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Applied general equilibrium models for energy studies: a survey

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Abstract

The importance of energy in any economy, developed or underdeveloped, became clear after the first oil shock in 1973. Since then, different studies were carried out to formulate energy policies and to study their impact on the economies. Since energy policy issues are related to various aspects of the economy such as price formation, output determination, income generation and distribution, consumption behaviour, government operation, etc., a coherent and systematic mechanism is required for such analysis. By offering such a framework of analysis, AGE models gained popularity among energy modellers. In the 1980s, the environmental issues have gained importance, and the focus shifted towards curbing and containing emissions of environmentally unfriendly gases resulting from the use of energy, AGE models, because of their capability to capture the complexities of the economy, have found relevance in analysing the economic impacts of controlling pollution and greenhouse gases. This paper surveys the literature on such general equilibrium models as applied to energy studies, and reports their special features, evolution through time as well as their limitations.

JEL classification: C68; Q41

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1. Introduction

The interest in the energy sector has dramatically increased since the first oil shock in the early 1970s. This gave an impetus to the development of different models for energy policy analysis. Some of these models concentrated mainly on the energy demand and supply options and the technologies involved, while some

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others started to investigate the energy–economy interaction. Applied general equilibrium (AGE) models found immediate use in the second category. In fact, the first analysis using an AGE model in energy studies, the Hudson–Jorgenson (1974) model, has set a new tradition of AGE modelling – the econometric tradition of models.

By the early 1980s, the interest has, however, shifted towards issues related to the environmental pollution. More and more efforts were and are being directed to understand the different effects of pollution and to formulate policies to contain the environmental degradation. Since issues related to the environmental pollution and global warming are global problems that manifest after long time lags, analysts have tried to adapt their models to take these aspects into account. As a result, another new tradition has developed which led to global, long-term AGE models. Since the energy sector is the major source of environmental pollution, many of these new models are offshoots of the old energy sector models. AGE models have thus entered into an era of growth and of new challenges.

We review here a certain number of AGE models used for energy and environmental policy analyses. In Section 2, the preferred areas of application of AGE models in energy studies are described; then in Section 3, we review some models by grouping them into different traditions of AGE modelling; and finally in Section 4, we discuss the lessons learned from the AGE modelling and raise some issues regarding their application to energy studies.

2. Different applications of AGE models to energy related studies

A wide range of energy related issues have been analysed using AGE models. All these analyses have one point in common – they aim to measure overall economic impacts in any economy due to changes in the energy sector. But the question that perhaps had greater appeal is concerned with the impacts of energy prices and taxes on economic growth, since it is well known that energy pricing cannot be analysed in isolation. A host of issues such as the interaction between energy supply and demand, interfuel substitution, government revenue, balance of payment, inflation, welfare of people, etc., are addressed through pricing policies. All these imply that a proper macroeconomic setting is required to analyse the immense complexity of the linkages of the economy. Since AGE models offer an elegant mechanism for coherent and systematic analysis of these issues, their use follows logically.

The first application of an AGE model to energy studies, the Hudson and Jorgenson model (1974) followed the first oil shock. In this model, a price-responsive interindustry production structure was combined with a long-run model of aggregate demand. This marked a significant methodological advance. This model was used to forecast the energy demand for the period 1975 to 2000, and analysed the effects of tax policies on energy use. Manne and Richels', (1977) model closely followed the Hudson–Jorgenson model but their approach was quite different. They used a detailed description of energy technologies while using an aggregated representation for the rest of the economy. These pioneering works have stimulated others to use economy-wide models for energy studies. As a consequence, other energy–economy models based on AGE tradition have appeared in the 1980s. Many of these models were developed outside the USA. Although the structure and focus of these models differ widely, the general emphasis on interactions between the energy and non-energy sectors has always been preserved.

The questions that are typically being asked for environmental analysis can be grouped into two broad categories.[1] First, what are the economic and welfare consequences of global warming? Second, what are the consequences of controlling the levels of green house gas emissions (Boreo et al., 1991)? AGE models are generally concerned with the second question. Here, one seeks to estimate the abatement costs of CO_2 (or GHG) emissions by comparing the costs of implementing alternative strategies to limit emissions with that in the absence of a carbon limit. Several variants of such questions can be encountered in the literature. For example, one can ask if the quantity of greenhouse gas emissions is restricted by a certain amount within a certain date limit, how the economy will be affected (measured typically in terms of loss in GDP, loss in welfare, etc.). Similarly, a variant of this type is to investigate the impacts of a certain amount of carbon tax on any economy. These questions can be asked at the national, regional or global levels. Typical issues related to such studies are: design of tax rates, distribution of revenues, nature of tax (consumption or production), and related uncertainties and ambiguities. In global models issues like trade effects of taxation, the sharply differing pattern of production and consumption of carbon-based energy sources, etc. can be taken into account. Since 'leakage' is linked to trade, models with international trade attempt to capture 'leakage' also.[2]

3. Different modelling approaches

In AGE analysis, models are often numerically specified for policy evaluation. The precise meaning of the term 'general equilibrium' is often not defined.[3] It appears, however, that a general equilibrium model is one in which all markets clear in equilibrium; there seems to be less agreement as to the essential elements of structure which underlie the equilibrium formulation (Shoven and Whalley 1984). It is thus not easy to classify different AGE models. Several criteria can be used to classify the models. Clarete and Roumasset (1986) propose some of the

[1] A number of studies survey the application of AGE models to global warming and other related issues in much more detail. See for example, Dean et al. (1993), Gaskin and Weyant (1993), Weyant (1993), Boreo et al. (1991).

[2] Two types of leakage can occur when some countries apply emission reduction measures unilaterally. The first is through reallocation of carbon-intensive industries from carbon-constrained to unconstrained locations. Another source is increase in carbon-intensive production in unconstrained locations.

[3] We shall not elaborate on this point. For a simple explicative example and a survey of tax related AGE models, see Shoven and Whalley (1984). For more detailed presentation, see Dervis et al. (1982).

following criteria: solution algorithm used, numerical specification (calibration or econometric estimation), and structural framework (neoclassical or nonneoclassical structures). Dervis et al. (1982) used a different criteria for the same purpose. They grouped AGE models into four categories: (i) models focusing on international trade, growth, economic structures, and/or income distribution, (ii) models of public finance, (iii) multi-country, international trade models, and (iv) energy related works. Since our interest lies in energy related models, evidently we cannot use this classification. A third possibility is to classify models according to their modelling tradition following Schubert (1993): (i) multisectoral growth (MSG) models following Johansen's tradition; (ii) Herberger, Scarf, Shoven and Whalley approach; (iii) structuralist and other social accounting matrix (SAM) based models; (iv) econometric models in the tradition of Jorgenson and his disciples; (v) intertemporal optimization models by Manne and his followers.[4] Models of each tradition can then be classified according to their spatial coverage (regional), national, multinational, global), sectoral disaggregation, periodicity (single period multiperiod), nature (static or dynamic), etc.

We shall follow the third proposition to review a certain number of models on energy studies. It is to be noted that the category to which a model belongs is not always evident for some models. For example, Bergman (1987, 1988, 1991) had used 'putty–clay' representation of technology, as Manne and Richels do in the ETA-MACRO. One can put Bergman's works in the same group as Manne and Richels's. On the other hand, Bergman's models follow closely the MSG tradition. Thus, one has to take a decision but it is neither absolute nor sacred. Moreover, we do not claim to present an exhaustive review of all existing models. Rather, we are trying to bring out important characteristics of each tradition, their evolution over time and finally their shortcomings.

3.1. MSG models

Johansen (1974) was the pioneer in implementing an AGE model without fixed input–output coefficients. He retained the fixed input–output coefficients for intermediate consumption while employing linear logarithmic or Cobb–Douglas production functions in modelling the substitution between capital and labour. There is only one representative household. He also developed a method to solve the resulting non-linear model to implement it using Norwegian data. He was the first to use the 'calibration' method to determine the unknown parameters describing technology and preferences. Thus, except for a few parameters for which he used econometrics, the model can be made operational using a single data point.

Later versions of the Johansen model and those based on his tradition retained the main structures but introduced more sectoral disaggregation and the so-called

[4] For classification, we have used somewhat different terms than in Schubert (1993) in some cases. For example, she used 'Models for the LDCs' which we have termed as structuralist and other SAM based models. Note that Bergman (1985) also followed a very similar classification.

Armington assumption.[5] The well-known models of this tradition include MSG models for Norway (for example, MSG-4 described in Longva et al., 1985) and other Scandanavian countries,[6] and ORANI developed in Australia. Table 1 gives some details of a few models. These are single country models with different degrees of disaggregation. The most disaggregated one is ORANI which in its standard version has 6159 variables and 2621 equations. It can also be noted that Bergman's models typically distinguish between old and new production units.

G-Cubed (McKibbin and Wilcoxen, 1993), a multisector, multiregion model used to study the link between the environmental policies and international trade, can perhaps be considered as a global MSG model. In fact, G-Cubed combines two AGE modelling traditions, namely, the MSG modelling tradition and the Jorgenson tradition. Compared to other global models, G-Cubed has a disaggregated production model in the Jorgenson tradition but used a representative household and the calibration method of the MSG modelling tradition. It also includes a rigorous treatment of financial assets. The authors first investigate how unilateral environmental regulations affect trade, exchange rates, output, etc., and then analyse how changes in international trade affect the attempts to reduce carbon emissions.

The main weakness of MSG models is the assumption of a representative consumer. It is not realistic to consider that all consumers behave alike. This appears to be a restrictive assumption particularly in energy studies since the energy sector affects different sections of the population differently.

3.2. *The Harberger–Scarf–Shoven–Whalley (HSSW) tradition*

This tradition is mainly involved in the fiscal policy analysis, which was first investigated by Harberger using a two-sector general equilibrium framework. The computer algorithm for numerical determination of the equilibrium by Scarf in 1967 gave an important stimulus to the widespread use of AGE models. Shoven and Whalley have extensively used AGE tax models to analyse national fiscal policy issues (such as integrating personal and corporate taxes, the introduction of value-added taxes, indexing tax system, etc.) and international trade policies.

The main characteristics of these models are:

(i) The representative consumer is replaced by a group of consumers, each having an initial endowment and a set of preferences. It thus recognizes the differences in preferences of consumers as a function of their endowments. Some treat explicitly the labour–leisure trade off. Market demands are the sum of each consumer's demand.
(ii) Models are calibrated, generally using a single data point as in MSG models.
(iii) These models contain a detailed formulation of tax structures.

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[5] The terminology is derived from Armington who treated the same goods of different countries of origin as imperfect substitutes.
[6] Bergman (1988) surveys some of them for energy related applications.

(iv) They follow closely the Walrasian theory of general equilibrium, analyse the welfare aspect of different policies.

Table 2 gives some applications of the HSWW tradition in energy studies. Goulder (1982) was probably the first to apply this modelling tradition to energy

Table 1
Some applications of MSG models in energy studies

Author[a]	Country	Some details
Hogan and Naughten (1990) ORANI short run	Australia	Base year 1977–78, 112 industrial sectors, to study the economy-wide effects of a 15% decline in production of crude oil
Hall et al. (1990) ORANI-LFT[b]	Australia	To identify the principal aggregate and structural impacts which result from a substantial switch from crude oil levy revenue to product excise revenue
Mckibbin and Wilcoxen (1993) G-Cubed	Global	A multiregional (six regions), multi-sector (12 sectors in each region), intertemporal model A nested CES function system describes the production process 1987 data
Bergman (1988) ELIAS	Sweden	Multiperiod model in which the agents had static or adaptive expectations Distinguishes ex ante and ex post technological constraints, as well as different vintages of production
Bergman (1991)	Sweden	Static CGE model of an open economy with 45 sectors, benchmarked with the 1985 data includes emissions and emission control activities, as well as markets, and market prices for tradable emission permits Distinguishes between old and new production units in some sectors Considers four types of domestic intersectorially mobile factors of production–capital, labour, electricity, and the natural resource base of the production sector
Bergman (1987)	Sweden	Seven producing sectors The ex ante production functions are defined as nested CES-Cobb–Douglas–Leontief functions. Ex post labour is the only variable input and labour productivity and energy input coefficients vary according to vintage
Hanson and Alfsen (1986)	Norway	A two-sector model to analyse the impacts of a tax on SO_2 emissions Generalized Leontief cost function with KLEM inputs Consumer's preference is represented by a CES function
Proost and Van Regemorter (1990)	Belgium	A two-period perfect foresight 25-sector model Dynamic input–output framework with constant return to scale and perfect competition describes the production possibilities

Table 1 (*continued*)

OECD (1993) GREEN	Global	12-region, dynamic model 15 producing sector of which 12 are energy related including seven back-stop technologies The model distinguishes between old and new capital goods. A nested system of CES (except fossil fuels) functions describes the production process A simple recursive dynamic structure is used

[a]Author refers here to the authors of articles referred in the reference who are not necessarily the model builders.
[b]ORANI-LFT consists of three modules. The major module is the standard framework of the ORANI model. This has been extended to an industrial sector interfuel substitution module called ORANI-FUEL. Finally, the liquid-fuel taxation module, LFT, which when considered with ORANI-FUEL, is termed ORANI-LFT.

policy analysis using a nine-sector model, of which five sectors were energy producing. But his model incorporated some methodological advances following Hudson and Jorgenson (1974) to account for the possibility of substituting other factors for energy as relative prices change. Twelve household groups, according to their incomes, were considered. Simulations covered the period from 1973 to 2001 at four-year intervals, giving a sequence of general equilibria.

Borgess and Goulder (1984) expanded the model to include 24 sectors while keeping the number of household groups same. They also attempted to isolate three components of the impact of energy, namely direct, dynamic and terms of trade[7] on long-term growth. Uri and Boyd (1992, 1994), Boyd and Uri (1991, 1993) and Boyd et al. (1994) have also followed the same tradition for analysing the impacts of energy tax incidence on the Phillipines and the United States, though the level of disaggregation and the model specification vary.

Whalley and Wigle (1991a) extended this tradition for assessing the effects of global CO_2 emission reductions. They used a single period, three regions[8] model, with three non-traded primary factors[9] as endowments in each region while

[7]Energy is a input to production, as are capital and labour. When the price of energy rises, GNP (defined as the difference between the value of production and the cost of inputs) drops. The direct effect of energy on growth is regulated by the elasticity of substitution between energy and other inputs. The savings (or dynamic) effect follows from the energy-capital complementarity. If energy prices increase, the demand for capital decreases and the rate of return of capital decreases. If savings is responsive to rate of return, the higher energy prices may translate to less investment and therefore slower economic growth. The terms-of-trade effect is connected with the loss in real income that takes place when the relative price of imports increases (Borgess and Goulder, 1984).
[8]The three regions are: the developed region with per capita income in 1986 more than US $2000 and with less then 25% of their exports made up of fuels; the developing region with per capital income less than US $2000 and with fuel exports accounting for less than 25% of total exports; and the oil exporting region where fuel exports accounts for more than 25% of exports.
[9]They are greenhouse energy resources, other energy resources, and primary factors.

Table 2
Some applications of HSWW tradition in energy studies

Author	Coverage	Some characteristics of models
Goulder (1982)	USA	Nine sectors of which five are energy producing ones; 18 consumer goods which are connected to nine producer goods through a fixed-coefficient conversion matrix A nested system of cost functions (translog KLEM) is used for each industry 12 categories of households are considered. Consumer demands are derived from a nested system of Cobb–Douglas and CES utility functions in which leisure, current consumption and future consumption are the principal arguments Benchmark year: 1973
Borgess and Goulder (1984)	USA	24 industrial sectors, 12 household categories, and 18 consumer goods are considered Three functional forms are tested to analyse the sensitivity of results: (i) fixed coefficient for interindustry transactions combined with a Cobb–Douglas nest for capital and labour; (ii) Cobb–Douglas specification for KLEM; (iii) a multi-nested structure to combine KLEM Consumer demands are derived from a nested system of Cobb–Douglas and CES utility functions in which leisure, current consumption and future consumption are the principal arguments Benchmark year: 1973
Boyd and Uri (1991)	USA	12 sectors, 13 consumer goods, 6 household categories are considered The substitution of capital, labour and land (for agricultural and forestry sector) is incorporated through a CES production function Consumer demands are derived from a nested system of CES utility functions in which leisure and current consumption are the principal arguments Benchmark year: 1984
Boyd and Uri (1993)	The Philippines	14 producing sectors, 14 consumer goods, and 3 household categories are considered The substitution of capital, labour, and land (for agricultural and forestry sector) is incorporated through a CES production function Consumer demands are derived from a nested system of CES Benchmark data: 1983
Whalley and Wigle (1991a)	Global	3 regions, three types of energy and two types of industrial output are considered. Production is represented by CES functions. Oil, gas and coal are not distinguished
Pezzey (1992) based on Whalley and Wigle (1991b)	Global	Same as Whalley and Wigle (1991a), only exception is there are 6 regions instead of 3 regions

producing five goods[10] of which three are traded. Production is represented by a CES function for each produced good in each region. The equilibrium involves full global market clearing in all three traded goods while for the non-traded goods (non-greenhouse energy products and composite energy) there is domestic market clearing in each region. The model is calibrated using 1986 data, and tested for four counterfactual modes. Their analysis focused on trade and the implications of different ways of applying taxes and distributing emission constraints. Whalley and Wigle (1991b) use six regions and extend the analysis upto 2030 using the 1982 benchmark data set.

Pezzey (1992) used the Whalley and Wigle (1991b) model to analyse the impacts of unilateral CO_2 control in the European Community and OECD. He investigated five policy formulations relating to CO_2 control for the 1990–2100 period and concluded that unilateral control will be environmentally ineffectual and sectorally disruptive but harmless because there are no welfare losses by its consumers. The model, however, has certain restrictive assumptions. It does not allow for interfuel substitution and assumes the same technology set available to all regions who use the same proportions as those in the 1982 benchmark equilibrium data set.

Using a dynamic AGE framework, Goulder (1994) examines the 'double dividend' proposition of an environmental tax. 'Double dividend' means that environmental taxes not only improve the environment but also reduce the overall non-environmental costs of the tax system. The model contains a detailed treatment of US taxes, much in the same way as his earlier model, that can address the effect of taxation on profit, investment by industries, household decisions regarding savings and consumption, labour supply, etc. Moreover, it incorporates capital adjustment dynamics, implying capital is imperfectly mobile. Simulations using this model reveal the importance of revenue recycling methods and of pre-existing taxes. Results suggest that a carbon tax generates larger gross distortionary costs than are produced by the major types of income taxes it might partially replace. The author explains these results in terms of 'narrowness of the base' of carbon tax and its focus on intermediate goods. His analysis strengthens the insights from the theoretical tax literature which claims that taxes on intermediate inputs cause larger welfare costs through distortions in labour and capital markets in addition to the effect on the input. He also found that welfare costs of carbon taxes are highly sensitive to initial conditions regarding the marginal rates on pre-existing rates. These results imply that analyses that ignore existing tax structures understate the costs of carbon taxes. Moreover, they show that the case for carbon taxes cannot be made without invoking the environmental benefits.

The strength and weakness of this tradition is related to their strong conviction in the Walrasian theory. Since these models treat explicitly the behaviour of economic agents, it is easy to analyse the welfare aspects and the change in behaviour of agents in view of policy changes. At the same time, their inherent

[10] Five goods are greenhouse energy products, energy-intensive goods, non-energy intensive goods, other energy products, and composite energy.

assumptions of perfect competition, absence of rigidity and uncertainties make them more vulnerable to criticism.

3.3. Econometric AGE models

The pioneering work of Hudson and Jorgenson (1974), destined to evaluating the impact of changes in energy policy in the long-term US economic growth, has marked the beginning of a new tradition of AGE modelling, known as econometric AGE models. This model, for the first time, has replaced the fixed input–output coefficients for interindustry transactions by econometric models of producer behaviour to generate the demand functions for inputs in each sector. For this purpose, three-step translog price possibility functions have been used. In the first two submodels, aggregate prices respectively for energy and material for each sector were generated from translog functions having five arguments.[11] In the third submodel capital, labour, aggregate energy and aggregate material were combined for each sector. Thus there are three equations for each industrial sector. In the next step, input–output coefficients were derived for each sector from these equations through mathematical manipulation. The second component of the model is a macroeconomic growth model that integrated the demand and supply conditions for consumption, investment, capital and labour. Preferences between present and future consumption, which determine the allocation of income between saving and consumption, are also taken into account. The final step is to determine the levels of output, employment and utilization of capital for each sector. This is done following the conventional input–output analysis.

Since then, the model has substantially changed. In the first version of the model, the prices of labour and capital were determined independently of the relative factor demands in the interindustry model. Later versions achieved a more complete integration (Goulder, 1982). Later versions used econometric models for consumer behaviour based on the principle of exact aggregation. Recent versions consider that households follow a three-stage optimization process. In the first stage, each household allocates full wealth across different periods. At the second stage, households allocate full consumption to goods and leisure. And finally, total expenditure is allocated among capital services, labour services and commodities. The household sector has been subdivided into demographic groups that differ by characteristics such as family size, age of head, region of residence, race and urban and rural location. Jorgenson and Wilcoxen (1993c) have considered 1344 households based on these criteria. In the production side, joint products are allowed for and productivity growth is made endogenous with the possibility for biased productivity growth for an industry. The size of disaggregation has increased to 35 sectors from nine sectors in the initial study of 1974. At the same time, the macroeconomic

[11] The arguments of the energy submodel are prices of coal, crude petroleum and natural gas, refined petroleum products, electricity, and that of gas as a product of gas utilities. Similarly, the arguments of the material submodel are prices of agriculture, non-fuel mining, and construction; manufacturing; transport; communication, trade and services; and that of competitive imports.

model has been replaced by separate models for investment, government and foreign trade. In order to evaluate environmental problems over a long period, the model has been made dynamic.

The advantages of the econometric parametrization over the calibration approach are stressed by Jorgenson in different works. The main advantage is that the responses of production and consumption patterns to changes in energy prices and environmental controls are derived from extensive historical experience. By modelling productivity growth at the industrial level, and allowing it to be an endogenous function of relative prices, the model captures better the historical changes in productivity and allows for technological changes endogenously. Another advantage is that parameters estimated from time series data are much less likely to be affected by the peculiarities of the data for a particular time period (Jorgenson and Wilcoxen, 1993a).

The main difficulty in realizing an econometric model is its huge data requirements. This is because the number of parameters to be estimated increases very rapidly with each increase in the number of industrial sectors or consumers. By contrast, parameters can be estimated from a single data point in the calibration method. This economy in data requirement is more appealing to model builders, especially where it is difficult to find long time series. This perhaps explains why the econometric estimation found very limited use (see Table 3 for some applications). Hazilla and Kopp (1990), who used a disaggregated 36-sector model but with a representative consumer, have remarked that relaxing the assumption of representative consumer by a detailed consumer model does not produce aggregate social welfare losses significantly different from the representative household model. However, such a disaggregation permits one to distribute the effects over demographic groups. Moreover, though the econometric estimation avoids the peculiarities of a particular year, it inevitably captures the extraneous factors like the impact of oil shocks. More importantly, the transition from the past experience to future always remains highly debatable, particularly when we are interested in very long term in the environmental analyses.

3.4. *Structuralist and other SAM based models*

In Taylor's (1990) words, 'structuralism is more a program of research and policy formation than a well-defined set of rules for putting a model in place'. Authors of these models recognize the importance of the factors like the distribution of income and wealth, the presence of 'economically powerful actors' (institutions such as the state or corporations, the private sector, different classes and groups of population, etc.), technical change, socio-political aspects, etc. in the functioning of an economy. These aspects are taken into account through five key features (Taylor 1990, pp. 3–7). First, economically relevant actors are identified and are related to a functional category of the income distribution or a production sector. Second, prices are considered to be under varying degrees of control by distinct groups in the economy and power plays a distinct role in price formation. Third, prices and income flows are considered in money terms. Fourth, some degree of

Table 3
Some applications of the econometric AGE models for energy studies

Author	Country	Some details
Hudson and Jorgenson (1974)	USA	Nine industrial sectors, of which five are energy related A two-stage KLEM translog price possibility frontier is used. Aggregate energy and aggregate material are generated from translog submodels A macroeconomic model provides totals for consumption, investment, government and export demand Data from 1947 to 1971 were used to estimate parameters econometrically The model presents projections of economic activity and energy utilization for the period 1975 through 2000
Jorgenson and Wilcoxen (1990a, 1990b, 1993a 1993b) Scherage et al. (1993)	USA	35 production sectors and 672 types of households are considered This is an intertemporal equilibrium model, the dynamics of which is based on intertemporal optimization by firms and households Data series: 1947–85
Jorgenson, and Wilcoxen (1993c) Jorgenson, Slesnick and Wilcoxen (1992)	USA	Similar to the detail in row 2, with the exception of 1344 households instead of 672 in those studies
Hazilla and Kopp (1990)	USA	There are 36 production sectors but relies on a representative household Translog cost functions are used for producing sectors It is also an intertemporal equilibrium model Data series: 1958–74

price-induced substitution and economic rationality are included in the model. Fifth, a model's 'closure' is chosen and justified on the basis of empirical and institutional analysis of the economy at hand. These models, thus, do not follow the strict neoclassical construct of AGE modelling.

A few structuralist models have been used for energy studies. Sarkar and Kadekodi (1988) used a ten-sector model for the Indian economy to analyse the issues related to energy pricing. In order to capture the issues like the administered pricing in many sectors including energy, government participation and control in core manufacturing sectors and agriculture, and the sectoral difference in output and price formation, they resorted to the structuralist approach. A similar model was used by Panda and Sarkar (1990) to examine the implications of increasing administered prices to finance public investment in India. Similarly, Choucri and Lahiri (1990) studied the issue of energy pricing by state-run oil refining and natural gas producing companies in Egypt.

There are some other models that use SAM as information system but not necessarily use the structuralist approach of analysis. Khorshid (1990), for example, used a dynamic model for Kuwait to address a set of polity issues, inter alia, related to oil production and prices, the impact of various investment programmes, etc. Seddighi (1985) has used a price endogenous AGE model combining a SAM-based information system with an optimization model and attempted to broaden the SAM-based models.

Clarete and Roumasset (1986) nicely summarize the weakness of models of this tradition. First, by drawing relationships from a variety of theories, the model structure becomes highly arbitrary. Second, models become non-transparent once various relationships are appended and it becomes difficult to identify 'what is running the model'. Third, 'non-neoclassical relationships undermines the welfare economics of general equilibrium'. Thus, by 'trading neoclassical structures for more "realistic" empirical results' they introduce elements whose statistical and welfare-analytic aspects remain unknown.

3.5. *Intertemporal optimization models*

Generally in an AGE model, the energy sector is treated in the same way as are treated all other sectors, i.e. through the use of production or cost functions. This treatment of energy sector technology is not quite satisfactory in cases where a new technology with a different input requirement is envisaged (which is often the case in energy) or the energy policy measure is linked to a particular technology (for example, a ban on nuclear power), or for long-term policy analysis like CO_2 abatement. An elaborate treatment of the energy sector technology is then needed. ETA-MACRO by Manne and Richels (1977) is such a model in which a process analysis for energy technology assessment (ETA) is merged with a macroeconomic growth model (MACRO) providing for substitution between capital, labour and energy inputs. Mathematically, ETA-MACRO is a multiperiod, non-linear optimization model but by the equivalence theorem, the solutions of the model can be interpreted as equilibria in a competitive economy (Bergman, 1988). The model contains a detailed description of the energy sector but the rest of the economy is aggregated into one single non-energy sector.

In ETA, energy demands are divided into two end products; electricity and nonelectric energy. The present value of costs incurred (this includes the cost of supply, conservation and interfuel substitution) annually during each five-year period over the time horizon of the study is minimized. The model takes into account a number of electric and non-electric technologies, including a set of new technologies available for the future. The supply of new technologies is controlled through a set of upper bounds (imposed to control the rates of market penetration for new supply technologies) and lower bounds (to ensure the older technologies will not be phased out too rapidly). In order to explicitly model the gradual adjustment of factor proportions over time as relative prices changes, a 'putty–clay' representation is utilized.

In MACRO, energy–economy interactions occur in two ways. Aggregate economic output is allocated between interindustry payments for energy costs and final demands for current consumption and investment. Again, aggregate output is assumed to depend upon four inputs: capital, labour, electricity and non-electric energy which are combined through a nested Cobb–Douglas production function. These identities imply that an increase in energy costs will reduce the net amount of output available for meeting current consumption and investment demands (Manne and Richels 1990a, 1990b, 1991).

The global version of the ETA-MACRO model, Global 2100, is used to analyse the costs of a carbon emissions limit on a global scale. It is a model with parallel computations for five regions[12] based on intertemporal optimization. It is benchmarked against 1990 base year data, and the projections cover 11 ten-year time intervals extending from 2000 through 2100. This model, however, does not allow for trade and strictly speaking, is not an AGE model. In later versions, uncertainty is taken into consideration through probabilistic models using decision-theoretic framework (Manne and Richels, 1991) or through expert judgement by probability polls (Manne and Richels, 1994). In such analyses, various scenarios of different parameter combinations have been used to arrive at a probability distribution for costs of CO_2 emissions abatement.

The Carbon Emissions Trajectory Model (CETA) by Peck and Teisberg, 1993, is a model based on Global 2100 but incorporates additional representations of greenhouse of gas accumulation, global mean temperature rise, and the adaptation/damage cost associated with this temperature rise. Peck and Teisberg (1993) also presented a probabilistic version of CETA using decision theoric framework.

The Carbon Rights Trade Model (CRTM) by Rutherford (1992) is similarly an extension of the Global 2100. This model shares a number of structural features (such as five regions, 10-year time intervals beginning in 2000 and extending to 2100, a process submodel that describes the energy sector) in common with Global 2100. But the main difference with Global 2100 is that CRTM is based on recursive rather than a forward-looking structure. Also, in CRTM there are two non-energy goods and energy sector decisions respond only to current rather than future prices. With these incorporations, CRTM appears to combine two modelling traditions, namely, that of optimization and HSSW.

Manne and Rutherford (1994) report a formal AGE extension of Global 2100 which was used to analyse the possible impact of carbon emissions restriction limits on future oil prices, the problem of leakage which could arise if unilateral limits on emission are imposed, and the gains from trade in carbon emission rights. This version uses a single representative producer-consumer within each of the five regions. Technological progress is introduced into the macroeconomic production function in a Harrod-neutral form. International oil and gas prices are projected endogeneously. Another static, three-region model, Manne (1983), was constructed for the specific purpose of estimating the effects of trade-balance constraints on oil imports and economic growth in the industrialised and developing regions.

Blitzer et al. (1992a, 1992b) have also used a multisectoral, intertemporal AGE

[12] Five geopolitical regions are: the USA, other OECD countries (Western Europe, Canada, Japan, Australia and New Zealand), the USSR and Eastern Europe, China, and the rest of the world.

model for country specific studies to evaluate the effects of restricting carbon and methane emissions. But they used a linear programming, rather than a non-linear model as in ETA-MACRO. By identifying and accounting for methane as well as carbon dioxide emissions, the authors believe that their model could be called a second generation environmental model.

Like the econometric tradition, AGE modelling based on intertemporal optimization has not received widespread support from other model builders. This is mainly because of the equivalence criteria, which equate the solution of the optimization problem to the solution of the macroeconomic model, used in these models. Since market distortions, fiscal policies, etc., cannot be included here, they have limited applications and thus has less appeal to others (Schubert, 1993). Similarly, though Manne's models contain a detailed energy technology specification, the aggregate macroeconomic specification fails to identify the sectors and the segment of population most affected under different policy options. Moreover, all criticisms against calibrated models also apply here, particularly so for long-term models that project impacts hundred years from now based on a single point present data.

4. Lessons from and issues in AGE modelling

The wide range of AGE models used in energy studies show that such models are suitable for studies on energy–economy interactions. Being issue specific rather than general purpose models, they have provided insights to various policy debates. They became more relevant in the environment and global warming related issues. As a consequence of these modelling efforts, the understanding of the interplay between energy prices and economic growth has improved. The effects of changed energy conditions on the production of, demand for and prices of other productive factors have been clarified, distributional and welfare consequences have been measured, and some potential dynamic effects have been incorporated. Moreover, the AGE modelling tradition has benefited from the experience of energy studies. Models have become truly dynamic and are systematically being used for long-term policy analyses. Even probablistic aspects are added to such modelling to take care of uncertainties. As already noted, their strength lies in providing a consistent framework of analysis incorporating various economic actors that can be solved numerically. However, since all models are simplified representations of the reality, and because models need a large quantity of data and parameter estimates, a number of issues are involved with this approach also that one needs to keep in mind.

First, is the problem of elasticity specification. It is generally agreed that the elasticity values are the single most important parameters that affect the results. In the economic literature, there is little consensus about different elasticities for energy products. Even 'the robustness of any elasticity value in the literature may mean little when used in conjunction with other elasticities in a large model' (Shoven and Whalley, 1984, pp. 1045). In a model, some elasticities are more sensitive than others and they do not affect the model results in the same manner. Some modellers have tried to use sensitivity analysis, but synthesizing the results so that a clear judgement on robustness can be made remains a problem. Since the robustness of the results is dependent on the parameter values and since there are no possible meaningful statistical tests of any model specification, the results should be interpreted with extreme care.

Second, is the specification of technology. In economic models, technology is specified through production functions that transform different inputs into outputs. They assume that markets work efficiently and under the cost-minimizing behaviour, all new investments result in the best techniques. All existing inefficiencies in an economy are implicitly incorporated in the model through parameter estimation. Thus technology becomes directly related to elasticities used and pose the same problems as mentioned above. Moreover, since a myriad of technologies having very different characteristics are used in the energy sector, using one average function for the sector perhaps does not do justice to these technologies. For example, specifying one equation for the electricity production may yield a very different result than in reality, since the electricity production depends on, inter alia, load characteristics, production technologies, and the generation mix. This problem becomes more serious in very long-term models since we presume that technology will have the similar characteristics as in the past, though in fact, they may be quite different. Moreover, because a model can implicitly treat a limited number of technologies, by inevitably excluding a certain technologies, there can be an in-built tendency for distorted results (for example, to overstate the abatement costs of GHG emissions reduction, Grubb et al., 1993). It appears that detailed treatment of the energy sector is very important for the very long-run models.

The third issue is related to the choice of a particular model structure before the policy analysis proceeds (what Shoven and Whalley 1984, termed as 'model preselection'). Modellers build their models on the basis of their perception and importance of the issues they want to analyse. By choosing a particular structure, some options are eliminated, while others are highlighted. Consequently, results depend on the model specification. Also, part of these differences in emphasis and approach reflect the difference in views on how economies work, and part is due simply to different time horizons (Dervis et al., 1982). Thus, 'conflicting economic theories are not resolved merely by putting numerical values on parameters in specified functional forms' (Shoven and Whalley, 1984).

Fourth, models carry the inherent limitations of the underlying theories. Since majority of the models are based on the neo-classical theory, they assume perfectly competitive markets, optimizing behaviour of agents, absence of externalities, etc. Structuralist models have tried to depart from this structure to incorporate more realism. As we have noted earlier, even here, the problem of interpretation arises once ad hoc structures are added, since it is difficult to identify what runs the model.

Fifth, the question of disaggregation has also appeared to be important in AGE models. With the availability of new computing facilities, more and more large models are being used. It is generally claimed that larger models offer more opportunity to anlayse the problems intimately. This however, depends on what one wants to analyse. Bopp and Lady (1982) used a two-sector GE model for the USA that produced results remarkably similar to those produced by much larger models for welfare loss due to increased in energy prices. This implies that a compromise based on the objective of the study, constraints on cost, time and other factors needs to be reached.

Sixth, most AGE applications to energy studies ignore the importance of non-commercial sources of energy in developing countries. It is well-known that a large section of the people in the developing world derive their energy needs from non-commercial sources. Since AGE models are price driven, it is difficult to incorporate such issues. Moreover, data related to non-commerical energy use are scanty, mostly ill documented, and probably unreliable. But this issue gains more importance when one considers the impacts of increase in prices and taxes of commerical sources, subsidy removal, or even imposition of a carbon tax on energy, etc. Since, a minimum amount of energy is a basic human need, disregarding these non-commercial sources from any analysis, at best, results in a partial picture.

Seventh, most of the long-term global models treat the developing countries in a very aggregated manner. It is also argued that the contribution of greenhouse gases from these countries will grow more rapidly in future as these countries develop. Since, there are wide variations in socio-political and economic conditions among them, a summary representation cannot capture their differences. More disaggregated developing country representation will lead to a better understanding of issues in those countries.

Eighth, while models have tried to take into account the long-term (100 to 200 years) impacts of greenhouse emissions in future, they neglect the impacts of past accumulation. In other words, the fact that the present crisis is due to the effects of development efforts during the past two centuries in the developed countries, are not recognized in such models. While such models are very active in considering the future energy consumption patterns in developing countries, by deliberately neglecting the past accumulation (or by using very simplified versions), they provide very biased policy recommendations.

Finally, for long-term models, problems related to uncertainty, discounting, and a host of others arise. Everybody knows that nobody knows what will happen. Even if some probabilistic features are incorporated in the models, uncertainty will remain. Similarly, discounting future is a difficult issue. Difficulties arise because of the failure to distinguish between time discounting and goods discounting. While time discounting is concerned with the utility trade off of different generations, it is through goods discounting any society decides whether to make an investment aimed to reducing today's consumption in order to increase consumption in the future (Nordhaus, 1990, 1993). So the results obtained from long-term policy models should be used with care.

5. Closing remarks

The energy sector has proved to be a good area for applying AGE models. These models have contributed to policy debates. Three distinct modelling features (econometric estimation, probabilistic application and very long-term modelling) have been developed to cater to the demands of energy–environment studies. It can probably be said that the tradition of AGE modelling has gained as much as they have contributed to energy policy analyses.

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