APPENDIX A DESCRIPTION OF THE STANFORD RESEARCH INSTITUTE ENERGY MODEL

A. INTRODUCTION

Over the past eight years, Stanford Research Institute (SRI) has developed a methodology for creating computerized models that describe complex and dynamic market situations typical of the energy field. An outgrowth of client-supported project work, SRI internal research, and Stanford University dissertation research, this methodology was designed to allow modeling of markets characterized by interproduct competition, regional differences arising from product transportation costs, depletable resources, changing technology, and government regulatory factors. Thus, the models generated by the methodology can be used to support analysis of energy-related decisions in areas such as plant capacity expansion, transportation, resource exploration, research and development strategy, and various aspects of government energy policy.

This modeling capability has been applied to develop a comprehensive, U.S. energy model, which was first used in a decision analysis of synthetic fuels strategy for a major U.S. oil company.1/ The SRI energy model covers all major energy forms, conversion technologies, transportation modes, demand sectors, and U.S. geographical regions; explicitly models supply elasticity, interfuel competition, and end-use demands; treats energy market dynamics such as investment, financing, technological change, demand growth, and resource depletion from the present out to the year 2025; and computes market clearing prices and quantities by balancing supply and demand.

1/ The model is used by SRI under an agreement with the Gulf Oil Corporation, and it is formally known as the SRI-GULF Energy Model. The data assumptions and model structure have been reviewed by a panel of energy experts assembled by the Council on Environmental Quality (CEQ) in connection with CEQ sponsored analysis on the economics of western energy resources. A preliminary version of the data set is found in Western Energy Resources Study-Economics: Data Review Package, E. Cazalet, et al, prepared for the Council on Environmental Quality, Executive Office of the President, May 1975. A revised version of this document will be issued shortly incorporating the changes in the data made for the synthetic fuels commercialization program application. A description of the output of the model, selected input assumptions, and sensitivity analysis is found in Chapter II of the main text and in Appendix H.

BLANK PAGE

The modeling approach is based on the economic concept of balancing supply and demand at a market clearing price. Normally, this concept is considered in terms of a single supply curve and a single demand curve with a single price that balances supply and demand; however, in the energy model this concept has been extended to the simultaneous balancing of thousands of supplies and demands that evolve over time and are connected by a complex network. The result is thousands of market clearing prices, each specifying the economics of a fuel at a particular location and time. Using submodels that incorporate engineering, geological, environmental, economic, and behavioral information and advanced computer modeling techniques has enabled implementation of a detailed, national energy model on a commercially available computer.

The principal outputs from the energy model are the regional market clearing prices for fuels over time, associated production quantities, flows through transmission links, capacities of conversion processes, and demands for distributed fuels. Clearly, these outputs can be sensitive to the inputs to the model. Thus, the energy modeling capability is most useful for decision-focused analysis in which the importance of uncertainty in the input information can be measured in terms of the effect on the choice among specific alternatives.

B. BACKGROUND: SYNTHETIC FUELS DECISION ANALYSIS FOR A MAJOR OIL COMPANY

During 1973 and 1974, SRI worked with the Gulf Oil Corporation to perform a decision analysis of alternatives for producing synthetic fuels. One of the important alternatives facing Gulf was whether to participate in potential coal gasification ventures in the Powder River Basin (Montana and Wyoming). Such an undertaking would require investments in a gasification plant costing approximately $0.5 billion, new coal mines, and a pipeline to deliver pipeline-quality synthetic gas to Chicago or other distant markets. This gas would compete there with natural or synthetic gas from other sources.

At the beginning of the decision analysis, intuitive arguments and conventional profit analyses demonstrated that the profitability of a gasification venture would be determined essentially by the future prices of pipeline quality gas in markets such as Chicago and the prices of coal in the Powder River Basin. The projections of these prices over the thrity- to forty-year construction and operating life of a gasification plant were highly uncertain. Although the technical and other business aspects of the venture were of concern, the major determinants of the venture's profitability - and hence the strategic decision to build or not - were the projections of future prices of gas and coal.

In 1973, the future price projections for gas were very confused bacause of uncertain government regulatory policy and uncertain natural gas supplies and consumption. Many energy specialists were forecasting a gap between the quantities of gas that consumers would buy at the projected prices and the quantities that would be produced at the projected prices. Some specialists argued that this gap provided an attractive market for synthetic gas. Their projected prices of gas, however, were considerably below the prices required for a profitable coal gasification venture. Clearly, the prices of gas would have to increase in order to bring supply and demand into balance; but when the prices would be high enough to justify production of synthetic gas was the important question to be resolved.

As a result of the confusion in future price projections for gas, the projections of future prices had to be built from more basic information on natural gas resources and the effect of higher prices on natural gas production. Similar information was required on other energy resources, as well as economic and technical information on energy use, conversion, transportation, and information on government regulatory policy. This additional information was required because interfuel competition in several markets geographically distant from each other and evolving over time has a major effect on the prices of coal and gas.

Synthesizing the basic information necessary for projecting prices requires a comprehensive dynamic model of energy supply, demand, and pricing. Simple models or hand calculations cannot cope with the necessary detail. The scope and detail of the SRI energy model are discussed below. It should be emphasized that this model was developed to address decisions on synthetic fuel ventures. Its basic purpose is to provide an understanding of the economic viability of synthetics in competition with imported and natural fuels in the U.S. energy economy.

C. MODEL OUTPUT

Figures A-1 through A-3 are typical of the output generated by the SRI energy model. Figures A-1 and A-2 show the prices and quantities that represent a dynamic supply and demand balance for the United States, and Figure A-3 gives some of the underlying detail in the price and quantity forecasts.

In Figure A-1, the prices of primary resources are shown to increase as those resources are depleted. (Note that the prices are expressed in constant dollars.) The price projection for natural gas is of most interest. In the near term, natural gas is attractively priced relative to other fuels and its usage increases. (The nominal case assumes no regulation of natural gas prices.) As the less expensive sources of natural gas are depleted, the price of gas increases. Eventually, the use of gas begins to decline as other, more economic fuels are substituted for gas in industrial and power generation markets. Finally, beyond about 2005, the price of natural gas rises to a level that is set by the price of synthetic gas from coal. The rate at which the price of natural gas increases is of great importance in determining the timing and profitability of a coal gasification venture.

Figure A-2 shows that as the prices of conventional sources such as crude oil, natural gas, and high sulfur (Eastern) coal increase, newer forms of energy such as nuclear, shale oil and low sulfur (Western) coal become competitive and assume significant shares of the market. Thus, beyond the year 2000 these newer sources tend to determine energy prices.

In Figure A-3, the total U.S. production of synthetic fuels is shown through the year 2025. These synthetic fuels draw upon eastern high sulfur coal, western low sulfur coal, nuclear fuel (thermochemical decomposition of water), and shale pictured in Figure A-2. Figure A-3 illustrates that methane production from coal and syncrude from shale grow rapidly from 1985 onward, but coal liquids, hydrogen, and low Btu gas are not economically attractive.

The data shown in these three figures are a small sample of the output from the model. In addition, prices and quantities at other major locations throughout the United States and prices and quantities of distributed products including synthetic fuels, electricity, and refined products were computed.

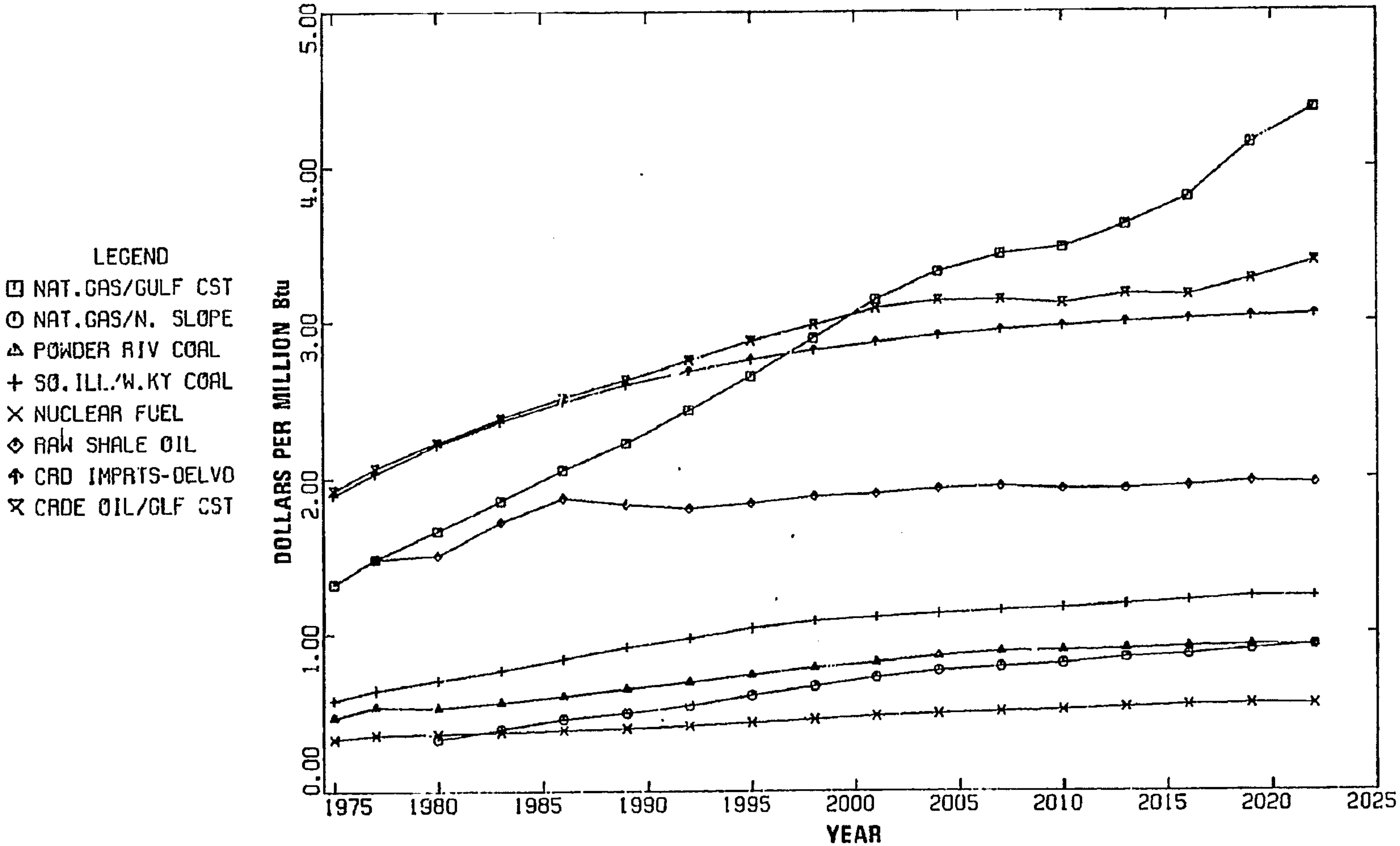


FIGURE A-1 NOMINAL CASES—PRICES OF SELECTED PRIMARY RESOURCES BY LOCATION

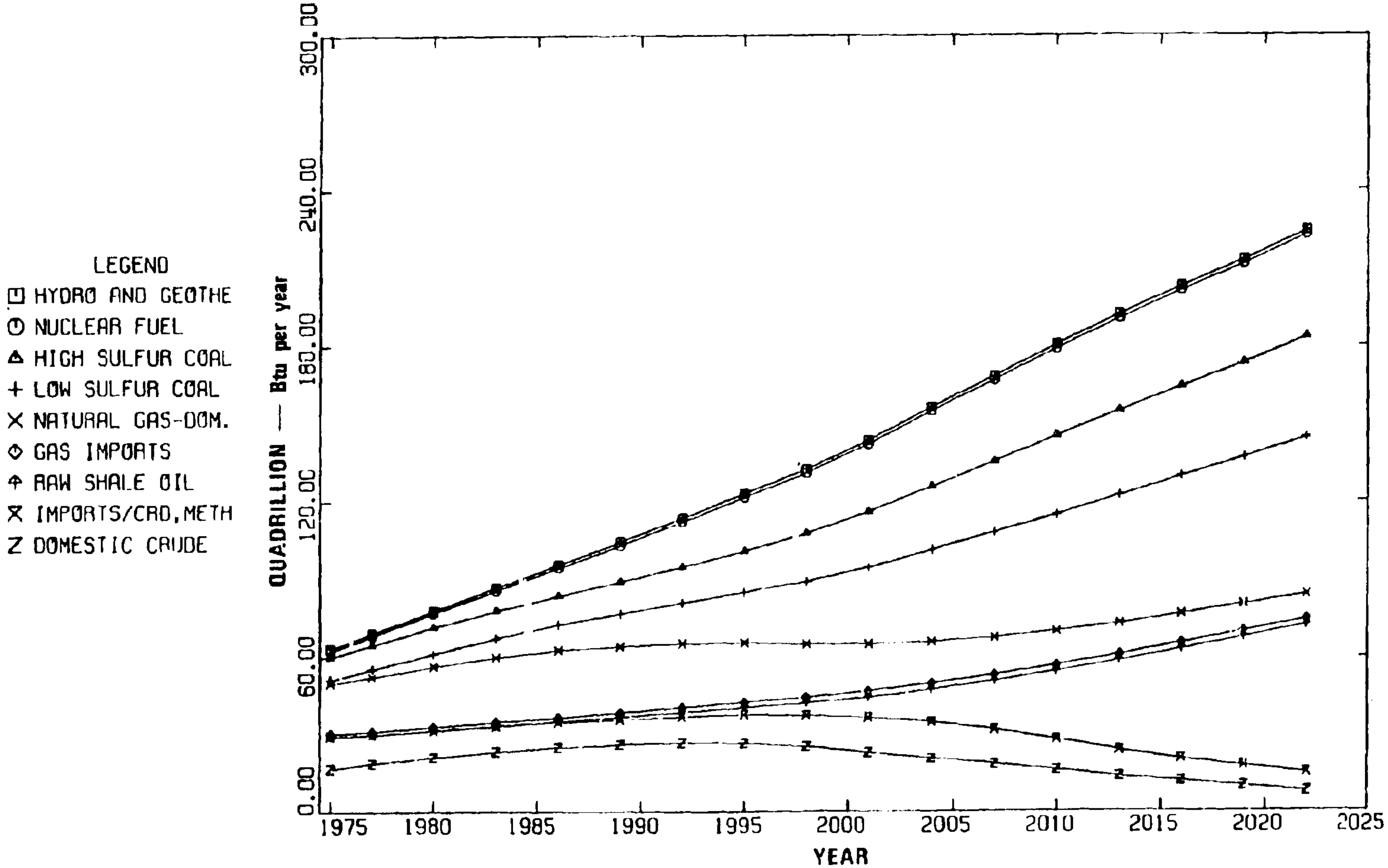


FIGURE A-2 NOMINAL CASE—TOTAL PRIMARY ENERGY

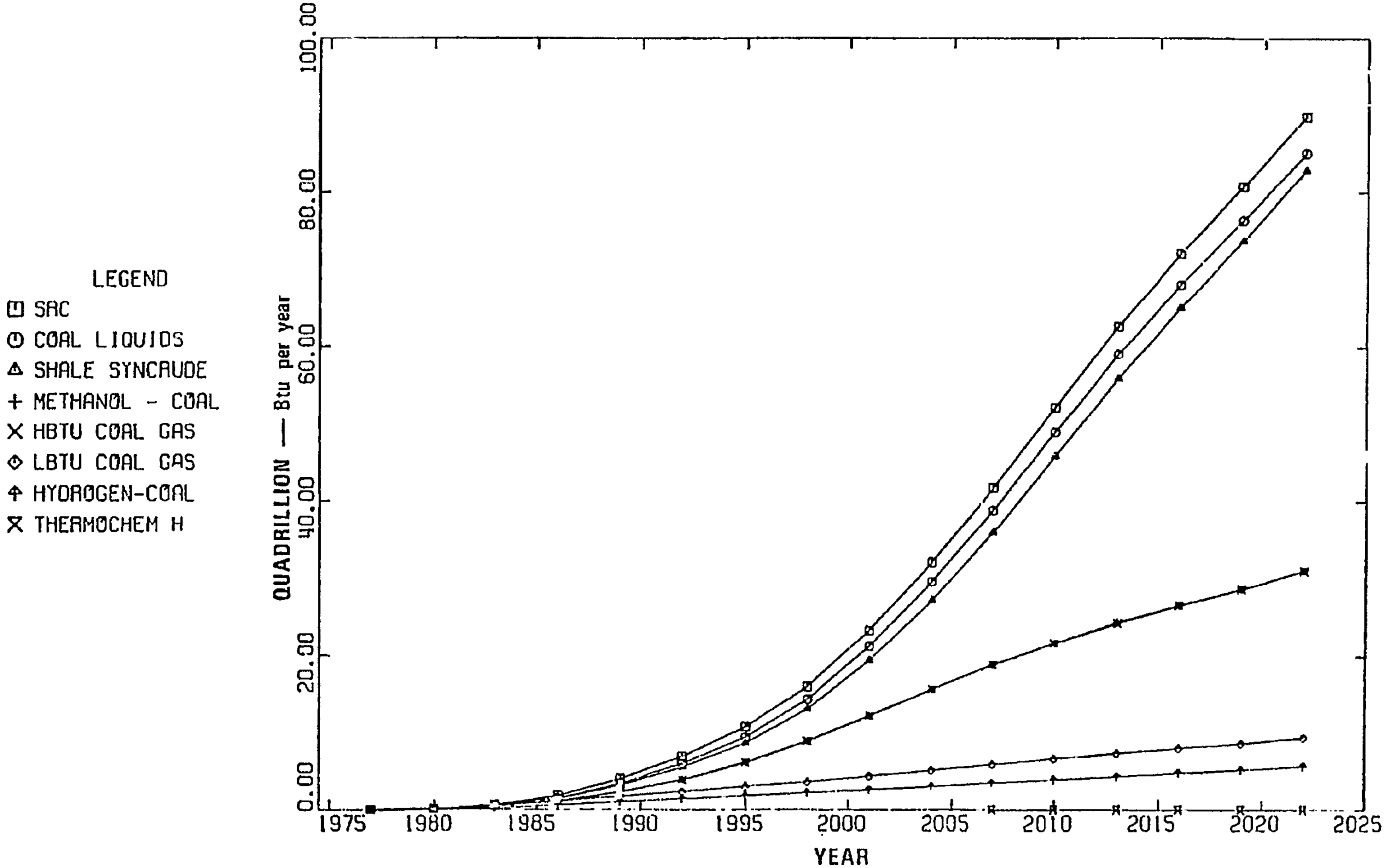


FIGURE A-3 SYNTHETIC FUEL PRODUCTION

The prices and quantities shown in Figure A-1 through A-3 are based on the nominal set among the many sets of input information used in the Synthetic Fuel Commercialization Program analysis. Several sets of input information were used to determine the sensitivity of the projections to changes in input information. For example, the effects of possible changes in the prices of imported crude oil, the costs of new technology, the growth in demand, and the potential reserves of domestic oil and gas were determined. Some of the projections were highly sensitive and some were highly insensitive to changes in input information. Thus, the projections in these figures should not be used without an understanding of the effects of the input information. The reader is referred to Chapter II of the main text and to Appendix H for a discussion of the sensitivity analysis carried out in the Synthetic Fuels Commercialization Program analysis.

D. FEATURES

Energy models must be tailored to specific decision problems. Features required in a model for one problem may not be required in the next problem, or the next problem may require additional features. On the other hand, considerable overlap often occurs between features required for one energy decision problem and those required in the next. With this in mind, we will describe some of the energy model features that are important in strategic energy decision problems such as commercialization of synthetic fuels.

1. Complexity

In most cases, a decision problem concerning a new energy conversion technology, such as coal gasification, is very difficult or impossible to isolate from the energy system within which it must operate. Often, the economics of end use, transportration, and resource production will play a major role in determining what resources are produced, how they are transported, and how they are used. The complexity of the modeling problem is illustrated by Figure A-4. This shows the various steps in the U.S. energy system - beginning with primary resources in the ground and their conversion into useful energy (heat in the living room or steam from a boiler).

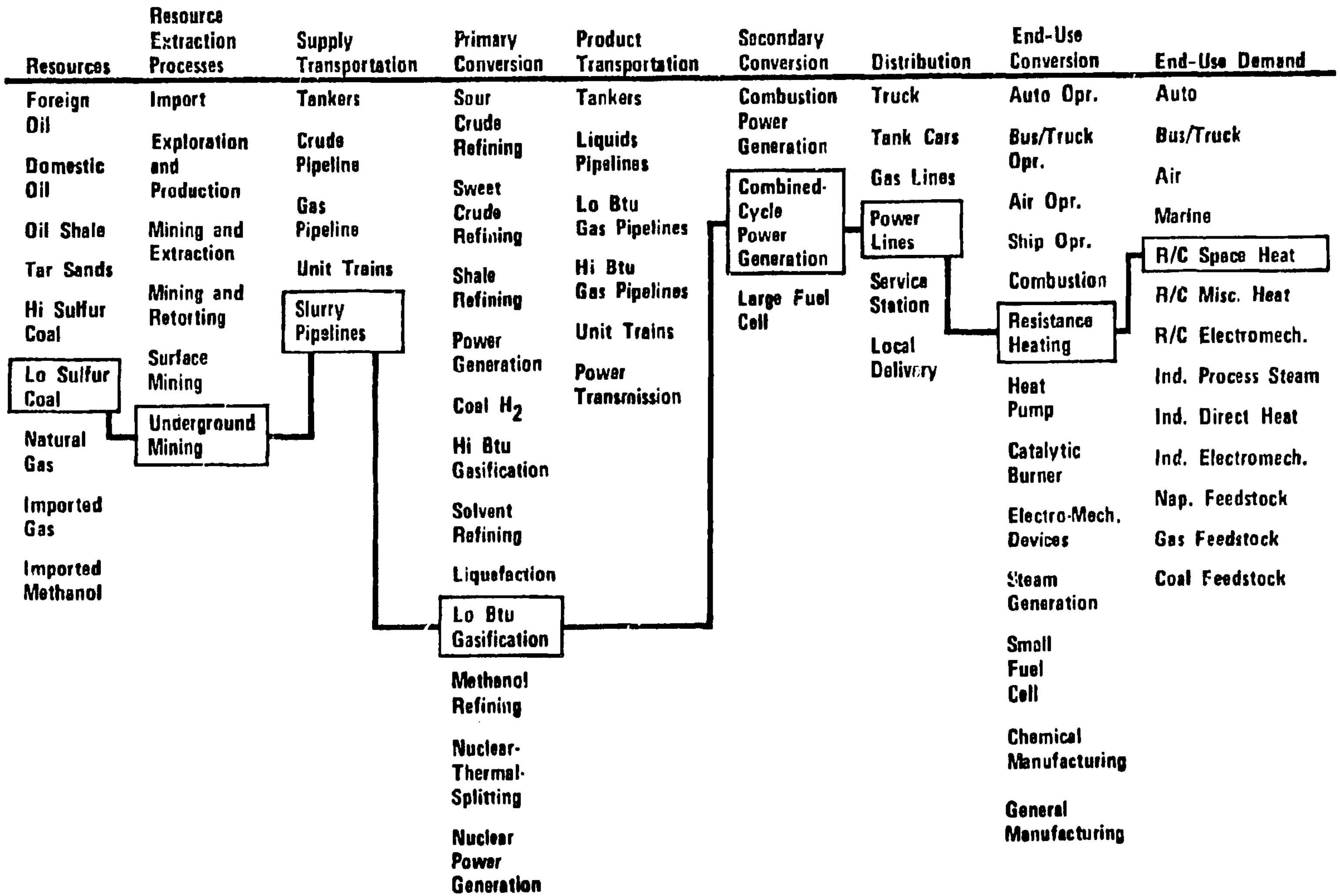
Within the U.S. energy system, thousands of different paths lead from availability of primary resources to satisfaction of end-use demands. The path in Figure A-4 begins with low sulfur coal that is mined underground, transported by slurry pipeline, converted into a gas, and used in a combined-cycle power plant to generate electricity that is distributed to residential consumers for use in a resistance-heating device to produce space heat in the living room. The version of the model used in the analysis of synthetic fuels commercialization incorporates all the possible paths represented in this figure.

2. Logistics

The cost of moving energy from one location to another can be a crucial factor in the overall economics of using primary resources to satisfy end uses. For example, the cost of transporting coal by train from Western mines to Eastern markets is such that the price of coal in the East can be three times the price of coal in the West. Whereas, if this coal is converted to a liquid fuel, the transportation costs over the same distance

FIGURE A-4

COMPLEXITY OF THE ENERGY MARKET



are relatively small. Thus, in problems where transportation costs are important, the model must be geographically segmented to allow for regional price differences. Figure A-5, a map of the United States, shows the eight demand regions and numerous coal, crude oil, natural gas, and shale resource basins used in the Synthetic Fuels Commercialization Program analysis.

3. Dynamics

Most corporate investment decisions and public policy decisions have implications over long periods of time. A model that characterizes the energy system only at specific points in time cannot reflect important changes in technology and demand nor the effect of depletion of the resource base. Also, the capacities of the energy system in any time period are highly dependent on previous investment, and current investment decisions depend on projections of future prices. Finally, in the short-term, secondary markets for scarce commodities such as pressure vessels, surface mining equipment, drilling rigs and human and institutional behavioral characteristics limit rapid change and have long-term consequences. All of these dynamic effects are incorporated in the general methodology and the existing SRI energy model.

4. The Basic Approach: Economics of Supply and Demand for Competing Fuels

Given that the supply and demand of a resource both vary with price, what is the price that will balance demand with supply? Every basic economics text discusses the solution for the case of a single resource, illustrated in Figure A-6, but real situations typically entail multiple competing resources and dynamic effects. Because of the resulting complexity, many approaches to energy modeling avoid explicit balancing of supply and demand at a market clearing price. In this methodology, a computer model is used to combine curves such as those in Figure A-6 with a network representation of the U.S. energy system and realistic models of the elements of the energy system such as transportation links and conversion industries. This gives the advantages of both the basic economic approach and the detail required for realism.

For example, the existing model uses supply curves to describe the total quantity of a primary resource that could be produced in a resource region at various prices. These curves are developed by holding costs and technology fixed and using available data and the judgment of exploration and production specialists to estimate the quantity of a resource that could ultimately be recovered at various price levels. Then the model is used to compute the cumulative production, plus required reserves of a resource

FIGURE A-5

U.S. ENERGY MODEL RESOURCE LOCATIONS AND DEMAND REGIONS

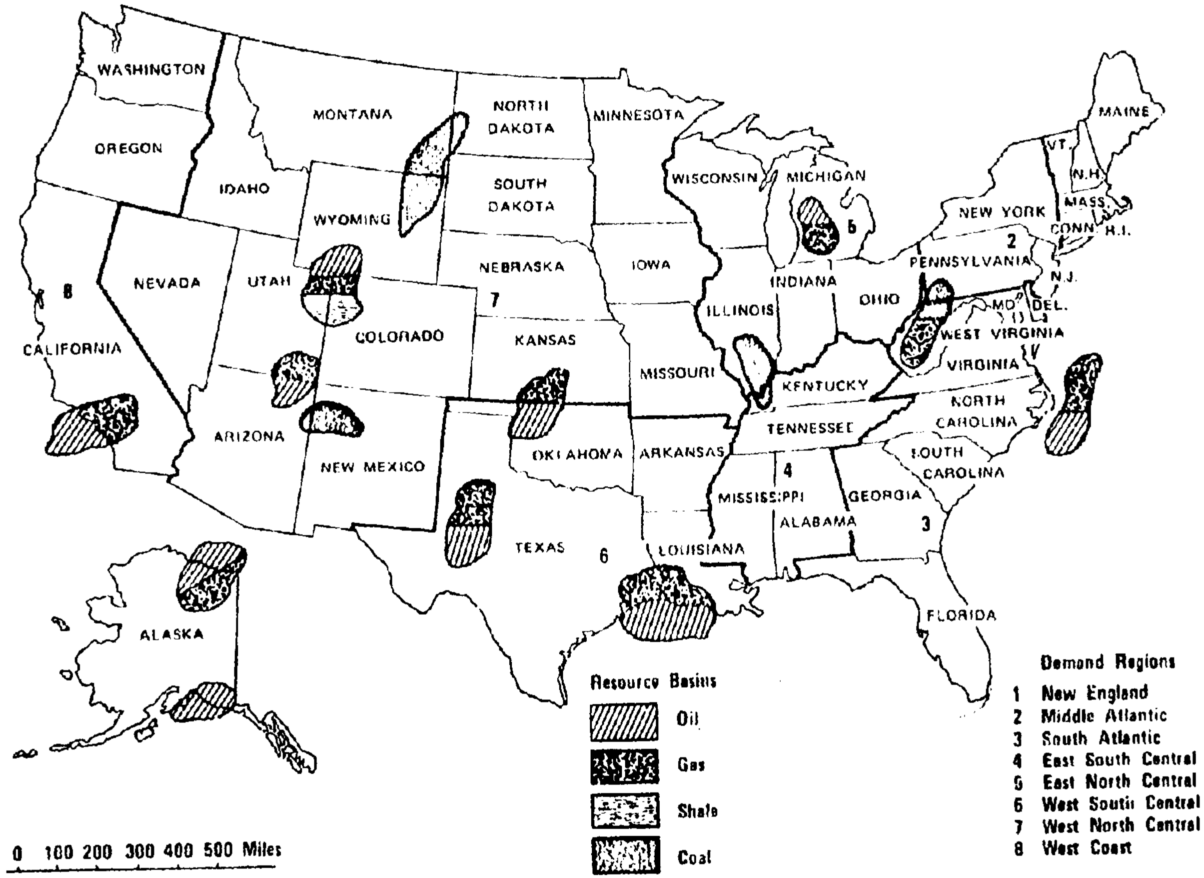
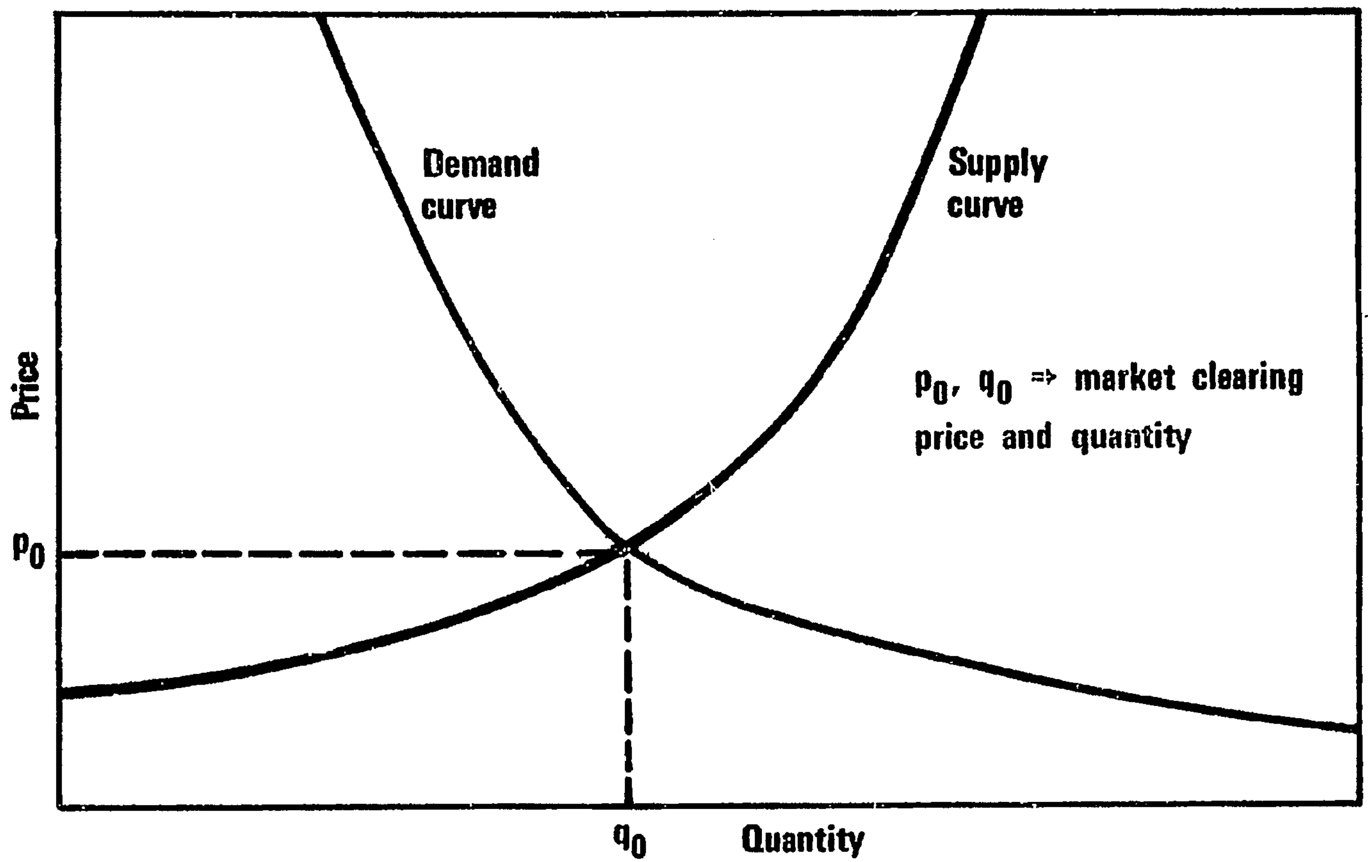


FIGURE A-6

FUNDAMENTAL ECONOMICS OF SUPPLY AND DEMAND



to a given year in a specific location. This quantity is then used to find the price on the supply curve that would be required for additional production in that location and year. Finally, these prices are adjusted for the effects of inflation, technological change, short-run dynamic effects, and economic rent (the difference between the price of a resource and its cost). The result is a realistic, dynamic description of resource supply that is consistent with basic economics.

5. Meaningful Data

A crucial aspect of any model is that the inputs be meaningful to those who must provide and review them. Some approaches to modeling use regression analysis or large amounts of historical data to determine the parameters of the equations that make up the model. Other approaches use abstract inputs such as cross-elasticity coefficients and input-output coefficients, or arbitrary constraints on growth rates and resource availability. The problem with such input is that the data are often unintelligible to specialists who have the knowledge to judge its accuracy. However, a model that decomposes an energy system into its basic elements - such as production, transportation, conservation, and end-use technologies and behavioral considerations - facilitates description of each of these elements in the most meaningful way. For example, the SRI energy model uses capital cost, operating cost, and thermal efficiency data obtained from industry specialists to describe conversion and transportation industries. Structuring model input into numerous specialized data areas enables experts with in-depth, specialized knowledge to contribute data without having to understand all of the details of the model. Furthermore, this form of data can be communicated easily to anyone who wants to understand the model.

6. Specific Features

Some of the specific features in the SRI energy model are described below:

- Economic Rent - Owners of energy resources will not sell their resources at cost plus return on investment if they believe that they can obtain a higher price. Thus, the price of a resource is determined not only by the cost of producing it, but also by competitive fuel prices and the scarcity of the resource. Economic rent, the increment above marginal cost that must be paid to a resource owner to induce him to sell, is large when the price of a resource is rising rapidly as a result of rapid depletion. This phenomena of economic rent is fundamental to energy pricing and incorporates lease bonus payments and windfall profits.

- End-Use Demand Elasticity - In response to higher prices of a fuel, users may reduce consumption by turning down the thermostat, using less steam, or driving less. Alternatively, they may substitute a less expensive fuel. In modeling end-use demand, it is important to distinguish between the effects of true reduction in the consumption of usable energy and the substitution of other fuels. The existing model emphasizes the substition effect because synthetic fuels decisions are sensitive to it. The existing model excludes usable energy elasticity because sensitivity analysis showed that the decisions were relatively insensitive of the price elasticity of usable energy over the range of prices encountered. Detailed price elasticities for usable energy demand could be incorporated within the existing model for analysis of problems sensitive to usable energy elasticity.

- Financing, Accounting, and Taxes - Significant differences in financing practice, accounting conventions, and taxation exist among the various sectors of the energy market. For instance, the financing of regulated public utility investments differs significantly from that of oil company investments. Also, accounting and tax conventions differ from project to project. The model explicitly accounts for these differences.

- Market Share - Under perfect competition, the allocation of demand among alternative sources is trivial - the demand is always allocated to the lowest priced source. In the real market, however, behavioral considerations and market imperfections such as consumer fuel preferences, discriminating pricing, and variations in costs all come into play. The model describes such phenomena by using empirically developed market share curves to relate market shares to prices.

- Initial Energy Balance - The current U.S. energy balance is a starting point for the evolution of the energy system over time. The current allocation of demand among existing sources must be included as input to the model so that the dynamic effects incorporated in the model are provided the proper initial conditions.

- Secondary Industries - In time of rapid expansion of capacity, growth is often discouraged by high prices of equipment and manpower used to construct new plants. Thus, the model includes approximate submodels of secondary industries producing such critical items as drilling rigs and surface mining equipment.

These submodels compute the prices of secondary items for a given demand pattern. When a higher price is required for a secondary item the result is higher capital costs for those plants requiring the items.

- Behavioral Lag - Most organizations and individuals respond slowly to changing economic conditions. We often wait to see proven success before we change our ways. In addition, lags are caused by the time required to plan and construct new facilities. The net effect is that economic actions respond in part to past prices as well as to current ones. Clearly, uncertainty and risk aversion contribute to this effect. Because of the importance of this effect, empirically determined lag parameters are used in the model.

- Technological Change - Learning effects are important in determining the prices of future energy products. Over time, technological improvements lower the capital cost of existing processes (expressed in constant dollars). In addition, entirely new technologies such as fusion or coal liquefaction become commercially available and must be included. Technological change is incorporated in the model by using simple learning curves and nominal dates for commercial availability.

The features described in the above paragraphs illustrate the degree of realism that is built into the SRI energy model. Many aspects of the national energy system are integrated into this energy model. A major by-product of the model is the understanding developed concerning how these aspects relate to each other and to decisions on synthetic fuel commercialization.

E. COMPUTATION

The application of the basic economic concept of balancing supply and demand to an imperfect market system that contains essentially thousands of supply and demand curves is an important consideration. The equilibrium mechanism of the market supplies a clue on how to apply this concept. If the market price is too low, demand exceeds supply and the price will rise to the point where supply and demand balance. Conversely, if the market price is too high, supply exceeds demand and thus the price will fall. The network price iteration algorithm that provides the foundation for the SRI methodology takes advantage of this basic market mechanism.

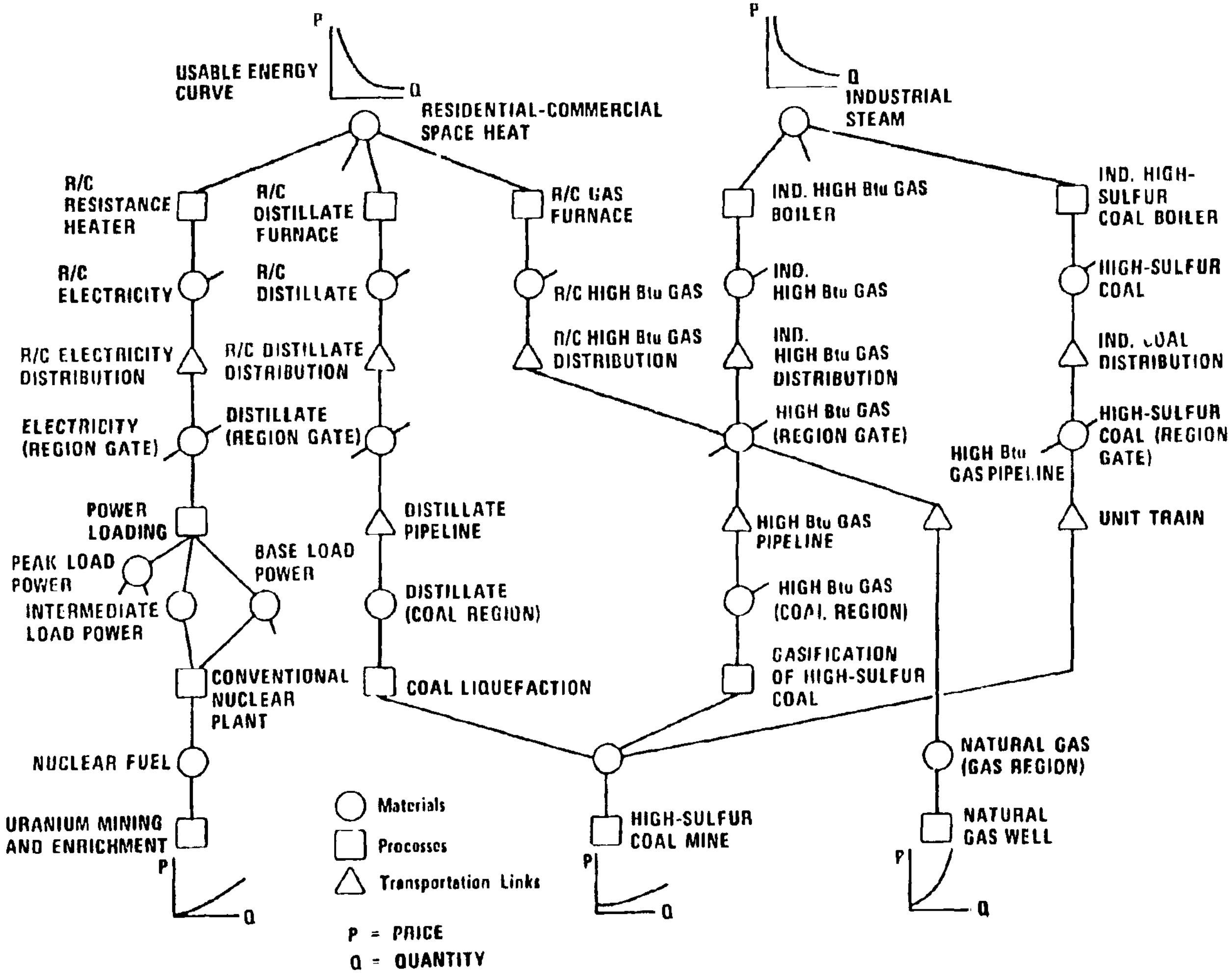
1. The Energy Network

To illustrate, we will use the partial network shown in Figure A-7. The resource supply curves are at the bottom; the usable energy demand curves are at the top. In between these curves is the network describing the entire energy system. The SRI energy model has about 2,400 materials, processes, and transportation links. A material is a primary resource, product, or usable form of energy at a specific location. A process represents a sector of the energy industry such as coal mining or gasification at a specific location or a class of consumers using a particular energy-consuming device. A transportation link represents the economics of moving a material from one location to another.

To get a sense of the many paths in the network, consider first the path where coal is mined, converted into synthetic (high Btu) gas, piped to a demand center in a demand region, distributed to industrial users, and consumed as boiler fuel to produce steam. The same end-use market could be supplied by coal transported by unit train, distributed to the same industrial users, and used in a boiler to produce steam. These two paths can be traced in Figure A-7. In the SRI energy model, there are fourteen end uses (such as industrial steam) in each of eight demand regions and thirty primary resource supplies (such as coal) in the various resource basins illustrated in Figure A-5. The alternative technologies in the model include all important types of electric power generation (producing base, intermediate, and peak load power), sweet and sour crude oil refining, shale oil refining, high- and low-Btu coal gasification, coal liquefaction, solvent refining of coal, methanol from coal, and hydrogen production from coal and nuclear fuel.

FIGURE A-7

ELEMENTS OF THE NETWORK



2. Network Price Itegration Algorithm

The network price iteration algorithm operates in much the same way that the U.S. energy system operates to determine the prices that result in a balance between supply and demand. To illustrate, we begin at the bottom of Figure A-7 and roughly estimate the quantity produced over time of each of the primary resources and products throughout the network.[2/] On the basis of these estimates of primary resource production, the resource supply curve and other dynamic information are used to compute tentative prices of primary resources in each time period.[3/]

We then move up the network along all paths simultaneously, and compute tentative prices of the products. These product prices are computed by using models that account for the capital and operating costs of each of the conversion processes that describe the energy network. Where two or more sources of a material compete, we use appropriate rules for determining the price of the material, given the prices from the sources. When we reach the top of the network, we have computed tentative prices of usable energy for each end-use sector in each demand region over time.

At the top of the network, we begin a downward pass. We apply the prices of usable energy to the usable energy demand curves to determine the quantity of energy needed for each end use in each time period (the present implementation fixes the quantity for each time period and end use). As we work down the network, we allocate the required quantity of materials to competing sources based on the tentative prices computed on the upward pass. In addition, the required quantities are increased to account for the thermal losses in energy conversion and transportation. When we reach the bottom of the network, we have a new estimate of the required quantity in each time period for each of the primary resources. We then repeat the iterative process: the new estimates of production lead to new prices that are passed up the network and result in new demands that are passed down the network. This iterative process is continued until it converges; that is until no significant change in prices and quantities occur on two successive iterations.

2/ In the current version of the SRI energy model, the time horizon is the year 2025. The 52 years from 1973 to 2025 are broken into 17 time periods. These time periods are of unequal duration to allow more detail in the years that are important for the decision problem.

3/ The price of a primary resource also depends on economic rent and the price of secondary materials such as drilling rigs and surface mining equipment.

This network pricing algorithm is summarized in Figure A-8. In practice, additional techniques are incorporated in the algorithm to guarantee convergence and to account for the behavioral and other features of the methodology mentioned earlier.

It is important to recognize that the dynamic aspects of this approach are not equivalent to using a static model in each of the time periods. Rather, the prices and quantitites in each period are determined by dynamic relationships that interrelate both past and future prices and quantities. Current prices depend on future prices because the price of a product required to justify a new plant to produce that product is affected by projections of future prices. Also, current capacity decisions depend on previous prices and decisions because of resource depletion, existing capacity, and behavioral lag.

Another important computational consideration is that models produced by this methodology are nonlinear and usually unconstrained. Linear programming is not used as a computational tool. The mathematics of this methodology reduce to the iterative solution of a system of nonlinear equations that are the economic, technical, and behavioral relationships that describe an energy system. The solution of these equations is the set of prices and quantities that form the output of the model. Arbitrary constraints on the availability of scarce resources such as limitations on plant capacity, primary resources, and surface mining equipment are not needed in the model as they are in some other approaches. In this methodology, we explicitly model the higher costs of such resources as they are depleted (resource supply curves) or when there is a temporary shortage (secondary industries model).

3. Driving Forces of the Model

A question that is often asked is, "What drives the model?" Paradoxically, supply and demand curves are the key inputs required to forecast supply, demand, and prices. The important difference between the input data and output forecasts is that the inputs are price-quantity curves while the outputs are market clearing (equilibrium) quantities and prices. To illustrate, in the textbook case of Figure A-6 supply and demand curves are inputs while the market clearing price and quantity, p_o and q_o are outputs. Many conventional approaches to energy forecasting attempt to directly predict market clearing prices and quantities over time whereas in this approach prices and quantities are calculated on the basis of more fundamental inputs such as supply and demand curves and the economics of conversion, transportation, and distribution. Thus, the model does not eliminate the need for expert judgment. Rather, it changes the task from directly predicting future prices and quantities to modeling relationships between prices and quantities.

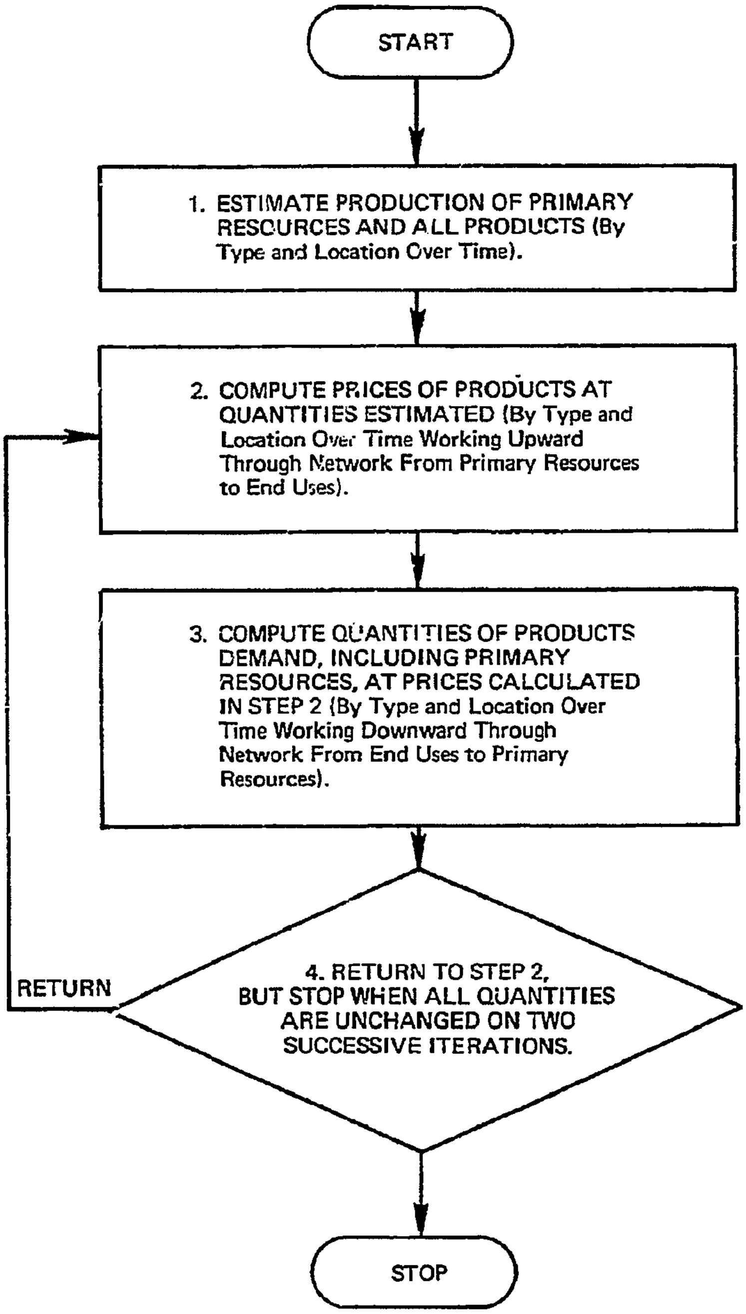


FIGURE A-8. NETWORK PRICE ITERATION ALGORITHM