PRELIMINARY DRAFT

(Not to be Quoted)

A STRUCTURAL COMPARISON OF ENERGY-ECONOMY MODELS USED FOR GLOBAL WARMING POLICY ANALYSIS

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Energy Modeling Forum
Stanford University
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PARTIAL DRAFT

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Please Note: This is a partial draft of a forthcoming EMF 12 study document. Its topic is the policy foci of the various models participating in EMF 12. It is based upon preliminary model summaries as of early August 1991, and does not include three recently-entered models. A revised partial draft, as well as final model summaries, should be completed by the EMF 12 meeting in Boulder on August 27. The entire model comparison paper will be finished soon thereafter.

I would like to thank Ming-Fai Sit for his help in preparing several of the model summaries; John Weyant and Hill Huntington for their comments on earlier versions of this paper; and the various modelers who have patiently answered my questions about their models. Any remaining screw-ups are, of course, my responsibility.

TABLE OF CONTENTS ("*" denotes section is included in this version)

LIST OF TABLES

INTRODUCTION

The possibility of an enhancement of the greenhouse effect and concomitant atmospheric warming is a messy problem. Any attempt at rational policy analysis will have to address a multitude of social, economic, political, technological, and scientific issues. Given the myriad dimensions of the problem, it is not surprising that the extant global warming policy analysis models exhibit considerable heterogeneity.

This is certainly the case for the group of eleven[1] energy-economy models participating in the current Energy Modeling Forum study on the impacts of greenhouse gas emissions control strategies (EMF 12). Among these models there are many non-trivial differences, both in terms of policy focus and model structure. In order to effectively integrate the policy-relevant insights of the various models and to interpret the differences among model results, it is useful to first ask the following questions.

What are the foci of the different models?

Why is a particular model constructed as it is, given its purpose?

How might a particular model's structure affect the nature of its results?

This paper is intended to help answer these questions in a relatively non-technical manner. First, a brief overview of each of the eleven models' relevance to the global warming issue will be given. In the ensuing sections, several of the interesting features which distinguish the models are discussed in light of the intended foci. These are grouped under three broad headings: the modeling of energy demand, energy supply, and environmental impacts. Finally, not all the information about each model can be included in the text, thus Appendix A is a model-by-model summary of technical details in a standardized format.

FOCI OF THE INDIVIDUAL MODELS

At the time of this draft, at least partial documentation exists for the following eleven models.

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[1] At the time of this writing, three more models have begun participation in the EMF 12 study: MARKAL (Sam Morris - Brookhaven), CRTM-RD (Tom Rutherford), and MINTZER (Irving Mintzer). These models will be included in the forthcoming version of the complete paper.

Table 1: Model Listing

1. CETA	Stephen Peck, Thomas Teisberg
2. DGEM	Dale Jorgensen, Peter Wilcoxen
3. ERM	Jae Edmonds, John Reilly, Dave Barns
4. FOSSIL2	AES Corporation (Roger Naill, Sharon Belanger)
5. GEMINI	Decision Focus Inc./EPA (DFI: Dave Cohan, Adriana Diener)
6. GLOBAL 2100	Alan Manne, Rich Richels
7. GLOBAL MACRO-ENERGY	ICF Inc. (Bill Pepper)
8. GOULDER	Larry Goulder
9. GREEN	OECD (Jean-Marc Burnaiux)
10. IEA EDS	International Energy Agency (Lakis Vouyoukas)
11. T-GAS	Alliance/BU/UNH (Bob Kaufmann)

The purpose of each of the individual models will be briefly discussed in the following pages. This includes what reduction policies -- "policy levers," in the vernacular -- a model can analyze, what other major mechanisms for energy demand or carbon emissions reductions the model can include, and what types of costs and benefits it can calculate. Also stated will be the model type[2] -- general equilibrium, generalized equilibrium, optimization, or regression model -- and the time horizon[3] -- short-, medium-, or long-term.

1. CETA - Peck/Teisberg This is a long-term intertemporal nonlinear optimization model which determines the "optimal" level of energy-sector Carbon emissions under various assumptions about the economic costs due to the emissions. (Emissions of other major greenhouse gasses, as well as non energy-sector CO_2, are specified exogenously and held fixed.) In the base case, the consumer perceives no

[2] See the last section of this draft -- "Model Type" for definitions of these terms. However, understanding them is not absolutely necessary for reading the policy section.

[3] For the purposes of this comparison, short-term models are those for which the time horizon is 1995 or before (0 - 5 years), medium-term are 1996 - 2040 (6 - 50 years), and the long-term are 2041 and on (more than 50 years). For different applications, of course, this typology may not make any sense.

environmental damages from fossil fuel use; in the other cases, however, the consumer perceives the damages and adjusts his use of fossil fuel accordingly. The difference in the levels of emissions between the two types of cases is the optimal level of Carbon reductions, and is contingent on the set of assumptions about the warming-related damages. Furthermore, each level of reductions implies an optimal Carbon tax which would in theory lead to the equivalent result. This tax would equate the marginal cost of the reduction and the marginal benefit of the avoided damages.

Major components of the model are a "representative" consumer who maximizes the discounted utility of aggregate global consumption; a global energy sector and macroeconomic production function in capital, labor, and electric and non-electric energy; and an atmospheric submodel. The atmospheric component can incorporate various forms of damage functions which represent lost economic output due to the level and rate of warming. The economic cost of the tax policy is reduced global output relative to the reference case. The energy sector contains minimal supply disaggregation, although both carbon- and non carbon-based energy supply technologies are included. Costs and performance parameters are set exogenously.

2. DGEM - Jorgensen/Wilcoxen DGEM is a long-term intertemporal general equilibrium model which includes a highly-disaggregated US region and a single-sector rest-of-world. It focuses on the GNP losses resulting from either exogenously-determined Carbon taxes or Carbon emissions constraints. Since it contains a detailed accounting of taxes, DGEM can analyze different methods of recycling the tax revenues.

It has 35 production sectors, including five which are energy supply related, and 672 household types, which allows for price-induced shifts in the composition of goods produced in the economy away from those containing fossil fuels, as well as for varying impacts on households. The factor demands for industries are based on econometric estimation of translog cost functions. These incorporate both price elasticities and price-driven technical change parameters, as it is assumed that there are no autonomous, i.e., non price-related, productivity trends or sector shifts.

The model uses similar factor demand equations when modeling the energy supply industries: electric utilities, gas utilities, coal mining, crude oil and natural gas, and petroleum refining. Hence no resource stock effects are assumed. Moreover, no carbon-based synfuels and no non-carbon energy sources are included explicitly in the model.

3. ERM - Edmonds/Reilly This is a long-term intertemporal recursive generalized equilibrium model of global primary and secondary fuel markets.

Energy consumer behavior is modeled as reference end-use energy service demand paths for each of the sectors in the ten global regions. Each path is derived from baseline income (GNP) levels and population projections. A given sector's demand level can be modified by changes in that sector's total energy expenditures and income level from the assumed baseline levels. GNP is, in turn, also sensitive to total fuel costs. All of these relationships, however, hold only within a single period; there is no intertemporal linkage between GNP loss in one period and future GNP growth. Through this mechanism, the model determines GNP losses from Carbon tax scenarios, as well as the resulting emissions.

The model has a relatively rich representation of global primary and secondary fuel markets. Region- and sector-specific prices are derived from the equilibrium international prices, dependent upon the transportation costs and tax structures. Moreover, the model has a process-network representation of resource extraction, conversion, and market allocation. A wide variety of carbon and non carbon-based supply technologies are included, with fuel shares in the primary, secondary, and final demand markets based on Logit market share algorithms. Behavioral equations for primary carbon-based resource supply, however, are somewhat ad hoc, price-inelastic supply functions. Other agents in the supply network are modeled as minimizing Leontieff cost functions.

4. FOSSIL2 - AES FOSSIL2 is a medium-term intertemporal generalized equilibrium model of the US energy markets, with a heavy emphasis on end-use demand technologies and energy supply possibilities. Again, a reference demand path for end-use energy services is projected for each of the model's 16 subsectors. Each subsector acts as a single agent and minimizes the energy services lifecycle cost to meet this demand by choosing a combination of fuels and end-use or conservation technologies. The model has a very detailed accounting of the technological characteristics, utilization, and dynamics of energy-using capital stock, and can modify the projected GNP through a simple single-period feedback mechanism.

The supply side is also represented in detail, with profit maximizing agents driving energy-market equilibrium. Moreover, exhaustible resource industries are treated as intertemporal profit maximizers facing increasing marginal costs of extraction. A wide variety of conventional and unconventional supply technologies are included in the model, as well as a conservation (demand reduction possibilities) supply curve. With these characteristics, this model lends itself to analysis of how energy use is affected by different assumptions about technological characteristics and costs, financial and tax incentives, and various government "command-and-control" policies.

5. GEMINI - DFI/EPA GEMINI is a medium-term intertemporal generalized equilibrium model of the US energy markets. Again, reference price/quantity demand paths for 20 sectors' end-use energy services are exogenously specified, around which price changes cause demand shifts through lagged price elasticities. However, in GEMINI, it is assumed that end-use service demand is insensitive to macroeconomic impacts of energy sector events GEMINI is similar to FOSSIL2 in its attention to supply and demand side technologies, and thus is well suited for the same types of policy questions. What distinguishes GEMINI is its detailed treatment of emissions, concentrations, and potential and realized temperature change.

6. Global 2100 - Manne/Richels The Manne/Richels model is the conceptual forerunner to CETA, discussed earlier. It has the same principle components -- a utility maximizing consumer, an energy sector, and a macroeconomic production functions. With this model, however, parallel intertemporal optimizations are performed for five global regions, and interregional oil trade is explicitly considered. This model does not have the detailed atmospheric submodel; it only considers Carbon emissions from energy supply. It does, however, have a slightly more disaggregated set of energy supply options. Moreover, the disaggregation of this model into five global regions is crucial to analysis of some issues.

The focus of Global 2100 is GNP loss under different assumptions about emissions constraints, costs and availabilities of energy supply technologies, the ease of substitution in the aggregate between energy and other factors of production, and energy efficiency improvements distinct from price-induced substitution. Associated with each level of emissions, the model also calculates a path of equivalent Carbon taxes for each sector, if no emissions trading is allowed, or the world price of internationally traded emissions rights. In a modified form, the model has also been used in a decision analytic framework to estimate the value of information about key uncertainties.

7. Global Macro-Energy - ICF Global-Macro is a long-term generalized equilibrium model of the global energy markets. Like the other similar models, it has a highly disaggregated treatment of end-use energy services demand, with 16 subsectors under the four main sectors in each of nine global regions. A unique feature is its versatility in modeling consumer demand: either a "top-down," macro approach (which is used in EMF 12) or a "bottom-up," engineering approach can be used to drive demand.

Also, the capital stock is sector-specific and vintaged in order to calculate efficiencies and non-fuel costs of energy-using equipment. The turnover rates, however, are exogenous, and are based on assumptions about fixed useful life. This prevents study of how policies can affect end-use demand capital, except indirectly through the turnover rate. The supply side modeling is similar to the Edmonds/Reilly model, where the mix of supply technologies and fuels is based on global energy market equilibrium. Thus this model can also be used to see how various financial incentives on the supply side affect market penetration of given technologies, as well as how changing energy service costs and fuel shares affect energy demand and carbon emissions.

8. GOULDER - Goulder This long-term intertemporal general equilibrium model is designed to examine industry and economy-wide effects of Carbon limits and other energy/environmental policy issues. It considers the short-run adjustment dynamics and the approach to long-run equilibrium after a new policy is instituted. it measures welfare costs in terms of either GDP losses or "equivalent (income) variation." It has considerable detail on how taxes affect industry investment incentives and profitability. Therefore, the model can analyze how the costs of a carbon tax differ according to the manner in which the revenues are recycled into the economy. It does not address the benefits of avoided emissions or any distributional impacts on households.

The model's disaggregated production sector allows for price-induced changes in the composition of goods and services purchased away from fossil-fuel intensive commodities; however, it does not allow for any non price-driven productivity improvements (except for labor-augmenting) or sector shifts. It extends the production function approach to the modeling of energy-related industries, thus energy costs are endogenous. But the model is not technology-oriented, although depletion effects on the costs of crude oil and natural gas extraction are included. It has a carbon-based backstop (synfuel) technology with endogenous rates of capital formation after a set introduction date, but has no possibility of non carbon-based energy sources, such as nuclear.

9. GREEN - OECD This model is a medium-term, intertemporal recursive general equilibrium model with a focus on the global energy markets. Its greater regional disaggregation -- six regions plus a reduced-form rest-of-world model -- distinguishes ,it from the other two general equilibrium models, DGEM and GOULDER, which focus on the U.S.; however, the time frame is considerably shorter with this model. The policy focus of GREEN is a Carbon tax, with the income tax rates adjusted to

retain revenue neutrality. The possibility of carbon rights trading can also be modelled. Both the tax and the Carbon limit are set exogenously. The measure of costs is GNP foregone relative to the reference case. In addition, GREEN can also look at non-energy trade issues associated with a Carbon tax.

As with the other general equilibrium models, GREEN contains enough sectoral disaggregation to allow for price-induced changes away from Carbon-intensive goods. Moreover, non price-related technical progress is also assumed. The energy supply options have a non-Carbon "backstop" technology, which includes solar, hydroelectric, and nuclear. Again, a production function approach is taken, with the final energy supply mix determined by model-wide equilibrium. Both consumers and producers are assumed to be single-period optimizers, thus the only intertemporal linkage is the amount of capital stock accumulated in previous periods.

10. IEA EDS - IEA The IEA model is a medium-term econometric model which attempts to forecast energy demand by fuel, and thereby Carbon emissions, in major energy-consuming sectors in eight global regions. The forecast is based on the historical relationships between energy demand and GDP, population, relative fuel prices, and various other technical inputs. One use of this model is to determine the levels of region-specific Carbon taxes necessary to achieve given emissions targets. The model can determine GDP loss from increases in the world oil price through a simple feedback equation, but ignores the mechanism by which Carbon tax revenues are returned to the economy.

11. T-GAS - Alliance/BU/UNH T-GAS is a medium-term model comprised of econometric response functions which attempts to forecast country- and sector-specific primary and secondary fuel intensities for coal, oil, gas, electricity, motor fuels, and heat based on exogenous economic forecasts. Fourteen countries are included, with six sectors in each country. With these projections for various policy scenarios, the model can determine total energy demand by fuel, and hence Carbon emissions.

OVERVIEW OF THE DISTINGUISHING MODEL FEATURES

The features which distinguish between energy-economy-environment models -- and hence between their results -- fit nicely into three categories: the modeling of energy demand, energy supply, and environmental impacts.

Energy Demand Under this heading comes (1) model type, e.g., general equilibrium, generalized equilibrium, or optimization models, which naturally includes macroeconomic impacts on energy demand; (2) regional, sectoral, and

Model	Demand-Side			Supply-Side		
	Regional and Sectoral Demand Aggregation[1]	Explicit Tax or Financial Incentives for Efficient Technologies	Efficient End-use Technology Mandates	Major Non-Carbon Supply Technologies	Explicit Tax or Financial Incentives for Efficient Technologies	Different Assumptions about Tech. Availability or Costs
CETA	global @ 1			renew's, elec. & nonelec. C-free backstop		X
DGEM	US @ 703, ROW @ 1			none		
ERM	3 OECD @ 3, 7 non-OECD @ 1			biomass, nuclear, solar, hydroelectric	X	X
FOSSIL2	US @ 16	X	X	many nuclear, many renewables	X	X
GEMINI	US @ 18	X	X	non-ag &waste biomass, solar, wind, others	X	X
GLOBAL 2100	5 global @ 1			hydro, nuc., 4 C-free elec. and nonelec.		X
GLOBAL MACRO-ENERGY	9 global @ 16			biomass, nuclear, solar, hydroelectric	X	X
GOULDER	US @ 28			none		
GREEN	6 global @ 7, 1 ROW @ 1			C-free electric backstop		
IEA EDS	9 global @ ?			C-free electric and nonelectric		
T-GAS	14 global @ 6 (doesn't incl. all regions)			nuclear, hydroelectric		

1 Does not include energy supply sectors.

Table 2: Policy Summary Table

Model	Time Horizon/ Interval	GDP Loss	Environ. Impacts (Costs)	Optimal Emission Level	Carbon Tax	Revenue Recycling Options	Carbon Limits	Emission Rights Trading
CETA	2200 x 10	X	X	X	X		X	
DGEM	2050 x 1	X			X	X	X	
ERM	2095 x 15	X			X		X	
FOSSIL2	2030 x 1	X			X		X	
GEMINI	2030 x 5				X		X	
GL. 2100	2100 x 10	X			X		X	X
GL. MACRO	2100 x 10	X			X		X	X
GOULDER	2065 x 1	X			X	X	X	
GREEN	2020 x 5	X			X		X	X
IEA EDS	2005 x 1	X			X			
T-GAS	2010 x 1							

subsectoral aggregation of energy services demand categories; (3) energy consumers' reactions to price and income changes; (4) factors affecting energy-using capital stock dynamics; and (5) energy efficiency improvements distinct from price-induced substitution, i.e., those due to economic or technological evolution or consumption preference changes..

Energy Supply This includes (1) the representation of current and future energy supply technologies, including depletion effects on exhaustible resource supply; and (2) the manner of determining the mix of supply technologies and fuels used to meet demands.

Environmental Impacts In this last category is (1) the comprehensiveness of the greenhouse gasses considered; (2) the conversion of emissions to concentrations; (3) the modeling of how concentration changes affect potential and realized temperature changes; and (4) any economic effects of changes in the atmosphere due to anthropogenic activities.

ENERGY DEMAND MODELING

Model Type There are four basic types of economic models: intertemporal general equilibrium models, intertemporal generalized equilibrium models, intertemporal optimization models, and regression models.

General equilibrium models have explicit representation of all agents, i.e., households, firms, governmental bodies or industries, in the economy (or economies), with the total number of agents dependent on the level of regional and sectoral disaggregation. The prices for the commodities exchanged in the model -- including capital (interest rates) and labor (wage rates) -- are determined through these agents' interactions such that supply and demand are equilibrated in all commodity markets over all time.[4] Thus the level and growth rate of economic output are entirely endogenous events, given the parameters of the model, and therefore so is the level and rate of growth of energy demand.

Any model which is not a general equilibrium model, yet which does have explicit representation of market interactions, is a *partial equilibrium* model. The classic first-semester textbook example of such a model involves only supply and demand in one market, with the rest of the economy assumed constant. For our purposes this will be called a *single-market equilibrium* model

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[4] As a technical point, there are general equilibrium models which explicitly include the *transition* to equilibrium, and thus supply and demand are not always equal (this is *dis*equilibrium).

Another partial equilibrium type is a *generalized equilibrium* model, which combines characteristics of both the single-market and economy-wide equilibrium models. This type has agents in a (proper) subsection of the economy (but more than a single market) modeled explicitly, while it abstracts from the details of the rest of the economy by representing it in some "reduced-form" manner. Prices are determined in this "slice" of the economy just as they are in the economy-wide equilibrium: they balance supply and demand of the commodities which are found in the "slice." A good example of such a subsection would be the energy supply sector, where there are markets for the various forms of primary, secondary, and end-use energy forms. The demands for end-use energy services from the rest of the economy then would be exogenously-specified, and may or may not be sensitive to events in the energy sector. In this example, overall economic output is an exogenous projection; and it also may or may not be impacted by energy sector events.

Optimization models are a third distinct type. Under certain conditions, these may be equivalent to general equilibrium models; most often, however, they are in effect equivalent to partial equilibrium models. (But this is an unnecessary topical detour.) What distinguishes this type of model is that it contains some form of model-wide optimization; whil on the other hand, the equilibrium models had many optimizations, one for each of the individual agents. The classic example is maximizing or minimizing a single (linear or nonlinear) objective function over some feasible region which is determined by a system of (linear or nonlinear) constraints. A variant on this type is the parallel optimization of several objective functions, with some iterative procedure to ensure model-wide consistency.

The final type is the *regression* model. Often these are called "econometric" models; however, what exactly is meant by the "econometric" title is, in practice, seldom clear. For example, DGEM, most definitely a general equilibrium model, is also an "econometric" model. Thus for our purposes, regression models will be classified as those models which do not explicitly represent at least one market interaction. The most obvious example is when the historical relationship between some quantity, say electricity demand, and a set of "explanatory" variables is determined through statistical regression. Then, given projections of the explanatory variables, a projection of the output variable can be made. Note that market interactions are implicit in these historical patterns.

Table 3: Model Typology

<table>
<tr><td colspan="2">General Equilibrium Models</td><td colspan="3">Partial Equilibrium Models</td><td rowspan="3">Regression Models</td></tr>
<tr><td rowspan="2">Pure General Equilibrium Models</td><td colspan="2">Optimization Models</td><td rowspan="2">Generalized Equilibrium Models</td><td rowspan="2">Single-Market Models</td></tr>
<tr><td>General Equilibrium Equivalent Optimization Models</td><td>Not General Equilibrium Equivalent Optimization Models</td></tr>
</table>

discussion of individual models . . . THE END.