ENERGY SYSTEM MODELING AND FORECASTING

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INTRODUCTION

The energy system consists of an integrated set of technical and economic activities operating within a complex societal framework. Energy is a vital component in the economic and social well-being of a nation and must be considered explicitly in the formulation of regional, national, and international policy. As the importance of energy in policy making has become apparent, research and analysis in the field of energy system modeling and forecasting has grown rapidly. The field has evolved from one almost exclusively the domain of planning groups in the major sectors of the energy industry and of government regulatory agencies to one in which many Federal and State agencies are active in the development and application of energy models and forecasts. Energy system models are now used extensively for regional, national and international forecasting and for policy formulation and analysis.

Energy system models are formulated using theoretical and analytical methods from several disciplines, including engineering, economics, operations research, and management science. Techniques of applied mathematics and statistics used to implement these models include mathematical programming, especially linear programming, econometrics and related methods of statistical analysis, and network analysis.

The purpose of this review is to provide an introduction to the scope, applications, methodology, and content of energy system models, particularly those developed and used in the U.S. In the following sections we discuss the purpose, scope, and applications of energy system models. The important methodologies used to implement these models are surveyed, a classification of models is provided, and representative models are reviewed. The review is not intended to be exhaustive, nor to provide a comparative evaluation of models designed for similar purposes. Rather, the models reviewed are intended to be illustrative of the structure of recent and current efforts by energy system modelers to provide useful and constructive analytical tools for understanding and solving energy planning and policy problems.

SCOPE OF ENERGY SYSTEM MODELS

The concept of a model usually evokes an image of a complex, computerized system of mathematical equations providing detailed information concerning the operation of the process being modeled. In fact, models may be simple or complex depending upon the purposes for which the model is intended. Simple, judgmental models may be most appropriate when monitoring the overall performance of a process. When more detailed information about the process is required and/or when the model is used for planning of complex decision steps, such as the choice of an optimal generation mix for an electric utility, then more complicated models employing theoretical specifications from relevant disciplines and techniques of applied mathematics will be appropriate. The choice of theoretical structure and of implementation methods, and the level of detail required to satisfy the purpose for which the model is being designed, represent the art, as distinct from the science, of modeling. The first order of business in evaluating any model is to determine the appropriateness of the detail, theory, and implementation methods given the purposes for which the model was designed.

In addition to the theoretical structure and the implementation methods, energy system models may be characterized in terms of the level of detail and number of processes and activities modeled, whether the model is intended primarily for predictive or normative purposes, the appropriate geographical detail, and the treatment of uncertainty.

The scope of energy system modeling ranges from engineering models of energy conversion processes (e.g., nuclear reactors) or components of such processes to comprehensive system models of the nation's economy in which the energy system is identified as a sector. While engineering or physical models of conversion processes, ecosystems, etc., are energy-related, they are not included in this review. The models or forecasts that are included are best characterized in terms of coverage of different fuel supplies and demand and by the methodology employed. In these terms, the scope of the models reviewed includes those addressing the supply and/or demand for specific energy forms such as natural gas and electricity, analysis of interfuel substitution and competition in a more complete energy system framework, and analysis of the interrelationships between energy, the economy, and the environment.

Energy systems are employed for both normative or descriptive analysis and predictive purposes. In normative analysis the primary objective is to measure the impact on the system of changing some element or process that is an exogenous, or independent, event in the model. Predictive models are used to forecast energy supply and/or demand and attendant effects over a particular time horizon. Most models have both normative and predictive capability and a partition of models into these classes can be misleading. Whenever such a classification is used here, it is intended only to identify the primary objective of the model.

Geographical detail appropriate for a given model will depend again upon the purposes for which the model is designed. A model of energy flow in a particular production process will be specific with respect to the plants in which that process operates. Such a model has no geographical dimension. On the other hand, a model of utility electricity distribution will have a very explicit regional dimension, defined by the market area of the utilities being modeled.

Treatment of uncertainty in a model is an important discriminating characteristic, and is closely related to the implementation methods chosen. Uncertainty may arise because certain elements of the process to be modeled are characterized by randomness, because the process is measured with uncertainty, or because certain variables used as inputs to the model may themselves be forecasted with uncertainty. The methods by which these problems are dealt with are important in evaluating the predictive capability and in validating the model. The validation of normative models is quite different from that of predictive models. Since normative models deal with how the energy system should develop, given some objective, the issues of validation deal more with the representation of the structure of the energy system and the accuracy of input parameters. For predictive models, validation includes both evaluation of the model's logical structure and predictive power. Three levels of predictive capability may be identified. First, there is the ability to predict the direction of a response to some perturbing factor, e.g., a decrease in GNP in response to a fuel supply curtailment. A second level of capability involves the ability to predict the relative magnitude of a response to alternative policy action or perturbing factors, and the third level involves the prediction of the absolute magnitude of the response to a perturbing factor. Validation against the requirement of the first two levels is a minimum requirement and a model may be quite useful even if it cannot be validated at the third level. At both the second and third level, validation is usually of a conditional form and restrictions on the perturbing factors and their range of availability must be specified. Perturbing events, such as acts of God, outside the scope of the model must, of course, be corrected for in evaluating predictive capability.

APPLICATION OF ENERGY SYSTEM MODELS

Energy system models are developed and applied in a wide variety of energy planning and policy making activities. Before reviewing specific models it is useful to classify the types of planning functions, and the requirements imposed upon models if they are to be useful in supporting these planning activities.

Ayres (1) provides a useful classification of modes and levels of planning. He defines three levels of planning, including policy planning, strategic planning, and tactical or operational planning. Policy planning involves the formulation of goals or objectives and may be done with little regard to technology so long as technical factors do not constrain the selection among alternative goals. Strategic planning concentrates on the development of a set of alternative paths to the desired goals and generally includes the establishment of criteria by which alternative strategies may be evaluated and ranked. Lastly, tactical planning deals with the determination of the steps necessary to implement a particular strategy.

Energy system models provide support at all three planning levels for regulatory agencies, and for industrial planning, planning, management and evaluation of research and development programs, and for national energy policy and strategy planning. The objectives of these planning activities and the requirements thereby imposed upon the models are discussed below.

Regulatory Planning

State and Federal regulatory agencies are engaged in both operational and strategic planning involving issues related to the regulation of natural monopolies, e.g., electric utilities and gas pipelines, the siting of energy facilities, and public safety. Typically, forecasts of such variables as demand for the regulated product are required for a 5 to 20 year time horizon corresponding to the life of the facility as a basis of justification of the need for expansion of capacity and new facilities. With the current interest in rate structure modification as a potential means of controlling energy demand, the role of forecasting models that include price effects will become increasingly important. This feature is also important in the prediction of the response on the supply side to higher prices. For example, the regulation of natural gas prices is now an important energy strategy issue and has stimulated considerable activity on price dependent supply and demand models for this resource (2).

State regulatory agencies have primary responsibility in the siting of new energy facilities. Although forecasting or predictive models are employed to analyze the need for capacity expansion, the siting problem also requires analysis of a normative or descriptive nature. Analytical models have been developed and applied to the problem of optimal plant location, although location is frequently constrained by political and other factors, and to evaluate the effect of a given plant on the air and water quality and ecology at a proposed site. The latter question involves both physical models of the ecosystem and energy-economic models that permit quantification of the trade-offs among the many attributes of a particular site.

Industrial Planning

The primary planning activity in the energy industries is at the tactical level and involves the scheduling of production levels and the routing of energy products. Petroleum companies in particular are faced with a complex transportation problem involving many supply and demand centers with associated storage facilities. Most companies use large optimization models to assist in solving the scheduling and routing problem and to optimize production scheduling.

The energy industry is also active in developing models for forecasting future demand for products and in planning for and siting new facilities. In these areas their energy modeling activity is similar to that outlined for the regulatory agencies. These forecasting and analysis activities are of great importance to the industries in view of the crucial role that they plan in the future development of individual companies.

Research and Development Planning

Industry and the Federal Government are deeply involved in planning, managing and evaluating energy research and development. Industry sponsored R&D is generally directed toward near-term applications in response to corporate goals and objectives. The energy R&D sponsored by the Federal Government, on the other hand, is much longer range and involves quite advanced and innovative technologies such as fusion, solar energy, and breeder reactors. The formulation of energy R&D policy at the Federal level requires a broad assessment of the technical, economic, and environmental characteristics of new technologies and of their potential role in the energy system. Forecasts of energy demand and of supplies of energy from established technologies are required with longer time horizons than is necessary for siting and regulatory policy. In addition to long-range forecasting models, analytical, or normative, models are required to estimate implementation rates and the competitiveness of new technologies with existing ones, and sophisticated management methods are employed to manage and evaluate the programs.

Strategic and Policy Planning

The formulation of an integrated national energy policy is currently in progress and is supported by a comprehensive modeling and forecasting activity. The nation's energy policy is closely interrelated with economic and social policy and with international developments. Questions of economic growth, balance of trade, and protection of the environment must be considered in a balanced way and complex trade-offs must be made among these and other national objectives. Once formulated and adopted, a national energy policy must be adaptive and must evolve as conditions and objectives change.

The Project Independence study performed by the Federal Energy Administration involved the development and application of a large-scale forecasting energy model (3). Similar policy-oriented studies are in progress at many research centers, with associated modeling research efforts. These modeling and associated data development efforts involve the integration of energy system models with macroeconomic and environmental models in an effort to measure and evaluate the important interactions between economic growth, societal goals as reflected in environmental policies, and national goals of energy independence, and future energy market conditions.

METHODOLOGIES

Energy system models are formulated and implemented using the theory and analytical methods of several disciplines including engineering, economics, operations research, and management science. Models based primarily upon economic theory tend to emphasize behavioral characteristics of decisions to produce and/or utilize energy, while models derived from engineering concepts tend to emphasize the technical aspects of these processes. Behavioral models are usually oriented toward forecasting uses while the process models tend to be normative. Recent modeling efforts, such as the FEA Project Independence model, evidence a trend toward combining the behavioral and process approaches to energy modeling in order to provide a more comprehensive framework within which to forecast the condition of future energy markets under alternative assumptions concerning emergence of new production, conversion and utilization technologies. In part this trend is the result of recognizing that formulating and evaluating alternative national energy policies and strategies requires an explicit recognition of technical constraints.

Methods for implementing energy models include mathematical programming, especially linear programming, activity analysis, econometrics and related methods of statistical analysis. Process models are usually implemented using the programming techniques and/or methods of network and activity analysis, while the behavioral models use statistical methods. The remainder of this section provides an introduction to these techniques and is intended to provide background information for the review of specific models presented in the next section.

Mathematical programming has been used in energy system modeling to capture the technical or engineering details of specific energy supply and utilizing processes in a framework that is rich in economic interpretation. In mathematical programming a series of activity variables are defined representing the levels of activity in specific processes. These are arranged in a series of simultaneous equations representing, for example, demand requirements, supply constraints, and any other special relationships that must be defined to represent technical reality or other physical constraints that must be satisfied. An objective function to be minimized or maximized must be specified, usually cost, revenue, or profit, and there are many algorithms available to solve very large programs (up to the order of 10,000 variables). The methodology of linear and nonlinear programming is described by Dantzig (4) and Wagner (5) along with numerous practical applications.

The linear programming technique has been used far more than other mathematical programming methods because of the ability to solve large problems very efficiently. Nonlinear relationships may be captured in such models by using piecewise linear or step function approximations. Nonlinear and dynamic programming techniques are also used for special purposes.

The mathematical programming methodology has especially interesting and useful economic interpretations. Associated with any linear programming problem formulated in quantities is a dual problem in terms of prices. The solution to the quantity optimization problem yields both the optimal activity levels in physical terms and the prices that reflect the proper valuation of physical inputs to the real process represented by the model, providing important information concerning the economic interpretation of the solution. Thus, the linear programming technique provides a natural link between process and economic analysis.

Mathematical programming models, and related optimization techniques such as calculus of variations and LaGrange multipliers, are generally classified as normative techniques since they presume the existence of an overall objective such as cost minimization or profit maximization. It is possible to reflect multi-objective criteria as some weighted combination of objectives and, indeed, some objectives such as environmental control can be expressed through special constraint equations in the model. Nevertheless, the validity of this technique as a predictive tool depends on the ability to capture and represent the objectives of the players in various sectors of the energy system and in those sectors of the economy and society that affect the energy sectors. The technique is normative in that it determines optimal strategies to achieve a specified objective given a set of constraints.

Interindustry techniques are frequently employed in energy modeling, primarily for descriptive purposes. 1/ Primary data for constructing interindustry sale and purchase accounts are collected by the government on the transactions between various sectors of the economy (agriculture, ferrous metals, electricity, oil, retail trade, etc.). These data are expressed in terms of a common unit, dollars, and are available for all census years for the period 1947 through 1967 (6).

The input-output approach has been adapted to energy studies by converting the inputs from the energy sector to other industry sectors from dollar flows into energy units such as the British thermal unit (7 , 8). In this format the direct energy inputs from, say, the oil sector to the agriculture sector are specified in the input-output matrix. The interindustry flow table may be converted into a coefficient table measuring the quantity of input from one sector required per unit of output for another sector. The coefficient matrix represents a model of the production process.

Important assumptions of the model include fixed technology and zero price elasticity since input proportions are assumed independent of relative prices. Given these assumptions the model may be used to estimate the total direct and indirect energy requirements necessary to produce a given level of final demand.

The input-output approach is limited by the difficulties and time delays in assembling the interindustry flow data, and by the apparent restrictiveness of the key assumptions. As noted, the most recent table currently available for the U.S. is based upon 1967 data. Recently, the Department of Commerce, the agency responsible for assembling and publishing the interindustry accounts, has initiated a program to develop and publish annual updates to the input-output table in order to provide more recent information. As regards restrictiveness of assumptions, Hudson and Jorgenson (9) have used econometric techniques to implement an interindustry energy model for which the input-output coefficients are explicitly a function of the relative prices of all inputs. These important developments will significantly increase the utility of input-output analysis for energy analysis.

Econometrics is concerned with the empirical representation and validation of economic theories and laws. [2/] Econometric methods involve the application of statistical techniques to estimate the structural parameters of one or more equations derived from economic theory, and to test hypotheses concerning these parameters. The method appropriate to a particular estimation problem will depend upon the assumptions concerning the statistical properties of the process generating the observed data.

The principal method of econometrics is regression analysis. The regression model combines the economic model derived from theory with a statistical model of the process by which the observed data are assumed to be generated. Statistical methods may be used to test hypotheses concerning the assumptions of the statistical model, as well as hypotheses concerning the economic model. Examples would include testing the hypothesis that a particular parameter is not significantly different from zero, that parameters in different equations of the model are not significantly different, or that combinations of parameters are equal to some specific value.

Econometric methods are used in modeling two types of energy processes, behavioral and technical processes. Behavioral processes are characterized by a decision making agent who is hypothesized to adjust behavior in response to changes in variables outside his direct control. An example would be a household hypothesized to choose the distribution of its expenditures between energy and other types of goods and services depending upon its income and wealth and upon the relative prices of energy and the other products, consistent with some household objective function.

Technical processes are characterized by purely technical relations. An example would be the production function of a firm in which maximum potential output is a function of the quantities of inputs available, say capital, labor, energy and other material inputs. Given a suitable functional form for this relationship and observations on capacity output and associated inputs, econometric methods could be used to estimate the parameters of the function. Alternatively, the technical relation might be used to derive behavioral relations concerning the firm's demand for input factors given the output level.

Econometric and engineering/process methods are sometimes alternative approaches to modeling technical processes. An example of the two approaches to modeling the supply of electricity in the U.S. is provided by the work of Griffin (13) and Baughman and Joskow (14), with Griffin using an econometric approach while Baughman and Joskow employ an engineering/process approach. Examination of these two models, to be reviewed in the next section, is illustrative of the contrasting characteristics of each approach.

The system dynamics approach (15) evolved from studies of specific industry operations to global applications. It involves simultaneous linear and nonlinear equations which are used to represent functional relationships between parameters of interest in a problem. Both flow and stock variables may be represented and feedback relationships may be taken into account. The technique arose in the engineering field and is quite powerful. A major difficulty in large scale models has been the development and verification of the functional relationships used and of the interrelationships and feedback mechanisms represented by the model structure.

The techniques of game theory (16) are receiving increased attention in energy modeling, particularly where decisions to be modeled are made on a basis other than optimization or market equilibrium. This methodology has promise for modeling some aspects of international trade of energy resources, fuels, and energy intensive products. Game theory deals with the quantification of the outcomes of interactions between two or more players where each player has options that can affect the outcome. The selection of a best strategy, given uncertainty regarding the strategy that will be used by another, includes consideration of the relative payoffs and risk aversion of the players.

REVIEW OF ENERGY MODELS

This review includes a representative sample of models that have been developed and applied to analysis of the energy system and to the development of forecasts for planning purposes. The objective is to emphasize the assumptions and methodologies of selected models rather than to provide an exhaustive review of all models. The selection of models is somewhat arbitrary and does not imply any superior capabilities in comparison with other models of the same generic class that are not discussed.[3/]

The energy models are discussed in several groups according to their scope, ranging from supply oriented models of a single fuel to models encompassing the overall energy system coupled to the economy. The four major groups of models and forecasts that will be reviewed are:

- -- Sectoral Models covering the supply or demand for specific fuels or energy forms,
- -- Industry Market Models which include both supply and demand relationships for individual or related fuels,
- -- Energy System Models which encompass supply and demand relationships for all energy sources,
- -- Energy-Economic Models that model the relationships between the energy system and the overall economy.

There is no unique categorization of energy models that can represent all of the important characteristics. Our classification is intended to highlight the scope of particular models. Within each of the above groups, both activity or engineering process oriented models and econometric models are used extensively. These approaches are frequently combined to capture the strengths of the process technique in representing technical detail and the ability of econometric methods to represent aspects of behavior.

Sectoral Models

Sectoral models are defined as relating to some specific energy process or activity forming a part of a specific energy industry market. Typically, models in this category focus upon either the supply or demand side of the market. Process models are used most often for characterizing energy supply and capacity expansion, while econometric models are used to characterize demand.

Process oriented supply models have been developed and applied most extensively to the analysis of oil refining and transportation operations. The refining of crude oil involves a series of unit operations including simple distillation, cracking of heavy molecules into lighter fractions by a number of techniques, hydrogenation, and desulfurization. The yield of lighter fractions such as naptha and gasoline can vary from 30% to over 80% depending on the process employed and on the characteristics of the crude. Oil refineries are generally designed to handle a specific type of crude oil; however, the demand for major oil products such as naptha for petrochemicals, gasoline motor fuel, light distillate fuel for turbines and heating, and residual oil for power generation, varies on a seasonal and shorter term basis.

The international scope of the transportation and allocation of crude oil and of refined products provides an important application for energy modeling. The characteristics of crude oils vary by gravity (density) and by the level of sulfur and other contaminants they contain. The allocation of this crude to the appropriate refineries and of the refined products to storage and demand centers is optimized by many oil companies using the linear programming technique. Although many of these are proprietary, the Energy Research Unit at Queen Mary College under the direction of Deam has published its model (68). This model is global in scope and includes 25 discrete geographical areas. 52 types of crude oil and 22 refining centers are represented along with 6 types of tankers that may be selected for transport.

The model includes the following refinery processes and products:

Processes

1. Crude distillation unit
2. Vacuum distillation unit
3. Alkylation
4. Catalytic reforming
5. Desulfurization
6. Hydrocracking
7. Catalytic cracking
8. Desulfurization
9. Coking
10. LNG regasification
11. SNG production

Products

1. Liquid petroleum gas (LPG)
2. Motor spirits (gasoline)
3. Petrochemical feedstocks (naptha)
4. Kerosene
5. Gas oil
6. Residual fuel oil
7. Bitumen
8. Coke

The linear programming matrix for this model is quite large (about 3500 rows and 13,500 columns). The exogenous inputs to the model include future demand for products by region, refinery technology, costs of product refining, and transport of specific crudes and products. The model is solved to determine the optimal allocation and routing of crude oil and products between sources, refineries, and demand centers at some future target date. The requirements for new refineries, tankers, and production facilities to satisfy the projected level and distribution of demands are also determined. Because the model includes the transport and refining costs for crude from specific sources, it provides a basis for analyzing the relative price of these crudes in a competitive market or in a controlled market where relative prices are set to reflect the differences in transportation and refining costs among the many sources.

Most sectoral econometric modeling efforts in the energy area have focussed upon the demand for a single energy input in one particular use. Such models are used principally to provide an analysis of the determinants of demand and to forecast demand, given estimates of the variables exogenous to the model, including price and other variables measuring the "market size" for the energy inputs (population, GNP, income, and so on). These models have been designed to focus on specific policy issues such as gasoline tax policy. Since they are of limited scope, they generally do not have broad policy applicability.

Taylor (23) has recently surveyed and evaluated econometric models of the short and long run demand for electricity in the residential and commercial sectors. The models surveyed are classified according to regional detail and the measure of electricity price used, and short and long run prices and income elasticities are summarized. Taylor reviews the special problems associated with modeling the demand for electricity. These include the fact that such demands are derived demands depending upon the stock and utilization rates of equipment, the characteristic of fluctuating utilization rates for the equipment (peak demands), the effects of the regulatory process upon the pricing schedules. Taylor concludes that to varying degrees modeling efforts to date have not dealt adequately with these problems, especially the problem of incorporating the appropriate price schedule. Table 1 summarizes classification information and elasticities for the models surveyed by Taylor and for other electricity demand models published since his review was completed.

Sweeney (35) has developed a model of the demand for gasoline designed for use in support of analysis of conservation policies affecting automobiles. Gasoline consumption for any time period is a derived demand depending upon the total vehicle miles driven and the average miles-per-gallon (mpg) for the fleet in operation during the period. The demand for vehicle miles is estimated as a function of per capita real disposable income, the unemployment rate and the cost per mile of automobile travel, including the cost of gasoline and time costs (permitting introduction of speed limits). The average mpg for the fleet is estimated by first predicting per capita new car purchases as a function of lagged automobile purchases per capita, per capita total vehicle miles, per capita real disposable income, and the unemployment rate. A sales weighted average mpg of new cars is estimated as a function of automobile efficiency and the price of gasoline. The mpg for the fleet is then estimated by forming a weighted harmonic mean of the mpg estimates for new cars and each vintage of old cars where the weights are the shares of each vintage in the total vehicle miles demanded.

Other models of the demand for gasoline have been developed by Lady (36), Verleger (37), McGillivray (38), and Windhorn, Buright, Enns, and Kirkwood (39), and Adams, Graham, and Griffin (40). The long and short term price and income elasticities for each of these models together with the measure of gasoline prices used and the type of data, is summarized in Table 2.

Industry Market Models

Energy industry market models include process and econometric models, as well as integrated process/econometric models, which characterize both the supply and demand for a specific or related set of energy products. Such models are very useful, having applicability to all energy use categories, although the greatest utility is in providing a consistent framework for planning industry expansion and for studying the effects of regulatory policy upon the industry. Much of the modeling work in this area involves the coupling of process and econometric techniques to exploit their strength in representing, respectively, supply and demand relationships.

Adams and Griffin (41) combined a linear programming (LP) model of the U.S. refining industry with econometric equations determining endogenously the prices, quantities demand and inventory adjustments for the major petroleum products. Exogenous inputs to the econometric-LP model are the refining process configurations, product quality specifications, factor input prices (crude oil, etc.) economic activity, and the stocks of petroleum consuming equipment. In the first step, the requirements for the various petroleum products are determined in the demand equations. Using these requirements as output constraints, the solution to the LP model indicates the volume of crude oil required, process capacity utilization, operating costs, and outputs of by-products such as residual oil. In turn, capacity utilization, inventory levels and crude oil prices determine the product prices. The structure of the model indicating the relationship of the macroeconomic model with the linear program is shown in Figure 1. The linear programming model has 227 equations and 334 variables. The combined econometric-LP model was applied to a sample period, 1955-1968, and traced the development of the industry over that period with good accuracy. No provision was made to reflect technological change in the LP production functions, but statistically estimated adjustments were made to the crude oil inputs to account for the implementation of more advanced refineries.

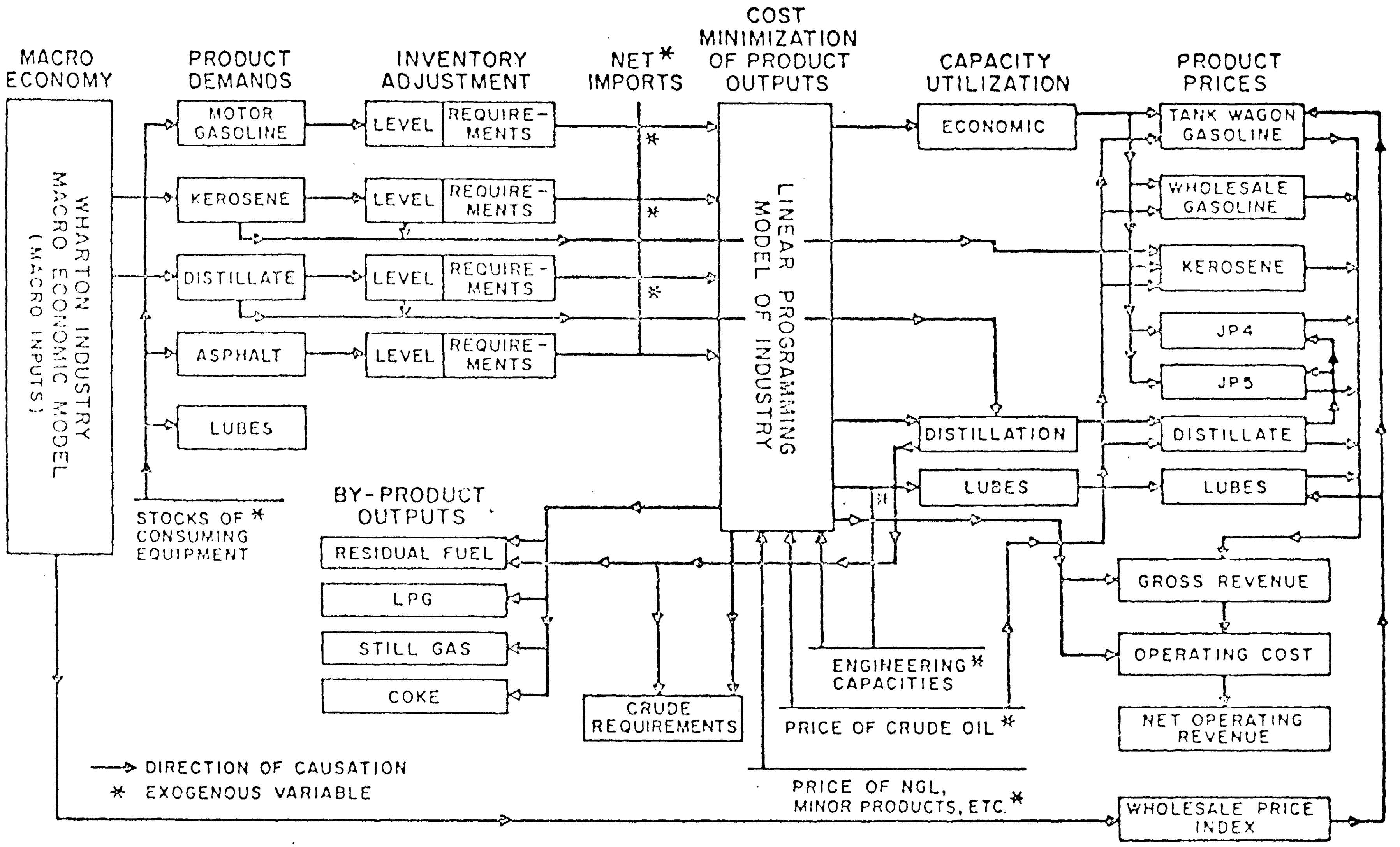

Figure 1. Structure of Adams-Griffin Petroleum Industry Model (41)

Mathematical programming has been used extensively in the analysis of electric utility operations and expansion plans. The review by Anderson (17) includes a description of over 50 models used in that industry. Methodologies discussed in the Anderson review cover marginal analysis and simulation and global models using dynamic programming, linear programming, and non-linear programming. In the electric utility optimization models, the electric demands and prices of fuels and facilities are usually exogenous inputs and the models are used to select the least cost investments to satisfy increased demands. The output generally includes specification of the type of plants to be built (nuclear, coal, oil, hydro, gas turbine, etc.), plant location for models that include regional definition, replacement, and the scheduling of plants on a weekly and/or seasonal basis.

A systems dynamics model of the coal industry is under development by Naill, Miller, and Meadows (42) to study the role of coal in the transition of the U.S. energy system from oil and gas to renewable resources over the period to the year 2100. The interrelationships in the coal production sector between demand, investment, labor, and production are modeled along with the oil and gas sector and the electric sector. Time delays associated with research and development, and plant construction, are included in the synthetic fuels sector where liquid and gaseous fuels are produced from coal. The demand for energy and the market shares of various fuels are determined endogenously as a function of price, GNP, and population. These variables are exogenous to this model, although in more comprehensive systems dynamics models they are also determined endogenously.

MacAvoy and Pindyck (2) have developed an econometric policy simulation model of the natural gas industry. The model has been used extensively to analyze the effect upon the industry of current and proposed federal regulation of the wellhead price of gas, and of permissible rates of return for pipeline companies purchasing and selling natural gas in interstate markets (2, 43). The model focuses upon the supply of reserve additions and the demand for gas by pipeline companies for sale in wholesale markets. The supply of additions to gas reserves in any period is the sum of new reserves discovered and extensions and additions to reserves. New reserves discovered in a producing region are the product of wells drilled, the proportion of successful wells and the average size of find. New discoveries of both oil and gas are estimated, since in exploration and development activity oil and gas are joint products.

An important feature of the MacAvoy-Pindyck model is that the drilling projects initiated depend upon driller choices between the intensive and extensive margin. The extensive margin refers to projects in new fields with lower probabilities of success but higher expected size of find if the project is successful. The intensive margin refers to projects in known fields with higher probabilities of success and corresponding lower expected size of find (since presumably the better projects will have been drilled first). This choice is modeled as a function of economic costs, and a measure of the risk averseness of the producer. The average success ratio for projects initiated is a function of this drilling choice. The size of discovery incorporates the effects of geological depletion by depending negatively upon the number of previous successful wells in the region, since better prospects are likely to be drilled first, and positively upon higher gas prices, since this shifts the producer's drilling portfolio toward the extensive margin. The model also estimates changes in reserves due to extensions and revisions, thereby providing a complete reserve accounting framework.

Production out of reserves depends upon the reserve base and the field price. The marginal cost of production depends upon the reserve level relative to the production level. Lower reserve to production ratios imply higher marginal costs, with the regulated price setting an upper bound upon marginal cost and, therefore, possible production levels.

The demand by the industrial customer and for the residential and commercial customers of the regail utilities depends upon the wholesale price of gas, the prices of alternative fuels, and such "market size" variables as population, income and investment levels. The wholesale price of gas is a function of the wellhead price and a pipeline markup which depends upon operating and capital costs and the regulated profits of the pipeline companies. The wholesale markets are also defined on a regional basis. The flows of natural gas between producing and consuming regions is estimated using a network model characterized by an input-output table of flow coefficients between each of the producing and consuming regions. The difference between the production flows and demand levels in the consuming regions is a measure of the excess demand for natural gas in each region.

Griffin (13) has developed an econometric model of the supply and demand for electricity. The model is estimated using national time series data. Major variables determined by the model include the demand for electricity in the residential and the industrial and commercial sectors, nuclear capacity expansion, distribution of generation requirements between nuclear, oil, gas and coal, and the price of electricity. [5/] Important exogenous variables include various measures of market size such as population, real disposable income, GNP, the price of oil, gas and coal, the GNP deflator, total generating capacity, construction costs, and other operation costs.

The model is simultaneous since the average price of electricity, a determinant of demand, depends upon the generating mix. The model has been used to conduct simulation studies of the impact upon demand and the generating mix of alternative projections of relative fuel prices.

Baughman and Joskow (14) have developed an engineering-econometric model of electricity supply and demand. The model combines an engineering supply model with an econometric demand model, linking the two with an explicit model of the regulatory process by which the price of electricity is determined. The supply model for electricity is regional, encompassing the nine Census regions. Each region is assumed to have eight potential plant types available, with a ninth type, hydroelectric, treated as exogenous. The plant types are

1. Gas turbines and internal combustion units,
2. Coal fired thermal,
3. Gas fired thermal,
4. Oil fired thermal,
5. Light water uranium reactors,
6. High temperature gas reactors,
7. Plutonium recycle reactors,
8. Liquid metal fast breeder reactors.

The model characterizes the decision process by which operation and expansion of the electricity supply system takes place based upon cost minimization techniques employed by the industry. The econometric demand model is based upon a State classification of data. Demands for electricity, natural gas, coal and oil are estimated for the residential and commercial and the industrial sectors as functions of fuel prices and various market size variables. 6/ The price of electricity is controlled by state regulatory agencies. Transmission and distribution requirements and costs are estimated using an econometric approach. The procedure is to first estimate requirements for five types of transmission and distribution equipment and then to estimate the maintenance and operating costs as a function of the installed capacity for these five types of equipment. The Baughman-Joskow model simulates the process by which electricity prices are determined based upon calculations of the rate base derived from inputs from their supply model and assumptions about the rate of return permitted by the regulatory agency, the rate of depreciation, and the effective tax rate.

The model takes as exogenous fuel and other operating costs, as well as construction costs and plant operating characteristics. Electric power supply industry is assumed to expand to meet expected demand based upon an exponentially weighted moving average with time adjustment of recent actual demands. This expected demand projection will, of course, differ from the actual consumption in any given period. Adjustments in operating capacity due to differences between projected and actual demand are assumed to take place in future optimizing decisions. Generation requirements by plant type are calculated using an estimate of the load duration curve (percentage of time that load equals or exceeds a given output level), and a merit order ranking of plant types by operating and fuel costs. Since the load duration curve and merit order ranking are independent of the projected demand, the fact that projected and actual demand may differ will not affect the order in which capacity is utilized to meet actual demands.

Energy System Models

Analysis and modeling of the overall energy system, including supply and demand sectors as well as all fuels and energy forms, was stimulated largely by the need to develop forecasts of total energy demand. Much of the initial work in this area involved the development of overall energy balances for the U.S. in which forecasts for individual fuels were assembled.

These forecasts highlighted many problems involving such factors as resource definition and interfuel substitution that must be handled in a consistent manner across all fuel types and sectors and led to increased modeling of the entire energy system.

One of the first systematic attempts to account for all energy flows in a consistent manner was that of Barnett (44). Barnett's approach involves obtaining a national energy balance of energy supplies and demands by type. The emphasis was on quantity flows expressed in physical units and a common unit, Btu's. This approach has been extended and refined by Morrison and Readling (45), and by DuPree and West (47). As an accounting approach, the energy balance system focuses attention upon a complete accounting of energy flows from original supply sources through conversion processes to end-use demands. The approach accounts for intermediate consumption of energy during conversion processes as well as efficiencies at various points in the energy supply system.

The energy balance methodology has been employed in forecasting studies in the following way. Independent estimates of demand by each of the major end-use sectors for each of the detailed energy types are developed by relating demand to aggregate economic activity and trends in energy consumption. Independent estimates of supply of major energy types are developed and compared with the demand estimates. Differences are resolved, usually in a judmental way, by assuming that one energy type is available to fill any gap that may exist between supply and demand. This energy type is usually assumed to be imported petroleum, including crude oil and refined petroleum products. The DuPree-West (47) study provides an excellent example of the execution of a forecast employing this methodology.

The National Petroleum Council (NPC) also employs the energy balance approach in developing forecasts of expected energy consumption. The NPC models (48, 49) employ econometric techniques in forecasting energy demands, and engineering and judgment models in forecasting supplies. However, the forecasts from the models are substantially modified by judgmental information provided from the various working groups of the NPC. The energy balance framework is used to ensure the consistency of the various component forecasts. An important feature of the NPC approach is that it permits incorporation of subjective, specialized industry information into an energy balance framework, and thus provides an important source of industry expectations about future energy markets.

The process type energy system models, encompassing all alternative fuels and energy sources, frequently employ network analysis in order to represent technical detail and to capture the interfuel substitution possibilities. The network is used to represent the spatial or interregional flows of energy as well as the alternative processes and fuels that may be used in specific demand sectors. This representation of the energy system may be augmented with optimization or simulation techniques or used simply as a framework to exhibit information and options.

The model developed by Baughman (50) for studies of interfuel competition uses systems dynamics to simulate the flow of resources (coal, oil, natural gas, nuclear) to the various demand sectors (residential and commercial, industrial, transportation, and electricity). The model has been applied at the national level but might also be formulated at the regional level. The model includes representation of the economic cost structure of the energy system along with investment decisions and physical constraints on the supply of coal, oil, natural gas, and nuclear fuels. Demands are developed in two components, a base demand that is not sensitive to price, and a market sensitive demand which includes incremental and replacement demands. The model is used to simulate interfuel competition and to develop the quantities and prices of fuels and energy sources that are used over time as demands and the availability and cost of resources change. The model has been used to develop projections of oil and gas use as relative prices change and is being extended to address regional analyses.

The Reference Energy System approach was developed by Hoffman (51) and applied to the assessment of new energy technologies and policies. This is a network description of the energy system in which the technical, economic, and environmental characteristics of all processes involved in the supply and utilization of resource and fuels are identified. All steps in the supply chain, including the extraction, refining, conversion, storage, transmission, and distribution activities are included along with the utilizing device (combustor, air conditioner, internal combustion engine, etc.). A Reference Energy System representing a detailed projection to the year 1985 is shown in Figure 2. Each link in the network corresponds to a physical process and is characterized by a conversion efficiency, capital and operating cost, and emissions of air and water pollutants per unit of energy input. The system is used to evaluate the role of new technologies and the possibilities of interfuel substitution. Substitution is heavily dependent on the characteristics of utilizing devices and these devices are represented in the network for all functional end uses such as space heating, air conditioning, and automotive transport. The resource, economic, and environmental impacts of new energy technologies are determined by inserting them

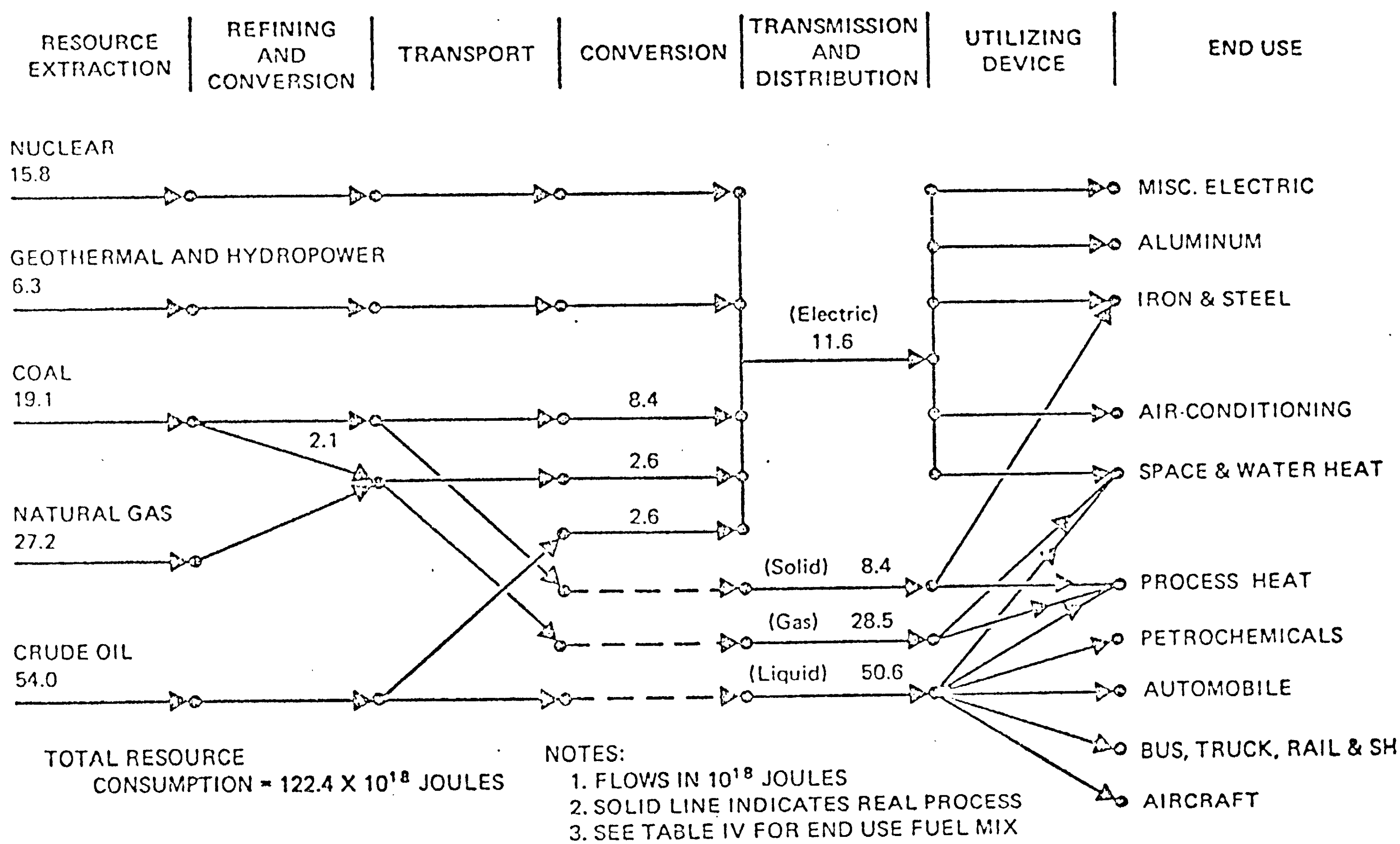

Figure 2. Reference Energy System - Projection to 1985 (52)

into the reference system at appropriate levels and efficiency, and recalculating the energy flows, cost, and emissions.

The Reference Energy System is supported by an Energy Model Data Base (53) which includes data elements for some 600 supply processes and 200 functional end uses. Both simulation and optimization models may be used to develop and quantify the Reference Energy System.

Cazalet (54) of Stanford Research Institute developed a network model of the U.S. energy system which is solved by a successive approximation algorithm using decomposition techniques. The model does not use an explicit optimization approach but looks for market equilibrium between energy supplies and demands using the marginal cost of resources and cost of supply and conversion technologies as the basis for energy prices. The network includes 30 supply regions, 8 demand regions, and covers 17 time periods of varying length with a time horizon to 2025. The demand sectors are defined on a functional basis as in the Reference Energy System. The input parameters include supply and demand curves for all regions where the quantities of fuels that would be forthcoming are specified as a function of price. The characteristics of conversion and delivery technologies are represented in the model and interregional transportation costs are identified. The important output information provided by the model includes regional prices for fuel by region and time period, resource production levels, interregional flows, and demands for fuels. The model has been applied by Gulf Oil to the analysis of synthetic fuel strategies; specifically, an analysis of the coal gasification option in the Powder River Basin of Montana and Wyoming. The model is also being used for the Council on Environmental Quality for the analysis of Western energy resource economics.

Debanne (55) has developed a network model of North American energy supply and distribution system. It accounts for physical interregional flows where the nodes in the network may represent oil, gas, coal, hydro, and nuclear conversion centers. The arcs represent pipelines and other appropriate transport facilities. The model determines optimal locations and expansion of capacity to satisfy increased regional demands. The model takes interfuel substitution into account and includes the interactions of price with supply and demand.

A number of linear programming models, similar to those employed for optimization of the generating mix in the electric sector, have been developed for the analysis of the complete energy system including both the electric and the non-electric sectors. The Brookhaven Energy System Optimization Model (BESOM) (56, 57) developed by Hoffman and Cherniavsky was designed to determine the optimal allocation of resources and conversion technologies to end uses in the format of the Reference Energy System. This model focuses on the technical structure of the energy system including the conversion efficiencies and environmental effects of supply and utilizing technologies. It is currently applied at the national level. The model may also be formulated for regional or interregional analysis. A wide range of interfuel substitutability is incorporated in the model and the load-duration structure of electrical demands may be expressed. The model is quantified for a future point in time. The energy sources compete in the optimization process to serve specific functional demands such as space heat, petrochemicals, and automotive transport. The energy demands to be satisfied, and the constraints on specific energy sources and environmental effects, are specified exogenously. These may be input as either fixed or price sensitive constraints.

scarce or finite resources when they run out. This backstop technology has been taken to be the nuclear breeder reactor producing electricity and hydrogen for electric and non-electric demands, respectively. The cost and efficiencies of all resources and technologies are reflected in the model along with demand and resource constraints. This model has been used to study the optimal allocation of scarce resources over time and, specifically, to evaluate current fuel production costs and the scarcity cost premium associated with the requirement that a more costly energy form must be substituted at some future time for any scarce resources that are used at an earlier date.

The Manne model (59) is formulated as a single region model. To focus on the resource exhaustion problem, there are only two energy demand sectors, electric and non-electric. Coal is viewed as a source of both electric energy and also synthetic fuels. Several nuclear reactor options are represented, including the light water reactor, the high temperature gas cooled reactor (HTR) and the fast breeder reactor. The fuel cycles for these systems are coupled and the high temperature reactor is viewed as a source of process heat, e.g., for thermochemical hydrogen. This model is also time phased covering the period 1970 to 2030 in three-year time steps. It has been applied to determine the benefits of the fast breeder reactor as a source of electricity and of bred nuclear fuel for the high temperature gas cooled reactor which in turn is used to produce hydrogen as a substitute for scarce oil and gas resources. The benefits of this technology were evaluated under various assumptions regarding the availability of petroleum imports and of domestic sources. An example of the output from the model is shown in Figure 3, illustrating the time phasing of various fuels used to

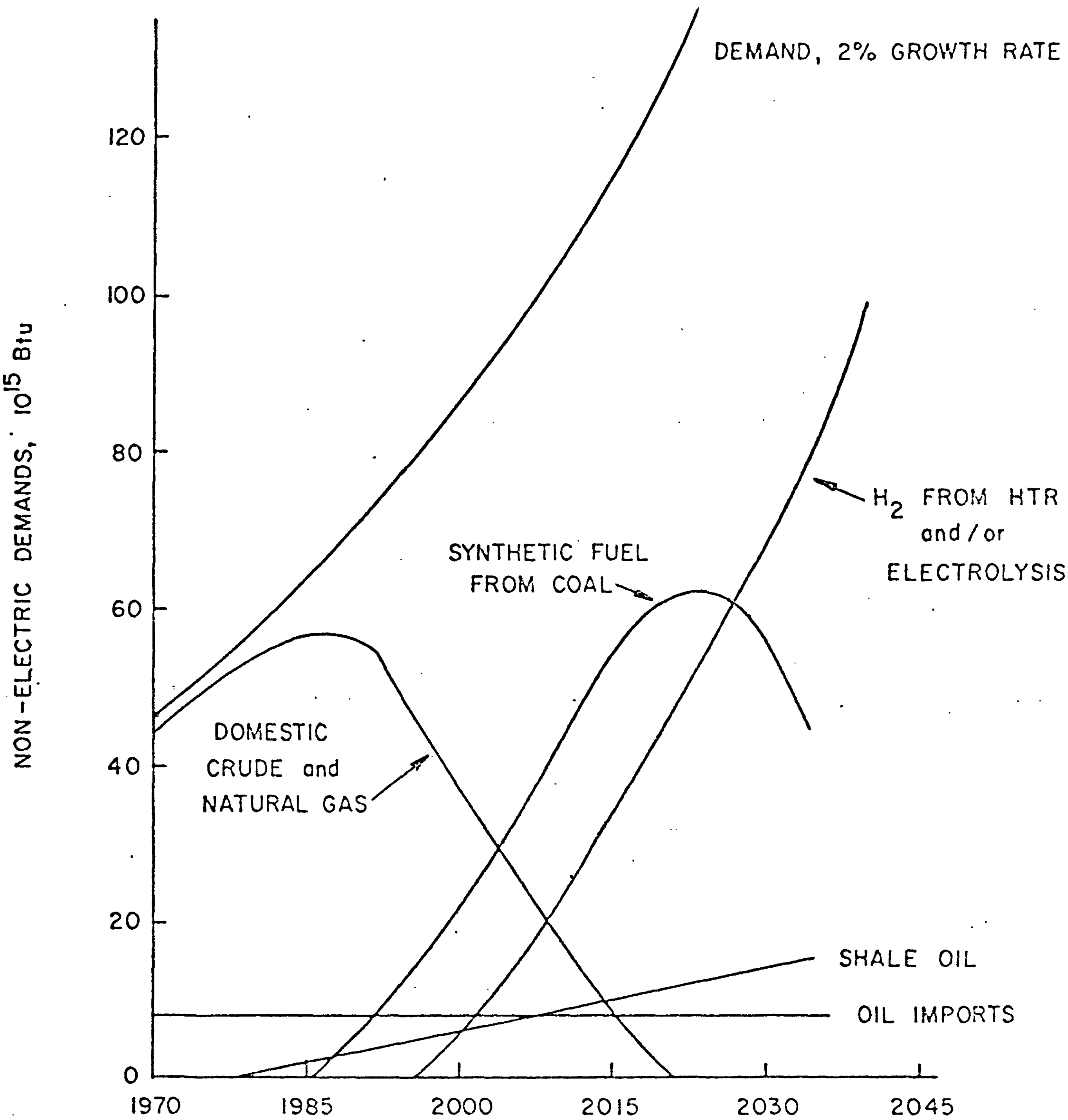

Figure 3. Nonelectric Energy Demand Trend and Fuel Mix (59)

The energy sources provided in the model include a number of alternative central station electric systems, general purpose fuels delivered directly to the consumer, and special systems such as solar energy and decentralized electric generators. The optimization may be performed with respect to dollar cost, social cost, environmental effects, resource consumption, or some combination of these factors.

The model has been applied to study the optimal implementation mode for new energy technologies, breakeven costs for new technologies, and strategies of interfuel substitution to conserve scarce resources.

A time-phased linear programming version of the BESOM model has been assembled by Marcuse & Bodin (57). This incorporates the same technical detail and constraints but treats plant expansion and capital requirements in an explicit manner. The inputs necessary to drive the model include energy demand requirements in each future time period, initial plant capacity (existing capital stock) and maximum permissible growth rate for each conversion process, maximum permissible growth for the extraction and supply of each energy resource, and a discount rate. Solution of the model determines resource usage, activity level of each conversion process, and new capital facility requirements in each time period. It has been applied to cost-benefit analysis of new energy technologies and to the determination of the optimal use of scarce resources over time.

Time-phased linear programming models have also been developed by Nordhaus (58) and Manne (59). The Nordhaus model covers 5 regions of the world, 9 time periods, and includes all major competing resources. A backstop technology is introduced which provides a long-term substitute of possibly higher cost but almost infinite availability that can be used to replace satisfy the demands for nonelectric end uses. These end uses are specified either as exogenous or as price-responsive. Similar curves are generated for the fuel mix in the electric sector.

Integrated Energy Economic Models

There is increasing research activity in the coupling of energy system models with models of the overall economy such as macroeconomic and input-output models. Many of the sectoral and energy system models discussed previously require that the energy demands be specified exogenously as input parameters. Of course, such demands must be related to trends in society (households, transportation pattern, etc.) and the economy (population, GNP, industrial production, and so on). This requirement has led to the extensive use of regression analysis and other macroeconomic modeling techniques in order to generate demand levels and other inputs to the process oriented models. Such coupling is relatively straightforward, however, and the major research activity in combined models is more fundamental in nature. The coupled energy-economic models reviewed here involve those that are used for analysis of the role of energy as a driving force and constraint on economic development. They involve a more integral relationship between the energy sector and the economy. In particular, the recognition that the cost and availability of natural resources has significant near and long-term implications for the economy has stimulated this modeling activity.

The process oriented energy-economic modeling has emphasized the use of input-output techniques. Herendeen (7) developed energy coefficients in physical units for coal, crude oil and gas extraction, refined oil, electricity, and gas sales in the 367 sector input-output matrix of the Bureau of Economic Analysis. The direct energy coefficients represent the Btu inputs per dollar of total output of each sector of the economy. This model is operational at the University of Illinois and has been used to analyze the energy inputs, both direct and indirect, to different products and activities.

Just (60) has developed a two-period dynamic 104 sector input-output model. In this model technological coefficients were developed for new energy technologies, providing for analysis of the expansion required in specific industries to support the implementation and expansion of new technologies such as coal gasification plants and gas turbine cycles.

Input-output analyses of the type developed for energy studies provide the basis for energy accounting. Many calculations have been performed of the energy inputs to capital projects, including the construction of nuclear power plants, shale oil facilities, and solar systems to determine how long the facilities must operate to return the energy invested in their construction. There are many approaches to such calculations and the basic problem involves the definition of the boundaries on the energy inputs to be considered. It is clearly valid to account for the energy required to produce the physical inputs such as steel and concrete, as well as the energy required to fabricate the materials into components and install them. It is less clear that the accounting should include the energy used in everyday activities at home by those who work on such projects although some analyses include this as an input.

The fixed nature of the technological coefficients in the input-output matrix raises some problems in using this methodology for future oriented studies. The fuel requirements corresponding to a projected GNP do not necessarily correspond with the quantities that may be available at that future time. Some interfuel substitution will take place in response to such limitations on specific fuels and provision must be made to revise the technological coefficients accordingly. A combined energy system input-output model (61) was developed by Brookhaven National Laboratory and the University of Illinois' Center for Advanced Computation to resolve this problem. This model combines the University of Illinois input-output model (62) with the Brookhaven Energy System Optimization Model (BESOM) (52, 56). Constraints may be placed on the availability of fuels and resources in BESOM, and the required fuel substitutions are determined. Coefficients in the input-output model are revised to reflect the new fuel mix and the input-output model is again solved with the revised mix. Several iterations are required between the two models in order to get a solution in which the energy demands and fuel mix are consistent in the two models.

Hudson & Jorgenson (9) have developed a macroeconomic energy model providing a new and innovative integration of traditional techniques of econometrics and input-output analysis. The model consists of a macroeconometric growth model of the U.S. economy integrated with an interindustry energy model. The growth model consists of submodels of the household and producing sectors with the government and foreign sectors taken to be exogenous, and determines the levels and distribution of output valued in constant and current dollars. The model determines the demand for consumption and investment goods, the supplies of capital and labor necessary to produce this level of output, and the equilibrium relative prices of goods and factors. The model is dynamic, having links between investment and changes in capital stock, and between capital service prices and changes in investment good prices.

The macroeconometric growth model is linked to an interindustry energy model by estimates of demand for consumption and investment goods, and the relative prices of capital and labor. The Hudson & Jorgenson interindustry model is based upon a nine sector classification of U.S. industrial activity. The sectors are:

<u>Energy</u>

1. Coal Mining
2. Crude Petroleum & Natural Gas
3. Petroleum Refining
4. Electric Utilities
5. Gas Utilities

<u>Non-Energy</u>

6. Agriculture
7. Manufacturing (excluding Petroleum Refining)
8. Transportation
9. Communications, Trade & Services

Production submodels are developed for each sector. These submodels treat as exogenous the prices of capital and labor services determined in the growth model and of competitive imports, and for each sector determine simultaneously the sector output prices and the input-output coefficients. Making the input-output coefficients endogenous is unique to this model and represents an important advance for input-output analysis.

The sector output prices are used, together with the demand for consumption goods from the growth model, as inputs to a model of consumer behavior which determines the distribution of total consumer demand to the 9 producing sectors. The distribution of investment, government and foreign, demand is determined exogenously, and completes the final demand portion of the model. Given final demands, the input-output coefficients may be used to determine the industry production levels required to support a given level and distribution of real demand.

The Hudson & Jorgenson model has been used to forecast long-term developments in energy markets within the framework of a consistent forecast of macroeconomic and interindustry activity. The model has also been used to analyze the impact upon energy demands of alternative tax policies, including a uniform Btu tax, a uniform energy sales tax, and a sales tax on petroleum products (63).

The Federal Energy Administration (FEA) has developed an integrated econometric/process model to assist in analyzing alternative strategies for achieving energy independence (3). The FEA model, the Project Independence Evaluation System (PIES) is summarized in Figure 4.[7/]

There are four basic input submodels to PIES including a macroeconomic model, an industrial production model, an annual demand model, and a supply model for oil and gas production. Associated input data includes estimates of coal production at alternative prices, and a major data base of resource input requirements per unit of activity output. The macroeconomic and industrial production models generate estimates of the level and distribution of real output in the economy as inputs to an econometric energy demand model. The demand model is a dynamic econometric model which forecasts demands for 47 primary and derived energy products conditional upon assumed energy prices, industrial activity levels, the level and distribution of real output, and certain energy consumption technology data. The model distinguishes the demand for fossil fuels between fuel and power uses in each of three major consuming sectors (residential, industrial and transportation) and industrial raw material uses. The model disaggregates the national forecasts to the census region level of detail by means of regional energy prices and various measures of regional "market size", such as population, GNP, and industrial output levels.[8/]

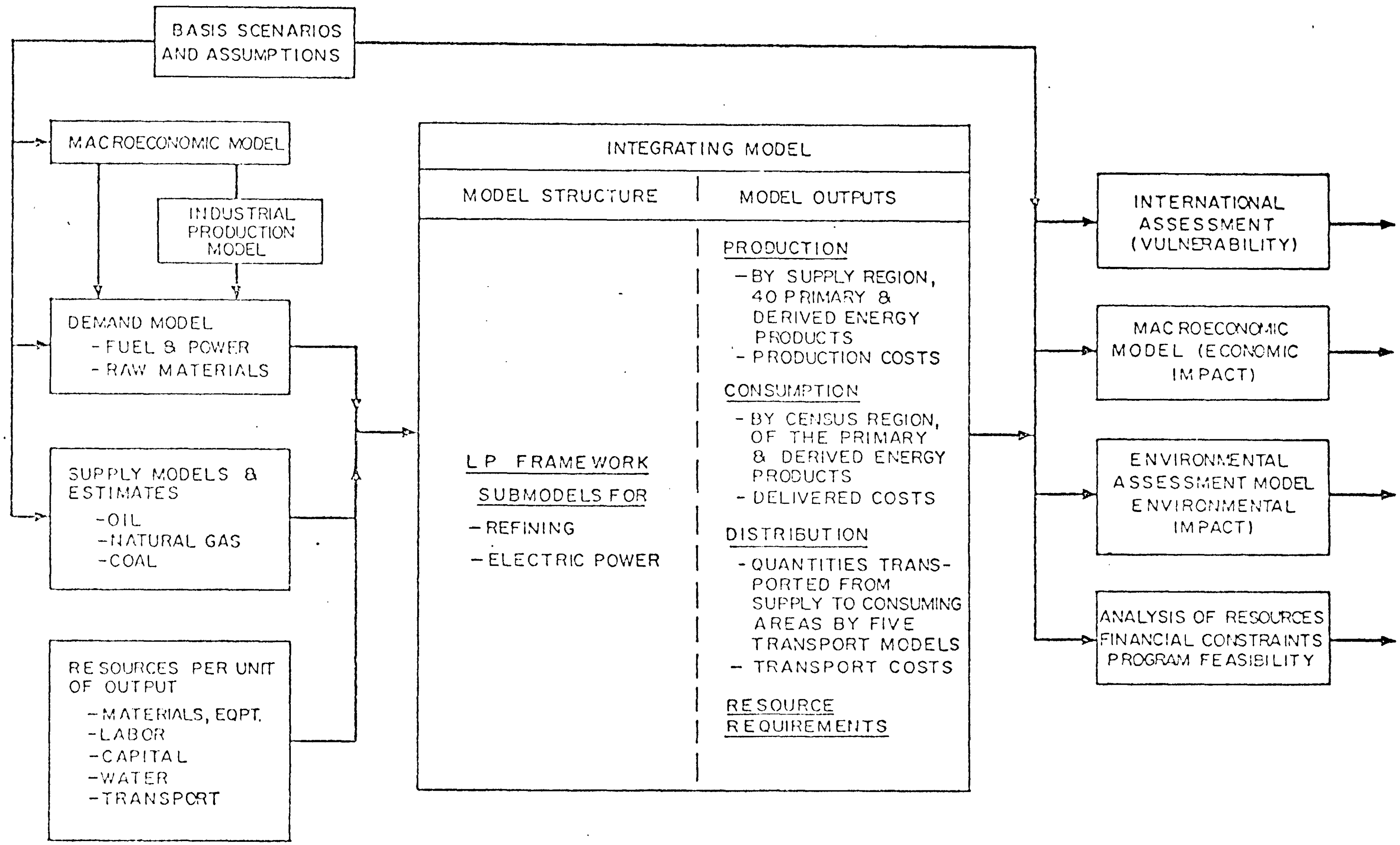

FIGURE 4. BLUEPRINT OF THE PROJECT INDEPENDENCE EVALUATION SYSTEM (PIES)

The Oil and Gas Supply Model is an adaptation of a process engineering model developed by the National Petroleum Council. The model estimates additions to reserves and production levels for 12 supply regions, given assumptions about crude oil prices, regional drilling programs, required rate of return on investment, the expected success ratio per foot drilled, and the projected reserve/production rate.

The heart of the PIES is the integrating model, a linear programming (LP) model which, given estimates of regional demands, prices and elasticities, regional supply schedules, and resource input requirements, calculates an energy market equilibrium. The relation between the demand model and the LP submodel which incorporates the supply schedules and conversion processes may be summarized as follows: the demand model is used to calculate a price-quantity coordinate on the demand curve for each of the primary and derived energy products in the system. Associated with each of these coordinates are measures of the sensitivity of the quantities demanded to small changes in each of the prices in the demand model (own and cross price elasticities). In the first iteration of the integrating model an LP problem is solved in which the minimum cost schedule of production, distribution, and transportation necessary to satisfy the given demand levels is calculated. Associated with the calculated supply quantities are implicit prices. If these supply prices differ from the original demand prices, then the solution is unstable and a new problem must be structured and solved. The procedure is to calculate new demand prices, equal to one-half the difference between the last iteration's supply and demand price, use the own and cross price elasticities to calculate the new demand quantities, and finally to solve a new LP problem for the new production, distribution, transportation schedules, and supply prices. This process is continued until the demand and supply prices are equal, at which point the energy market is assumed to be in equilibrium.

The outputs of the integrating model are then used as inputs to certain "interpretive" models including a macroeconomic model, an environmental assessment model, and an international assessment model. In addition, the integrating model outputs are analyzed to determine if potential limitations exist upon the availability of the necessary resource inputs.

Another type of energy-economic, or energy-societal, modeling work involves global modeling of the type described in Limits to Growth (65). The energy sector is not described in sufficient detail in that model to warrant discussion in this review. Efforts are in progress to develop more detailed models of the energy system that may be embedded in global models. The most significant global model in which this has been done is that of Mesarovich and Pestel (66). This model encompasses energy, resources, economics, the environment, and population. The energy sub-models consist of an energy resource model, a demand model, and an energy supply model. The resource model includes statistical information on energy resources allowing for the uncertainty of the resource and the feasibility of recovery. It also incorporates a simulation of the production of the resources. The demand model describes the demand for energy as a function of GNP and the supply model links these demands to resources. The supply model covers 13 primary and 7 secondary energy forms along with 27 conversion processes in a simulation framework.

Footnotes

1. Input-output analysis originated with Leontief for which he was recently awarded the Nobel prize. See (68) for the original development and (69) for a recent compendium of research in input-output analysis.

2. There are many excellent econometrics textbooks, including (10, 11). An advanced treatment is given in (12).

3. Several general reviews of energy models have been completed and others are underway. Anderson (17) surveyed mathematical programming approaches to analysis of the electric sector and Decision Sciences, Inc. (18) conducted a survey of energy models under a contract with the Council on Environmental Policy. Broad surveys of energy system models are now underway at the International Institute of Applied Systems Analysis in Laxenburg, Austria (19). Several major conferences have been held on energy modeling and the proceedings (20, 21, 22) of these conferences include detailed descriptions of a variety of energy models. Taylor (23) has completed a review and evaluation of demand models for electricity.

4. Table 1 is based upon Taylor (23), Table 4, with the additional entries for Griffin (13), Baughman & Joskow (34, 24), and FEA (3).

5. The income and price elasticities for the Griffin model are presented in Table 1.

6. The income and price elasticities for the Baughman & Joskow model are presented in Table 1. The model for the residential and commercial sector is described in Baughman & Joskow (34), while the industrial sector model is discussed in Baughman & Zerhoot (67).

7. This description of PIES draws heavily on the review of the Project Independence Report prepared by the MIT Energy Policy Study Group for the National Science Foundation (64).

8. See (3), Appendix II for a detailed discussion of the FEA demand simulation model.

Table 1. Summary of Price and Income Elasticities for Models of Electricity Demand[4]

Type of Demand	Type of Price	Price Elasticity Short-Run	Price Elasticity Long-Run	Income Elasticity Short-Run	Income Elasticity Long-Run	Type of Data
Residential						
Houthakker (24)	M	-0.089	NE	1.16	NE	CS: Cities (U.K.)
Fisher & Kaysen (25)	A	≈-0.15	≈0	≈0.10	SMALL	CS-TS: States
Houthakker & Taylor (26)	A	-0.13	-1.89	0.13	1.94	TS: Aggregate U.S.
Wilson (27)	A*	NE	-2.00	NE	≈0	CS: SMSA's
Mount, Chapman, & Tyrrel (28)	A	-0.14	-1.20	0.02	0.20	CS-TS: States
Anderson (29)	A*	NE	-1.12	NE	0.80	CS: States
Lyman (30)	A	(≈-0.90)		(≈-0.20)		CS-TS: Areas Served by Utilities
Houthakker, Verleger, & Sheehan (31)	M	-0.90	-1.02	0.14	1.64	CS-TS: States
Griffin (13)	A	-0.06	-0.52	0.06	0.88	TS: Aggregate U.S.
Commercial						
Mount, Chapman, & Tyrrel (28)	A	-0.17	-1.36	0.11	0.86	CS-TS: States
Lyman (30)	A	(≈-2.10)				CS-TS: Areas Served by Utilities
Industrial						
Fisher & Kaysen (25)	A	NE	-1.25			CS: States
Baxter & Rees (32)	A	NE	-1.50			TS: Industries (U.K.)
Anderson (33)	A	NE	-1.94			CS: States
Mount, Chapman, & Tyrrel (28)	A	-0.22	-1.82			CS-TS: States
Lyman (30)	A	(-1.40)				CS-TS: Areas Served by Utilities
Baughman & Zerhoot (67)	A	-0.11	-1.28			CS-TS: States
FEA (3)		NE	-1.33			TS: Aggregate U.S.
Residential & Commercial						
Baughman & Joskow (34)	A	-0.13	-1.31	0.08	0.52	CS-TS: States
FEA (3)		NE	-0.44		1.90	TS: Aggregate U.S.
Industrial & Commercial						
Griffin (13)	A	-0.04	-0.51			TS: Aggregate U.S.

Note: NE: Not Estimated; CS: Cross-Section; TS: Time-Series; M: Marginal Price; A: Ex Post Average Price; A: Average Price for a Fixed Amount of Electricity Consumed per Month

Table 2. Summary of Price and Income Elasticities for Selected Models of Gasoline Demand

Model	Price Elasticity		Income Elasticity		Measure of Gasoline Price	Data
	Short	Long	Short	Long		
Sweeney (35)	-.12	-.72	.85	.78	Retail Exc. Taxes	Annual TS: U.S.
Lady (36)	-.16	--	.48	--	" " "	Monthly TS: U.S.
Verlager (37)	-.16	-.54	.32	1.06	" " "	Quarterly TS-CS: States
McGillivray (38)	-.22	-.69	--	--	" Inc. "	Annual TS: U.S.
Windhorn, et al. (39)	-.14	-.93	--	--	CPI, Gas & Oil	Annual TS: U.S.
Adams, et al. (40)	-.90	-1.5	.5	1.0		

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