STRUCTURAL COMPARISON OF THE MODELS IN EMF 12

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This paper analyses the structures of the energy and economic models represented in the recently completed Energy Modeling Forum (EMF) study, EMF 12: Economic Impacts of Policies to Reduce Energy-Sector Carbon Dioxide Emissions. *The 14 models in the study are heterogeneous, which has a number of advantages. Chief among these is the greater number of insights obtainable by comparing the models' results in and across global warming policy scenarios. To fully appreciate the results, however, it is necessary to understand how a model's structure affects its output. The disadvantage of a diverse set of models is that it complicates structure comparison, and thereby the interpretation of results. The relevant model characteristics fall into three broad areas of comparison. The first is the model type, including market representation. Despite the many differences among the models, five distinct classes of market representations are seen within which models have great similarity. This simplifies understanding the remaining areas of comparison: energy demand and supply modelling. The foci here are the representation of capital stock dynamics and market penetration of carbon free energy sources respectively.*

Keywords: Energy models; Model comparisons; CO_2 emissions

During every Energy Modeling Forum (EMF) study the structures of the energy and economic models represented in the study are compared in order to better interpret their results. This effort has been particularly important due to the heterogeneity of the 14 models in the recently completed study, *EMF 12: Economic Impacts of Policies to Reduce Energy-Sector Carbon Dioxide Emissions*. The following examples of structural differences manifest this diversity:

- One model has 672 household types for the USA alone; another has one representative consumer for the entire planet.
- One model contains explicit representation of 30 non-energy sectors in the US economy which interact to determine prices and output; others implement energy-sector effects on the rest of the economy with several aggregate feedback equations.
- Some models have agents with perfect foresight about future prices; others have agents who only consider current prices when making current decisions.
- One contains approximately 100 distinct energy supply technologies available in the USA; another has five supply technologies, none of which is explicitly non-carbon.
- Some models allow the stock of capital, eg buildings, vehicles, equipment, to be perfectly malleable and costlessly mobile among economic sectors, with the level adjusting to the long-run optimum in every period; others include explicit or implicit rigidities encountered or costs incurred when changing the level of capital.
- Some have detailed modelling of international trade in non-energy goods; others allow no international trade or trade only in crude oil.
- Some are relatively short-term (2010) models based on statistical estimation of fuel demands; others are very long term (2100) models containing parameters judiciously chosen by the modeller (albeit with reference to the econometric estimates).

This variety has a number of advantages, chief among which is the greater number of insights obtainable by comparing the models' results in and across various global warming policy scenarios. To fully appreciate the results, however, it is necessary to understand how a model's structure affects its output. The disadvantage of a diverse set of models is that it complicates structure comparison, and thereby interpretation of results. The 14 energy and

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Table 1. The core models of EMF 12.*

CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck, Thomas Teisberg
CRTM (Carbon Rights Trade Model)	Thomas Rutherford
DGEM (Jorgenson–Wilcoxen) (Dynamic General Equilibrium Model)	Dale Jorgenson, Peter Wilcoxen
EDS (IEA Energy Demand System)	Lakis Vouyoukis, Niko Kouvaritakis (IEA)
ERM (Edmonds–Reilly Model)	Jae Edmonds, David Barns
FOSSIL2	Sharon Belanger, Roger Naill (AES)
GEMINI	Dave Cohan (DFI), Joel Scheraga (EPA)
GLOBAL 2100	Alan Manne, Rich Richels
GLOBAL MACRO-ENERGY	Bill Pepper (ICF)
GOULDER	Larry Goulder
GREEN (GeneRal Equilibrium ENvironmental)	John Martin, Jean-Marc Burniaux (OECD)
MARKAL (MARKet ALlocation model)	Samuel Morris (BNL)
MWC (Model of Warming Commitment)	Irving Mintzer
T-GAS (Trace Gas Accounting System)	Bob Kaufmann

* AES Corporation, *An Overview of the Fossil2 Model*, Prepared for the US Department of Energy Office of Policy and Evaluation, Arlington, VA, 1990. Ronald D. Beaver, *Technical Summaries of EMF 12 Models*, Energy Modeling Forum, Stanford University, Stanford, CA, 1992. Ronald D. Beaver and Hillard G. Huntington, 'A comparison of aggregate energy demand models for global warming policy analyses', *Energy Policy*, Vol 20, No 6, 1992, pp 568–574. J.M. Burniaux, J.P. Martin, G. Nicoletti and J. Oliveira-Martins, *Green – A Multi-Region Dynamic General Equilibrium Model for Quantifying the Costs of Curbing CO_2 Emissions: A Technical Manual*, OECD Department of Economics and Statistics Working Paper No. 104, Paris, 1991. Decision Focus Inc. *Gemini: An Energy-Environmental GEMS Model*, Report Number C2023001.01, Los Altos, CA, 1990. Energy Modeling Forum, *Aggregate Energy Elasticity*, EMF Report 4, Stanford University, Stanford, CA, 1980, (reprinted in *Energy Journal*, April 1981). Energy Modeling Forum, *Economic Impacts of Reducing Energy-sector Carbon Emissions*, MIT Press, Cambridge, MA, forthcoming. J. Edmonds and D.W. Barns, *Estimating the Marginal Cost of Reducing Global Fossil Fuel CO_2 Emissions*, PNL-SA-18361, Pacific Northwest Laboratory, Washington, DC, 1990. J.A. Edmonds and D.W. Barns. *Use of the Edmonds–Reilly Model to Model Energy Sector Impacts of Greenhouse Gas Emissions Control Strategies*, Washington DC, Pacific Northwest Laboratory, Prepared for the US Department of Energy, Draft, 1991. J. Edmonds and J. Reilly, *Global Energy: Assessing the Future*, Oxford University Press, New York, 1985. L.H. Goulder, *Effects of Carbon Taxes in an Economy with Prior Tax Distortions*, Working Paper, Stanford University, Stanford, CA, 1991. H.G. Huntington, J.P. Weyant and J.L. Sweeney, 'Modeling for insights, not numbers: the experiences of the Energy Modeling Forum', *Omega: The International Journal of Management Science*, Vol 1, No 5, 1980, pp. 449–462. ICF Incorporated, *Global Macro-Energy Model*, Summary, Fairfax, VA, 1988. D.W. Jorgenson and P.J. Wilcoxen, 'Environmental regulation and US economic growth', MIT Center for Energy Policy Research, Cambridge, MA, from MIT *Workshop on Energy and Environmental Modeling and Policy Analysis*, 31 July–1 August 1989. D.W. Jorgensen and P.J. Wilcoxen, *Global Change, Energy Prices, and US Economic Growth*, Harvard University, Cambridge, MA. Prepared for the Energy Pricing Hearing, US Department of Energy, 1990. A.S. Manne and R.G. Richels, 'Global CO_2 emission reductions – the impacts of rising energy costs', *The Energy Journal*, Vol 12, No 1, 1991, pp 87–107. S. Peck and T. Teisberg, *CETA: A Model for Carbon Emissions Trajectory Assessment*, draft, Electric Power Research Institute, Palo Alto, CA, 1991. S. Piccott, T. Lynch, J. Layman, R. Kaufmann, C. Cleveland and B. Moore, *Development of a Trace Gas Accounting System (T-Gas) for 14 Countries*, Draft, Alliance Technologies Corporation, 1990.

economic models participating in the core set of EMF 12 scenario are listed in Table 1.

Model structure comparison: what to look for in the EMF 12 models

In EMF 12 the fundamental issue is the economic impact of policies designed to achieve a reduced level of energy-sector carbon emissions. It is implicitly assumed that the costs of these policies can be looked at separately from any environmental costs or benefits due to the constraints on carbon emissions. Although the environmental impacts may, for instance, displace investment in productive capital, thereby affecting economic growth and consequently emissions growth, this assumption can be justified by reasonable arguments.[1] In addition, EMF 12 need not have analysed solely energy-sector carbon emissions. However, CO_2 is the most significant single anthropogenic greenhouse gas and its main source, fossil fuel combustion, is relatively easy to trace.[2]

The EMF 12 model comparison concentrates, therefore, on the mechanisms which are most relevant to determining a model's reported economic costs due to carbon emissions limits. The measure of this economic cost is taken to be reduced GDP (or national income) relative to a no policy scenario. Therefore, the primary effect of interest is the policy's impact on the level of goods and services produced in the economy. This is intimately related

Table 2. Model types and distinguishing characteristics.

Market representation	Distinguishing features	Models	Time horizon	Data
Disaggregated economic equilibrium	Market equilibrium for all goods: capital, labour, energy forms, intermediate and final goods and services Consumers choose labour and investment GDP determined within the model Some international trade, and explicit government sector Little detail in energy sector	CRTM DGEM GOULDER GREEN	2100 2050 2030 2050	Parametric Econometric Parametric Parametric
Aggregate economic equilibrium	Market equilibria for capital, labour, electric and non-electric energy Consumer determines labour and investment GDP produced from aggregate production function with capital, labour, electric, and non-electric inputs Moderate detail in energy sector	CETA GLOBAL 2100	2100 2100	Parametric Parametric
Energy-sector equilibrium	Equilibrium in energy sector's markets: primary fossil, renewables, secondary, electric etc No markets for non-energy goods Price and/or GDP effects on reference service demands through consumer's cost minimization and/or aggregate feedback equations Great technology detail or multiple global regions	GEMINI FOSSIL2 GLOBAL MACRO ERN MWC EDS	2030 2030 2100 2095 2095 2005	Parametric Parametric Parametric Parametric Parametric Econometric
Energy-sector optimization	Model-wide objective function: minimize total US energy sector cost of meeting given energy service demands Energy-sector market equilibrium implicit in optimal solution, but no explicit prices No economic effects outside energy sector, no effects of higher cost of energy on service demand, energy use reduced only through introduction of efficient technologies Extreme supply and demand technical detail	MARKAL	2025	Parametric
Energy-sector regression	Exogenous inputs: prices, GDP, population Energy intensity by sector and global region determined from regressions and inputs Demands for converted fuels derived from calculated secondary fuel demands and conversion coefficients; some user control over electric-sector parameters to reflect changing mix of technologies over time	T-GAS	2010	Econometric

to the relative ease of price induced substitution away from energy containing goods, energy in general and relatively high carbon energy in particular; and the rate of change of energy intensity of production and consumption that is independent of relative price changes.^{3}

The model characteristics which affect these determinants fall into three broad areas of comparison. The first is the general model type, which includes a model's market representation, time horizon and data sources. These distinctions highlight the policy questions a model is best suited to answer, in addition to providing insight into its results. Moreover, despite the many differences among the models, five distinct classes of market representations can be distinguished within which models actually have great similarity. This simplifies the analysis in the remaining areas of comparison: energy demand and supply modelling. The foci here are the representation of energy using capital stock dynamics and of the market penetration of carbon free energy sources respectively.

Model type: focus and policy relevance

The first of the three dimensions of structural comparison is the model type, the most important feature of which is the model's market representation. The broadest distinction that can be made with respect to this feature is whether the model is an energy–economy or energy model.

The energy–economy models tend to treat the energy sector in a more aggregate fashion, and have no explicit energy demand technologies but rather a homogeneous capital good which could be a tractor, skyscraper or water heater. These models are then able to contain more detail on markets and/or agents in the rest of the economy or economies, and to project the prices which equate supply and demand over time in the various markets for energy, other factors of production eg capital, labour and materials, and consumption goods and services eg consumer durables and financial services.

Energy models, on the other hand, tend to focus on the various markets for energy forms (fossil fuels, renewables, electric power and refined fuels), on agents in those markets, and on specific energy conversion and/or end-use technologies. The rest of the economy is treated in some aggregate fashion.

For this paper's purposes there are two classes of energy–economy models: disaggregative and aggregate economic equilibrium models.[4] The distinction is the level of disaggregation of the non-energy sectors. There are also three classes of energy models: energy-sector equilibrium,[5] optimization, and regression models. The distinction here is the manner in which energy-sector prices are modelled. The salient characteristics of each class are summarized in Table 2, along with a listing of the models included in each.[6]

Disaggregate economic equilibrium models

Disaggregate economic equilibrium models represent domestic markets for various energy forms, labour and capital, as well as for intermediate materials and other goods and services. All four models in this class have some form of international trade in a variety of commodities, including crude oil.

These models represent the agents in the model – households, producers and governments – as reacting to prices in such a way that a price is found which equilibrates supply and demand in each market over time. Because the production, investment and consumption decisions of the agents in the economy are determined within the model, the rate of growth of aggregate economic output (GDP) in each region is an entirely endogenous event, given the model's technology and preference parameters and resource and policy constraints. Sectoral disaggregation also allows a look at the impacts outside the energy sector, eg in heavy manufacturing, due to carbon constraints. Moreover, international trade in non-energy goods is another avenue for adjustment to increases in the price of energy or fossil energy, and has great policy relevance. Finally, because these models also include a governmental sector and tax structures throughout the economy, they can be used to analyse the effect of various means of recycling the revenues generated by carbon taxes or carbon rights auctions. The effects of these aspects are discussed in detail in a later section.

Aggregate economic equilibrium models

The aggregate economic equilibrium models do not model any non-energy sectors other than the primary factor markets (capital and labour). They also have markets for non-electric and electric energy, in which a variety of energy technologies and fuels compete for market share. GLOBAL 2100 has representative consumers in five global regions, with international trade in crude oil only. CETA has a single representative global consumer, so international trade in all four factors of production is implicit.

Each model's agents interact so that supply and demand is balanced in each domestic and international market over time, with gross domestic output in each region modelled by an economy-wide production function in the four primary commodities. The consumers choose their investment and consumption levels to maximize the value of their consumption streams over time; therefore the rate of economic growth is again determined entirely within the model given the resource and policy constraints and technology and preference parameters. These models have a richer representation of energy supply technologies, moreover, and so are able to study how a policy's cost is affected by different assumptions about the costs and availabilities of efficient and carbon free energy supply technologies. Finally, the models have a transparent representation of the rate of aggregate energy-efficiency improvement unrelated to energy price increases, so the effect of this uncertainty on a policy's costs can easily be assessed.

Energy-sector equilibrium models

The energy-sector equilibrium models are conceptually similar to the economic equilibrium models; however, they only represent the energy sector ie the group of markets for primary fossil fuels, renewables, refined fuels, and electricity. Energy prices adjust to balance supply and demand in both domestic and import markets for the various primary, secondary, and end-use energy forms, resulting in equilibrum in each market.

None of the models contains non-energy markets eg for capital, labour or materials; therefore some form of reference projection of the sources of energy demand is necessary and is typically based on other economic and demographic forecasts. The only agents that are explicitly modelled, if any, are those that make energy production, conversion and consumption decisions. Price and/or GDP changes relative to the reference assumptions may alter energy demand through explicit reactions of end-use consumers to relative price changes and/or through aggregate energy–GDP feedback equations. These are discussed later.

The omission of markets in the rest of the economy allows a more detailed treatment of the energy markets. GEMINI and FOSSIL2 take advantage of this by modelling many energy supply and demand technologies in the USA, with international trade in some energy forms. GLOBAL MACROENERGY, EDS and ERM, however, model energy supply sectors in various world regions and have detailed representations of international trade in fuels, but do not model end-use demand technology choice.

These models are able to look in depth at the effects on fuel and technology market shares under a variety of different assumptions about technology availabilities and policies. GEMINI and FOSSIL2 can also look at how tax, subsidy and/or command and control policies speed the introduction of more energy-efficient demand technologies, e.g. advanced water heaters, and carbon free energy sources.

Energy-sector optimization model

The energy-sector optimization model, MARKAL, is similar to the US energy-sector equilibrium models. It focuses solely on the energy sector and has an extensive array of energy demand and supply technologies and fuel forms competing for shares of primary energy, conversion and end-use demands. In this model, however, the equilibrium market shares for the various energy forms and technologies are determined not by individual agents reacting to prices until an equilibrium is reached, but by the model-wide minimization of the present value cost of meeting the various energy service demands specified for the model.

Since MARKAL contains great technology detail, it, too, can be used to look at the supply and demand oriented policies intended to reduce energy consumption and relative fossil fuel use. It cannot, however, model the effects of GDP loss.

Energy-sector regression model

The energy-sector regression model, T-GAS, uses economic and demographic projections from other sources to determine the energy intensity of output (average energy use per unit output) in various sectors of 14 global regions, based on the historical relationship between a set of explanatory variables, eg energy prices, economic output and population, and the sectoral energy intensities.

Other aspects: time horizon and data sources

Two other model aspects which define a model type are the time horizon and the source of data for the model. These characteristics are also summarized for each model in Table 2. The time horizons are typically long, given the nature of the global warming issue. The longer horizon models, which extend to around the year 2100, include CRTM, CETA, GLOBAL 2100, ERM, GLOBAL MACRO-ENERGY, and MWC. The relatively medium-term models have horizons which range from 2025 to 2050. They include DGEM, GOULDER, GREEN, FOSSIL2, GEMINI and MARKAL. The short-term models are T-GAS and EDS, which extend to 2010 and 2005 respectively.

The data sources distinguish a model as parametrized or econometric. Econometric models are derived mostly or entirely from statistical analysis of historical data; T-GAS and EDS include some energy supply and conversion parameters. The parametrized models have data which are derived partly from the modeller's reading of the relevant econometric literature and other historical information, and partly from his or her judgment about the future. Although uncertainty about model input data increases with distance into the future with both judgmental parameters and econometric estimates, the econometric models typically have shorter time horizons since the assumption that the historical relationships underlying their estimation remain valid becomes increasingly untenable.

The short- to medium-term models are concerned primarily with the transition to a carbon constrained world ie what technologies are important, what early adjustment rigidities are encountered etc. The longer-term models focus on the implications once the adjustment has occurred ie what technologies will replace fossil fuels on a large scale, what their costs will be and how that will affect GDP. The two short-term econometric models can capture the adjustment difficulties, for example, the slowness of the capital stock to adjust to suddenly higher relative energy prices, in their regression equations, and are thus helpful in studying the very near-term consequences of carbon limits.

Energy demand: the effects of capital stock rigidities

Energy itself is of little use; the demand for energy is derived from the demand for energy services during the production of intermediate and final goods and services eg steel, airline travel or plastic milk cartons, and in the direct satisfaction of end-use needs for energy eg space or water heating and lighting.

As the price of energy rises relative to other productive inputs, and as the price of high carbon energy rises relative to low or no carbon energy, consumers of energy shift away from high carbon energy, away from energy towards capital and labour, and away from high energy content goods and services. This transition is constrained, however, by the immutable fact that energy must be converted into an energy service by some form of capital good, and these capital goods eg machinery, automobiles or water heaters, cannot be thrown away overnight and replaced with new ones that use energy in a more economical manner. In other words, capital is rigid. Any discussion of changes in energy demand due to relative price movements, therefore, must take place in the context of capital stock dynamics. The following simple model will illustrate this connection.

The macroeconomic effects of a high carbon tax: a simple model

Imagine an economy subjected to the immediate introduction of a very high carbon tax. Further imagine that this economy produced aggregate output (denoted Y and measured in, say, dollars) using capital, labour, and fossil and renewable energy (FE and RE, respectively) as its primary inputs. Taking the standard definition of gross domestic product (GDP) as payments to capital and labour, GDP is aggregate output less expenditures on energy:

$$GDP = Y - X_{FE} - X_{RE}$$

Supposing for simplicity that the economy does not trade with any others, GDP is identically equal to investment (I) and consumption by households on energy services and other goods and services (C_E and C_O respectively):

$$GDP = Y - X_{FE} - X_{RE} = I + C_E + C_O$$

The stock of capital in the productive sector of the economy is dominated by the old vintages ie those put in place before the carbon tax increased the dollars paid for a unit of fossil energy or for goods and services produced using relatively large amounts of fossil energy, like steel. With the sudden price increase, therefore, there is little freedom in the short term to substitute away from fossil energy or from fossil energy intensive goods. This has the primary effect of increasing X_{FE} relative to Y, and thereby lowering GDP.

Moreover, the stock of energy end-use capital in households (eg water heaters and furnaces) is also dominated by the older vintages, and although demand for energy services can be decreased (thermostats set lower, for instance), there is again little freedom to move away from energy use in the short term. Hence C_E increases as the carbon tax increases the price of electricity, gasoline and other secondary energy forms.

Rearranging our equation from above as

$$GDP - C_E = I + C_O$$

we see that the reduction in GDP and increase in expenditures on household energy services means that investment and consumption of non-energy goods and services must decrease. (It is an empirical observation that *both* typically decrease under normal circumstances.) The reduced consumption of non-energy goods then puts further downward pressure on gross output, and after the economy has stopped adjusting to the carbon tax the effect is reduced GDP, investment and consumption relative to the no constraint case. The reduced consumption is the cause of the current period's welfare loss due to the carbon tax; and the reduced investment lowers the stock of productive capital in the economy below the level that would otherwise have obtained.

This also lowers the ability of the economy to produce output (income) in future periods, consequently causing future welfare losses as well. However, the reduced future demand for goods and services also reduces the need for future energy services and thereby carbon emissions. This decreases the amount by which future emissions need to be reduced, and thus decreases the cost of doing so. Whether the net effect on welfare of the reduced investment is positive or negative in this circumstance is difficult to determine in general.

What is AEEI?

Energy demand can be affected even without relative price changes through a mechanism dubbed autonomous energy efficiency improvement, or AEEI. The first component of this effect, technical change, is largely tied to capital stock dynamics as well: as old, less energy-efficient capital is retired and replaced by new more efficient capital, and the aggregate efficiency of energy use is increased. This occurs to some extent even without increases in relative energy prices. A second mechanism is known as sector (or product) shift. For example, as an economy matures there is a movement away from energy intensive heavy manufacturing towards less energy intensive service and information industries. The result is less energy use per unit of GDP; therefore energy demand can grow at a slower rate than GDP even with constant relative prices.

In the case where AEEI lowers the rate of growth of carbon emissions over time, and therefore decreases the amount by which emissions need to be constrained, the macroeconomic impact of a given constraint will also be lower.

Regional and sectoral disaggregation

Given this understanding of the two broad mechanisms by which energy demand is affected over time and the role played by the dynamics of the capital

Table 3. Regional and sectoral disaggregation.

Model	Global regions	Non-energy production sectors	Sectoral demand categories
CRTM	5	Intermediate materials, aggregate production	
DGEM	USA, ROW	USA, 30 industries, government, 672 households	
GOULDER	USA, ROW	USA: 7 industries, government, one household	
GREEN	12	Agriculture, energy intensive and non-energy intensive industries	
CETA	1	Aggregate economy	
GLOBAL 2100	5	Aggregate economy	
GEMINI	USA only	Industrial	Direct and indirect heat, feedstocks, electromechanical, metallurgical coal
		Commercial	Heat and cooling, light, other electric, other gas
		Residential	Heat and cooling, water heating, light, appliances, other gas
		Transport	Auto, air, rail, truck and ship
FOSSIL2	USA only	Industrial	Steam, process heat, machine drive, feedstocks
		Commercial	Heat and cooling, other heat, appliances and light
		Residential	Same as above
		Transport	Light duty, trucks, air, miscellaneous, freight
GLOBAL MACRO	9	Industrial	Steel, cement kilns, boilers
		Commercial	Heat and cooling, water heat, cooking, light, refrigeration
		Residential	Heat and cooling, water heat, appliances
		Transport	Rail, road, air
ERM & MWC	9	Industrial, commercial, residential, transport	
EDS	9	Industrial coke and other, commercial, residential, transport	
MARKAL	USA only	Industrial	Iron and steel, aluminium electrolytic, steam, machine drive, other heat, light, fabrication
		Commercial	Heat/hot water, cooling, miscellaneous
		Residential	Heat and cooling, water heat, miscellaneous
		Transport	Rail, auto, heavy and light trucks, bus, air, ship
T-GAS	14	Industrial, commercial, residential, transport	

stock, the next step in understanding how models represent energy demands and the means of adjusting to carbon constraints is to look at their disaggregation of demands by global region and economic sector. This was mentioned in the context of market representations in the preceding section; Table 3 gives a more detailed listing.

Disaggregated economic equilibrium models

The four disaggregated equilibrium models are similar in that each has a level and rate of change of GDP that is determined in the model by the level of investment and the output (value-added) that each sector contributes in equilibrium. Underlying this commonality, however, are four very different models.

CRTM and GREEN are global models with little sectoral detail. CRTM has an aggregate production sector and an intermediate materials sector (which produces energy intensive goods like steel). GREEN has an agricultural production sector and energy intensive and non-energy intensive sectors. Both models have exogenously set savings rate parameters which determine the fraction of national income that is invested. This supply determines the price of capital, and the amount of new vintage capital demanded by each sector depends on their respective production functions.

The ability of these economies to reduce carbon emissions is constrained in several ways. CRTM can only adjust the mix of inputs in the current vintage of productive inputs; the use of energy relative to other inputs and of the carbon intensive intermediate material relative to the other inputs is fixed in the older vintages of capital. The rate of retirement of this capital is governed by a fixed depreciation rate, and the amount of new capital is determined by the level of investment. GREEN is similar, except that the rate of turnover of old capital is governed by the depreciation rate and also a supply elasticity parameter that reflects the malleability (read: the cross-sector adaptability) of the old capital.[7]

The myopic behaviour of the agents in both models also restricts the ability to adjust to carbon constraints, since the capital stock does not begin to adjust until the constraint is actually imposed.

Both models have exogenously specified rates of energy-efficiency improvement that reduce the amount of energy needed to generate a given level of energy services; but this is applied only to the new capital stock to reflect technical change. The effect of this improvement is moderated therefore, by the reduced investment levels under a carbon tax.

GREEN, however, includes a governmental sector, so the effect of recycling the revenues from a carbon constraint can be analysed. If capital formation was subsidized by, say, an investment tax credit, then investment would increase. This increase in the rate of new capital formation would result in an increase in the relative amount of newer, more energy-efficient technologies, and also mitigate the future GDP losses from lost investment.

Finally, both models have endogenous world trade in the carbon intensive intermediate good. This allows for the exporting of carbon emissions to regions with less restrictive carbon constraints. There may not be a corresponding reduction in *global* emissions, however.

The remaining two models, DGEM and GOULDER, are similar in that they include many sectors in the US economy and an aggregate rest of world sector (ROW). Both have agents which possess perfect foresight and can therefore begin to react to future carbon constraints before they are imposed, thus easing the transition and decreasing the costs of the policy. Beyond these similarities, however, there is little in common.

The aggregate stock of capital in DGEM is perfectly malleable and costlessly mobile, meaning that one can buy a tractor and turn it costlessly into a water heater overnight. Moreover, the mix of productive inputs can adjust to the long-run optimal levels in each time period with respect to the prices in the economy. This allows the maximum ease of adjusting to price changes, and hence least GDP and investment reduction due to a carbon constraint. Technical progress and sector shift is modelled as a change in the cost share of the various goods consumed by industry or households over time; thus the aggregate energy-efficiency change depends on myriad effects throughout the economy.

GOULDER, on the other hand, has sector specific capital and includes an explicit treatment of the cost associated with adjusting the level of capital stock. The model allows for the substitution away from energy and energy containing goods at several levels with the new vintage of capital. The only technical change in this model is labour augmenting, which increases the effective labour force over time.

Aggregate economic equilibrium models

The two aggregate equilibrium models, CETA and GLOBAL 2100, are conceptually similar. CETA has one global consumer and a global productive sector, while GLOBAL 2100 has five regional consumers and productive sectors.

Aggregate output is produced from capital, labour, and electric and non-electric energy. The substitution parameters govern the ability of the economy in aggregate to move away from energy use. GLOBAL 2100, however, allows substitution among productive inputs in only the new vintage of production; CETA allows all vintages to shift relative input utilization.

Both also have rates of energy-efficiency improvement for each region that reduce the actual energy needed to produce a given amount of output, independent of price changes. In GLOBAL 2100 the rate is applied to the new vintage of capital of reflect technical progress and sectoral shift, while it is applied to the entire stock in CETA.

Finally, GLOBAL 2100 allows economies to trade emissions over time so that cumulative emissions are below some limit, instead of constraining them at each point in time. This eases the adaptation to the constraints by allowing the economy to pick the least-cost emissions trajectory that satisfies the overall constraints. Because of the extremely long residence time of CO_2 in the atmosphere, the hypothesis is that this does not significantly alter the long-run concentration but affords a considerable reduction in GDP losses.

Energy-sector equilibrium models

There is a natural distinction between the five energy-sector equilibrium models. GEMINI and

FOSSIL2 cover the USA only and represent energy consumers' choices among fuels and energy related technologies directly; GLOBAL MACRO-ENERGY, ERM and EDS are global models with no explicit treatment of energy consumer choice.

GEMINI and FOSSIL2 represent a variety of energy uses in four aggregate sectors of the economy: transport, residential, commercial and industrial. GEMINI has a reference time path of energy service demands and unit prices for each use category, and FOSSIL2 has a reference time path of energy service demands. GEMINI allows for modification of these demands through a price elasticity, but the model does not allow for any energy price feedback on GDP. FOSSIL2 has a direct response of price increases on energy service demands, and allows GDP to be affected by energy price changes: this also affects energy service demands.

In both models the consumers in each subsector minimize the present value cost of meeting the equilibrium energy service demands by choosing the fuel and technology combinations. FOSSIL2 allows retirement of old vintages of energy using capital only after expiration of their fixed useful life. GEMINI allows the consumers in each sector to choose the utilization, retirement and addition of all technologies as economically appropriate. Here the useful life is the time at which the unit operations and maintenance (O&M) costs begin to increase.

FOSSIL2 allows for technical change and sectoral shift in the industrial sector to decrease energy intensity. Sector shift is implicit in the reference service demand paths in GEMINI, which represents the evolutionary technical changes in new capital as either efficiency improvements or capital cost reductions; aggregate energy efficiency is dependent on the mix of capital vintages in use.

GLOBAL MACRO-ENERGY, ERM and EDS each include nine global regions. GLOBAL MACRO represents a variety of energy demands in the four sectors of each regional economy, while ERM represents only the sectoral aggregate energy service demands. EDS, in contrast, has regession equations for fuel by sector.

GLOBAL MACRO is the closest conceptually to the previous two models in that is has an explicit representation of capital stock. However, the turnover is dependent upon a fixed useful life assumption with straight-line depreciation, with the addition of new vintages not driven by price considerations. The reference demands in each category are modified based on population, GDP, and per capita income growth over time, with GDP and consequently per capita income reflecting energy cost changes. Unit energy cost depends on non-fuel costs (capital and O&M), fuel prices, conversion efficiencies, and equilibrium fuel shares (the determination of which is discussed in a later section).

ERM also has an energy cost sensitive GDP level, but the growth rate is *fixed*. Thus the next period's reference GDP is this period's reference GDP modified for energy price changes and increase at the fixed growth rate. Energy costs affect demands directly and also indirectly through the GDP feedback. Sector shift and technical advance cannot be tied to the capital stock, which is not modelled explicitly, so they are included as rates of reduction in the amount of fuel actually needed to satisfy a unit of energy service demand. As with GLOBAL MACRO, fuel shares depend on a market share algorithm discussed in the next section.

EDS takes forecasts of GDP and population and the model determined equilibrium fuel prices and determines fuel demand by region and aggregate economic sector. These fuel demand equations are sensitive to own fuel price and prices of substitutes. Substitution possibilities, technical change and sector shift are therefore implicit in the regression equations.

Energy-sector optimization model

MARKAL is a USA only model and, like GEMINI and FOSSIL2, contains great detail on energy demand technologies. The model is based on energy service demand paths for several categories of energy use in the usual four economic sectors. The model chooses the mix of technologies and fuels to meet these demands which minimizes the present value cost. Demands can be reduced by choosing explicitly modelled conservation technologies if they are economical. Costs for energy end-use technologies and conservation technologies are determined by levelized capital and O&M costs and an energy-efficiency parameter. There is a fixed useful life for capital equipment, but the model determines the optimal usage levels of the various capital vintages.

Energy-sector regression model

T-GAS has a set of region and sector specific regression equations that calculate energy intensity (energy per unit output) over time, given inputs like population, energy prices, sectoral value-added. Thus interfuel substitution, macroeconomic effects of energy price increases, sector shift and technical advance are implicit in the regression equations.

Energy supply: the shift from carbon based energy

The focus of the energy supply comparison is the representation of carbon free energy supply alternatives and their market penetration. The same five classes of models again serve as a useful organization of the discussion.

Disaggregated economic equilibrium models

The economic equilibrium models determine the utilization of different forms of energy in the same way as they do the other goods and services ie the supply is consistent with economy-wide equilibrium in all markets. CRTM represents the energy supply sector exactly as does GLOBAL 2100, which is detailed in the next section.

GREEN represents the three main primary fossil energy forms, coal, natural gas and crude oil. The production of the latter two is a fixed ratio of proven reserves, and reserve additions are a fixed ratio of the remaining undiscovered resources. The remaining resources can be increased or decreased with the market price of the fuel to reflect the fact that more resources become economical to extract at higher prices. The model also includes a carbon based backstop (some form of synfuel, for example) which becomes available in 2010, as well as uranium fuel for nuclear reactors. The utility sector – electric, gas, and water – demands the primary fuels to produce its output, with the ability to switch from fossil to non-fossil constrained by the capital rigidities discussed in the previous section. A carbon free electric backstop technology becomes available in 2010.

Neither of the remaining two models, GOULDER and DGEM, explicitly model carbon free sources of energy. They are included as capital in the production functions of the various industries. The effects of this on model results are subtle, and are greatly affected by the capital stock rigidities discussed in the previous section.

GOULDER has an oil/gas aggregate sector which is modelled like the other sectors in the model except that it includes an increasing marginal cost of extraction and an overall resource constraint, the effect of the latter being to include the opportunity cost (or Hotelling rent) in the price of the output. Coal is assumed to be inexhaustible so its representation is the same as the other sectors in the model. The carbon based synfuels industry can begin to accumulate capital in 2010. The gas and electric utility sectors are modelled as the other sectors with the capital–energy ratio of the old vintages of capital stock fixed. This means, for instance, that a coal based power plant previously in service cannot be converted overnight to a nuclear plant; this decision can only be made in the current capital vintage.

DGEM is similar in that it models the energy supply sectors exactly as it does the sectors in the rest of the model. It does not, however, include a constraint on total exhaustible oil/gas and coal resources or depletion effects on marginal cost; thus all resources are assumed inexhaustible in the time frame of the model. The utility sectors (gas and electric) have perfectly mobile capital stock, like all the others in the economy. Since carbon free fuel sources are treated as capital, the electric utility sector can implicitly switch a coal plant to nuclear overnight as the relative price of carbon based energy rises.

Aggregate economic equilibrium models

In both models the total supply of electric and non-electric energy is sufficient for the production of each region's aggregate economic output. The share of competing technologies in each market is determined on the basis of marginal cost, with lower cost technologies chosen before higher ones, and is constrained by upper and lower bounds on rates of introduction and decline on several technologies.

GLOBAL 2100 models low- and high-cost crude oil and natural gas with a fixed production to proven reserves ratio, where reserve additions are bounded above by a fixed fraction of remaining undiscovered resources. The model includes carbon based synfuels, renewables based secondary energy, and a non-electric backstop with constant levelized unit costs. The latter becomes available in 2010. Electricity is produced using traditional fossil energy forms, nuclear or hydro (including geothermal and other existing renewable energy sources). Advanced, more efficient electricity sources become available from 2000 to 2010, and include coal, natural gas and advanced high-cost and low-cost carbon free technologies. CETA has similar technologies, except it has an oil/gas aggregate with a constant marginal cost of extraction and an overall resource limit.

Energy-sector equilibrium models

By definition the energy-sector equilibrium models model the prices which balance supply and demand of fuels in the various global or domestic energy markets.

GEMINI determines long-run US fuel market share based on relative price, with the actual share dynamics lagged to reflect the slowness of energy supply capital formation to react to price movements. Capacity addition, utilization and retirement are chosen so as to minimize present value costs of meeting demand. Costs of fuel/technology combinations include a levelized capital and O&M portion, and, for conversion technologies, a fuel portion which depends on the price of the input fuel and the conversion efficiency. Technical change is represented as decreasing capital cost or increasing fuel efficiency. There are seven types of primary fossil fuels, ranging from Gulf Coast crude to eastern and western US coal to unconventional natural gas. The price is marginal cost plus opportunity cost of extraction, and marginal cost increases with cumulative extraction. There are eight non-fossil primary energy sources, among which are included photovoltaics, solar, wind and biomass, the supply of which is determined by exogenously specified marginal cost curves which shift over time to reflect technical change. Electricity can be generated using a variety of traditional fossil sources as well as nuclear and renewables such as geothermal and photovoltaics.

FOSSIL2 determines domestic fuel market shares based on relative fuel prices and base year shares to reflect the inertia of the capital stock. Conversion technologies are chosen to maximize the individual supply industries' profits, with precise modelling of investment and capacity utilization. Like GEMINI there are a variety of fossil and non-fossil primary energy forms, but FOSSIL2 contains an extremely detailed treatment of the electricity generation sector and non-utility generators.

GLOBAL MACRO and ERM determine fuel shares in the global and regional markets in a manner similar to the above, using base year fuel shares and relative prices. There is no explicit choice by agents among technologies, however, although a variety of fossil and non-fossil based energy forms are available to meet demand and are modelled in a similar fashion to those above. Given EDS's fuel demand equations, prices adjust until interfuel substitution allows supply and demand to equilibrate in the international and regional energy markets. Several non-carbon energy forms are available to fill the demand, including nuclear and geothermal.

Energy-sector optimization model

MARKAL contains roughly 50 process technologies for converting energy, 25 primary fossil energy forms, 15 renewable energy forms, and 50 electric conversion technologies. The domestic market share of these fuels is determined by the model-wide optimization of the present value cost of meeting the exogenously given energy service demands, with the cost of each technology consisting of levelized capital, O&M, and fuel components.

Energy-sector regression model

In T-GAS the electricity and direct-use demands are given by the regression equations discussed in the previous section. The demands for primary fossil and non-fossil energy are based on conversion parameters which the user can control to reflect the changing make up of the utility sector over time. The historical pattern of technical advance and price induced substitution among fuels is subsumed in the regression equations; here there are no prices modelled in the energy sector.

Summary

The comparison of 14 such diverse models must necessarily be on a very high level; for a more detailed and technical comparison of the models and a discussion of the common scenarios in and across which their results were compared see Energy Modeling Forum publications. For more detail on each of the models see the documentation cited in the note to Table 1.

[1] For example, the environmental impacts may affect only enjoyment of the environment, any monetary impacts may affect mostly consumption and not investment, or the marginal effect on GDP of any change in investment may be negligible.

[2] The combustion of fossil fuels in the supply of energy is responsible for roughly 95% of anthropogenic CO_2 emissions. Despite the putative attractiveness of a comprehensive greenhouse gas budget, the sources of other greenhouse gases such as methane and CFCs are multifarious and their control requires more extensive, and hence more difficult to implement and model, policy measures. These gases' roles as greenhouse gases and precursor chemicals are also not as well understood as that of CO_2.

[3] Energy intensity could also change in the absence of price movements if production is not characterized by constant returns to scale or if demand is non-homothetic ie if income changes result in a change in the share of income allocated to energy service purchases.

[4] The two models listed in Table 2 as aggregate economic equilibrium models are often called optimal growth models; however, two of the disaggregative economic equilibrium models, DGEM and GOULDER, are also optimal growth models, although their formulation is different from the classic Solow version. Optimal growth means that consumers choose their consumption and investment streams over time to provide themselves with the maximum value subject to the resource, technology and policy constraints they face. CRTM and GREEN, however, use marginal savings rate parameters to approximate this optimization, so technically are not called optimal growth models.

[5] These models are often called generalized equilibrium models; the distinction 'energy-sector' equilibrium is used here because I believe it is more precise.

[6] It should be noted that all of the models are intertemporal ie they extend for more than one time period, but none incorporates uncertainty about future events. GLOBAL 2100 has a stochastic programming variant which incorporates uncertainty about several warming-related impacts; this ability was not used in EMF 12: see Manne and Richels. Peck and Teisberg have also used their model to analyse the value of perfect information on various economic and environmental uncertainties.

[7] Electric power plants are not malleable, because they have little use outside of the electricity generation sector; automobiles and trucks or computers, however, are useful in many sectors.