A comparison of aggregate energy demand models for global warming policy analyses

Ronald D. Beaver and Hillard G. Huntington

This paper compares the treatment of the demand for all fuels (aggregate energy) in 11 models that are being used for analysing the economic and energy-sector impacts of global warming policy. Some models explicitly consider the linkages between the economy and the energy sector (energy–economy models), while others focus on the energy sector in more detail (energy models). The paper discusses demand model inputs and outputs, time horizon, regional and sectoral disaggregation, energy consumer behaviour, energy using capital stock and energy efficiency improvements, and incorporating uncertainty.

Keywords: Energy demand; Environmental policy; Modelling

The persistent growth in the concentrations of greenhouse gas emissions in the earth's atmosphere may have long-term and possibly serious consequences for the planet's climate. Concerns about this problem have led to various proposals to limit greenhouse gas emissions. Proposed efforts to control the emission of CO_2, an important but not the only greenhouse gas, are focused on reducing the use of fossil fuels. Broadly speaking, this reduction would be accomplished by two mechanisms: reducing overall energy demand and accelerating the shift towards non-carbon based fuels.

In response to the growing interest in this issue, there have been many efforts to assess the impact of carbon limits on the energy sector and the economy. These studies have rekindled a keen interest in energy models, prompting an intensive effort to refine existing systems and develop new ones. Results from many of these models based upon standardized scenarios are currently being compared by an Energy Modeling Forum (EMF)[1] working group in order to understand better the models' uses and limitations.

Policy makers are often unaware of the diversity of models being used for such analyses. While the models project similar outputs (eg energy use, emissions and GNP losses), differences in model structure exist depending upon the planned use when the model was built. The failure to appreciate this diversity in modelling approaches is partly due to the fact that documentation for many of these models is often not readily accessible.

This paper seeks to redress this problem by providing a broad overview of one central component of these models – their representation of energy demand and the ways to reduce its growth.[2] A more detailed and technical description of both the supply and demand dimensions of each model can be found in Beaver.[3] Individual model characteristics described in this paper may change as these systems undergo revisions and refinements.

An overview

In analysing the economic aspects of the global warming issue, a range of models has been used to develop internally consistent scenarios of future energy needs and the economic costs of limiting the growth in fossil fuel combustion, and hence CO_2 emissions. Each model has its own structure for representing the principal interactions in the energy and economic sectors. The model projects energy demands based upon this structure and key input assumptions about future economic conditions, population growth, and energy availabilities. When carbon limits are imposed, the models reveal the effect on fuel prices and quantities and on economic output (usually GDP). If carbon based fuels can be easily phased out, through either demand reduction[4] or fuel switching, the ultimate impacts on the energy

---

The authors are with the Energy Modeling Forum, 408 Terman Engineering Center, Stanford University, Stanford, CA 94305-4022, USA.

0301-4215/92/060568-07

sector and the economy will be relatively mild. On the other hand, limited or more expensive substitution will result in significant costs to the economy. The estimated impacts of limits on future carbon emissions growth will therefore depend upon the growth in fossil fuel use in the absence of any new policies, as well as the ease of substitution away from carbon-based energy when policies are enacted. How a particular model accomplishes this substitution depends upon its modelling of economic growth and consumer behaviour, its sectoral disaggregation and its representation of capital stock dynamics and energy efficiency improvements. Here we discuss these demand issues in a non-technical manner; we do not address supply topics such as the increased availability of renewable fuels.

With few exceptions, these models do not address the possible benefits of mitigating greenhouse gas emissions. Despite this limitation, the model outputs are still valuable, as they can help policy makers better understand the relationship between economic costs and the amount of carbon emissions reduction. Additionally, the results can guide the design of more efficient policies by emphasizing the significant differences in the economic costs of achieving carbon reductions in the various global regions and economic sectors.

The models

The models listed in Table 1 represent a blend of new and existing energy and economic models. They are currently being used for policy analysis in such organizations as the Internal Energy Agency, the Organization for Economic Cooperation and Development, the Electric Power Research Institute, the US Department of Energy, and the US Environmental Protection Agency.[5] The table indicates the organization providing recent support for global warming policy analysis in the last column.

The Edmonds–Reilly Model (ERM) was developed at the Institute for Energy Analysis of the Oak Ridge National Laboratory and is now maintained by Battelle Pacific Northwest Laboratories. The Organization for Economic Cooperation and Development's (OECD) GREEN model and the International Energy Agency's (IEA) EDS model are in-house modelling systems in Europe.[6] The Dynamic General Equilibrium Model (DGEM), Global 2100, and Goulder models are housed at US universities.[7] The remaining models are maintained by private US consultants for various government agencies.[8]

ERM was one of the first systematic attempts to model the energy emissions problem. It has been followed by other modelling systems – GEMINI, Global, Macro-Energy, IEA EDS and T-GAS – developed specifically for global warming policy analyses over the last several years.

Some models were initially developed to study other issues and have been revised to address greenhouse gas emissions policy concerns. DGEM was initially developed by Dale Jorgenson and his associates to study energy–economy interactions and economic productivity trends. GREEN was originally developed to study the impacts of agricultural policy, and FOSSIL2 to analyse energy market trends and national energy plans. Global 2100 is based upon the Energy Technology Assessment-Macroeconomic Model (ETA-Macro) devloped by Alan Manne to study such issues as energy–economy interactions and the effects of nuclear moratoria.

Model types

The major economic and demographic inputs required by the 11 models currently being used in the EMF study are shown in Table 1. The first five models are energy–economy models; they project supply and demand balances over time in the various energy markets as well as in the markets for other factors of production (eg capital, labour and materials).[9] The models determine the effect of policies on aggregate investment in the economy through their explicit representation of the capital market. In this way, policies can affect GDP, and hence energy demand, in the future as well as the present. The GDP path is determined by the model, based partly upon assumed trends in population growth, productivity and government fiscal (tax and spending) policy.[10]

The remaining systems listed in the table are energy models that focus on the markets for fossil fuels, electric power and renewables. The supply and demand for other non-energy inputs are not represented explicitly, thus allowing for a more detailed representation of energy supply and demand conditions. Models 6 and 7 explicitly consider the competition among end-use technologies which utilize fuels and electricity. Most energy models include simple feedbacks that directly reduce GDP, and hence energy demands, when energy prices are higher. Reference economic and demographic projections from another source are used in estimating fuel demands directly or to drive various activity variables, such as housing stocks, commercial floor space, and income, which influence energy service demands.

Table 1. Economic and demographic inputs and basic approach for determining energy demand.

Model	Key demographic and economic inputs (1)	Approach for determining energy demand (2)	Authors (3)	Current sponsor organization[a] (4)
1 DGEM	Population Fiscal policy Trade	Demands for energy, materials, labour and capital derived from sector specific cost functions and household demand functions	Jorgenson and Wilcoxen (Ref 7)	US EPA
2 Goulder	Population Fiscal policy Productivity	Demands for energy, materials, labour and capital derived from sector specific cost functions and household demand functions	Goulder (Ref 7)	US EPA
3 GREEN	Reference GDP Land supply Productivity	Demands for energy, materials, labour and capital derived from sector-specific production functions and household demand functions	Burniaux *et al* (Ref 6)	OECD
4 CETA	Population Productivty	Demands for electric and non-electric energy and capital derived from aggregate production function	Peck and Teisberg (Ref 8)	EPRI
5 Global 2100	Population Productivity	Demands for electric and non-electric energy and capital derived from aggregate production function	Manne and Richels (Ref 7)	EPRI
6 FOSSIL2	Population GDP Housing Floor space	Within each end use, competition among technologies on the basis of lifecycle cost and other factors	AES Corporation (Ref 8)	US DOE
7 GEMINI	Population GDP Housing Floor space	Within each end use, competition among technologies on the basis of lifecycle cost and other factors	Decision Focus Inc (Ref 8)	US EPA
8 ERM	Population Income (GDP)	Energy service demand response functions with judgemental parameters	Edmonds and Reilly, Edmonds and Barns (Ref 5)	US DOE
9 Global Macro-Energy	Population Income (GDP)	Energy service demand response functions with judgemental parameters	ICF Inc (Ref 5)	US EPA
10 IEA EDS	Population GDP	Fuel demand response functions with statistical parameters	–	IEA
11 T-GAS	Population GDP Sector mix	Fuel intensity demand response functions with statistical parameters	Piccot *et al* (Ref 8)	US EPA

[a] Abbreviations: DOE, Department of Energy; EPA, Environmental Proection Agency; EPRI, Electric Power Research Institute; IEA, International Energy Agency; OECD, Organization for Economic Cooperation and Development.

Demand model inputs and outputs

The demand sector of each of the 11 models solves for the amount of fuels and electric power demanded over time for any given set of energy prices and key input assumptions (column 1 of Table 1). These demands include electricity and the major fossil fuels – oil, natural gas and coal – and frequently renewable energy as well. Oil and natural gas are combined in models 1, 2 and 4.

All but one of the models search for a set of energy prices that will balance the quantity of each fuel that energy consumers are willing to buy with the quantity that producers are willing to supply. The latter results from the interactions among various processes within the energy supply network as represented in each model. The final energy demand levels reported for a particular scenario are those quantities that are consistent with the internally generated set of energy prices. As currently specified, model 11 assumes exogenous prices, although it can be coupled with other models focusing on energy supply.

The second column in Table 1 indicates how the model determines the demand for different fuels. The first three, all energy–economic models, use sector-specific production functions to determine individual fuel demands jointly with the demand for

Table 2. Key energy demand features of models.

Model	Regions (1)	Time horizon (2)	Years per period (3)	Economic producing sectors[a] (4)	Energy demand sectors (5)	Consumer end-use demands (6)	Foresight (7)	Demand response (8)	Capital stock (9)	Capital vintaging (10)
1 DGEM	1 (USA)	2050	1	36	na	na	Perfect	Estimated	General	No
2 Goulder	1 (USA)	2065	1	14	na	na	Perfect	Judgement[b]	Specific	Yes
3 GREEN	8 (World)	2020	5	8	na	na	None	Judgement	Specific	Yes
4 CETA	1 (World)	2200	10	1	na	na	Perfect	Judgement	General	No
5 Global 2100	5 (World)	2100	10	1	na	na	Perfect	Judgement	General	Yes
6 FOSSIL2	1 (USA)	2030	1	na	4	16	None	Judgement	Specific	Yes
7 GEMINI	1 (USA)	2030	5	na	5	19	Perfect	Judgement	Specific	Yes
8 ERM	3 (OECD) 6 (Other)	2095	15 1	na	3	na	None	Judgement	Implicit	na
9 Global Macro-Energy	9 (World)	2100	10	na	4	16	None	Judgement	Specific	Yes
10 IEA EDS	9 (World)	2005	1	na	1	na	None	Estimated	Implicit	na
11 T-GAS	14 (World)	2010	1	na	6	na	None	Estimated	Implicit	na

[a] Excludes household groups. [b] Parameters based upon estimated responses used in DGEM.

labour, capital and intermediate inputs.[11] They assume that producers select the mix of energy and other inputs which minimizes total costs in the sector, based upon the price of each input. In a similar way, the next two use an economy-wide production function to determine the demand for electric and non-electric energy; the latter is allocated to individual fuels based upon the costs and capacity limits of individual technologies. Energy demand adjustments in 2, 3 and 5 occur only in the new vintage of installed productive capacity; relative input proportions remain unchanged in old capital.

Models 6 and 7 determine the fuel mix based partly upon which technologies meet the energy service demands in various end-use markets at the lowest cost. In this process, the model considers information on energy prices, capital costs, operation and maintenance costs, performance, and availabilities of the competing technologies. The models include imperfect or lagged responses to price changes to represent the market frictions that constrain the speed of adjustment. The demands for the non-energy inputs are not included explicitly.

The remaining models use parameters to represent the response of end-use energy service demands (in 8 and 9) or of fuel demands (in 10 and 11) to changes in prices and economic activity. Cost minimization is implicit in these response functions, which incorporate both short- and long-run adjustments in energy demand.

Time horizon

Further details on the structure of energy demand in the various models are provided in Table 2. The time horizon for most models (except 3, 10 and 11) extends at least to 2030. The focus on long-run conditions is a relatively new development in energy modelling and is particularly important for global warming policy analysis.

Regional and sectoral disaggregation

There is a clear trade off between regional and sectoral detail in the models. The first two are energy–economy models which provide considerable detail on the US economy, disaggregating by industry or economic sector.[12] The remaining energy–economy models (3, 4 and 5) extend coverage to other regions by sacrificing sectoral detail. Model 5 is the only model that explicitly considers regional supply–demand balances in the world trade for non-energy goods. This feature allows it to analyse how trade in carbon intensive non-energy commodities is altered by various policies, and how this affects the regional distribution of CO_2 emissions.

The energy models disaggregate by energy demand sector (eg residential, commercial etc) and/or end-use service demands (eg direct heat) rather than by economic sector. The first two energy models (6 and 7) represent many alternative demand-side technologies (eg residential gas fired water heaters) for meeting many different energy end-use service demands within the USA. The other models are global (or nearly so), covering from 9 to 14 regions. Only 9 disaggregates world energy demand by end use.

Energy consumer behaviour

The modelling of consumer expectations about future conditions is important and controversial. Some models endow decision makers with perfect foresight, so energy consumers and producers anticipate the paths of future energy prices (those projected by the model) and begin making adjustments immediately. This behaviour contrasts with the situation where energy consumers behave myopically, reacting to current prices only. Clearly, these two cases represent extremes in assumptions about consumer expectations. Except for model 3, the energy–economy models adopt the perfect foresight assumptions. On the other hand, except for 7, the energy models adopt the assumption of myopic behaviour.

Critical to each model is the response of fuel or energy service demands to changes in prices and GDP (income). Only a few models base these responses strictly upon historical experiences. The responses to all variables in models 1, 10 and 11 are derived statistically from historical data; those in 2 are based upon the estimated parameters in 1. The remaining models determine parameter values for each of these responses, based partly upon their reading of the historical experience and partly upon their expectations about how future demand responses will change. As a test of their assumptions, several modellers have reviewed how well their parameter values have simulated the historical experience.

Energy-using capital stock and energy-efficiency improvements

Long-run energy-efficiency improvements are realized through the gradual turnover of the energy-using capital stock and through shifts in the final demand for goods and services.[13] These improvements can be induced by energy prices (as described above) or by other factors. Among the latter may be the adoption of new technologies based on criteria unrelated to energy costs. Alternatively, these non-price induced improvements may result from the changing composition of goods and services towards higher value-added products or away from energy-intensive heavy manufacturing as an economy matures.[14]

Three models (1, 10 and 11) derive statistical estimates of the rate at which efficiency changes occur independently of price changes. Time or other indices of economic maturity are entered directly into the estimating equation. Other models (2, 3, 4, 5, 8 and 9) judgementally determine an aggregate rate of improvement in the energy efficiency of new or existing equipment.

The two remaining models (6 and 7) endow specific end-use technologies with efficiency parameters which can change over time. In addition, changes in the composition of goods and services are incorporated implicitly in the demand paths for energy services. Thus the aggregate rate of change in energy efficiency depends on the mix of technologies and capital vintages as determined by the model. The rate of depreciating or removing old capital is fixed in all models except 7, where economic factors can make it cost effective to scrap certain equipment early or to maintain it longer.[15]

These last two models can provide a more technology rich explanation for the economy's rate of energy-efficiency improvement because they explicitly represent different types of energy using equipment eg more efficient water heaters or buildings with different thermal integrity. In contrast, the five energy–economy models (1–5) treat capital in more aggregate terms. Old and new capital is differentiated in 2, 3 and 5. Furthermore, models 2 and 3 impose adjustment costs or other restrictions on capital shifts between sectors. These assumptions reduce the degree to which capital can be shifted when energy prices increase. All capital in model 1 is perfectly interchangeable between sectors.

Uncertainty

Several of the models have been used to explore the uncertainty inherent in projecting CO_2 emissions over decades. Reilly *et al*[16] have used ERM to simulate a large number of scenarios from alternative sets of values for key input parameters. These input values were selected from probability distributions representing uncertainty in the value of each parameter. The results generated from this Monte Carlo technique reveal information about the uncertainty of possible future CO_2 emissions. In each scenario, the parameter value is revealed at the beginning of the projection period. As a result, decisions in each scenario are made after the uncertainty in input assumptions has been resolved.

Manne and Richels have adopted a different approach with a variant of Global 2100.[17] Decisions in the early years are made before the uncertainty is resolved. Decision makers acquire better information in the later years about greenhouse impacts and mechanisms, energy efficient end-use technologies, and the prospect for low-cost carbon free supply alternatives. As a result, decisions during the later years are made after these uncertainties are resolved. In this stochastic programming approach, the optimal path for carbon emissions is different under uncertainty from when all conditions are known with certainty.

Undoubtedly, more modellers will intensify their efforts to incorporate uncertainty into global warming policy analysis over the next few years.

Summary

This paper has briefly reviewed several important determinants of energy demand in models that are being used to study the impacts of limiting carbon emissions. The structural differences represented in these models are substantial. Policy makers and analysts should be aware of this diversity when reviewing the results from any one study.

Additional work is needed to know how differences in model structure affect the projections of energy use and emissions. One approach is to observe differences in results from standardized scenarios in which all models use a minimal set of common input assumptions. This process is currently under way in the EMF study cited previously and leads to many interesting questions and insights. For example, some models estimate lower economic and energy impacts due to restrictions on carbon emissions growth because they project lower growth in fossil fuel demands in the no policy case. Are these differences attributable to the way economic growth or energy saving technical progress is modelled?

The impacts will also be less when the economy can substitute more easily away from carbon based fuels as their prices increase. This point also raises several interesting hypotheses to investigate. Is this substitution response substantially different in parameterized models from that in statistically estimated models?[18] Does greater substitution occur in models which allow more opportunities to substitute between final products (eg 1 and 2) or which allow capital to flow more freely between sectors (eg 1)? And finally, does anticipation of market conditions make consumers significantly more responsive to steady increases in energy prices? Further analyses of such standardized results may help to resolve these types of questions.

We have benefited greatly from the discussion of the EMF 12 working group, chaired by Darius Gaskins. We particularly would like to acknowledge the participating modellers who spent considerable effort to improve our understanding of their models and to suggest improvements in this paper. These people include Dale Jorgenson, Peter Wilcoxen, Lawrence Goulder, John Martin, Stephen Peck, Thomas Teisberg, Alan Manne, Richard Richels, Sharon Belanger, David Cohan, Stephen Haas, Jae Edmonds, William Pepper, Lakis Vouyoukas, and Robert Kaufmann. We also thank John Weyant and Ming-Fai Sit for their suggestions. We retain responsibility for any errors or omissions.

---

[1] The Energy Modeling Forum process for comparing models is explained in 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 10, No 5, 1982, pp 449–462. Each EMF study is comprised of two major parts: (1) a comprehensive comparison of the model structures, and (2) an analysis of the major policy findings from comparing the model results. We summarize in this paper the different model structures related to energy demand; policy implications of the scenarios are currently being developed and will be discussed separately in a later report.

[2] The models consider all energy used within an economy rather than just one fuel or sector. Hence, we refer to them as aggregate energy or energy–economy models.

[3] Ronald D. Beaver, *Structural Comparison of EMF 12 Models*, Energy Modeling Forum, Stanford University, Stanford, CA, 1992.

[4] Demand reduction for carbon based fuels includes the more efficient conversion of primary fuels into energy services as well as direct energy service demand reductions.

[5] Most of these studies are currently in progress; the Atmospheric Stabilization Framework used in a previous EPA study (D. Lashof and D. Tirpak, *Policy Options for Stabilizing Global Climate: Report to Congress*, US Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC, 1990) based its energy demand projections on Global Macro-Energy (ICF Inc, *Global Macro-Energy Model*, Summary, Fairfax, VA, 1988), which itself was adapted from the Edmonds–Reilly model: see J. Edmonds and J. Reilly, *Global Energy: Assessing the Future*, Oxford University Press, New York, 1985; 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*, Draft prepared for US Department of Energy, Pacific Northwest Laboratory, Washington, DC, 1991.

[6] 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, Resource Allocation Division, Paris, 1991.

[7] 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. Jorgenson 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, 1988; A.S. Manne and R.G. Richels, 'Global CO2 emission reductions: the impacts of rising energy costs', *The Energy Journal*, Vol 12, No 1, 191, pp 87–107; A.S. Manne and R. Richels, 'Buying greenhouse insurance', *Energy Policy*, Vol 19, No 6, July/August 1991, pp 543–552; L.H. Goulder, *Effects of Carbon Taxes in an Economy with Prior Tax Distortions*, Working Paper, Stanford University, Stanford, CA, 1991.

[8] AES Corporation, *An Overview of the FOSSIL2 Model*, Arlington, VA, prepared for the US Department of Energy Office of Policy and Evaluation, 1990; Decision Focus Inc, *GEMINI: an Energy–Environmental GEMS Model*, Report Number C2023001.01, Los Altos, CA, 1990; S. Peck and T. Teisberg, 'CETA: a model for carbon emissions trajectory assessment', *Energy Journal*, Vol 13, No 1, 1992, pp 55–77; Draft, Electric Power Research Institute, Palo Alto, CA, 1991; S. Piccot, 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.

[9] The first three are general equilibrium models which solve for market clearing prices in a number of different industries and sectors within the economy. Models 4 and 5 are optimization models focusing on the macroeconomy as an aggregate. In the optimization, the representative consumer maximizes the sum of the discounted utility derived from aggregate economic consumption.

[10] GNP can be calibrated to a reference path by adjusting a few key parameters in models 3, 4 and 5. This feature allows these models to use standardized GNP assumptions, as was done in the EMF study.

[11] Models 1 and 2 use a cost function for each sector that is related to a production function if cost minimizing behaviour by firms is assumed.

[12] The number of economic sectors in Table 2 includes the number of industries as well as the government sector. Household types are excluded. The number of final consumers can vary among the models from a single decision maker (4 and 5) to as many as 672 household types (1).

[13] Based partly upon the preliminary findings of the current study, the next EMF working group will be focusing on energy conservation.

[14] Although some of these shifts in economic structure are induced by changing energy prices, it appears that many are not.

[15] In model 2 capital in the oil and gas industry is scrapped when rising costs through depletion make it no longer economic to utilize such capital.

[16] J.M. Reilly, J.A. Edmonds, R.H. Gardner and A.L. Brenkert, 'Uncertainty analysis of the IEA/ORAU CO_2 emissions model', *Energy Journal*, Vol 8, No 3, July 1987, pp 1–29.

[17] *Op cit*, Ref 7, Manne and Richels (2).

[18] Such differences were clearly evident in a previous Energy Modeling Forum (1980) study on energy demand: Energy Modeling Forum, *Aggregate Energy Elasticity*, EMF Report 4, Stanford University, Stanford, CA, 1980 (reprinted in *Energy Journal*, April 1981).