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RECENT ENERGY MODELS: A REVIEW OF METHODOLOGIES

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ABSTRACT

In the wake of the oil crisis of late 1973, policy makers have become greatly concerned with energy issues, and have increasingly turned to analytical researchers to help them grapple with these complex problems. However, the modeling of socio-economic systems is far from perfected, and policy makers need to be aware of the limitations of the techniques used by their analysts. Consequently, this paper reviews the commonly used methodologies of optimization (linear programming), econometric methods, input-output analysis and system dynamics simulation with frequent reference to their applications to energy policy. A table of important recent work in energy modeling is included at the end of the paper.

Introduction

Since the Organization of Petroleum Exporting Counties (OPEC) unilaterally quintupled the world market price for oil in late 1973 and early 1974, the attention of policy makers has increasingly been drawn to energy issues. The early proposal by the new Carter Administration to establish a Department of Energy, and the severe energy problems in the U.S. and Canada during the unusually harsh winter of 1976-77 dramatize the critical nature of these concerns.

The complex nature of energy policy has also caused governments to turn to analytically trained researchers for aid in understanding and coping with these problems. Although the use of formal analytical techniques for energy policy evaluation is relatively new, a large number of universities, government agencies

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and companies are developing or using a wide variety of such modeling methods. It is the intent of this paper to review briefly the basic methodologies employed and to discuss their limitations. Examples are drawn from among the most important of recent contributions, and a Table of Energy Models at the end of the paper summarizes much of this work.

Most studies are variations of four basic approaches: optimization, primarily of the linear programming variety, econometric models, input-output analysis, and simulation of the system dynamics type (structural analysis). Usually one technique forms the basis for the model being developed, but often several methods are employed. Edward A. Hudson and Dale W. Jorgenson, for example, have attempted to integrate econometric modeling and input-output analysis, while Michael Kennedy has used a linear programming framework to develop an oil refining sub-model to his econometric model of the world oil market.

Models

OPTIMIZATION: LINEAR PROGRAMMING

The first important methodological distinction in energy modeling is between simulation and optimization models. Simulation models answer questions of the "What if . . .?" variety. A real system that is too complex to deal with is abstracted. That is, a model (mathematical analog) of the system is built in order to understand how the system will perform under given conditions (model manipulations). Such an approach is especially useful for studying mutually interacting processes which involve non-linearities and time lags. It constitutes a powerful aid to decision-makers and planners.

Nevertheless, optimization models, especially those of the linear programming (LP) kind have been used far longer. There is an established tradition in industrial economics of using linear programming to represent refinery construction and operation options [1, 2]. Pioneering work was done by Manne and Symonds [1]. However, the public sector policy applications of such models have been less widespread, partly due to the fact that they are "large, cumbersome, and complex, . . . require the specifying of a great many technical coefficients within the model structure" [3, 4], and make excessive demands on computer storage space and time. Although there have been recent important advances in the technology of large scale linear programming models, ". . . the LP model often remains a black box that does not show the user the route to the optimum that it produced [4, 5]."

Despite these problems, one ambitious large scale optimization model is currently under development. This is the World Energy Model of Queen Mary College, London. However, it owes a heavy debt to the early, smaller scale studies of individual oil companies. An energy research unit was formed at this college in 1972 under Professor Robert Deam who had acquired his fifteen years of modeling experience with British Petroleum (BP). BP has used computer modeling as an aid to management decisions for many years; and the basic tenant of this world energy model is that the BP system created for one company within one industry can be extended to cover the global energy system, the difference being only one of complexity, particularly as regards political and social constraints [6-9]. This seems a questionable premise but the model is not yet far enough along for a definitive judgment.

In addition to the problems of scale, there are a number of other drawbacks to the optimization approach. Formulation of the problem for an "optimizing" procedure necessarily distorts the objectives in a number of ways. It requires ignoring some objectives completely, specifying arbitrary and rigid constraints to represent others, and combining the remaining objectives in a welfare function or performance criterion which purports to express their relative importance. Furthermore, it is necessary to force the model of the economy into more restrictive forms for the mathematical process of optimization [10]. These necessary distortions in the basic formulation of the objectives and of the model raise serious doubts about whether the "optimum" thus found is really the best solution—or even a good one—in terms of all relevant considerations. It is, therefore, easy to understand the preference of many planners and decision makers for simulation models on which they can try out their own necessarily imperfect solutions which might involve barely quantifiable, perhaps because half-formed, political and social constraints.

Perhaps, then, Michael Kennedy has identified the best use of optimization techniques for energy policy studies. He uses the LP framework to model the refining sector of his regional, multi-commodity economic model of the world oil market [11]. Thus, he confines use of the technique to that area where it has been proved successful, thereby avoiding the weaknesses outlined above.

ECONOMETRIC MODELS

Econometric models are typically distinguished from other analytical approaches by their use of time series data and statistical techniques—primarily some form of regression—to study the relationships between variables and to estimate model parameters.

Moreover, most econometric models estimate shifts, that is, changes rather than totals in measuring variables over time; and the relationships between the variables are generally of a simple type. That is, they are either linear or can be transformed into linear form by taking logs. It is this simplicity of linearity and additivity, which is so attractive to modelers. Finally, it should be noted that the relationships between the variables of these models usually have some basis in economic theory, though "econometric" seems to be used broadly today to describe models which employ this particular kind of statistical analysis [12].

There are three important objections, however, to this type of general approach. First, there are a number of relationships that might be included in a model concerned with energy policy that might not lend themselves to econometric techniques. Time series data could be unavailable, limited or of such poor quality as to be useless. In addition, to the extent that the observed data represent situations that are under structural change, econometrically fitted functions may not represent the future, and simulations based upon them could be misleading. But even more important is the fact that it is quite often possible to produce a number of very different models with different input factors producing very different predictions, but all having statistically significant parameters [13].

Despite these criticisms, the technique is employed widely by energy analysts in the industrial nations where its statistical power is emphasized. One important econometric energy model has been developed by Dr. Robert S. Pindyck and Professor Paul W. MacAvoy at the Sloan School of Management at MIT to assess the potential magnitude of the growing shortage of natural gas in the U.S. and the likely impacts of alternative regulation policies [14-16].

But while this model manages to get further away than most such models from the almost ritualistic approach of setting up a log-linear equation in the hope of finding statistically different parameters by regression analysis, and while it appears to have a good deal more imagination incorporated in it than most econometric treatments, it still does not entirely escape the general objections to this type of model as noted above [3].

INPUT-OUTPUT APPLICATIONS TO ENERGY

Leontief defines the input-output method as "an adaptation of the neoclassical theory of general equilibrium to the empirical study of the quantitative interdependence between interrelated economic activities." It was originally developed to analyze and measure the connections between the various producing and consuming sectors within a national economy, but has also been applied to studies of economic systems ranging from large, integrated private enterprises to metropolitan areas, to international economic relationships.

Nevertheless, in all cases, the approach is basically the same. The interdependence among the individual sectors of the given system is described by a set of linear equations giving a detailed picture of the flow of goods and services that individual industries buy from and sell to each other in a year. The system's specific structural characteristics are consequently reflected in the size of the coefficients of these equations. These coefficients must be determined empirically. In the analysis of the structure of a national economy, they usually are derived from a so-called statistical input-output table constructed from published data.

Over the past several years, there has been a rising interest in the application of input-output analysis to energy problems. Input-output computations have been used by American government agencies and private organizations to assist in forecasting shortages of fuels and other industrial outputs during the 1973 Arab oil embargo. They have also been used to estimate the impact of these petroleum shortages on employment and prices and to analyze the long-term economic effects of prospective changes in energy technology [17]. These problems require a detailed economic systems approach because they involve many interdependent industries and consumers. Studies of new energy technologies, for instance, must bridge the gap between technical specifications that call for particular inputs—steel, construction, computers, instruments, etc.—and production and employment in all sectors.

Two important examples of applications of input-output analysis to energy considerations are the studies of Anne P. Carter and William A. Reardon. Carter has constructed a closed dynamic input-output model to evaluate the effects of specific pollution abatement and new energy technologies on the rate of economic growth and on the relative importance of sectors in the U.S. economy over the next ten to fifteen years [18], while Reardon's major contribution has been the construction of direct and direct-plus-indirect energy coefficients for 1947, 1958 and 1963 for thirty-five economic sectors [19]. The importance of this work is that examination of the time trend of the coefficients suggests the trend of energy consumption per unit output in the individual sectors and in the economy as a whole (all sectors).

Another important contribution here is the Hudson-Jorgenson attempt to integrate input-output analysis with the econometric approach [20]. The principal innovation of the interindustry model of their complex, imaginative study is that the input-output coefficients are treated as endogenous variables rather than exogenously given parameters. Their model for producer behavior determines the input-output coefficients for each of the economy's nine sectors as functions of the prices of products of all sectors, the prices of labor and capital, and the prices of competing imports. The prices of all nine products and the matrix of input-output coefficients are determined simultaneously. In conventional input-output analysis, the technology of each sector is taken as fixed at any point in time. Prices are determined as functions of the input-output coefficients, but the input-output coefficients themselves are treated as exogenously given parameters.

Hudson and Jorgenson link this interindustry model to a macro-econometric growth model which integrates the determinants of demand and supply. Given this framework, the model then provides a reference point for the analysis of energy policy by establishing detailed projections of demand and supply, price and cost, and imports and exports for each of the nine industrial sectors. The projections for the five industrial sectors that form the energy sector of the U.S. economy provide the basis for translating the detailed projections into an energy balance framework. That is, the demand is equal to the supply in physical terms for each type of energy. In addition, demand and supply are consistent within the same structure of energy prices.

Input-output analysis is the only method now available for dealing empirically with the types of problems concerning Carter and Reardon. However, there is a danger that the convenience of the approach will obscure its limitations. Even the enormous U.S. data base is considered "modest as compared with those of other countries where the system has been used more in energy and other applications" [21]. In addition, some of the information needed to solve current problems is not yet available, and input-output studies have much greater data requirements than either the econometric or the demanding optimization models. Consequently, the Hudson-Jorgenson study in treating input-output coefficients as endogenous variables suggests a new and promising way to overcome these difficulties.

SYSTEM DYNAMICS MODELS

A markedly different approach from those discussed previously to study energy policy questions has been suggested by Jay W. Forrester. It is his basic theme that the human mind is not adapted to interpret how complex societal systems behave. Social and economic systems belong "to the class called multi-loop non-linear feedback systems;" and it has not been necessary until recently for man to understand these systems. Consequently, man has not been equipped through evolution to properly interpret the dynamic behavior of the systems of which he is a part [22]. His mental models are "fuzzy," or "incomplete," or imprecise; and his intuition is, therefore, inadequate to understand and deal with the "counterintuitive nature of social systems" [20, 23].

It is clear then, that many mathematical models are limited—some because they are formulated by techniques and according to a conceptual structure that will not accept the multiple feedback loop and non-linear nature of real systems—others because the people who have developed them lack the necessary knowledge or are deficient in perception [24]. Forrester suggests a model that is different from those that are most common in the social sciences. Such a model is not derived statistically from time series data (an econometric model), nor is it an attempt to optimize performance within certain constraints (a linear programming model), nor is it a matrix of interdependent relationships in an economy described by a set of linear equations (input-output analysis). A system dynamics model is, instead, a statement of system structure that is designed specifically to study the behavior of a system as it follows from the individual relations between system components. In physics or chemistry, there is normally a theoretical base to a model's structure, and quantitative relationships can be verified with experiments. It is highly questionable, however, that the variables and relations determining the behavior of the world's economic systems can be modeled based solely upon economic theory. In fact, many of the functional relationships in a system dynamics model are ones for which there is no explanatory theory, evidence or experience. Thus, Forrester's approach explicitly recognizes that a model is only as good as the expertise that lies behind its formulation. That is, although it might not be possible to derive satisfactory econometrically determined parameters, simulation of the problem of interest under assumed parametric values can provide the decision maker with useful information for bracketing the probable outcomes of policy changes.

This type of approach has the crucial advantage of enormous flexibility in modeling complex situations, the behavior of which cannot be easily understood or explained [25].[1] However, this

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[1] While structural analysis has often formed a part of socio-economic models (including energy models), it has been used as a last resort; that is, when econometric techniques have been impossible to employ. In contrast, Forrester's approach represents a firm commitment to structural analysis as a methodology.

advantage can also be regarded as a serious weakness. Because statements in the model are not necessarily functions of particular theoretical statements, because parameters are often not subjected to rigorous statistical tests, and because judgments are made by the modeler at every step of the work from equation formulation to calibration to data, the methodology has been attacked as little more than a glorified and mystified qualitative analysis by proponents of other modeling methodologies.

Two important system dynamics energy models have been attempted thus far. The first is the comprehensive energy model developed by Michael H. Rothkopf and H. deVries for Shell Petroleum [26, 27]. It projects total global energy demand until 2020 and calculates a supply pattern of this demand for oil and gas, coal, nuclear power and other energy sources. It has been designed so that it can be used as a sub-model in a system dynamics simulation of the world such as that first suggested by Forrester in *World Dynamics* and later expanded, first by Meadows, et al. in *The Limits to Growth*, and then by Mesarovíc and Pestel in *Mankind at the Turning Point* [28-30].

The strength of this model is that it allows explicitly for assumptions about technological progress, economies and diseconomies of scale, and the rate of substitution of cheaper energy sources for more expensive ones. This allows a number of alternative scenarios of the world energy market to be simulated. However, a significant limitation of this model is apparent: the influence that the amount spent on energy may have on the development of Gross World Product is omitted; and this is, of course, a matter requiring immediate attention.

The second important system dynamics energy model is the preliminary investigation of the U.S. energy system's dynamic structure and behavior being conducted at MIT under the direction of Professor David C. White [31, 32]. The model is a highly aggregated one which focuses on some of the important relationships between energy, the economy and the environment. Since it considers total energy supply and demand, with no disaggregation for the various fuels, the model does not permit the investigation of interfuel competition or the depletion of any single fuel [33].[2]

[2] Dr. Martin L. Baughman of MIT has developed an interfuel competition model in the aggregated U.S. as his Ph.D. dissertation in electrical engineering. While the model is valuable in itself, it is intended to eventually be incorporated into this preliminary comprehensive model of the U.S. energy system. Dr. Baughman is an important member of Professor D. W. White's Program on Energy Analysis and Planning which is developing this tool.

Yet it does provide a framework to study the macroeconomic problems of investment demand, the effects of energy as a whole on demand and its growth, and the effects of environmental measures on the dynamics of energy supply.

Of particular importance is the way in which energy demand is treated. The basic drive for demand is considered to be population, and energy demand is assumed to be correlated with GNP. Furthermore, the model also considers the economic implications of the rising cost of energy on investment. It suggests that as energy costs rise, the fraction of GNP allocated to the purchase of energy will go up, and that part of GNP available for investment will go down [34].

Nevertheless, the very preliminary nature of this model must be emphasized. The authors feel that only when the model has become more comprehensive through expansion and the substitution of experience for pure postulation wherever possible, will it become more useful as a policy tool. So far, the model is not far enough along so that research on how it might be employed to suggest appropriate policy actions can be productive [34].

Final Comments

This last statement deserves more attention. In fact, it is clear that it is applicable to most of the energy modeling attempts reviewed above. This reflects the state of the art of public sector model building. While some approaches (e.g., linear programming) have been applied with success to certain types of industrial problems, applications to socio-economic systems have been much less fruitful. In fact, all the approaches that have been discussed are still undergoing development—largely in the fields of operations research, econometrics and regional science. Nevertheless, it is difficult to imagine coming to grips with problems as critical and complex as energy issues without such aids. Certainly the problems of the closing years of the twentieth century will be no simpler than those of today. Old methods will be increasingly insufficient. Work such as that reviewed in this paper requires additional support to speed its development so that it may provide the new methods so urgently needed.

Table of Energy Models

Name(s) of modeler(s)	*Institutional sponsorship or affiliation*	*Primary analytical technique(s) employed*	*Geographical concern*	*Single or multi-commodity model*	*Primary focus of analysis*
Robert Deam et al.	Queen Mary College, London	optimization (linear programming)	World	multi (all sources of primary energy although only oil and gas have been considered thus far)	supply, demand, pricing and market share
Robert S. Pindyck, Paul W. MacAvoy	Sloan School of Management (MIT)	econometric modeling	U.S.	single (gas)	supply, demand, and regulation
Decision Sciences Corporation TERA Model—Limaye, Sharko, Dawson, Pennington, et al.	American Gas Association	econometric modeling, structural analysis	U.S.	multi, although centered on gas	supply, demand, and pricing
Decision Sciences Corporation—Sharko, Pennington, Limaye, et al.	U.S. Office of Science and Technology	econometric modeling, structural analysis	World	single (oil)	supply, demand, and pricing
Energy Modeling Group	Department of Energy, United Kingdom	econometric modeling, structural analysis	U.K.	multi (coal, petroleum, gas, and electricity)	supply, demand, and regulation
Michael Kennedy	Harvard University	econometric modeling, optimization (linear programming)	World	multi (gasoline, kerosene, distillate fuel, residual fuel and crude oil)	supply, demand, and pricing
Edward A. Hudson and Dale W. Jorgenson	Date Resources, Inc. (Hudson); Harvard University (Jorgenson)	econometric modeling, input-output analysis	U.S.	single (*i.e.*, "energy" is considered in the aggregate)	supply, demand, and pricing
Program on Energy Analysis and Planning—David C. White et al.	MIT	system dynamics	U.S.	single (i.e., no disaggregation for the various fuels)	supply and demand

Michael H. Rothkopf and H. deVries	Shell Petroleum	system dynamics	World	multi (coal, oil and gas, nuclear, and all other conventional sources)	supply, demand, and market share
J. G. Debanné	University of Ottawa	operations research, network theory	North America	multi (oil, gas, coal and nuclear)	supply, demand, distribution, and pricing
Martin L. Baughman	MIT	system dynamics	U.S.	multi (coal, oil, natural gas and nuclear)	market share
R. D. Doctor, K. P. Anderson, et al. W. E. Mooz and C. C. Mow	Rand Corporation	econometric modeling	California	single (electricity)	demand
Lester Lees and E. J. List	Caltech	econometric modeling	South Coast Air Basin (California)	single (commercial and industrial electrical energy)	demand
U.S. Bureau of Mines	U.S. Bureau of Mines	econometric modeling	U.S.	multi	demand
NPC's Committee on U.S. Energy Outlook	National Petroleum Council	structural analysis, econometric modeling	U.S.	multi (oil and gas)	supply and demand
Philip K. Verleger	Data Resources, Inc. (in cooperation with H. Houthakker and Dale Jorgenson of Harvard University) for the Ford Foundation Energy Policy Project	econometric modeling	U.S.	multi	demand
H. Wein	Federal Power Commission	econometric modeling	U.S.	single (natural gas)	supply
Fisher	Resources for the Future	econometric modeling	U.S.	multi (gas and petroleum)	supply

Table of Energy Models (Cont.)

Name(s) of modeler(s)	*Institutional sponsorship or affiliation*	*Primary analytical technique(s) employed*	*Geographical concern*	*Single or multi-commodity model*	*Primary focus of analysis*
Paul W. MacAvoy	Sloan School of Management (MIT) supported by the Brookings Institution's Program on Studies in the Regulation of Economic Activity	econometric modeling (summarized in a non-technical essay in the *Bell Journal*)	U.S.	multi (gas and electricity)	supply
E. Erickson and R. Spann	North Carolina State University—supported by Resources for the Future	econometric modeling	U.S.	single (natural gas)	supply
J. D. Khazzoom	Federal Power Commission	econometric modeling	U.S.	single (natural gas)	supply
Kenneth C. Hoffman	The Polytechnic Institute of Brooklyn and the Brookhaven National Laboratory	optimization (linear programming)	U.S.	multi (hydropower, nuclear, coal, oil and natural gas)	optimal supply-demand configuration
William A. Reardon	Battelle Pacific Northwest Laboratories for the U.S. Office of Science and Technology	input-output analysis	U.S.	multi	demand
Anne P. Carter	Brandeis University	input-output analysis	U.S.	multi	demand

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