MATHEMATICAL MODELING AND SIMULATION METHODS IN ENERGY SYSTEMS

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Contents

Summary

This paper presents an overview of the modeling approaches that are used to represent, understand and control the interactions between the economy of a region, its energy production / consumption system, and the environmental impact of these activities.

1. Introduction

Energy systems are closely linked with economic development. Our modern societies depend largely on a complex network of technologies that extract, transform, deliver and utilize different energy forms to provide a set of services like comfort (air conditioning), transport, power, light, household needs, industrial heat, force, etc… Energy flows pervade the whole economic system in both the production and consumption sides.

The oil crises of the seventies, the accompanying supply disruptions and sudden price jumps with the subsequent painful economic adjustments, eloquently demonstrated that the economy could not take for granted a steady supply of cheap fossil fuel; consequently a battery of models have been developed to explain the interdependence between the economy at large, and the energy sector, in particular. The aim was to study the best way one economy could adapt, for example, to an abrupt change in availability of crude oil as a primary energy source. The models developed at this occasion are typically PIES (a partial equilibrium model developed for the DOE), EFOM (a linear programming model developed for the European Commission), MESSAGE (a linear programming model developed at the IIASA) and MARKAL (a linear programming model developed for the IEA). Let us also mention MEDEE, a simulation model for the demand of energy that has been very influential in the European Union.

These acronyms refer to only a few of the large number of models that have been built to capture the complex interactions between technologies, energy options, economic development, and social acceptance of energy policies. However these models are archetypal and indicate the main concerns and challenges faced by the decision makers and that the models should help to clarify: (i) Energy demand (like e.g. gasoline demand) is a derived demand; there is a consumption of a service (typically here private transportation) and, due to the use of particular technology, this translate into a demand for gasoline… The same is true for many other services. Therefore the energy demand is fundamentally related to technology choices. This could be described in great details, either in optimization models (EFOM, MARKAL) or in simulation models (MEDEE). In optimization models one implicitly assumes that the technologies are adopted on the basis of a 'cost-efficiency' analysis, whereas in simulation models one may try to include other factors influencing the adoption of technologies by a consumer of energy services (for example a switching from an oil furnace to a wood furnace may not be uniquely triggered by cost considerations but could also be based on consumer subjective preferences). (ii) Energy is a fundamental resource for the economy. Therefore energy demand will be influenced by 'macro-economic' adjustments taking place in other economic sectors (e.g., an energy tax may lower the production of energy intensive industrial sectors and thus reduce their energy demands). Furthermore, the supply and demand of different energy forms should balance on markets that could have a variety of structures, from purely competitive, to monopolistic, not to mention the oligopolistic market structures that characterize the world oil or coal markets. In brief, the models should permit a detailed representation of new technology / energy options and should also permit a coupling with more detailed economic models and a representation of the different market structures in the energy sector.

The oil crises were followed by a return to normal life and low world price of oil... The motivations for the definition of global or national energy policies were receding. Not for long, because, then, came the concern about global climate change... This time, fossil fuels were not threatened to be quickly exhausted, but, being the major culprits in emitting too much green-house gases in the atmosphere, their use in particular for power generation and transportation should be severely curtailed in a sustainable economy. This has given a new impetus to the development of energy-economy-environment (E3) models. MARKAL for instance has had developments in many different directions, with a new improved version called TIMES; its coupling with a macro-economic aggregated model has been realized in MARKAL-MACRO, following a precursor called ETA-MACRO. Joint implementation for several world regions or countries, or for a developed and a developing country exchanging emission rights have been successfully performed. Implementation at a local level (city or canton or urban community) has been successful, in particular in Sweden and Switzerland. Other models following alternative modeling approaches (see below) have also continued their successful development to address the interplay between the energy sector and the economy, in particular in the context of global climate change.

Our aim in this paper is to provide a first account of the general structure and potential use of these mathematical and simulation models of energy systems. The paper is organized as follows. Section 2 gives a first taxonomy of energy-economy-environment (E3) models, following their main modeling approach. Section 3 proposes an alternative classification, detailing different model purposes. Section 4 discusses technology ranking and Section 5 some issues in energy modeling (technological change issue, uncertainty issue and discounting issue). The environmental issue is finally addressed in Section 6.

2. Bottom-up versus Top-down Modeling

Often one classifies the E3 models in the *bottom-up* or *top-down* categories. The bottom-up approach follows a techno-economic philosophy that leads to disaggregated models representing the energy sector with great details. By contrast, the top-down approach follows a macro-economic philosophy that leads to aggregate models in the sense that they use aggregate economic variables.

In bottom-up models, one proceeds with a complete list of energy forms and energy technologies. These models distinguish in particular production technologies (e.g., refineries, power plants) that transform primary energy (e.g., crude oil, wind) into secondary energy (e.g., gasoline, electricity), and distinguish also demand technologies (e.g., vehicles, light bulbs) that transform final energy (namely secondary energy that has been distributed to consumption points) into energy services (e.g., mobility, lighting). A detailed accounting is kept of energy input and output in every technology uses and balance conditions (energy conservation) are maintained everywhere when needed. Aggregating all theses energy flows one obtains the global energy accounts for the region under study. Bottom-up models are driven by a description, generally exogenously given, of demands for the different energy services. These models enable one to select the least-cost energy configuration (energy forms and technologies) that satisfies in particular energy demands and eventually pollution limits. Examples of such models are EFOM, MESSAGE and MARKAL.

In top-down models, one considers a broader equilibrium framework where one computes demands—for goods and services—and supplies from the main economic sectors (energy, but also agriculture, industries and services). These models are usually based on macroeconomic theory and econometric specifications using economic aggregates as observables. Top-down models enable one to capture more economic feedbacks between the energy sector and other economic sectors, but usually without representing explicitly energy technologies. Energy use is indeed rather defined as the result of economic equilibria: considering for instance the market of a given commodity whose supply and demand is computed, energy consumed by firms to produce this commodity is typically determined by the relative price of energy compared to the one of the other production factors (e.g., capital, labor, materials). Notice that this choice among different production factors depends also on elasticities of substitution, which represent degrees of substitutability among these factors. Examples of top-down models are EPPA (a computable general equilibrium model developed at MIT), GEM-E3 (a computable general equilibrium model developed for the European Commission), and MACRO (a Ramsey-type optimal growth model).

These two categories of models are complementary as they permit one to address different questions posed by the rationalization of energy production and usage. Bottom-up models are appropriate for assessment of new technologies and marginal cost analysis. Top-down models are more adapted to the analysis of the macro-economic impacts of energy policies.

As with every taxonomy, this classification of E3 models between bottom-up and top-down ones is clearly limited, as for instance hybrid models are developed which try to incorporate within the same framework both modeling approaches, as discussed in particular in the forthcoming Section 3.2. To go beyond this limitation, we propose in Section 3 an additional taxonomy that classifies E3 models based on their main purpose.

3. Simulation vs. Optimization

Mathematical models are used to give a formalized representation of the energy system so as to permit computer-based operations that provide insight concerning different possible energy policies. In *simulation* models, the emphasis is put on the consistent treatment and exploitation of a large techno-economic database. In *computable economic equilibrium* models, one tries to capture the basic economic equilibrium adjustments that should drive the energy system in a competitive world. Optimization and simulation models are differentiated on another level: simulations and trend analysis models focus more on the most likely outcomes whereas optimization models look for 'ideal' outcomes (e.g., best technologies and energy forms satisfying exogenous constraints).

3.1 Simulation and Future Tendency Predictions

Simulations for future energy use are based on predictions emanating from knowledge of accumulated data from the past; the more relevant data available, the more accurate the simulation. Consider, for example, the demand for electricity, or the demand for light fuel oil in a given region. This demand is the result of a very large set of technology choices made by the households, the industries, the transport users, etc. To understand how the demand could evolve in the future, given a wide range of technologies, both old and new, the modelers have been prompted to build large and comprehensive data bases that could be exploited numerically to provide consistent evolution scenarios over a relatively long term. A good example of that strand of models is MEDEE, which has been widely used in the EU to analyze energy demand formation. In these models the mathematical sophistication is reduced; the model boils down to an accounting system.

This accounting system analogy leads one to classify simulation models as bottom-up in nature as the aggregated demand from all possible energy uses is supplied by the accumulation of all possible energy supplies and services.
In a related methodology, econometrics provides forecasting based on economic models identified through statistical methods (e.g., regression analyses, simultaneous equations models with endogenous and exogenous variables, etc.) in order to extrapolate the past observations to predict future tendencies. One weakness of econometric methods is that it is based on a statistical analysis of past energy market behavior; therefore it might be difficult to represent in an econometric model the impact of new technology options. This has led to other techniques such as trend analysis.

Trend analysis looks at the history of an economic variable to make predictions. The introduction of new technologies can be represented in trend analysis and predictions are made based on logical assumptions integrated in *decision rules*. An example would be domestic electrical power consumption, where past decreases in domestic energy consumption came after the introduction of more efficient technologies, e.g. more efficient refrigerators, lighting, and other appliances. The prediction for future power consumption could be assisted by the knowledge gained in observing the outcome of these power efficient devices. The uncertainty in the complicated social behavior of the consumer will, however, limit the predictive capability of trend analysis.

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Biographical Sketches

Alain B. Haurie, has obtained a degree in mathematics in 1961, a doctorate in applied mathematics in 1970 and a doctorate in physics in 1976. He has been professor at the Graduate Business School of the University of Montreal, Canada (1963-89). Since 1989 he is professor of operations research in the department of management studies (HEC) at university of Geneva, Switzerland. During his academic career he has occupied positions of department chairman (1974-1976 in Montreal, 1989-1992 in Geneva) and has been the founder and first director of a research centre dedicated to decision analysis (GERAD in Montreal 1980-1089) which became one of the leading research centre in Canada for OR. He has authored or co-authored over 150 scientific papers and co-authored 3 books. He has been in charge of orienting continuing education programs at the university of Geneva (1996-2001). During various academic leaves he has also taught at Ecole Polytechnique de Montréal (1970-74), INSEAD, Rabat, Morocco (1976-1978), University of California, Berkeley, USA (1980), Victoria University, Wellington, New-Zealand (1993), Ecole des Mines de Nantes, France (1993-1995). Currently he teaches operations research, decision support systems and environmental management in various undergraduate and graduate programs of University of Geneva. He is the director of a continuing education program on environmental management for the firms. He is directing several research projects that deal with the economics and finance of environemental management. He is also directing a project of the Swiss virtual campus program that implements a distance learning modular course on sustainable development.

Olivier Bahn, received in 1989 an MSc in Information Technology from the Conservatoire National des Arts et Métiers (Paris, France) and in 1994 a Ph.D. in Management Sciences from the University of Geneva (Switzerland).He is currently assistant professor of Management Sciences at HEC Montréal (Canada).Between 1995 and 2003, he was working as Scientific Officer in the General Energy Research Department of the Paul Scherrer Institute (PSI, Switzerland). During his stay at PSI, he was in particular serving as Deputy Principal Investigator for the Swiss NCCR Climate Project, working on a world integrated assessment model to analyse climatic policies that take into account risks of extreme climatic events. He was also serving as Project Leader for PSI participation in several research projects funded by the European Commission (DAT-GEM-E3, DYN-GEM-E3 and TCH-GEM-E3), working on the general equilibrium model GEM-E3 for Switzerland. Besides that, he has participated in several other research projects, in particular the SAPIENT project of the European Commission (working on the development of an energy model that treats endogenously technological progress and analysing research and development policies aimed at fostering the development of cleaner and more efficient energy technologies) and the ETSAP project of the International Energy Agency (analysing using energy models international strategies to curb energy related CO_2 emissions).He has been an Expert Reviewer for the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, Working Group III). He has also written many scientific articles in books and journals and participated in numerous international scientific conferences as well as university courses.His research interests include applied mathematics (computation of economic equilibria, convex and stochastic programming), energy-economy-environment modelling (general equilibrium and optimisation equilibrium models, bottom-up engineering models) and sustainable development (promotion of policies that would prevent in particular drastic climate changes).

Daniel S. Zachary, is a physicist specializing in environmental modeling. His recent work has included the design of an urban air quality (ozone) model used in the optimization framework. Currently he is involved in global climate change analysis applications in the optimization framework. His particular domain of interest involves uncertainty and time-scale analysis relating to the coupling of models of different speeds (example climate and energy-economic models). Dr. Zachary has a background in nuclear physics (modeling correlated particle momentum in relativistic heavy ion collisions) and astrophysics (Ph. D. MIT, 1994 and M.S. MIT, 1986) and is currently part of the physics faculty at the American University of Sharjah (UAE) where he teaches environmental physics. Dr.Zachary remains active in research with the University of Geneva and the Swiss Global climate change assessment research group (NCCR WP4).