrated by adjusting input-specific technical change parameters. Carbon emissions are an output of the model derived directly from primary energy consumption by applying fuel-specific emission factors.

Carbon Emissions

In 1990, total carbon dioxide emissions from the combustion of fossil fuels in the United States were 1,350 million metric tons of carbon. Model results show that total carbon dioxide emissions continue to rise as fossil fuel consumption increases and emissions reach 1,871 million metric tons by 2020. This amounts to a 39 percent increase in total emissions and an emissions growth rate of 1.1 percent per year. Reference case carbon emissions were shown earlier in Figure 1.

Gross Domestic Product

The two most important determinants of GDP are population growth and rates of change in productivity. Total population levels for the United States were taken directly from AEO97. United States population grows from 250 million in 1990 to 323 million in 2020. This represents an annual population growth rate of 0.85 percent per year.

GDP for the United States was matched to AEO97 projections by changing the total factor productivity parameter for the 'everything else' sector. Beginning with the 1990 GDP of 6.1 trillion dollars, the economy grows at nearly 2 percent annually to reach 10.6 trillion dollars by 2020.

Energy Consumption

Total energy consumption from 1990 to 2015 was calibrated to within 2 percent of projections from AEO97. Energy consumption by fuel is shown for the United States in Figure 2. Total consumption increases from 86 EJ in 1990 to 118 EJ in 2020. This increase represents an average annual growth rate of 1.1 percent over that period. The annual growth rate in energy consumption declines over time and by 2020 decreases to 0.5 percent per year.

Petroleum remains the major source of energy through 2020, but its share of total consumption declines over time, giving way to natural gas and, to a lesser extent, renewable energy sources. Coal is the third largest source of energy and its consumption grows steadily at slightly less than 1 percent per year. Nuclear energy's contribution to energy consumption declines over time.

[Figure 2. Energy Consumption – United States Reference Case]

Energy consumption does not grow as fast as GDP, which results in the energy-GDP ratio falling over time at an average annual rate of 1.0 percent per year. Figure 3 shows the energy-GDP ratio generated by the SGM for the United States reference case.

[Figure 3. Energy-GDP Ratio – United States Reference Case]

Electricity Generation

Projections of electricity generation are similar to those of the AEO97. SGM total electricity generation results are higher than the AEO97 projections by approximately 10 percent. Electricity generation from natural gas is the reason for the higher result. Total electricity generated in 1990 is nearly 11 EJ, which grows at 1.5 percent per year and expands to 17 EJ by 2020. The major source of electricity is the combustion of coal; however, electricity generation from natural gas plays a significantly larger role with time. In 1990, electricity generation from coal contributed 53 percent of the total generation, while that from natural gas combustion contributed 17 percent of the total. By 2020, the shares of electricity generation from coal and natural gas are closer. Electricity generation from coal and natural gas comprise 44 and 34 percent shares of the total, respectively. Highly efficient and low-cost natural gas combined cycle power plants incorporated into the SGM contribute to the growth of natural gas as the choice fuel for electricity generation. Nuclear power's contribution to the overall demand for electricity declines with time as existing power plants are retired and no new additional plants are constructed.[4] Renewable energy sources for electricity generation include hydroelectricity, solar photovoltaics and others. Generation of electricity from renewable sources increases slightly from 1990 to 2020; however, renewable energy's share of total electricity remains below 10 percent of the total.

COST OF EMISSIONS MITIGATION

[4] The assumption of no new starts reflects a de facto nuclear moratorium. Were nuclear power to be allowed to compete against other energy forms on the basis of price alone, the model would continue to build new facilities.

Although this exercise employed the 12-region version of the SGM, discussion of results in this paper will focus on the United States. The SGM provides output on regional GDP and its components and a detailed description of the composition of energy supply. In this analysis, we focus on the broad economic impacts to the economy. Specifically, we discuss the permit prices required to meet the various mitigation requirements and the costs to the United States economy of undertaking such policies. We also discuss the impacts of the domestic carbon taxes on energy consumption.

Permit Prices

Table 3 shows the permit prices by trading regime required for the United States to meet its emissions targets under the four mitigation scenarios. Permit prices in the United States must reach $108 per metric ton of carbon to reduce United States emissions to 1990 levels in 2010 in the independent mitigation case. This price increases significantly with the tighter constraint imposed under the M1990-10% case. Permit prices in the M1995 and M1990+10% scenarios are very similar as only 5 TgC separate the constraints in the two cases in 2010.

Table 3. United States Carbon Taxes Required to Meet Policy Goal
Eastern Europe & FSU Allocated Reference Case Permits
(1992 US$ per Metric Ton of Carbon)

EE+FSU have higher permits in Kyoto – Also umbrella + 6 gases lower

	Independent Mitigation		Annex I Joint Mitigation		Annex I Mitigation with Global Trade	
	2010	2020	2010	2020	2010	2020
M1990	108	170	72	87	26	27
M1990+10%	60	110	42	58	16	18
M1990–10%	173	260	109	122	38	36
M1995	61	112	70	106	26	32

Permit prices fall as more regions are included in the market for carbon permits. In the independent emissions mitigation case, carbon emitters in the United States may undertake emissions mitigation options available only within the United States. In the Annex I joint and global permit cases, however, regions are included that have mitigation options with significantly lower costs, thereby lowering the marginal cost to the carbon permit market of meeting the desired emissions targets. As we will discuss, this 'where' flexibility in meeting emissions targets has a significant impact on costs as well as permit prices.

A fixed emissions level and an increasing reference case emissions level imply both a rising percentage emissions reduction and a rising price of meeting the fixed emissions target. Increasing population in the United States, and the economic growth that accompanies it, put upward pressure on emissions that, in turn, forces larger shifts away from coal toward natural gas and renewable energy sources. The availability of relatively inexpensive abatement options in the developing world allows the permit price to remain relatively constant over time in those cases.

As the permit prices decrease across trading regimes, the United States purchases increasing quantities of permits from abroad, thereby enabling it to emit more than its allocated permits alone would allow. Figure 4 shows United States emissions for the M1990 case across the three trading regimes. Under the independent emissions mitigation regime, the United States is limited to emitting only what it is allocated under the scenario, its 1990 emissions level. With Annex I trading, however, the United States purchases 209 TgC worth of permits in 2010 and 244 TgC in 2020 from the Former Soviet Union and Eastern Europe. The purchases increase to 316 TgC and 436 TgC in 2010 and 2020, respectively, under the global trading regime. Again, 'where' flexibility reduces the amount by which a permit-buying region must reduce its emissions and, therefore, reduces the cost to the region.

[Figure 4. United States Carbon Emissions – M1990 Cases]

The M1995 Annex I trading case is the only case in which the United States sells permits to other regions. The permit price under independent mitigation in 2010, as shown in Table 3, is less than that shown under Annex I trading. Because the United States can mitigate emissions less expensively in 2010 than other Annex I regions, it reduces its emissions beyond the required 1995 target and sells permits to other Annex I regions. By 2020, however, the United States begins to purchase permits from Eastern Europe and the Former Soviet Union.

Energy Consumption

Emissions mitigation is achieved primarily through two mechanisms: energy conservation - reduction in total energy consumption - and replacement of coal-fired capacity with less carbon-intensive fuels such as natural gas and renewables in the electricity sector. In the no-trading cases, fuel switching from coal to natural gas and renewable fuels in the electricity generation sector accounts for roughly 60 percent of the reduction in total emissions. Energy conservation makes up the remaining 40 percent of the reduction. The domestic carbon tax of $108 in 2010 in the M1990 case results in a reduction of total energy consumption by 14 percent relative to the reference case. Consumption of coal drops by 57 percent while consumption of petroleum drops by 7 percent. Consumption of natural gas, however, increases by 4 percent due to fuel switching. Figure 5 shows energy consumption by fuel in the year 2010 for the four mitigation scenarios. Note that even when emissions are returned to 1990 levels, the scale of the total energy system is not. The fuel switching mentioned above allows the emissions targets to be met without reducing total consumption by the same percentage as the required reduction in emissions.

[Figure 5. United States Energy Consumption in 2010]

Fuel substitution in the electricity sector results in the share of electricity generated from coal dropping from 45 percent in the reference case to 20 percent in the M1990 case. The reduction in electricity generation from coal is compensated for by increased generation from natural gas. The share of electricity generation from natural gas increases from 29 percent in the reference case to 51 percent M1990 case.

As discussed above, the domestic cost of stabilizing emissions at 1990 levels in 2010 without trade is $108 per metric ton carbon. This cost roughly reflects the cost of abandoning existing coal-fired power generation capacity and replacing it with a new combined-cycle natural gas-fired unit. A $108 per metric ton tax adds approximately $0.02 per kilowatt-hour to the operations and maintenance (O&M) cost of power generation in a coal-fired plant. This additional cost makes the O&M cost of the coal plant higher than the levelized cost of installing a new gas-fired combined-cycle unit, roughly $0.05 per kilowatt-hour. The $108 tax, therefore, provides an emissions mitigation plateau for permit prices that is not exceeded until most of the existing coal capacity is replaced.

Certain caveats apply to the discussion above concerning the marginal cost of substituting natural gas-fired electricity generation capacity for existing coal-fired capacity. The cost analysis requires that the tax be levied indefinitely. If the tax policy is believed to be only temporary, the amount of substitution is likely to be much less substantial and the tax level required for stabilizing emissions could be higher. The tax level required for mitigation also depends on the cost of developing the infrastructure necessary to supply natural gas to potential new users. Extending pipelines to particular areas, for example, might increase the cost of gas enough so as to discourage switching from coal-fired plants in those areas.

Cost Calculations

A very convenient way to characterize the response of any SGM region to a carbon tax is by constructing a marginal cost of carbon curve. Figure 6 is a scatter plot of various carbon taxes applied to the United States economy and the corresponding reduction in carbon emissions. Data points plotted in Figure 6 are from the four independent mitigation scenarios for the United States. Note that a positive tax is required to achieve any reductions in carbon emissions.

[Figure 6. Marginal Cost of Carbon]

The marginal cost curve is used to calculate one measure of cost that we will call the *direct cost*. For any level of carbon emissions mitigation, the direct cost is defined as the area under the marginal cost curve up to that amount of mitigation.[5] While the first units of emissions reductions are very inexpensive; successive units become more and more expensive. So, as the constraints on emissions become tighter across cases and over time, the cost of mitigation increases. Figure 7 shows the direct costs for the United States for the four independent mitigation scenarios. Direct costs are shown at 5-year intervals through 2020 as a percentage of GDP. These costs are plotted as negative numbers.

[Figure 7. Cost of Emissions Mitigation – No Trading]

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[5] Note that these costs do not include the costs of establishing a domestic or international permit trading system nor do they include the transaction costs associated with permit trading among firms and/or regions.

Figure 8 focuses on the M1990 case and shows how costs to the United Sates are reduced with trade in emissions permits between countries. The 'independent' cost line shown in Figure 8 is the same as the M1990 cost line in Figure 7. In 2010, costs are reduced somewhat with Annex I trading and reduced by about one-half with global trading. In later years, the flexibility in where emissions reductions are undertaken impacts mitigation costs even more significantly.

[Figure 8. Illustration of 'Where' Flexibility – Costs for M1990 Cases]

Cost calculations for the emissions trading cases are different than in the independent case. Costs for the trading case take into account the value of permits traded. For a buyer of permits, such as the United States, net cost includes the direct cost plus expenditures on carbon permits. A breakdown of these two cost components is shown for the M1990 Annex I trading case in Figure 9. Direct cost is roughly half of the net cost. The remaining cost, the difference between the 'direct cost' and 'net cost' lines in Figure 9, is the value of emissions permits that would be purchased from other Annex I countries.

[Figure 9. Cost Breakdown – M1990 Annex I Trading Case]

Impact of Alternative Permit Allocation Approach

The results discussed thus far have been based on the assumption that Eastern Europe and the Former Soviet Union are allocated permits equal to the minimum of their reference-level emissions and the policy-level emissions. This section will discuss the impacts of an alternative permit allocation method in which Eastern Europe and the Former Soviet Union are granted permits equal to their policy-level emissions in every period. Recall that 'policy-level' refers to the emissions target set by the chosen mitigation policy. For example, the policy-level emissions in the M1990 case would be 1990 level emissions starting in 2010, and for the M1995 case they would be 1995 level emissions beginning in 2010. This assumption results in the 'paper credits' discussed earlier that significantly impact the permit prices required to meet Annex I emissions targets in the Annex I and global trading cases.

Table 4 shows the permit prices required to meet the policy goal under the policy-level permit allocation approach. The prices required for independent mitigation in the United States do not change from Table 3 above because the paper credits in those cases are not available for purchase outside Eastern Europe and the Former Soviet Union. Permit prices also remain unchanged under the M1995 case because by that time the two regions have already suffered the worst of their economic downturns so that emissions levels are at their lowest point in the 1990 to 2020 time frame. The permit prices under the other trading scenarios are significantly less under this allocation approach, however, because the regions are able to sell the paper credits without incurring any cost domestically. In the M1990 case in 2010, the paper credits allocated to Eastern Europe and the Former Soviet Union account for 37 percent of the emissions reductions necessary for the remaining Annex I regions to meet their target emissions. This addition of permits available for purchase reduces the permit price by $33, or by 46 percent, relative to the permit price under the reference-level allocation approach. Figure 10 shows the difference in permit prices for the M1990 case with Annex I trading between the two permit allocation approaches in 2010 and 2020.

Note that the difference decreases over time as emissions in Eastern Europe and the Former Soviet Union approach the policy goal.

Table 4. United States Carbon Taxes Required to Meet Policy Goal Eastern Europe & FSU Allocated Policy-level Permits (1992 US$ per Metric Ton of Carbon)

	Independent Mitigation		Annex I Joint Mitigation		Annex I Mitigation with Global Trade	
	2010	2020	2010	2020	2010	2020
M1990	108	170	39	73	15	22
M1990+10%	60	110	6	35	2	11
M1990–10%	173	260	88	124	31	36
M1995	61	112	70	106	26	32

[Figure 10. Permit Prices under Alternative Permit Allocation Methods for EE & FSU – M1990 Annex I Trading Case]

The lower permit prices under the policy-level approach result in lower total costs of emissions mitigation to the United States. In the M1990 Annex I trading case, costs as a percentage of GDP are reduced from 0.18 percent under the reference-level allocation approach to 0.12 percent under the policy-level approach in 2010. Figure 11 shows costs as a percentage of GDP for the M1990 Annex I trading case for both allocation methods.

[Figure 11. Cost of Emissions Mitigation under Alternative Permit Allocation Methods for EE & FSU – M1990 Annex I Trading Case]

DISCUSSION

In this section, we summarize some of the insights gained from our modeling activities using the SGM. First, economic costs depend a great deal on our assumptions about future carbon emissions. Second, several measures of cost are available from the SGM. Third, the distribution of costs among countries in a system of global permit trading is sensitive to assumptions on exchange rates as well as the initial allocation of permits. Fourth, any system of global trade in carbon permits implies potentially large transfers of wealth from one region to another. Finally, we discuss how some of our assumptions affect the results on costs.

Role of Reference Emissions in Shaping Marginal Mitigation Costs

All of the results in this study depend on assumptions used to create a reference emissions scenario from the present to 2020. The amount of mitigation required to return to 1990 levels depends directly on reference case emissions for each region. In the Annex I trading cases, carbon permit prices are particularly sensitive to reference scenarios for potential sellers of permits, especially Eastern Europe and the Former Soviet Union.

Among the Annex I countries, projecting future carbon emissions is especially uncertain for Eastern Europe and the Former Soviet Union. Of particular importance is when emissions in these regions will once again reach 1990 levels. If this point is reached before 2010, then we model EE and FSU just as any other Annex I country. If this point is reached after 2010, then emissions restrictions are not binding in EE and FSU until that point in time.

Measuring and Reporting Costs

At least two measures of cost are available from the SGM and from other models as well. The first measure, which we call the *direct cost*, can be thought of as either a deadweight loss or the integral under the marginal cost curve for carbon. Using either approach, direct cost is approximately equal to one-half of the carbon tax (or permit price) times the reduction in carbon emissions. For the permit trading cases, direct costs are then adjusted by the value of transfer payments required to purchase or sell permits. This measure of net cost is simple to construct and is comparable across models.

Of ultimate interest, however, is the net impact on some broader measure of economic activity (such as GDP) or on economic welfare (such as real consumption). There are many reasons why the change in GDP (or real consumption) is different than direct cost net of transfer payments. These other components of cost include the effects of pre-existing distortionary taxes, changes in terms of trade, and how tax revenues are recycled. In addition, measurement of GDP (or real consumption) depends on the choice of index and base year used to construct that index. This reflects real-world problems in constructing a quantity index for GDP when relative prices are changing.

Foreign Exchange Rates

Permit prices for the global permit trading cases are very sensitive to assumptions about exchange rates. And while the United States follows a largely free market approach to exchange rates, most developing nations do not. Therefore it may be perfectly reasonable to assume that over the long-term the United States exchange rate with other free market trading partners would tend toward the purchasing power parity rate, this assumption is questionable with other partners. This is particularly true for developing countries where market exchange rates, in local currency per U.S. dollar, can be three to five times the corresponding exchange rate based on purchasing power parity. A global permit price of $100 per metric ton translates, at market exchange rates, into a much higher relative price in the developing countries than in the United States.

Exchange rates based on purchasing power parity are usually used to compare income levels between countries, but market exchange rates must be used for goods actually traded between countries. This creates a potential problem for developing countries considering participation in a global permit trading program; carbon permits would be traded at market exchange rates, while GDP losses are better measured using purchasing power parity. For developing countries, losses in GDP could be greater than the value of carbon permits sold.

International Transfer Payments

We have modeled an international system of carbon permit trading that implies potentially large wealth transfers from buyers to sellers of permits. These transfers also change the pattern of other goods traded internationally. For a buyer of permits, this annual transfer of wealth is equal to the annual quantity of permits purchased times the world market price of the permits. The size of these transfers depends directly on the initial allocation of permits between countries. The initial allocation determines not only the amount of permits traded by each country, but also whether a country is a buyer or seller of permits.

For this study, the initial allocation of permits among Annex I countries is simply the emissions targets defined by the four mitigation scenarios. Non-Annex I regions were allocated permits equal to reference case emissions. These four mitigation scenarios represent only a few of the many possible ways of setting global emissions limits and allocating emissions rights among countries to meet those limits. Each allocation implies a different pattern of wealth transfers among countries.

Each region in the SGM is assigned a period-by-period balance of payments constraint. Buyers of carbon permits must, therefore, export more of other traded goods than otherwise to pay for the purchased permits. Conversely, sellers of permits use the permit revenues to increase imports of other goods.

Sensitivity of Costs to Model Assumptions

Economic costs reported by the SGM for the United States are sensitive to many of the model inputs. These include the choice of exchange rate, the inclusion of paper permits, and the method of revenue recycling.

If purchasing power parity exchange rates were used instead of market exchange rates for the developing countries, then any given world permit price would translate into a lower carbon tax in that country's local currency. For global trading cases, this would increase the global permit price needed to meet a global emissions limit, and the SGM would report higher costs for the United States.

For Eastern Europe and the Former Soviet Union, carbon permits were allocated based on their reference case, and not on 1990 emissions. If we had allocated permits based on 1990 levels, these extra 'paper credits' would create a less-stringent Annex I target. The model would then report a lower permit price for the trading cases, and a lower cost to the United States.

In this study, we assumed that all revenues from a carbon tax would be recycled as a lump sum to consumers. Another option is to use the carbon tax revenues to offset other taxes. This has the potential to reduce overall costs, since carbon tax revenues would displace other distortionary taxes.

KEY OBSERVATIONS

Economic costs are reduced with a permit-trading program that equalizes the marginal cost of carbon between countries. The least expensive emissions reductions are taken first, regardless of where they occur. Costs shown in Figure 8 provide a good example of the importance of this 'where' flexibility.

For the four mitigation scenarios in this study, economic costs to the United States remain below 1% of GDP through at least the year 2020. This was the case even in the scenarios where the United States met its mitigation targets without international trading of carbon permits.

Each region in the SGM can be characterized by a marginal cost of carbon curve, as was shown in Figure 6. This shows the approximate carbon tax required for any given level of carbon emissions reduction. For the amount of emissions reductions needed in 2010 to return to 1990 levels, a carbon tax of $108 per metric ton of carbon is required.

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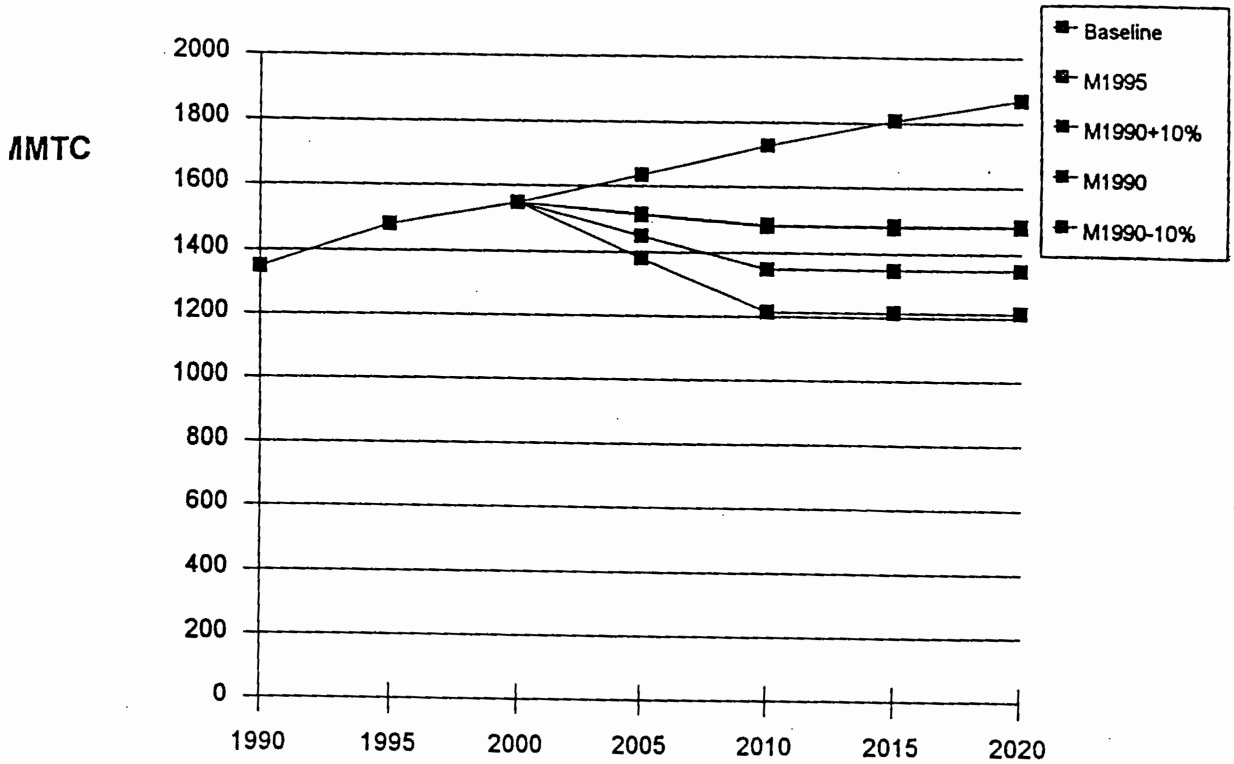
Figure 1. Carbon Dioxide Emissions Scenarios for the United States



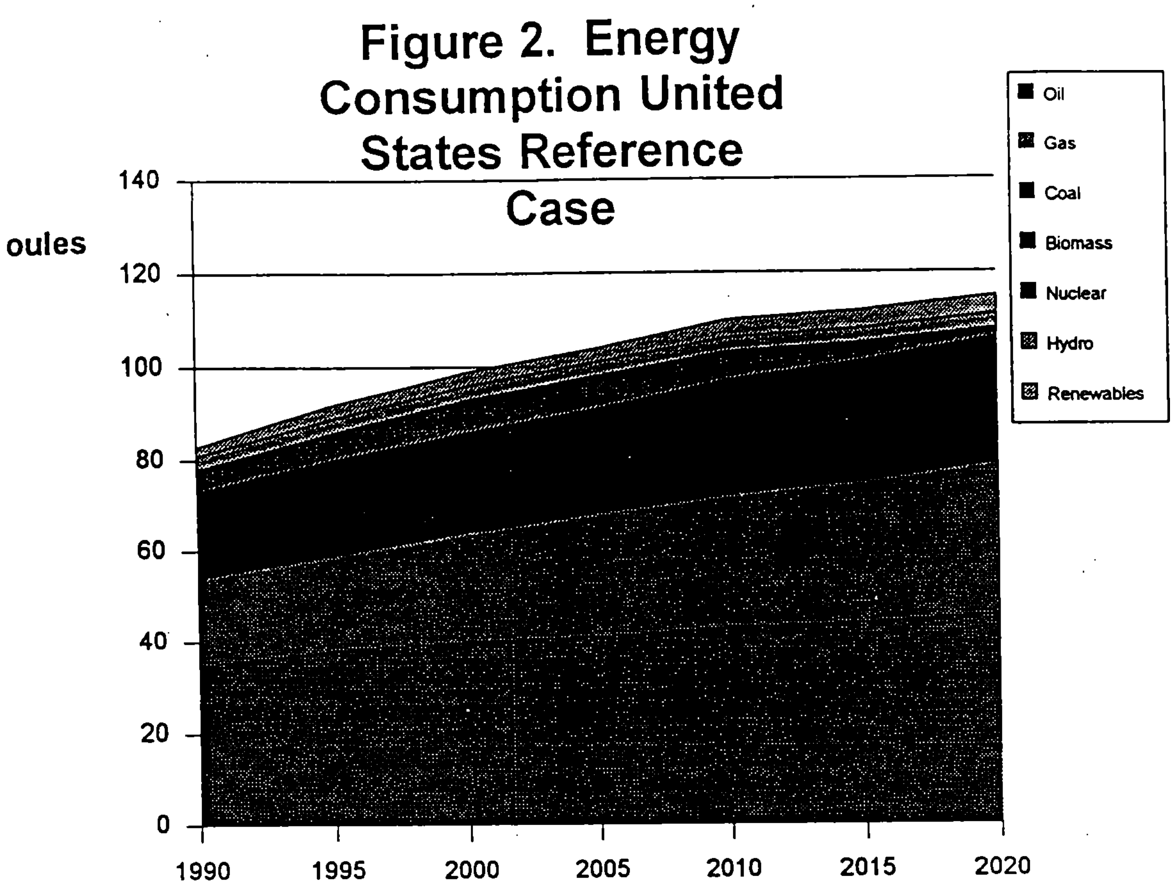


Figure 2. Energy Consumption United States Reference Case
oules
140
120
100
80
60
40
20
0
1990
1995
2000
2005
2010
2015
2020
Oil
Gas
Coal
Biomass
Nuclear
Hydro
Renewables

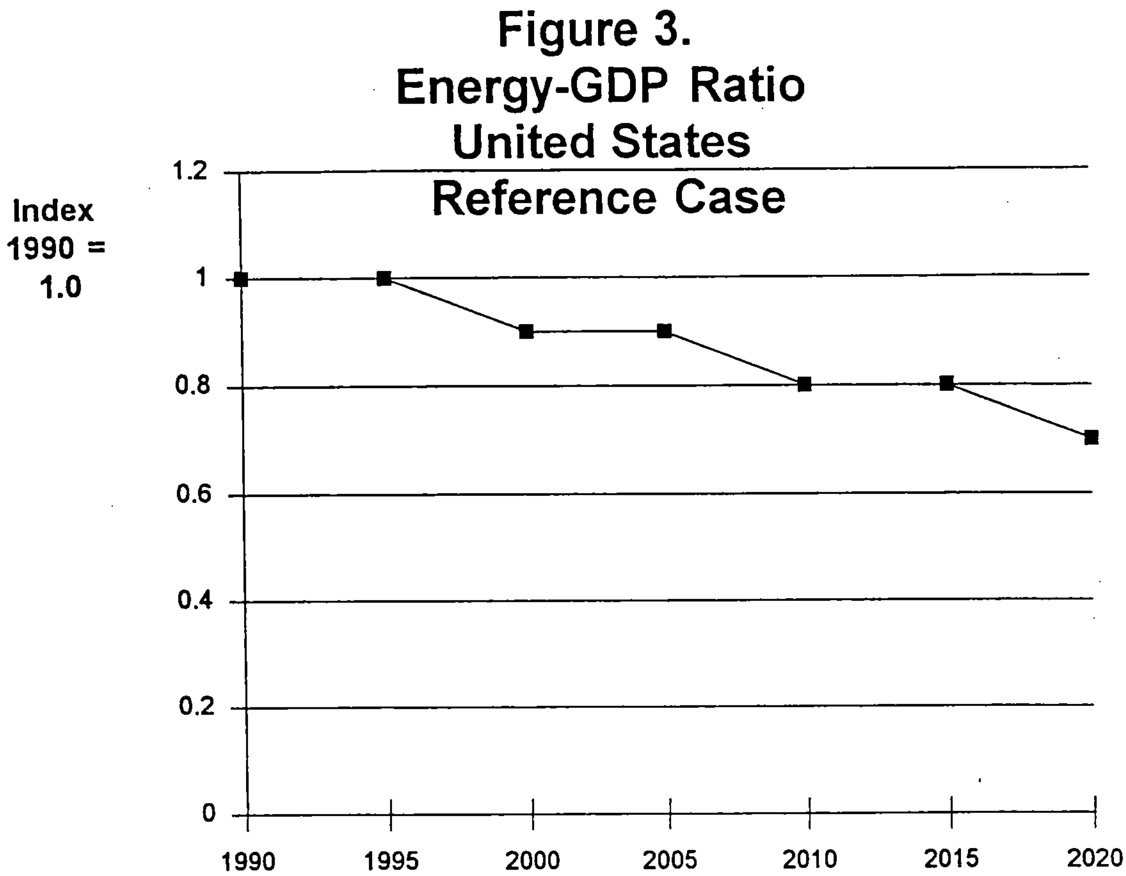
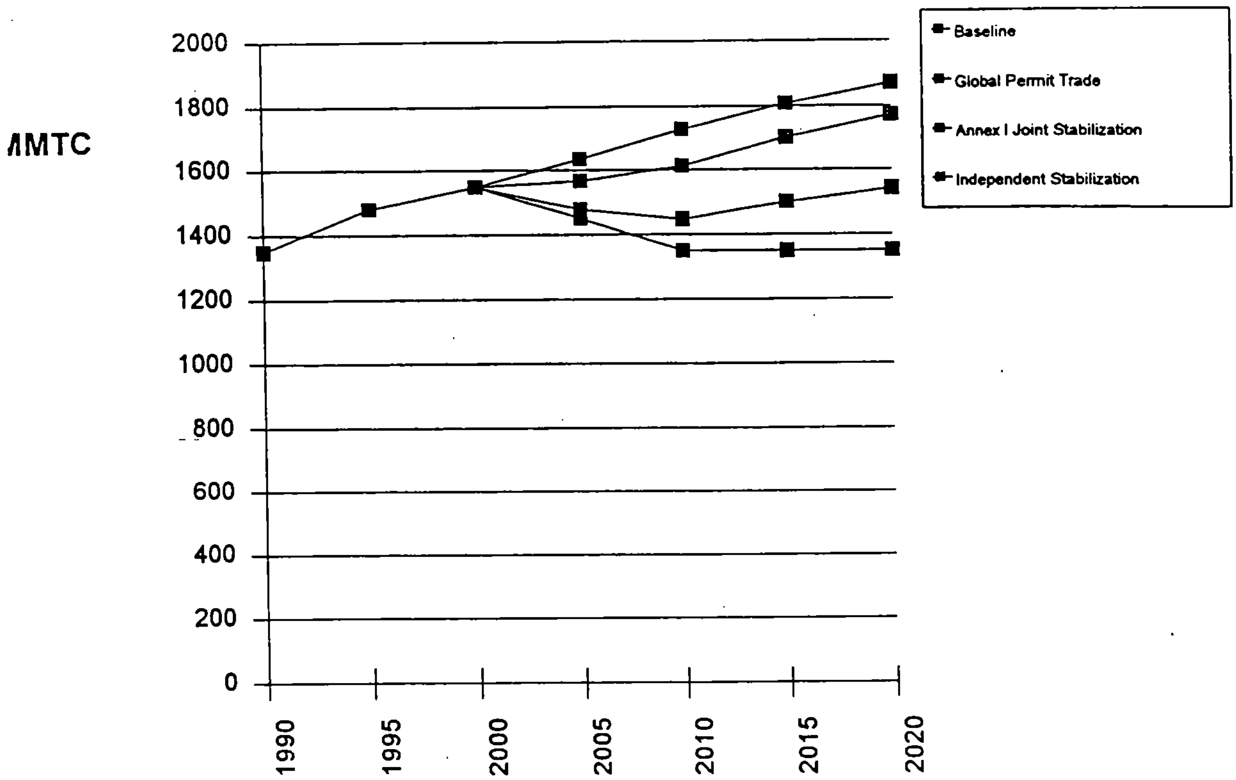


Figure 3.
Energy-GDP Ratio
United States
Reference Case
Index
1990 =
1.0
1.2
1
0.8
0.6
0.4
0.2
0
1990
1995
2000
2005
2010
2015
2020

Figure 4. United States Carbon Dioxide Emissions M1990 Cases



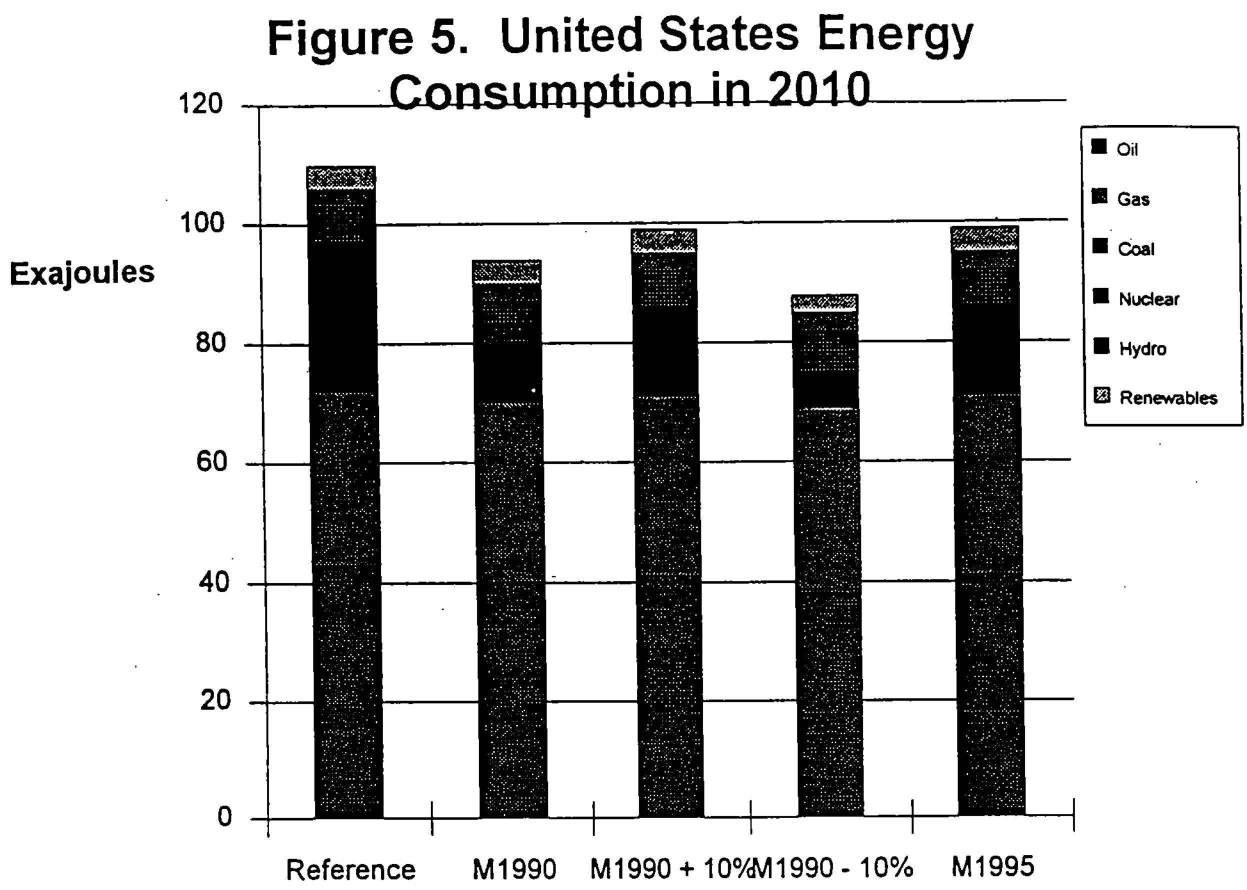


Figure 5. United States Energy Consumption in 2010
Exajoules
120
100
80
60
40
20
0
Reference
M1990
M1990 + 10%
M1990 - 10%
M1995
Oil
Gas
Coal
Nuclear
Hydro
Renewables

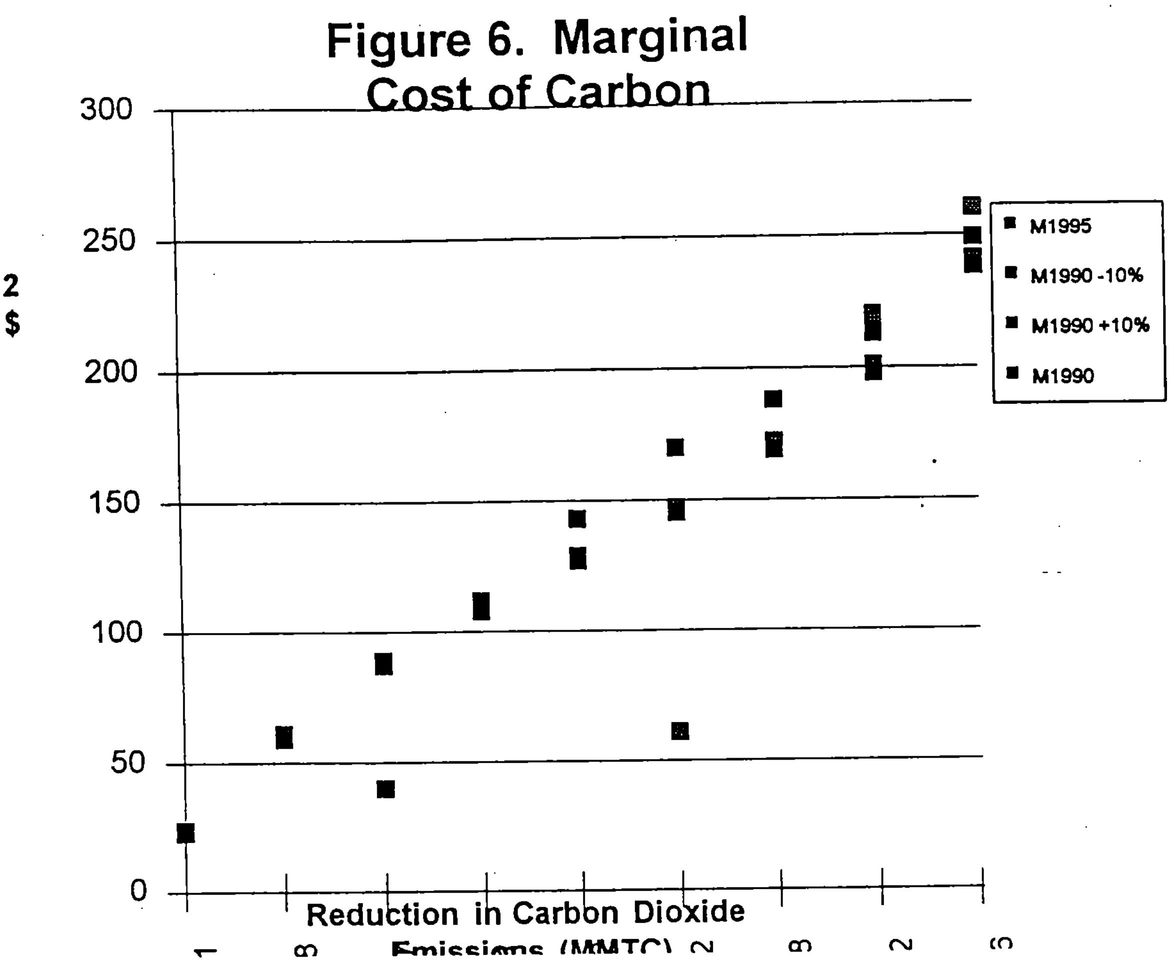


Figure 6. Marginal Cost of Carbon
300
250
200
150
100
50
0
2
$
M1995
M1990 -10%
M1990 +10%
M1990
Reduction in Carbon Dioxide Emissions (MMTC)

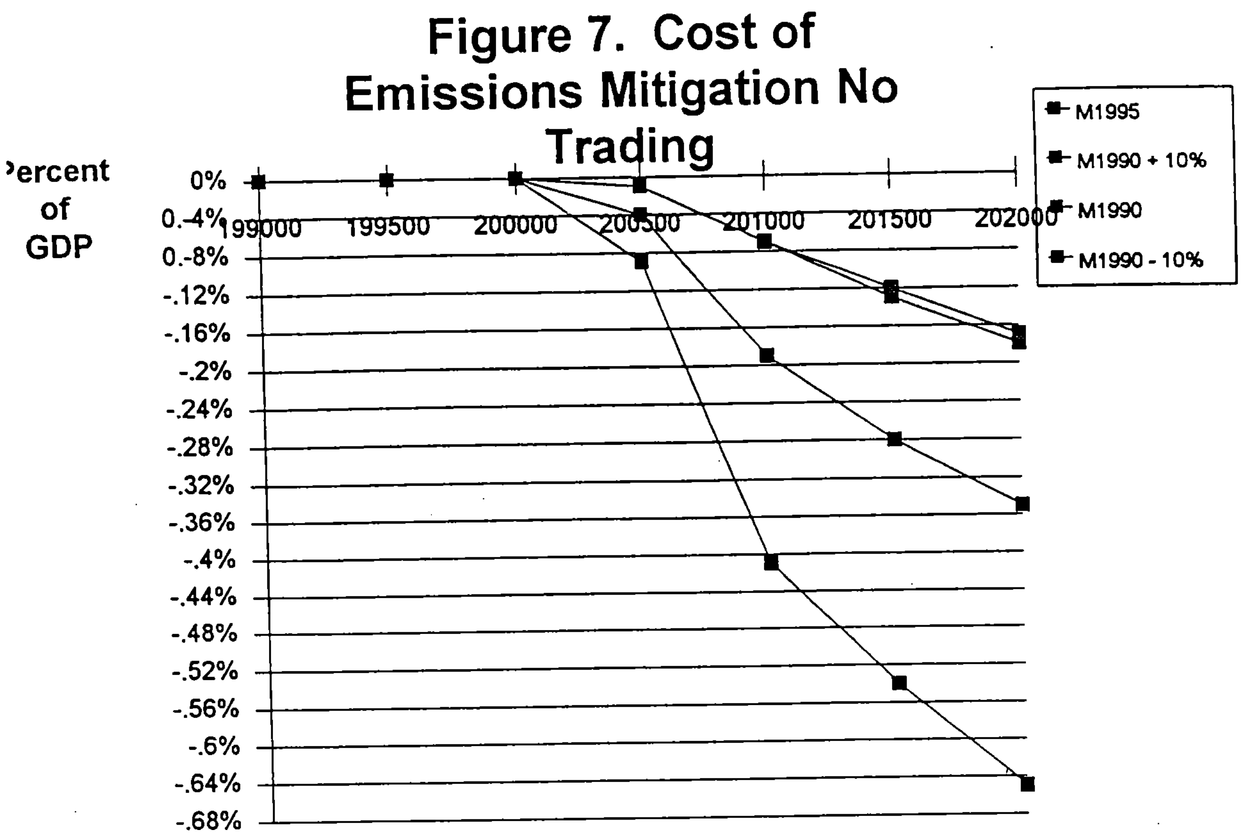


Figure 7. Cost of Emissions Mitigation No Trading
Percent of GDP
0%
0.-4%
0.-8%
-.12%
-.16%
-.2%
-.24%
-.28%
-.32%
-.36%
-.4%
-.44%
-.48%
-.52%
-.56%
-.6%
-.64%
-.68%
199000
199500
200000
200500
201000
201500
202000
M1995
M1990 + 10%
M1990
M1990 - 10%

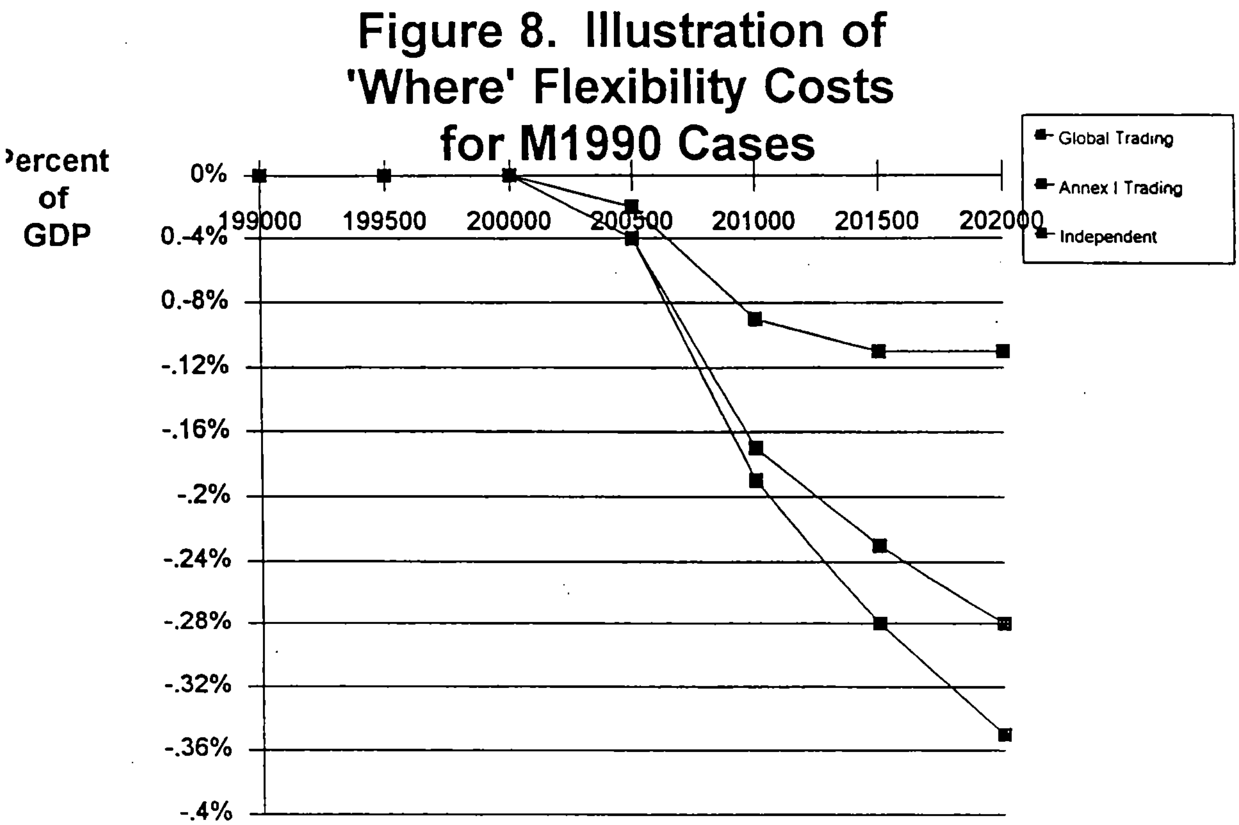


Figure 8. Illustration of
'Where' Flexibility Costs
for M1990 Cases
Percent of GDP
0%
0.-4%
0.-8%
-.12%
-.16%
-.2%
-.24%
-.28%
-.32%
-.36%
-.4%
199000
199500
200000
200500
201000
201500
202000
Global Trading
Annex I Trading
Independent

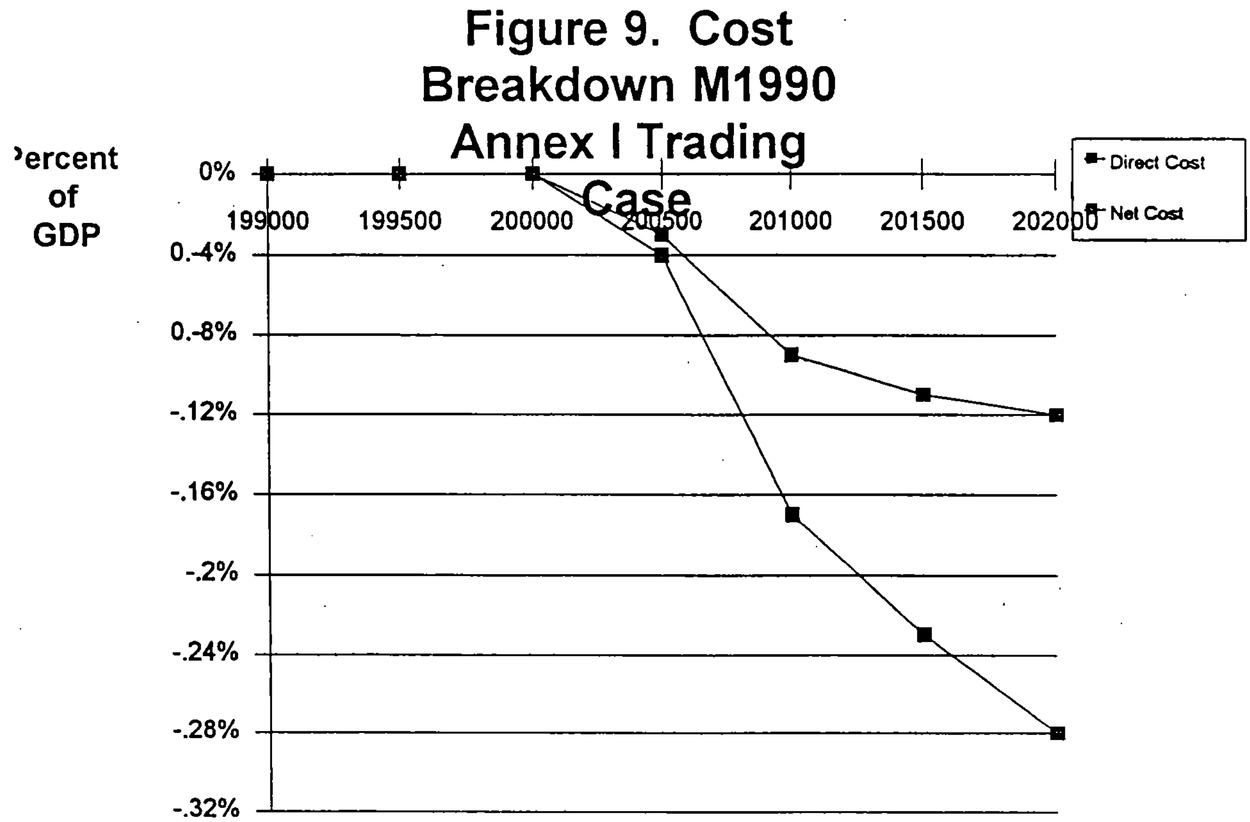


Figure 9. Cost Breakdown M1990 Annex I Trading Case
Percent of GDP
0%
0.-4%
0.-8%
-.12%
-.16%
-.2%
-.24%
-.28%
-.32%
199000
199500
200000
200500
201000
201500
202000
Direct Cost
Net Cost

Figure 10. Permit Prices under Alternative Permit Allocation Methods for EE & FSU: M1990 Annex I Trading Case

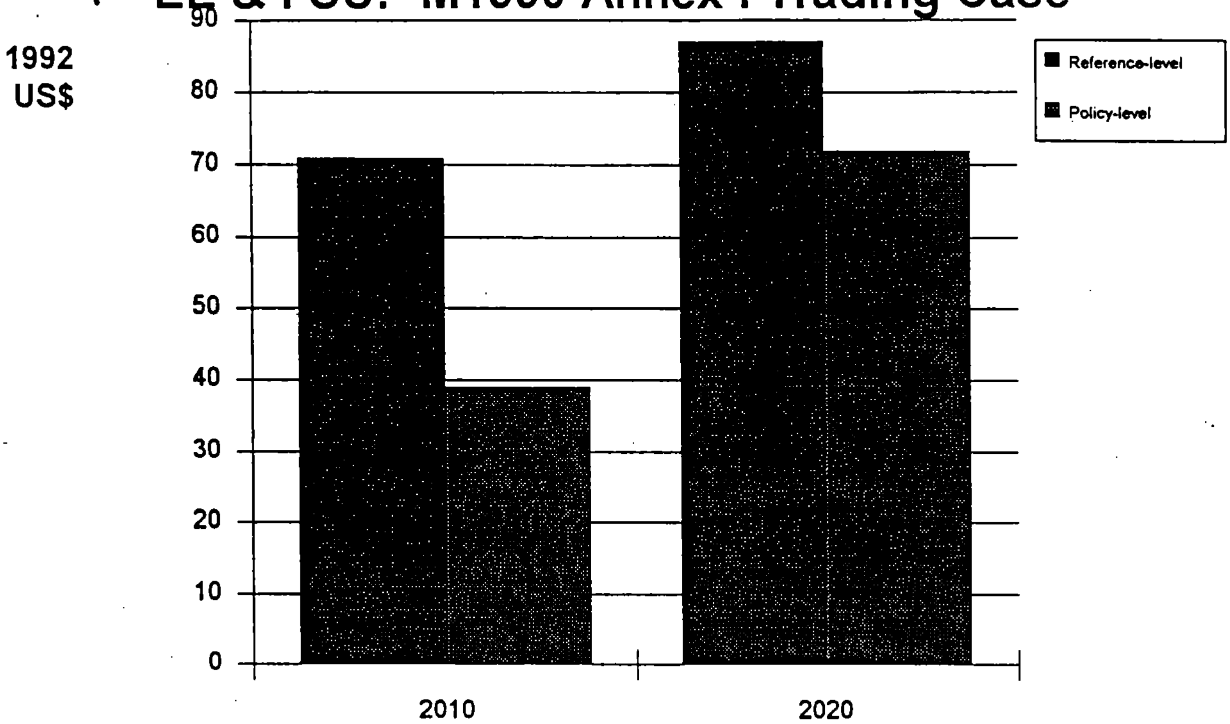
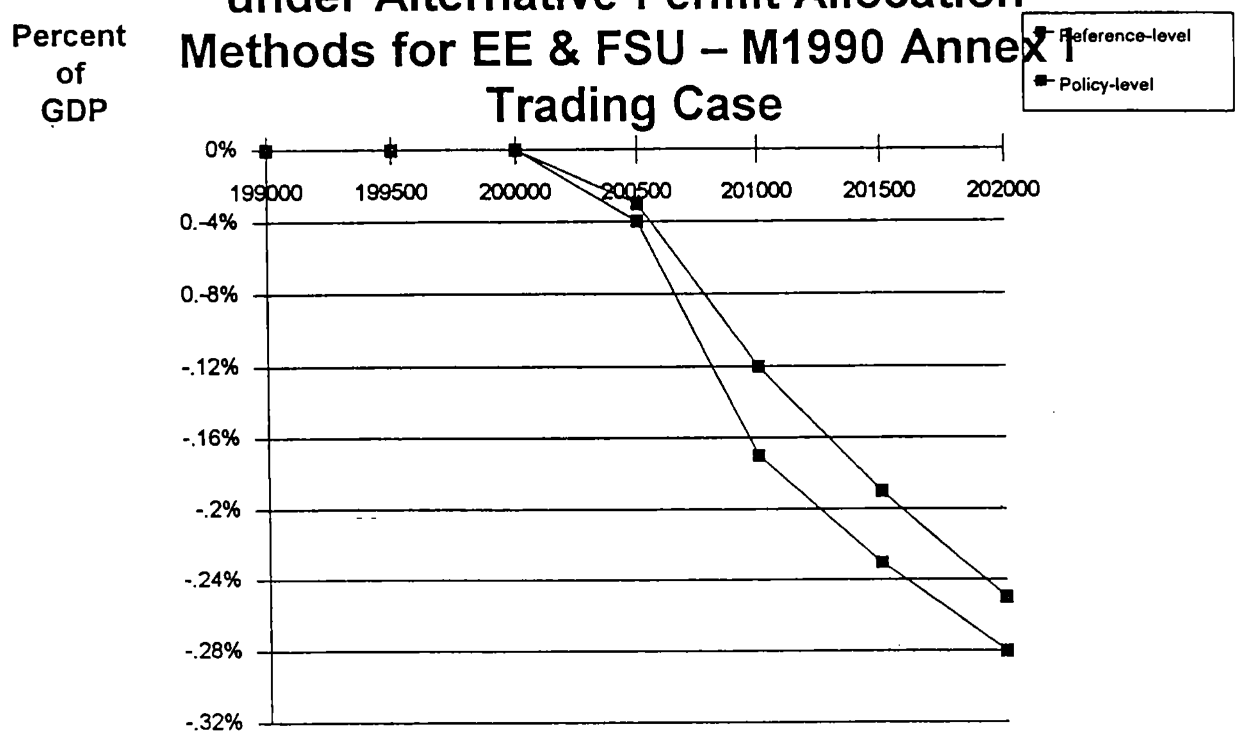


Figure 11. Cost of Emissions Mitigation under Alternative Permit Allocation Methods for EE & FSU – M1990 Annex 1 Trading Case



Ancillary Benefits

Research Briefs

RESOURCES FOR THE FUTURE

Impacts of Climate Change Mitigation on Other Environmental Problems

Mitigation policies for reducing the risks of climate change may have a variety of other effects on the environment. For example, policies to promote energy efficiency also are likely to reduce pollution associated with energy use, which can improve air quality and reduce harmful water pollution. Some effects could prove harmful, such as an increase in exposure to indoor radon from tighter buildings that may be constructed to improve energy efficiency or to avoid the effects of climate change. Similarly, wetlands could be damaged from the construction of floodwalls. Climate change may also alter baseline conditions for pollution risks -- that is, a warmer climate could enhance the formation of harmful pollutants under some conditions.

Building on recent research that has assessed pollution rates for specific industries and established the importance of regional characteristics in factoring the impact and costs of pollution, researchers at Resources for the Future (RFF) are examining this issue of co-control benefits. They are analyzing changes in the structure and regulation of the electric utility industry to provide a more comprehensive characterization of the benefits of different policies.

Several recent studies have employed dynamic computable general equilibrium models of the United States economy to estimate the compliance costs of various to reduce carbon dioxide (CO_2) emissions. An important aspect of these policies, says RFF's **Dallas Burtraw,** project coordinator, is the non-climate change benefits that may result. Preliminary research has looked at how these mitigation policies could affect emissions of pollutants other than CO_2 as well as possible economic benefits. But, says Burtraw, it has not accounted for regional profiles of emissions and their associated environmental impacts.

From WEB Page

In the project's first phase, researchers are investigating how emissions of NO_x* and sulfur dioxide (SO_2) and concentrations of related pollutants associated with different CO_2 control policies are affected by restructuring in the U.S. electric industry. They are using the regional power trading and reduced form atmospheric transport components of PREMIERE (Primary Regional Environmental Model in Electricity Restructuring), a model developed at RFF to analyze the effects of increased inter-region power trading on regional air pollution as a result of restructuring.

In the project's next phase, researchers are creating a simulation model that takes selected results from CGE models, and adds a state or regional profile for projected changes in economic activity and associated emissions. This revised model will also include a library that shows geographic and demographic changes in population that are expected over time, and a reduced form atmospheric transport model to track concentrations of various pollutants, similar to the one constructed in PREMIERE.

Finally, researchers will use this model to incorporate RFF's health benefits model and other environmental models to construct a geographic and temporal profile of co-control benefits. Uncertainty will be explicitly modeled using a Monte Carlo analysis. The model will then be used in subsequent phases to investigate a variety of climate-related policy instruments. They seek to estimate their nonclimate-related benefits and test the validity of average estimates for economic benefits that have been used in previous studies. Researchers will pay special attention to co-control benefits in an international context, and, where possible, will develop new "rules of thumb" for transferring benefit estimates to other venues.

The project is part of RFF's Climate Economics and Policy Program, which aims to increase understanding and knowledge of the complex issues that must be addressed to design appropriate domestic and international climate change policies that are reliable and efficient.

# # #

* Many discussions of nitrogen-based air pollution refer to nitric oxide (NO) and nitrogen dioxide (NO_2) together as nitrogen oxides (NO_x). NO_2 is a brownish gas which is produced when NO emitted from power plants combines with oxygen already in the atmosphere. In the presence of sunlight and volatile organic compounds, NO_2 can contribute to the formation of ground-level ozone, or smog. NO_x can transform to nitrates in the atmosphere which, as a fine particulate, has effects on human health. Of the three electricity-related pollutants most responsible for current environmental damage -- NO_x, particulates, and sulfur dioxide -- NO_x currently merit the most immediate policy attention because emissions of NO_x are neither capped by environmental regulation nor controlled as effectively as particulates with current technology.

# # #

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weathervane

FEATURE

The Kyoto Protocol: Unresolved Issues

By Raymond J. Kopp, Richard D. Morgenstern and Michael A. Toman

JANUARY 8, 1998 -- On December 10 1997, 160 nations reached an historic agreement in Kyoto, Japan on limiting emissions of carbon dioxide and other "greenhouse gases." The Kyoto Protocol calls for the industrialized nations — the so-called Annex I countries – to reduce their average national emissions over the period 2008-2012 to about five percent below 1990 levels. The U.S. pledged to reduce its emissions by seven percent below 1990, slightly less than the European Union and slightly more than Japan. The Protocol permits some industrialized nations to modestly increase their emissions and makes special provisions for the members of the former Soviet Bloc. None of the developing countries, including those with large and growing emissions such as India and China, is required to limit its emissions.

The protocol is broader than previous agreements in that it includes all the major greenhouse gases and takes into account emission changes resulting from changes in forest and land use patterns. The Protocol also contains the elements of a program for international trading of greenhouse gas emissions. Such trading would employ market incentives to help ensure that the lowest-cost opportunities for emissions reductions are pursued.

The Kyoto agreement is a significant victory for advocates who have sought to convince world leaders to address climate change. It is intended to signal to governments, businesses, and households that limits will be placed on future emissions of greenhouse gases, and that now is the time to begin developing the necessary technologies. Advocates also express the hope that acceptance by industrialized countries of binding emission limits would make developing countries more willing to take emissions-limiting actions appropriate to their own circumstances.

A protocol that is both workable in practice and capable of being ratified by the Senate must come to grips with three basic questions:

- Does it represent a sound framework for attaining long term global emission-reduction goals, and is it clear enough to serve as a sort of international contract to which parties can commit?
- How costly are the targets and timetables for greenhouse gas reduction agreed to by the U.S. and other Annex 1 countries – are they as affordable as the Administration says, or as burdensome as the fossil fuel industry has asserted?
- What measures would the U.S. deploy in order to achieve the goals laid out in the Protocol?

As we discuss in the balance of the article, the Protocol itself has significant gaps; the costs of meeting the stipulated targets are not tremendous but not trivial either; and there is a great deal still to settle with respect to the domestic policy agenda.

Unresolved Issues with the Protocol

The negotiators deferred action on several important but controversial elements to a subsequent meeting scheduled for the Buenos Aires in the fall of 1998. President Clinton has indicated that he will not send the Protocol to the U.S. Senate for ratification until more progress is made on these issues. We believe that, at a minimum, several issues must be addressed before ratification and implementation can occur:

The rules and institutions that will govern international trading of greenhouse gas emissions among Annex I countries must be better established. Article 6 of the Protocol provides for emissions trading, but only in the vaguest of terms. How the trading program is carried out greatly affects the capacity to hold down compliance costs. A program that establishes a freely functioning, largely private market in emissions permits, where private entities may execute trades with minimal bureaucratic red tape, will be the most efficient and will lead to the greatest cost savings. In contrast, a market permitting only trades by governments, or a market where private trades are hamstrung by overly restrictive rules, will sap the cost savings.

The rules and institutions governing joint implementation (the so-called Clean Development Mechanism) must be developed in detail. Under Article 12 of the Protocol, Annex I countries can jointly undertake projects with developing countries to reduce emissions in the latter countries, and count those reductions toward compliance with their own commitments, where it is possible to establish meaningful baselines against which reductions can be measured. Again, however, the Protocol does not address how such projects can be undertaken. A well supervised, but freely functioning market combined with credible certification and enforcement of reductions would yield real greenhouse gas reductions at lower cost. An overly restrictive and bureaucratic system would sap possible gains.

The criteria used to judge compliance, and any penalties for noncompliance, must be clearly articulated. The protocol contains a number of technical provisions for assessing national performance in measuring emissions and meeting emissions control objectives. These provisions build on previous efforts under the Framework Convention but are complicated by the more comprehensive nature of the new protocol. Beyond these technical questions, the fundamental issue is what actions, if any, would be taken if a country was found not to be in compliance. The emissions goals of Annex I countries are taken to be binding under international law, but the protocol itself contains no stipulations for sanctions in the event of noncompliance.

A binding agreement on the part of the major developing countries to limit their emissions at some specified point in the future must be obtained. The Framework Convention clearly states that developing countries do not bear the same obligations as developed nations for emissions control in the short term. Nevertheless, the Protocol could and should contain commitments from developing countries to limit their emissions *growth*. This can be achieved through the pursuit of "no regrets" measures that would be prudent to undertake in any case, and agreements to eventually cap emissions as countries' economic circumstances improve in exchange for assistance in adopting clean technologies. The lack of any early commitment by developing countries not only aggravates short-term concerns in the U.S. and other industrial countries about international competitiveness, but also raises the specter of developing countries becoming "locked in" to more fossil-fuel-intensive technologies.

To make longer-term objectives more credible, moderate but specific near-term goals should be set for Annex I countries and these countries should be able to use early emissions reductions to meet longer-term requirements. Other than a passing reference in Article 3 to the need for "demonstrable progress" in achieving commitments by 2005, the Protocol is silent on interim measures. Yet, without interim targets, prospects for achieving more ambitious longer-term goals become problematic, and the incentives to engage in long-term investments in new capital and technology are undercut. Incentives for cost-effective reductions before 2008 to meet long-term requirements also are limited since the Protocol makes no provision for emitters to "bank" such reductions.

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FEATURE

The Kyoto Protocol: The Realities of Implementation

By Raymond J. Kopp, Richard D. Morgenstern and Michael A. Toman

On December 10 1997, 160 nations reached a historic agreement in Kyoto, Japan on limiting emissions of carbon dioxide and other "greenhouse gases." The Kyoto Protocol calls for the industrialized nations — the so-called Annex I countries – to reduce their average national emissions over the period 2008-2012 to about five percent below 1990 levels. The U.S. pledged to reduce its emissions by seven percent below 1990, slightly less than the European Union and slightly more than Japan. The Protocol permits some industrialized nations to modestly increase their emissions and makes special provisions for the members of the former Soviet Bloc. None of the developing countries, including those with large and growing emissions such as India and China, is required to limit its emissions.

JANUARY 15, 1998 -- In the runup to Kyoto, a number of experts pointed out that both the environment and the economy might be served by following a slower path to emissions control than the Protocol stipulates, while developing the technologies for more aggressive and affordable emissions reductions later. Others disputed this view. In any event, the agreement reached in Kyoto sets the stage for discussion and for future debate in the Senate.

Some partisans have claimed that meeting the Protocol's targets ultimately will be inexpensive or even free because there is a large untapped reservoir of cheap energy-efficiency opportunities available today and new technologies will materialize in the near future. Other partisans predict economic collapse.

In our judgment, while neither extreme view is correct, there is a substantial likelihood that the proposed target and timetable will impose significant costs on the U.S. and the global economy, even after accounting for new technology stimulated by domestic policies. The limit agreed to by the U.S. implies a reduction of about one-third compared to what the U.S. Department of Energy estimates carbon dioxide emissions will be by the end of the next decade. Even with the flexibility to reduce emissions of other gases, achieving emissions reductions of such magnitudes in at most 15 years will lead to higher energy prices and thus costs that will be borne throughout the economy. These costs in turn will also give rise to serious debates about fairness. Recent public opinion polling indicates increased concern about climate change and some willingness to shoulder burdens to curb greenhouse gas emissions, but there is no compelling evidence that the public is ready to accept significant increases in energy prices or other costs. In light of these costs, it is an open question whether the Senate is willing to ratify the target and timetable stipulated in the Protocol.

A First Step Toward Implementation: Understand the Benefits and Costs

An important first step in fostering a productive debate nationally and in the Senate over the Protocol is better understanding of its benefits and costs. Advocates should dispense with the pretense that emissions reductions of the scale and speed proposed can be achieved at negligible or even negative cost, or that reductions necessarily doom the economy. To shine a brighter light on the costs and consequences of the Protocol requires an investment in better and more inclusive analysis and review of estimates, so that competing claims can be adjudicated and new ideas introduced.

Even after questions about the Protocol itself are settled, domestic policy options for achieving the targets and timetables require more thorough consideration. The U.S. deserves credit for advancing some specific measures. Still, the proposal the Administration offered in October – $5 billion in incentives for new technology – will not be enough to move the economy from where it is today to where it needs to be to meet the Kyoto goals.

Ultimately, if the U.S. is to even approach the Kyoto goals, energy prices must rise enough – especially for coal, the most carbon-rich fossil fuel – to induce enough conservation, energy efficiency, fuel switching, and the development and deployment of new technologies and energy forms. How large this price rise will have to be depends on what domestic policies are used. No agreement yet exists on this policy menu. Even if an efficient mechanism like emissions trading is used within the U.S., important questions of who gains and loses from the policy remain to be settled.

The Key to Cost-Effective Climate Policy: Market Incentives

To meet the Kyoto goals as cost-effectively as possible, the Clinton Administration should commit itself to the use of incentive-based market policies for domestic emissions control. Well-intentioned but costly proposals to mandate energy efficiency through rigid command-and-control measures must be avoided. In addition, policies aimed at encouraging the development and dissemination of low-emissions technology need careful scrutiny to avoid waste (for example, through an ill-focussed subsidy policy).

The institution of some modest interim measures to limit greenhouse gases would be important for establishing the credibility of longer-term reduction goals. A domestic emissions trading program with looser controls than are required by the Protocol is one example. Such a program would be combined with a "safety valve" that would cap the price of a tradable emissions permit at some prespecified level which would rise over time, with the government offering additional emissions permits as needed to maintain the price caps.

Such an approach is complementary to the policies the Administration already has announced and would provide valuable information about how emissions control policies work as well as their costs to the economy. It also would offer such near-term benefits as improved air quality from reduced conventional air pollutants and encouragement for the development of lower-emissions technologies. Even stronger incentives for early demonstrable progress would be provided if any early emissions reductions below an established baseline (for example, actual 1997 emissions levels) could be banked for use in meeting subsequent binding constraints.

***Raymond J. Kopp** directs RFF's Quality of the Environment Division, where **Richard D. Morgenstern** is a visiting scholar on leave from the U.S. Environmental Protection Agency. **Michael A. Toman** directs RFF's Energy and Natural Resources Division.*

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John Weyant

Description of what Energy Modeling Forum (EMF) is planning to do to assess impact of Kyoto

The Design of Post-Kyoto EMF Scenarios

An Activity of the

Target and Burden Sharing Study Group of

EMF 16: Integrated Assessment of Climate Change - Post-Kyoto Analyses

Outline

- Rationale for Post Kyoto EMF Scenarios
- Summary Description of New Scenarios
- Reporting Regions
- Variables to be Reported/Compared

During the First Part of 1998 We Will Pursue a Two-track Course of Action to the Design of Post-Kyoto EMF Scenarios

- Initially, parameterize the assumptions made about the potential for off-sets to the year 2010 carbon equivalents targets from sinks and non-carbon GHGs .
- Collect information and analysis on sinks and the non-carbon GHGs to enable the modeling teams to endogenize them in subsequent model comparison scenarios.

Three Types of Scenarios

1 Modelers Reference Scenario

2 Kyoto Implementations

- Vary Assumptions About Sinks
- Vary Assumptions About Other GHGs
- Vary Assumptions About Emissions Trading
- Vary Post-Kyoto Objectives and Commitments

3 Alternatives to Kyoto Style Scenarios

Maximum Sink Potentials

- United States: 300 MMT
- European Union/Western Europe: 150 MMT
- Japan: 0
- Canada/Australia/New Zealand: 300 MMT
- Eastern Europe/Former Soviet Union: 300 MMT
- China: 300 MMT
- India: 300 MMT
- Mexico & OPEC: 300 MMT
- Rest of World: 300 MMT

Three Sets of Sink Assumptions

Reference   1/6 Maximum Potentials in 2010 & 1/3 in 2020-2100.

Pessimistic   0 in All Years

Optimistic   2/3 Maximum Potential in 2010 & Maximum Potential in 2020-2100.

Three Sets of Assumptions About Reductions in Emissions of Other Greenhouse Gases

Reductions in other greenhouse gases covered by the protocol result in a

- –10%,
- 0%,
- or +10%

change in the carbon equivalents target for each Annex I countries specified in the protocol in 2010

Three Different Levels of International Emissions Trading

No Trading Among Countries/Regions,

Annex I Trading,

- Annex I Country/regions Allowed to Satisfy No More Than 1/3 of Its Emission Reduction Requirements With Purchased Emissions Rights.
- Sinks Increase Non-Annex I Baselines by 10% and Each Non-Annex I Country is Permitted to Sell Emissions Rights via the Clean Development Mechanism up 15% of the Amount it Would Sell Under a Full Global Emissions Trading Regime.

Full Global Trading With No Restrictions.

Two Options for the Required Emission Reduction Beyond 2010

- Freezing Commitments At The 2010 Level, Or
- Pursuing an Emissions Trajectory That Leads To Stabilization of the CO2 Concentration in the Atmosphere at 550 PPM Driven By:
  - Further Emission Reductions By Annex I Countries
  - A Graduation Clause Based On Income For The Non-Annex I Countries That Would Lead To Them Reduce Emissions As Well.

Two Cost Minimizing Scenarios

- Follow the Kyoto protocol targets through 2010 and then minimize the cost of limiting the concentration of CO_2 in the atmosphere to no more than 550 PPM
- Minimize the cost of limiting the concentration of CO_2 in the atmosphere to 550 PPM without observing the targets proposed in the Kyoto protocol.

Scenario	Offset Provided by Other GHGs	Contribution of Sinks	Emissions Trading	Post-2010 Objectives
1. Modelers Reference	Run your normal emissions reference case (using your preferred set of population, economic, and energy inputs) assuming the Kyoto protocol is never implemented.			
2. Kyoto Reference	0%	1/6 (1/3) of Max. Potentials In 2010 (2020-)	Annex I Only (See Specification Above)	Kyoto Forever
3. Minimum Offsets	-10%	0	Annex I Only (See Specification Above)	Kyoto Forever
4. Maximum Offsets	+10%	2/3 (All) of Max. Potentials in 2010 (2020-)	Annex I Only (See Specification Above)	Kyoto Forever
5. No Trading	0%	1/6 (1/3) of Max. Potentials In 2010 (2020-)	None	Kyoto Forever
6. Global Trading	0%	1/6 (1/3) of Max. Potentials In 2010 (2020-)	Full Global Trading	Kyoto Forever
7. 550 PPM CO2 Limit	0%	1/6 (1/3) of Max. Potentials In 2010 (2020-)	Annex I Only (See Specification Above)	Kyoto, Then Limit CO2 to 550 PPM
8. Kyoto Plus Min. Cost 550 PPM	0%	1/6 (1/3) of Max. Potentials In 2010 (2020-)	Annex I Only (See Specification Above)	Kyoto, Then Min. Cost of 550 PPM
9. Min. Cost 550 PPM Limit	0%	1/6 (1/3) of Max. Potentials In 2010 (2020-)	Annex I Only (See Specification Above)	Min. Cost of 550 PPM

Regions for Which Results Are to be Reported

- US
- OECD- Europe
- CANZ
- Japan
- OECD Total
- EEFSU
- non-OECD Annex 1
- Annex 1
- China
- India
- Mexico & OPEC
- ROW
- Non-Annex 1
- Non-OECD Total

Variables for Which Results Are to Be Reported

- Carbon Taxes/Emissions Rights Purchase Costs
- Emissions
- Total Primary Energy
- Total Fossil Fuel Primary Energy
- Emissions Rights Bought/Sold
- GDP
- Macroeconomic Consumption
- Discounted Present Value of Loss in Macroeconomic Consumption

o E prices