ENERGY USE AND THE ENVIRONMENT: THE EFFECTS OF ENVIRONMENTAL QUALITY STANDARDS ON THE SUPPLY, DEMAND, AND PRICE OF FOSSIL ENERGY

A Dissertation

Presented to

the Faculty of the College of Business

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In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy in Business Administration

by

Rodrigo Joseph Lievano

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ABSTRACT

A normative economic model is developed in this study for analyzing the effects of changes in (1) resource availabilities, (2) resource prices, (3) operating environment (e.g., energy and environmental policy), and (4) patterns of energy demand, on the supply, demand, and price of fossil energy resources. The model is developed by interfacing (1) a normative economic model of oil and natural gas supply, and (2) an econometric demand model for the important fossil fuels and electricity, through a linear programming model of the energy conversion industries. This interface utilizes the economic theories of resource allocation and valuation, and of competitive markets and economic equilibrium.

The model is used to evaluate the effects of currently announced limitations on waste discharges to the water and air by industrial sources on the supply, demand, and price of fossil energy resources. Four cases representing different levels of restrictions on waste discharges to the water and air are evaluated for 1985.

The overall results indicate that:

1. If oil and natural gas prices are allowed to reflect the value of oil and natural gas as substitutes for air emission control equipment, supply and demand equilibrium could be achieved at any level of environmental quality standards likely to be imposed by 1985 at prices similar to those being paid today for "new" oil and deregulated (intra-state) natural gas.
2. Sufficient adjustment can be made at these prices by both energy producers and consumers in the long run to allow virtually zero growth in oil consumption, a reduced growth rate in total energy

consumption, and the elimination of oil imports.

3. Strict environmental restrictions do not increase total fossil energy use. The relatively large increase imputed on the value (price) of clean fuel counteracts any increased energy requirements for operating control equipment.

4. Air emission restrictions increase energy price and industrial natural gas and electricity use, water consumption, and solid waste discharges more than restrictions on waste discharges to the water

5. Restrictions on waste discharges to the water increase industrial production costs and capital requirements more then restrictions on air emissions.

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INTRODUCTION

Environmental Quality Standards And Energy Resource Scarcity

Within the past decade, growing concern for degradation of the environment has resulted in the passing of federal legislation for the control of the discharge of pollutants to the water and air. The major emphasis in this legislation is the control of water and air pollutants emitted from productive processes. Current environmental policy plans involve the imposition of increasingly-restrictive water quality standards during the next decade, with the ultimate objective of eliminating all discharge of pollutants to the water by 1985. Air quality standards have similar but more immediate goals, particularly on the discharge of particulates and sulfur oxides. Recently, particularly during the OPEC oil embargo, these and other environmental objectives began to restrict the production and use of energy. It became increasingly clear that the production, conversion, and use of energy and environmental degradation were intimately related. All options for expanding domestic energy production have significant environmental implications. Similarly, continued economic and population growth imply continued growth in energy consumption and, even with controls, its environmental consequences. Given that the United States wishes to decrease -- and even eliminate -- its dependence on foreign energy resource supplies, there is a need to identify and evaluate the effects of the additional constraints imposed upon the energy system by the imposition of severe environmental quality standards.

In the United States, the rapid economic development of the last forty years has been characterized by the availability of inexpensive and abundant fossil energy, and the capacity of the environment to absorb ever-increasing impacts from productive activities has been taken for granted. Many of the technological changes in productive activities since 1946 have displaced older processes by newer ones for the sake of convenience, durability, appearance, or efficiency. Natural fibers have been displaced by synthetic fibers; lumber by plastics; soap by detergents; natural rubber by synthetic rubber; land by fertilizers; railroads by trucks. All of these displacements, as well as others, have had major impacts on both energy use and the environment. Just as these changes came about in response to changing relative costs and availabilities of different productive inputs such as labor, capital and alternative raw materials, it is possible that the new and rapid change in the price and availability of energy and environmental resources would influence a corresponding set of changes in the use of these resources. Several questions arise and need to be answered in this context, among which the most important are:

(1) How will energy resource producers respond in the long run to higher prices of energy resources?

(2) If mandatory limits are placed on the type and amount of wastes discharged to the water and air by productive processes, penalizing or prohibiting dirty processes, how will the prices and use of energy resources be affected?

(3) How will these restrictions and increasing energy costs affect

production costs?

(4) As these higher costs are reflected in product prices, how will consumers respond in the long run?

(5) What will be the net result of these energy supply, demand, and price changes on imports of foreign energy resources?

The answers to these questions are of major importance for evaluating the trade-offs between different levels of environmental quality standards, and between energy and environmental quality objectives. This study develops an objective and systematic method for analyzing the effects of changes in (1) resource availabilities, (2) resource prices, (3) operating environment (e.g., energy and environmental policy), and (4) patterns of energy demand, on the supply, demand, and price of fossil energy resources, and uses this method to evaluate currently announced air and water quality standards in this context.

Energy System Analysis

Previous Studies

The energy system of the United States can be described in terms of these components: (1) the primary energy resource extraction component, or the supply of crude petroleum, natural gas, coal, etc.; (2) the energy conversion component, consisting of petroleum refining, natural gas processing, petrochemicals, and electric power generation; and, (3) the final use (demand) component, consisting of the residential, commercial, industrial, and transportation sectors. Previous economic studies of the United States' energy system (for a review of representative recent studies see Related Studies, in this paper), for reasons of modeling scope, emphasis, breadth or depth, have failed to include detailed models of each of the components or suffer from one or more of the following deficiencies:

(1) The modeling methods used cannot account for occurrences out of the range of historical experience;

(2) The model lacks one or more of the components listed above;

(3) The model lacks sufficient economic detail in one or more of the components listed above, or lacks a sound theoretical basis for economic behavior;

(4) The model fails to treat energy prices endogenously;

(5) The model which represents the energy conversion component lacks flexibility to choose among production processes.

These deficiencies impede the detailed analysis of the effects of major changes in the economic factors affecting energy production, conversion, and use, and lead to results which are entirely too dependent on the assumptions on which the model was based.

The purpose of this study is twofold: first to develop an integrated modeling procedure which will overcome the deficiencies listed above, and, secondly, to evaluate the effects of restrictions on waste discharges to the water and air on the supply, demand, and prices of fossil energy resources in the United States in 1985. The chapters which follow give first an overview of the modeling concepts and procedures for this study, and then develop these in detail.

MODELING CONCEPTS AND PROCEDURES

Conceptual Basis

In order to analyze the effects of major departures from historical experience, such as large and abrupt changes in resource prices and new restrictions on production processes, it is necessary to develop an economic model which does more than merely extend past trends. The model must be allowed to choose new trends which depart from past behavior. To do this, the model must be based on sound normative economic theory.

The modeling effort for this study was guided by the following general concepts:

(1) There is a set of energy resources which have to be allocated among competing uses. The owners of these resources will supply varying amounts according to the price of energy resources, subject to physical capacity constraints;

(2) For a given set of energy resource prices, energy users will choose among energy sources based on the relative prices for competing energy sources, and will choose that energy source which fulfills their requirements at least cost;

(3) For a given set of energy resource prices, energy conversion industries will choose among energy resources based upon the relative prices for competing energy sources, and will use the conversion processes which will fulfill output requirements (fuels, feedstocks, chemicals, electricity) at least cost

subject to physical (production capacity, physical laws) and imposed constraints (environmental standards).

Prices, then, enter into the system in two ways. There is a market for primary resources and another for products derived from energy resources. The interface between the two markets is the energy conversion component. The primary resource supply component offers a given amount of these resources to the conversion component at a given price. The conversion component will process varying amounts of each energy resource depending upon the requirements placed upon it by the final demand component. These requirements are dependent upon the prices of products which are, in turn, dependent on the prices of the primary resources. The problem which has to be solved, then, is whether the amount of primary resources supplied at a given price is less than, exceeds, or is just equal to the amount required to fulfill the final demand requirements. This suggests that the problem is one of economic equilibrium, or, in reality, partial economic equilibrium, as the analysis focuses exclusively on energy supply and demand. Given this problem in partial economic equilibrium, then, what is required is a methodology which makes use of the normative economic theory of competitive market equilibrium and its accompanying attributes of economic efficiency and resource valuation and allocation. It can be shown (and is shown elsewhere in this paper) that an optimal solution to a linear programming problem satisfies the normative economic theories of efficiency and resource valuation and allocation. What is usually lacking is a way to relate the resource values and quantities and output values and quantities resulting from that optimal solution to resource supplies and prices and to final demand prices and quantities. This study combines a set of economic models which represent: (1) primary energy resource producers, (2) the energy conversion industries, and (3) final energy demands into one interactive economic model of the United States' energy market with which to seek the partial equilibrium level.

The models for energy resource production and conversion are both structural economic models which describe the responses of these components to changes in the price and availability of energy resources in normative terms. The final demand component is represented by an economic model which takes into account both the macro and microeconomic factors affecting energy demand. These component models are combined through a consistent set of normative economic theories. The combined model can, within certain limits imposed by technological and socio-economic factors (e.g., population growth, growth in GNP, inflation), identify possible new trends in fossil energy production and use, energy resource use in productive processes, and fossil energy prices.

Model Operation

The central component of the model is a linear programming model of production in the energy conversion industries. The other components are used to modify the supply and demand price and quantity structure of the linear programming model interactively. The iterations are continued until equilibrium conditions have been satisfied in both the resource and product markets. For purposes of illustration, the linear programming model may be described as follows:

Minimize $C'X$ (1)

Subject to:

$$A_d X \geq D \tag{2}$$

$$A_s X \leq S \tag{3}$$

$$X \geq 0 \tag{4}$$

Where (1) is the total production cost function, (2) is a set of output requirements, and (3) is a set of energy resource supply limitations. It can be assumed that the matrices A_d and A_s contain the input/output coefficients which relate output requirements to energy resource use. Successive solutions to the program at various levels of D determine a function $V_s = f(D)$, which represents the price at which the conversion industries will supply an additional unit of output. Similarly, successive solutions varying S determine a function $V_s = g(S)$, which represents the derived industry demand curve for energy resources, i.e., the price which industry is willing to pay for an additinal unit of an energy resource. Additionally, the market is represented by energy resource supply functions $S = h(P_s)$, where P_s is the supply market price, and final demand functions $D = t(P_d)$, where P_d is the market demand price. The prices P_s are the prices input to the program and form a subset of vector C. The objective is to find the energy market equilibrium price vectors P^*_s and P^*_d and their associated quantity vectors S* and D*. The algorithm for finding this equilibrium set is as follows:

(1) Initial price and quantity vectors P^o_s, P^o_d, S^o, and D^o are determined;

(2) The linear program represented by equations (1) - (4) is

solved using these initial values, resulting in a set of prices V_s^1 and V_d^1 ;

(3) The market supply and demand quantities are computed using V_s^1 and V_d^1, yielding new supply and demand quantities S^1 and D^1;

(4) The linear program is solved again using V_s^1, S^1, and D^1, resulting in a new set of prices V_s^2, V_d^2;

(5) The process is continued for a number of iterations, say n, until:

a) inequalities (2) and (3) are satisfied as equalities, and;

b) the market prices and the prices derived through the linear program converge, i.e., the differences are small enough such that they may be considered approximately equal. Then:

$$P_s^* = V_s^n \; ; \; S^* = S^n$$
$$P_d^* = V_s^n \; ; \; D^* = D^n$$

This final solution yields a set of partial equilibrium supply and demand prices for fossil energy resources and products, along with the related supply and demand quantities. Associated with this equilibrium price-quantity set are the quantity of crude oil imported, and production costs, production quantities, pollutants discharged to the air and the water, and capital requirements in the energy conversion industries.

For a complete description of the component models used in this study see the chapter on Economic Models in this paper. The chapter An Economic Model of the U. S. Energy Market discusses the relationships between linear programming and economic theory, and the synthesis and operation of the economic models used in this study.

Cases Analyzed

The method described above is used to evaluate the effects of waste discharge restrictions to the air and water on the supply, demand, and prices of domestic petroleum, natural gas, and coal. Four separate evaluations, representing current and proposed levels of air and water quality standards, are made for 1985:

(1) A base case for 1985 which assumes that Best Practical Technology (BPT) water quality standards but no air quality standards will be imposed in 1985,

(2) A case for 1985 which assumes that Best Available Technology (BAT) water quality standards and air emission standards on particulates and sulfur dioxide will be imposed,

(3) A case for 1985 which assumes that Zero Discharge water quality standards but no air standards will be imposed,

(4) A case for 1985 which assumes that Zero Discharge water quality standards and air emission standards on particulates and sulfur dioxide will be imposed.

The final solution to each evaluation yields the associated levels of domestic crude petroleum, natural gas, and coal production, crude petroleum imports, total energy resource use by type and sector, and domestic market-clearing prices for crude oil, natural gas, and coal. The results are given in detail in the chapter <u>Results of the Analysis</u>.

Hypotheses on the Results

The discharge of wastes to the air and water resulting from industrial energy use--nitrogen, carbon, and sulfur oxides, hydrocarbons, and particulates to the air; heat, minerals, and organic matter to the water--has been an activity the cost of which has been borne by others than those directly involved in the decisions concerning the production processes requiring the use of this energy. An interesting and important consequence of the imposition of restrictions on waste discharges to the air and water is the internalization of the costs of environmental degradation resulting from industrial energy use. Those directly involved in the decisions concerning productive processes must now bear the costs of potential impacts on the environment. Industry has essentially four alternative ways for reducing the impact of waste discharges to the air and water:

(1) Continue with the same processes and add some means of effluent control or treatment,

(2) Continue with the same processes and discharge wastes into specially-designated and controlled areas,

(3) Continue with the same processes and divert waste discharges to another medium (e.g., air to water; water to land),

(4) Change productive processes to those which generate less pollutants.

Which of these alternatives are possible depends on the severity of the waste discharge restrictions and on whether these restrictions are placed on waste discharges to the air, to the water, or to both. When, in addition to waste discharge restrictions, there is a scarcity of the preferred energy resources, industrial energy users will tend to bid up the prices of those energy resources which can effectively substitute for effluent control equipment or other methods of reducing the environmental impact of energy use. Increasing the severity of waste discharge restrictions to the water and air should increase the value of environmentally clean fuels. Furthermore, hypotheses can be made concerning the separate effects of restrictions on waste discharges to the water and restrictions on waste discharges to the air. The effects of restrictions on waste discharges to the water on energy use are largely direct effects resulting from the need to operate control equipment. There is little motivation for energy users to use clean fuels to reduce water-borne waste discharges, as the principal waste discharged to the water due to energy use is heat. This is a function of the amount of heat required for a productive process, and not of the type of fuel used. The options for restricting pollutant discharges to the air are much more limited and the methods more complex and expensive, as air is a more intractable medium than water. There is significant motivation to use clean fuels when pollutant emissions are restricted, as by so doing the need for control equipment could be entirely avoided. Restrictions on air emissions, therefore, have important induced as well as direct effects on energy use. The value of clean fuels should reflect the fact that they serve as effective substitutes for control equipment.

The interactive effects of the simultaneous imposition of restrictions on waste discharges to both the air and water should further enhance the value of clean fuels and of productive processes which reduce the generation of water and air pollutants, as various substitution possibilities are eliminated (*e.g.*, diverting pollutants from the air to the water or vice-versa). The results obtained in this study lend support to these hypotheses.

WATER AND AIR QUALITY STANDARDS

The period 1970 - 1974 saw the passage of significant new legislation concerning the protection of the environment. During that period, bills were passed which set standards for air quality, water quality, noise control, and resource and land use. Much, if not all, of this legislation impinges directly on energy resource production and use.

Air Quality

Under the Clean Air Act Amendments of 1970 (P.L. 91-604), the Environmental Protection Agency (EPA) is responsible for establishing national standards of ambient air quality--primary standards to protect health, and secondary standards to protect the public welfare, specifically property, vegetation, and esthetics. In April, 1971, the EPA established standards for major air pollutants--sulfur oxides (SO_x), particulates, carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and photochemical oxidants[10]. These standards became the basis for state plans which require polluters to install control technology or to take other steps which would permit the standard to be achieved. New plants, or existing plants being extensively modified, must meet standards achievable through the use of the best demonstrated technology for emission control. The target date for achieving the primary standards under the Clean Air Act is 1975. An immediate problem with these state plans was that many of the states chose to control SO_x emissions by regulating the sulfur content of the fuel to be burned, but domestic supplies of low-sulfur fuels were inadequate to meet the sudden increase in demand. Many electric utilities chose to meet the standards through the use of low-sulfur fuels because they considered the alternative--flue-gas desulfurization systems--an unproven technology and because many state utility commissions allowed the automatic pass-through of the higher costs of low-sulfur fuels [10]. In the period 1970 - 1973, a total of 19 million tons per year of coal-fired electric power generation capacity had been converted to oil (equivalent to approximately 208,000 barrels per day), mostly in Air Quality Control Regions (ACQR's) where ambient air quality levels for sulfur dioxide exceeded health-related standards [27]. In order to alleviate the situation during the winter of 1973 - 74, sixty-four variances were granted for the use of high-sulfur residual fuel oil and thirteen variances for the use of high-sulfur coal by electric utilities. The need for greater flexibility in the EPA's authority to suspend and modify fuel or emission limitations, specially in emergencies, led to the passing of the Energy Supply and Environmental Coordination Act of 1974 [10].

The major part of the burden for complying with the Clean Air Act will fall on the transportation and the electric power generation sectors. The methods through which these sectors will achieve compliance have not been uniformly decided upon. The transportation sector is still experimenting with various emission control methods, attempting to balance emission limitations and operating efficiency. The electric utilities have basically three options for achieving compliance: (1) burning low-sulfur fuels, (2) installing flue gas desulfurization and particulate emission control systems, and (3) intermittent controls.

The option of burning low-sulfur fuels is constrained by the relative scarcity of these fuels at present. The reliability, effectiveness, and cost of operation of flue gas desulfurization systems, known as stack-gas scrubbers, is a point of controversy. The electric utility industry maintains that the systems are unreliable and costly, and create difficult sludge disposal problems. The EPA, on the other hand, considers that the technology of these systems is sufficiently advanced and their reliability sufficiently demonstrated to warrant widespread use of these systems by the electric utility industry [10]. The use of intermittent controls is another point of controversy. These are methods which disperse and dilute pollutants by the use of tall stacks and various other practices, including the switch to low-sulfur fuels during unfavorable meteorological conditions. The industry favors their use, and believes that they are methods with which to meet ambient air standards in a relatively inexpensive way, using less energy, with less solid waste disposal problems, and encouraging the use of domestic energy resources, such as coal. The EPA opposes their permanent use, claiming that it is not authorized under the Clean Air Act. This claim was upheld in February, 1974, when the Fifth Circuit Court ruled that intermittent control systems are acceptable only if permanent controls are not achievable or feasible [10].

Water Quality

The Water Quality Act of 1965, which amended the Federal Water Pollution Control Act, established water quality standards for interstate and coastal waters. The stated purpose of those standards was to protect the public health and welfare and enhance the quality of the nation's waters to serve a variety of beneficial purposes, such as public water supply, recreation, protection of aquatic life, and industrial and agricultural uses. The Water Quality Improvement Act of 1970 was aimed primarily at the problem of oil spills, providing absolute liability for clean-up costs, regardless of negligence. These two acts emphasized ambient water quality, rather than placing specific effluent controls, and gave the states the primary responsibility for establishing the standards, subject to review and approval by the EPA [9]. The Federal Water Pollution Control Act of 1972 (P.L. 92-500), shifted the emphasis to the control of effluents from point sources and increased direct EPA control. This act requires that every point source discharger of pollutants must obtain a permit which specifies the amount and composition of his discharge and the dates by which the discharger will achieve compliance. States which have met EPA requirements will issue their own permits, subject to EPA review. The EPA itself will issue the permits in those states without an approved program [10]. The national goal of P.L. 92-500 is the elimination of all pollutants into navigable waters by 1985. This is to be accomplished in a series of increasingly restrictive standards. Industrial discharges must achieve application of the "best practical control technology currently available" (BPT or BPCTA) by July 1, 1977. By July 1, 1983, industrial discharges must receive application of the "best available technology economically achievable" (BAT or BATEA). The feasibility of eliminating pollutant discharges by 1985 is to be studied by a National Study

Committee[10]. Municipal treatment plants must provide secondary treatment by July 1, 1977, and "best practical waste treatment technology" by July 1, 1983 [10].

The EPA has made substantial progress in the development of effluent standards. Final regulations defining secondary treatment by municipal waste treatment plants were issued in August, 1973. Through July, 1974, the EPA had published effluent guidelines for 30 industrial subcategories, and is in the process of establishing guidelines for an additional 130 subcategories. These guidelines are based on an analysis of the type of pollutant discharged and the analysis of the available control technology for each industrial subcategory [10].

RELATED STUDIES

The sudden increase in world oil prices announced by the Organization of Petroleum Exporting Countries (OPEC) during the November, 1973, oil embargo dramatized the world petroleum supply problem and forced the United States and other industrialized countries to reassess their positions regarding energy supply, demand and prices in the long-run. In the United States, the government, research organizations, academic institutions, and other concerned groups became involved in studying the problem. A number of energy studies had been completed prior to 1969, but these were of limited scope and consisted of projections of trends in energy supply and use [5]. The newer studies realize that the energy problem is extremely complex, and has broad technological, economic, social, and institutional implications. It is beyond the scope of this paper to include a comprehensive survey of the many studies which have been completed since 1973 concerning the energy problem. Instead, included are brief reviews of selected studies which are primarily concerned with the effects of energy prices on energy supply and demand, effects of energy use on the environment, and the effects of restrictions on waste discharges on the choice of manufacturing processes.

Energy Supply Studies

Federal Energy Administration [15]

This study was undertaken under the FEA's Project Independence studies for the purpose of analyzing the response of crude oil producers to higher prices. The method of analysis consists of an economic model which assumes profit-maximizing behavior by oil producers, who compare the expected returns from oil production to other investment opportunities. These expected returns depend on the amount of exploratory drilling and its success, profit-constraining policies, and the availability of land for exploration and development, as well as oil prices and the costs of exploration and development. Specific analyses were made under two sets of assumptions for 1977, 1980, 1985, and 1990. The conclusions of the study were that domestic petroleum production would continue to decline in the short-run regardless of higher prices or policy changes because of the long lead times required for new petroleum production. In the longer run, at oil prices of $7 to $11 per barrel, domestic oil production would reach 11.1 to 12.2 million barrels per day (6 - 16% above 1974 levels) in 1980 and 11.9 to 15.5 million barrels per day (13 - 44% above 1974 levels) in 1985 even without specific policies for accelerated development (except price deregulation).

University of Houston [19]

Performed under the auspices of the Texas Governor's Energy Advisory Council, this study consists of a set of models evaluating the response of profit-maximizing producers of oil and natural gas to changes in the price of their products as well as interest rates, production costs, and other physical and economic factors which directly influence investment and operating decisions. The model is composed of two sub-models. Model 1 describes the exploration process, the development process, and the production process over time from newly-found reserves. The output of Model 1 gives the profit-maximizing schedule of production of oil and natural gas over time from new reserves found in 1972 and following years. Model 2 gives the profit-maximizing schedule of oil and natural gas production from reserves known to exist before 1972. The decline rate in production is modified according to the results from Model 1. The final output of the model is the profit-maximizing schedule of oil and natural gas production from reserves discovered both before and after 1972.

An analysis for Texas using this model indicates that a 96% increase in the price of crude oil from $4.55 per barrel to $8.95 per barrel, and a 143% increase in the field price of natural gas from $0.28 to $0.68 per thousand cubic feet (all in 1974 dollars) would result in a 77% increase in crude oil production and a 76% increase in natural gas production in Texas in 1985. The increase is measured by a comparison of the time paths of production under the two prices. A three-year exploration and development lag was assumed; limits on the yearly availability of drilling equipment suggested by industry representatives were included in the analysis.

<u>Ford Foundation</u> [16]

In their studies for the Ford Foundation Energy Policy Project, Davidson, Falk, and Lee provide empirical estimates of the elasticity of supply in oil production measured through rent payments to property owners.

The function used to estimate this elasticity is derived through a production function approach, and represents the elasticity of the industry's long-run marginal resource cost function. The derivation assumes perfect competition in the product market and in the market for oil-bearing property.

Recent data for estimating the elasticity of supply for the onshore United States was not available. Estimates using data for the period 1929-1940 indicated a supply elasticity with respect to payments to property owners of 1.1 to 3.1 (i.e., a 1% change in the payments to property owners would result in a 1.1 to 3.1% change in oil production), for that period. Estimates were obtained for Outer Continental Shelf properties using data published by the United States Department of the Interior for the period 1953-1971. The average elasticity over that period was estimated to be 1.3685.

Energy Demand Studies

The identification of the factors which influence the demand for energy poses a more complex problem than that posed by supply estimation. The diversity of choice available to the energy consumer, the large variety of uses, the lack of detailed data, and the difficulty of specifying a model of consumer behavior all contribute to this difficulty. The estimation of the response of energy users to energy price is further complicated by changing technology, economic and social structures, population growth, and, in the United States, the relatively small change in the real price of energy products (the money price relative to a price index) in the past 25-30 Years. Because of these difficulties, estimates of the price elasticity of demand (the percent change in quantity demanded relative to a 1% change in price) vary widely. Although there is general agreement that price is a factor in the demand for energy, opinions vary with respect to its importance. The estimates discussed below are classified according to what has become the generally-accepted categorization of energy users: (1) the residential and commercial sector, which includes households, businesses not engaged in manufacturing, institutions such as schools and hospitals, agriculture, and governments at all levels, (2) the industrial sector, including all extractive and manufacturing industries, and (3) the transportation sector, including private and public motor vehicles, private and public aircraft, railroads, and vessels. Occassionally, two additional groups are identified separately because of their importance in energy use: (1) electric power generation, and (2) industries in which energy resources are used as raw materials in the production of non-energy products such as chemicals, plastics, or fertilizers. This sector is usually termed the non-energy sector.

The Residential and Commercial Sector

One of the earliest and most respected studies in energy demand was by Balestra [4] in 1967, who estimated the response of residential and commercial natural gas users to the price of natural gas, the price of competing energy sources, per-capita income and population and weather factors. His methodological study indicates that natural gas use in this sector is relatively insensitive to price; in new facilities, however, the use of natural gas may decrease 7% with a 10% increase in price.

Baughman and Joskow [7] in 1974 estimated residential and commercial demand for different fuels used for house heating, water heating, clothes drying, and cooking. Their results indicate the importance of fuel prices in the selection of appliances in residential and commercial use. The use of energy in this sector was estimated to decrease less then 2% with a 10% increase in fuel price in a one-year period, and to decrease 5% in a period of more than one year. Significant regional differences in the response of demand to price were indicated.

Anderson [3] in 1973 used data for 50 states for 1969 to estimate the demand for electricity in the residential sector. He estimated that, in the long run, residential electricity use decreases approximately 9% with a 10% increase in the average price of electricity, and increases 11.3% with a 10% increase in the personal income of consumers.

The Federal Energy Administration, in their Project Independence studies [15], completed in November, 1974, estimated total energy consumption, electricity demand, and market shares for natural gas, oil products, and coal in the residential and commercial sector. The use of energy in this sector was estimated to decrease 2.3% with a 10% increase in the average price of energy and to increase 6.4% with a 10% increase in per-capita income. A 10% increase in the price of electricity is estimated to reduce consumption by 4.2%, while a 10% increase in the price of competing energy sources would influence a 2.8% increase in electricity consumption. The FEA's estimates did not differentiate between short and long-run response.

The Industrial Sector

Industrial demand for energy differ basically from demands for other major uses because they are intermediate rather than final consumer demands. In addition, industrial users have many opportunities to substitute processes and inputs used to produce a given set of outputs. Because of these substitution possibilities, the structure of industry may significantly change with changes in the relative prices of inputs such as energy. Structural change generally limits the usefulness of statistical techniques for estimating these changes. Normative methods, such as linear programming, must be used to estimate the economic demands for energy by industry when structural change is significant. Thompson, et al.[25], developed structural economic models for a petroleum refinery/chemical/electric power complex in the NSF (RANN) Project "National Economic Models of Industrial Water Use and Waste Treatment." The results from these models for the evaluation of energy demand in these industries indicate that with a 67% increase in the price of crude oil (from $3.00 to $5.00 per barrel), oil use in the complex decreases by 17.5%. Further increases in crude oil price to 15.00 per barrel result in a cumulative decrease in crude oil consumption of 25%.

Erickson, et al. [14], used statistical methods to estimate the economic demands for energy in the heavy fuel-using manufacturing industries. National Census of Manufacturers' data for 1962 was used for two-digit Standard Industrial Classification (SIC) categories. The industrial use of natural gas as a fuel in the production of chemicals (SIC 28) was estimated to decrease 21% with a 10% increase in the price of natural gas, while in petroleum refining (SIC 29) the use of natural gas as a fuel was estimated to decrease 53% with a 10% increase in price. The use of oil products as fuels in chemical production was estimated to decrease 26% and in paper manufacturing 15% with a 10% increase in oil price.

The Federal Energy Administration [15] estimated energy demand in the industrial sector as a function of the price of energy and the level of industrial activity. The total demand for energy in this sector is estimated to decline by 4.1% in a one-year period and 7% in a longer period with a 10% increase in the average price of energy. The industrial demand for electricity is estimated to decrease 12% both in the short and the long run with a 10% increase in electricity price.

The Transportation Sector

The majority of the studies concerning energy demand by the transportation sector concentrate exclusively on the highway use of motor fuels, as these constitute approximately 80% of the energy use in this sector. Houthakker and Verleger [20] estimated in a 1973 study that the use of motor fuels would decrease 3.4% in a one-year period and 6.7% in a longer period with a 10% increase in price. Data Resources Incorporated [11] in 1973 estimated that the use of gasoline would decrease 3.4% in a one-year period with a 10% increase in price, and 4.1% in a period longer than one year. Both studies fail to evaluate explicitly the effects of fuel price on the type of motor vehicles purchased and used.

Adams, et al. [1], in 1974 evaluated the effects of higher gasoline prices on both the use of gasoline and the types of automobiles purchased and used. They estimated the economic demand for gasoline in 20 Organization for Economic Cooperation and Development (OECD) countries and estimated that gasoline use decreased 9% with each 10% increase in gasoline price. This is interpreted as a long-run response. The applicability of the results to the United States is unknown.

The Federal Energy Administration [15], estimated a 2% decrease in gasoline consumption in a one-year period and an 8% decrease in a longer period for a 10% increase in gasoline price. A 10% increase in per-capita income would influence a 1.5% increase in gasoline consumption in a period of one year, and a 6% increase in a period longer than one year.

In regional studies, Thompson, *et al.* [26], estimated that gasoline consumption in Texas would decrease 1.7% in a period of one year and 9.7% in a period of more than one year for a 10% increase in the price of gasoline. Consumption of gasoline would increase 1.5% in one year and 8.8% in a longer period with a 10% increase in per-capita income.

Energy System Studies

Several recent studies have focused on the interactions between the supply, demand, and prices of energy for the purpose of analyzing the intermediate and long-run effects of various energy and energy-related policies. These studies commonly have an economic structure as the conceptual basis, with various methodologies being utilized to develop the relationships between economic variables and the pertinent physical, technological, and policy variables which characterize the energy system. The reviews presented here illustrate various different approaches to the problem. Table 1 at the end of this section gives a comparison of the results of the studies discussed.

The Project Independence Report [15]

The comprehensive study of the national energy problem evaluates the impacts and implications of a wide range of energy and energy-related policies. The study includes the analysis of the physical, technological, and economic characteristics of the production of oil, natural gas, coal, oil shale, electricity, and solar and geothermal energy. Estimates of 1985 supplies of these energy sources are made under various assumptions concerning world oil prices and development strategies. The factors influencing energy demand in the residential and commercial, industrial, and transportation sectors are analyzed statistically, and various strategies for reducing the growth rate in energy demand are evaluated. Both supply and demand under a particular set of assumptions concerning world oil price, energy development strategies, and energy conservation strategies are integrated through the Project Independence Evaluation System (PIES). This system receives as input the economic characteristics of energy supply and demand, interregional transportation links, refinery capacities, capital availability, manpower and other resource availability, electric power generation capacities, energy resource prices and conversion and transportation costs. The output of the system is a feasible set of energy supply and demand flows, and regional prices for each energy source. The environmental impact of these final results is evaluated in terms of pollution loadings on the air, water, and land resulting from energy production, conversion and use. These pollution loadings reflect installation of control systems for the control of water pollutants to the level required under BAT standards and control of air emissions to the level required by the Clean Air Act Amendments of 1970 (See Water and Air Quality Standards). Results are given for 8 sets of assumptions combining two world oil prices ($7 and $11 per barrel), two energy resource development strategies (Business-as-Usual and Accelerated Development) and two energy conservation strategies.

Methodologically this study represents one of the most sophisticated analyses of the energy problem. It combines statistical and mathematical programming methods in an innovative manner to provide a consistent and powerful analytical tool for policy evaluation. The regional nature of the models used add an important dimension to energy policy analysis. Two possible drawbacks are the lack of a detailed model of the energy industries, and the lack of a complete representation of the resource supply component. It is understood, however, that some tradeoff had to be made between regional detail and industry detail in order to maintain the model at a manageable size.

Energy Analysis and Planning Group - MIT [6]

The purpose of this study was to combine many economic studies of energy supply and demand for different energy sources into a medium to long-range dynamic model of the United States' energy system. The emphasis is on modeling the decision processes by producers and consumers of energy in order to be able to analyze the effect of events out of the range of historical experience.

The supply component is represented by functions which determine the level of development of known resources in response to price and demand. The rate of development is constrained by time lags for resource allocation and construction activities. Both short and long-run supply responses are modeled. Exploration activities are assumed not to be functions of price and are exogenous inputs to the supply models. Imports are also exogenous to the system.

The demand models are composed of two sectors. One sector is termed the base demand and is assumed to be insensitive to price. The other sector is termed the market-sensitive demand and is composed of two subsectors, termed replacement and incremental demand. The replacement demand is that portion of consumers who periodically reassess their fuel choice. The incremental demand represents new consumer needs or growth in that sector. The model assumes that the demand sector growth rates are exogenous, and that prices do not affect the total demand for energy. The energy demand functions for the residential and commercial, industrial, and transportation sectors are represented by time series. Prices determine the distribution of fuel use. The implication of this assumption is that if prices for all energy sources were to increase proportionately, the level of total demand would not change.

The operation of the model to describe the interaction between supply and demand begins with the specification of total energy demand by sector and that portion of demand which is price sensitive. This initial demand is specified by fuel. The total fuel demand is the sum of each sector's demand for that fuel. For a given set of supply parameters (cost per unit, discount rate, recoverable resources), this demand defines a point on the cost curves in the supply models, which defines a wholesale price. These prices determine the "distribution factors" (price elasticities) which are used to reallocate the market-sensitive sector's demands among the different fuels.

The dynamic nature of this model provides an effective framework for analyzing the intertemporal effects of events which affect the U. S. energy system. The restrictive nature of some of the assumptions, however, plus the lack of technological detail in the model components (although some is embodied in the input data) would tend to make long-run forecasting with this model somewhat tenuous. The model as formulated does not explicitely account for the derived nature of energy demand. In the long run, substitutes for energy can be found, especially in industrial uses, and all demands become price-sensitive. Energy users do have the choice of changing their stock of energy-consuming equipment, not only to change the energy source required but to change the energy efficiency of this equipment (e.g., changes to smaller automobiles, process changes in industry).

The Hudson-Jorgensen Model [21]

This model represents an entirely different approach to the analysis of U. S. energy policy by combining a macroeconomic growth model of the economy with an input-output model of production in nine industry groups, a model of producer behavior, and a model of consumer demand. The major innovation is the formulation of the input-output coefficients of the interindustry model as variable in response to the prices of labor, capital, and competing imports. In this manner technological change is endogenously determined.

The model operation is initiated by the generation of primary input prices by the macroeconometric growth model. These primary input prices are used as input to determine the input-output coefficients for the nine sectors in the interindustry model, and the simultaneous determination of the prices of outputs. With this set of prices and total current dollar expenditures for personal consumption, private investment, and government purchases given by the growth model, a consistent set of final demands is estimated. These final demands are then used in the input-output model to generate total output and the pattern of industry purchases. This step provides the market-clearing condition of equality of demand and supply for all commodities. Since all prices are endogenously determined, this final solution satisfies the conditions for economic equilibrium. The solution is in terms of constant dollar transactions. Conversions to BTU's or physical units are performed by applying BTU/constant dollar or physical unit/constant dollar ratios to the fuel entries in the dollar transaction matrices.

The major advantages of this model for energy policy analysis are its relative compactness, the endogenous determination of equilibrium prices and quantities, and the fact that it identifies the interrelationships between energy price and supply to non-energy price input, output, and consumption patterns. Some major limitations are the lack of detail on the characteristics of oil and natural gas extraction (the model has no supply functions, as such), the limitations of econometric methods for predicting future behavior, and the difficulty in specifying alternative technologies through a highly-aggregated set of input-output coefficients.

The IEA Model [22]

The explicit purpose for which this model was designed - long-run analyses up to the year 2040 - place it in a somewhat different category from the other models presented in this section. For such long-run analyses, estimates of economic relationships which could be expected to hold reasonably well in the short and intermediate term become invalid. For this reason, the model was constructed in a flexible manner, and its economic structure based on only the broadest aggregate relationships.

The model is based on a flexible set of components described in terms of physical data and explicit policy assumptions. The total demand for energy is based on population and the level of economic activity as measured by the gross national product. The energy demand by each sector is derived from these parameters and independent technical factors. Various sets of demand projections are made for each consuming sector under different assumptions concerning energy consumption efficiencies, new technologies, and fuel mixes. Oil, natural gas, and nuclear fuel supply estimates are developed under low, intermediate and high estimates of ultimate recoverable resources in the ground. Production levels of electricity and synthetic fuels are functions of technical growth rates. Coal supply is developed through various assumptions regarding coal conversion (to synthetic fuels), direct use, and production rates. New energy sources - geothermal, solar, fusion, and solid wastes - are viewed primarily as alternatives fuels for electric power generation, and supplies of these are projected under alternative assumptions of introduction of "take-off" dates. Several sets of electric power generation options are also developed, reflecting assumptions on fuel mixes, nuclear generation growth, and various nuclear technologies.

The generation of a complete set of energy supply and demand levels for a particular year consists in choosing a set of supply options, summing the quantities of liquids, gases, and electricity supplied and comparing them to the projected demands. If the supplies and demands are reasonably close, the match is considered to be operationally feasible, and it is assumed that the price system would make the necessary marginal adjustments.

This model presents a flexible, simple, and feasible method for assessing long-run developments and testing the feasibility of alternative policies and assumptions. Its major advantage is that it is quick and simple to use, and the necessary calculations could even be done by hand. Its major drawback is that the solutions indicate technical feasibility, with no indication of the economic feasibility. Additionally, the method of choosing among the supply and demand options does not insure the internal consistency of assumptions. A user not familiar with the basic assumptions underlying the options may choose an infeasible set.

The University of Houston Model [26]

Energy policy questions are particularly important to Texas because of its traditional position as the nation's largest oil and national gas producer. The need to be well-informed on energy matters prompted the creation of the Governor's Energy Advisory Council. This body, consisting of political leaders, industry representatives, academic representatives, and specialists, undertook the organization and administration of a large number of energy and energy-related studies. These studies were performed at various universities, research organizations, and public agencies throughout the state. The study discussed here had as its objectives to estimate: 1) the response of oil and natural gas producers to price, 2) the response of major energy users to price, and 3) 1985 oil and natural gas prices mutually acceptable to producers and consumers (market-clearing prices).

The study was accomplished through the formulation of various economic models of energy supply and demand. An economic model of oil and natural gas production was designed. This model has been previously discussed under Supply Models above. In addition, statistical models of the demand for gasoline and residential electricity in Texas were estimated, and the results of a previous study [4] were adapted for Texas. The use of energy in the industrial sector was analyzed through a large-scale linear programming model of production in petroleum refining, petrochemicals, and electric power generation.

The third objective, 1985 market-clearing prices, is the phase of the modeling which is comparable to the studies previously discussed. In order to estimate these prices it was necessary to design a modeling structure which represented the national energy system. An interactive model was designed with energy supply, conversion, and demand components. The energy supply component consists of the oil and natural gas supply model modified to represent the aggregate response of national oil and gas producers (on-shore lower 48 states only) to price. The conversion component, which transforms the primary energy sources to fuels, non-fuel products, and electricity, is represented by the linear programming production model, and the demand model consists of a set of price-sensitive final demand extimates for the major energy sources (gasoline, natural gas, fuel oils, electricity). This set of models was operated interactively, beginning with a set of supplies and demands based on oil prices of $4.00 per barrel and $0.25 per thousand cubic feet for natural gas (1972 dollars). This set of supplies and demands was then entered as parameters to the industry model. The solution to the model indicated the imbalance between supply and demand at those prices and indicated the direction and magnitude by which the supply prices should change. These new prices were input to the supply and demand models, yielding new quantities. These were input to the industry model, which was again solved, yielding new demand and supply imbalances and required price changes. These iterations continued until (1) supply of and demand for oil and natural gas were equal, and (2) the supply and demand prices were approximately equal. This final solution yielded a set of market-clearing supply and demand quantities and prices.

This method for analyzing the economic effects of energy policies has the advantages of being based on a structural economic model of the energy industries. This model allows for the modification of energy use patterns in industry through process substitution. The processes for manufacturing a given product may be changed either to reduce energy (or other input) use or to substitute one energy source for another. In this manner, the model chooses the technology which minimizes the costs of production. Additionally, the system determines the supply and demand quantities and prices endogenously, and thus arrives at an economically-consistent solution. The technical consistency is assured through the supply and industry models. The model is complex and time-consuming to operate, however, and the number of iterations necessary for convergence to a solution cannot be determined beforehand. In addition, the model lacks a macroeconomic basis from which to analyze the feedback effects of high energy prices on the economy. Also, the demand model lacks detail, both in the number of energy sources considered and in the degree of interfuel substitution allowed in response to changing relative prices of energy sources.

Comparison of Results

Table 1 lists the projected 1985 consumption of fossil energy resources (crude oil, natural gas, coal) given in each of the studies discussed above. This comparison is given for illustrative purposes only, and is not intended as a comparison of the relative merits of the studies. When more than one set of results was given for a study, that set for which the underlying assumptions most nearly conformed to the assumptions of the other studies was chosen. Table 2 lists estimates of 1985 crude oil, natural gas, and coal prices when these were parts of the results or assumptions of the study.

Environmental Studies

The Strategic Environmental Assessment System (SEAS) [10]

SEAS is a system of special-purpose models which estimate: (1) Annual water and air pollutants and solid wastes generated in the most

TABLE 1

1985 FOSSIL FUEL CONSUMPTION ESTIMATES*
(Quadrillion BTU)

	UH	HJ	FEA	MIT	IEA
OIL	35.32	44.55	37.98	41.26	38.80
NATURAL GAS	30.75	28.84	24.78	29.54	22.30
COAL	18.53	16.54	22.86	30.27	24.70
TOTAL	84.60	89.93	85.62	101.07	85.80

TABLE 2

PROJECTED 1985 FOSSIL FUEL PRICES*

	UH	HJ	FEA	MIT
OIL (1974 $/bbl)	8.95	7.48	11.80	13.16
NATURAL GAS (1974 $/mcf)	0.68[a]	1.34[b]	1.34[b]	0.55[a]
COAL (1974 $/ton)	15.05	15.57	11.62	7.34

a - Field Price   b - Delivered Price

*UH - University of Houston [26]

HJ - Hudson and Jorgensen - Base Case [21]

FEA - Federal Energy Administration - "Business-As-Usual", $11.00 oil, no conservation [15]

MIT - Massachussetts Institute of Technology - Case Study No. 2 [6]

IEA - Institute for Energy Analysis - Scenario 11 [22] important industry groups, (2) investment and operating costs for air and water pollution control in industry, (3) the demand for transportation and the resulting pollutants, (4) energy demand in the residential and commercial sector and the resulting pollutants, and (5) the amount of wastes from non-industrial sources, the expected disposal method, and the associated costs. These models are linked to INFORUM [2], a large (185 sectors) input-output model of the U.S. economy. Given a set of economic projections, INFORUM generates the level of economic activity in each of the 185 sectors. This information is used by the SEAS submodels to generate a set of regionalized projections of economic activity, pollution loadings, and energy use. The output includes emission and effluent levels both before and after the application of controls.

This model provides a straight-forward and effective method for the evaluation of assumptions on economic growth, aggregate demand, labor force participation, and their impact on the environment. The overall effects of environmental and energy policies can likewise be evaluated. Unless it is constantly revised and updated, however, the unchanging technological structure implied by an input-output model would tend to bias the results of medium and long-run analyses.

MERES [10]

MERES is not a model in the formal sense, but rather a method of calculating the level of abatement costs, air pollution, water pollution, solid wastes, land use, and occupational health and safety associated with a particular level of energy production and use. The effects of energy use on the environment are detailed through each step from extraction to use, along with the associated efficiencies, for a large variety of energy sources.

MERES serves as a valuable source of extremely important data for analyzing the effects of particular energy systems -- e.g., the use of coal-fired electric power generation, from coal extraction to final use -- on the environment and on the industry involved. Broad strategies for supplying the energy requirements for a particular use can be rapidly and comprehensively evaluated. Linked with economic models describing energy supply and demand, MERES could become part of a comprehensive and effective model for analyzing the effects of alternative energy and environmental policies.

ECONOMIC MODELS OF ENERGY SUPPLY, CONVERSION AND DEMAND USED IN THIS STUDY

The Supply of Crude Petroleum and Natural Gas

The model representing the response of crude petroleum and natural gas producers to price is a normative economic model consisting of two components [19]. These have been discussed before in general terms (see University of Houston in the chapter Related Studies). Model 1 consists of two submodels. The first describes the effects of prices and historical experience upon drilling rates and the results of drilling. The second submodel describes the effects of prices and costs upon the development level of reserves found by the exploration model and the production of natural gas, crude oil, and natural gas liquids from these new reserves. Model 2 describes the production of natural gas, crude oil, and natural gas liquids from reserves known to exist in 1972.

The Exploration Model

This model describes the time path of exploratory effort and the time path of additions to reserves of non-associated natural gas and crude oil from that effort. The exploration response of United States oil and gas producers to oil and gas prices and the success ratio (the ratio of productive wildcat wells to total wildcat wells drilled) was estimated statistically. The estimated equations allow the estimation of exploratory drilling for any given year with the prices of oil and natural gas and an initial value for the success ratio as inputs. This estimate is explicitly constrained to an expansion rate of no more than 20% per year regardless of price. The level of this constraint was selected on the basis of historical rates and industry estimates. The additions to reserves of oil and natural gas result from drilling and developing new finds and from revisions to reserves in the light of additional information or improved technology. The finding rate for oil is a statistically-derived function which defines the additions to crude oil proved reserves per foot of drilling in any given year as inversely proportional to U.S. cumulative proved reserves at the start of the year. The revisions are estimated as functions of discoveries.

The Development-Production Model

This model determines the economically "optimal" production level of development of new reserves and the production path over time from these new reserves. The producer has two choices: (1) produce the oil and/or natural gas over a long time-horizon with low capital and operating costs and a small rate in decline in reserves, or (2) produce the oil and/or natural gas over a short time horizon with high capital and operating costs, and a high decline rate. The optimal choice depends upon the revenues, costs, and discount rate required for investment in this type of activity. This optimal level was determined under the assumption that the owners of oil and natural gas reserves will expand capacity by drilling more development wells until the marginal discounted value of revenues is equal to the marginal discounted value of costs. The revenues are derived from the sale of crude oil and/or natural gas at wellhead prices. The costs are development costs assumed to start at the end of year $t = 0$ and continue at a uniform rate until year

$t = \ell$ (ℓ = lag time for development), and operating costs which are assumed to start at $t = \ell + 1$ and continue at a uniform yearly rate until the wells are economically depleted.

The Production Model

This model describes the production of oil and natural gas from reserves known to exist at the start of 1972. This model takes into account the reserves added as revisions to reserves. This is accomplished by adjusting the production decline rate to slow the decline in production over time in response to changes in the estimates of available proved reserves.

The aggregate level of crude oil and natural gas production over time is the sum of the production from new reserves and old reserves plus revisions. The overall model requires as input the time horizon desired, the development lag in years, the wellhead prices of crude oil and natural gas, the required discount rate, the average capital and operating costs per development well, and the initial capacity per well. The outputs of the model are yearly production schedules for crude oil, hydrocarbon liquids (crude oil plus natural gas liquids), non-associated gas, and marketed production of (dry) natural gas.

Appendix A lists the input values for these supply parameters used in this analysis.

Energy Demand

Model Specification

The energy demand model estimates the 1985 final demand for distillate fuel oil, residual fuel oil, natural gas, gasoline, coal, and electricity as a function of the prices of crude oil, natural gas, coal (high and low sulfur) and electricity. The model consist of two submodels. Submodel 1 calculates the delivered prices of the different fuels given the wellhead price of crude oil, the field price of natural gas, and the mine-mouth price of coal. These delivered prices are obtained adding average national unit transportation, distribution, and tax costs given in Foster [17] to the input prices of the primary energy source. Submodel 2 consists of a set of vector functions which adjust the base demands for changes in relative prices in the fuels used in each sector. The base demand is projected assuming pre-embargo prices of crude oil ($4.40 in 1974 dollars), natural gas ($0.33 in 1974 dollars) and coal ($9.00 in 1974 dollars). The demands are adjusted by sector (residential and commercial, industrial, transportation) through a set of own and cross-price elasticities of demand for each of the fuels in each sector. The functional form of the adjustment equations are as follows:

$$\text{Ln } D_i = \text{Ln } BD_i + PE_i \, (\text{Ln } P_j - \text{Ln } BP_j) \tag{5}$$

where:

D_i = Vector of final demands by sector i. Elements $[d_j]$ are quantities of fuel j demanded by sector i.

BD_i = Vector of base-case final demands by sector i.

PE_i = Matrix of price elasticities for sector i. Elements $[e_{jk}]$ are the price elasticities of demand for fuel j with respect to the price of fuel k.

P_j = Vector of prices of fuel j. Elements $[P_i]$ are prices of fuel j in sector i.

BP_j = Vector of base prices of fuel j.

The total demands for fuel j are then the vector sum across all sectors, or:

$$DT = \sum_i \exp(\text{Ln } D_i) \tag{6}$$

where:

DT = Vector of total final demands. Elements $[f_j]$ are total final demands for fuel j.

The form of equation (5) implies that the elasticities are constant regardless of the level of fuel prices. In order to reflect changing elasticities with respect to the fuel price level, the particular matrix PE used in equation (5) is dependent upon the price of crude oil. Three different PE matrices are used for each sector, one when the price of oil is between $4 and $7, one when the price of oil is between $7 and $11, and another when the price of oil is greater than $11.

Estimation of Elasticities

The elasticity estimates used in matrices PE in equation (5) were developed by the Federal Energy Administration for the Project Independence study [15]. The method of estimation consisted of first generating a macroeconomic forecast to establish the economic environment for the demand forecasts. The macroeconomic forecast was then combined with a large system of demand functions which estimate demand as a function of macroeconomic variables and prices. The solution to this system of demand functions establishes the base case demand for each fuel by sector, along with the base prices. Holding all non-price variables constant, the base price vector BP is systematically changed for one fuel at a time. The system of equations is then solved again using the new price P_k for fuel k, yielding a new vector of quantities D of all fuels demanded. The price elasticity of demand for fuel j with respect to the price of fuel k is then estimated as:

$$e_{jk} = \frac{\dfrac{D_j - BD_j}{\dfrac{D_j + BD_j}{2}}}{\dfrac{P_k - BP_k}{BP_k}} = \frac{D_j - BD_j}{D_j + BD_j} \cdot \frac{2\ BP_k}{P_k - BP_k} \qquad (7)$$

for $j \neq k$, equation (7) yields an estimate of the cross-price elasticity, for $j = k$ equation (7) yields an estimate of the own-price elasticity. The set of all elasticities obtained from varying the prices of all fuels then gives the matrix PE of own and cross-price elasticities.

This method for calculating elasticities has the advantage of being consistent with a macroeconomic environment which is in itself consistent with population, price, disposable income, and economic activity levels. The elasticities calculated, however, are strictly local around the base price at which they were calculated. Equation (5) is an approximation to the demand model which uses the elasticities calculated at the base prices for all price levels. Figure 1 shows the correspondence between the quantities calculated from the demand model and the quantities calculated from equation (5). As can be seen, the quantities obtained from both curves are precisely equal at price BP, at which point the slopes of the curves are also equal. At prices close to BP, the quantities obtained are reasonably close. As prices depart from BP the approximation becomes progressively worse. In order to

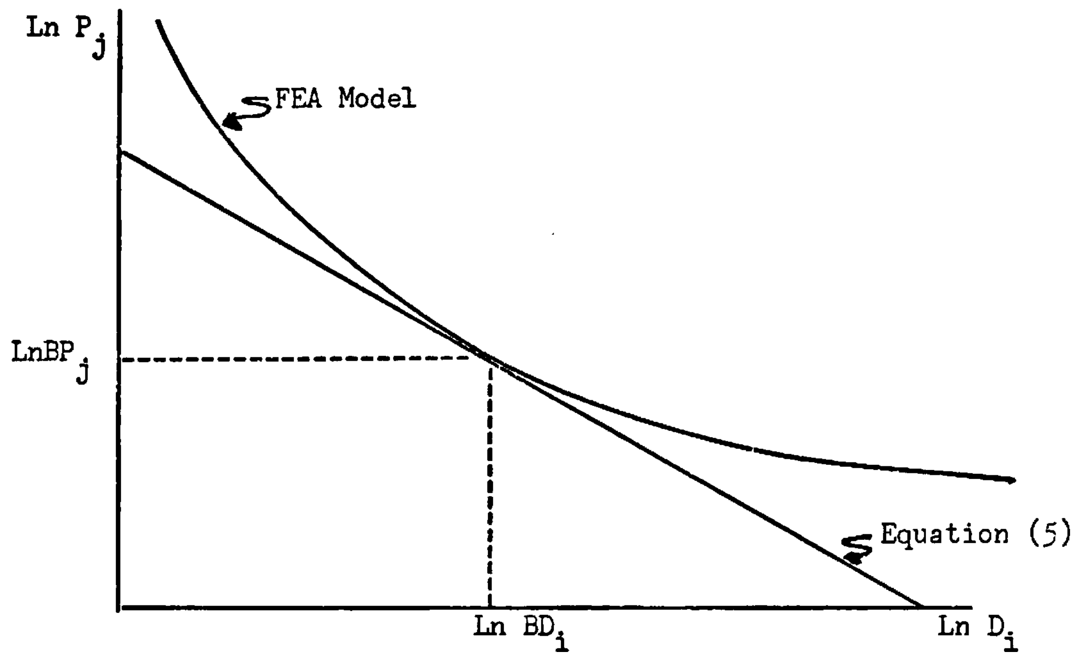

Figure 1. The FEA Energy Demand Model and approximation by equation (5)

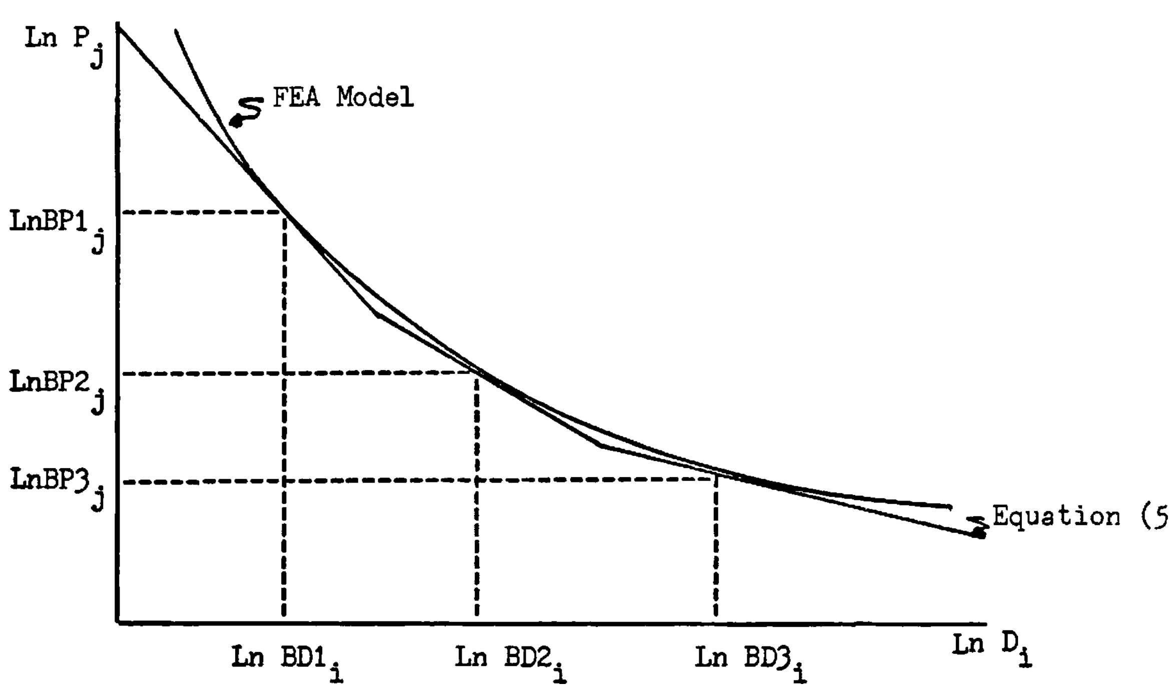

Figure 2. The FEA Energy Demand Model and approximation by equation (5) with variable elasticities

lessen this inaccuracy, three different sets of elasticities were estimated, at base prices for crude oil of $4, $7, and $11. The resulting approximations are shown in Figure 2.

Appendix B lists the values of BD_i, BP_j, and PE_i used in this study.

Energy Conversion and Intermediate Use

The third and central component model is a structural economic model of production in eight industries: petroleum refining, organic chemicals, inorganic chemicals, cyclic crudes and intermediates, alkalies and chlorine, synthetic rubber, nitrogenous fertilizers and electric power generation (steam fossil) [25]. These eight industry groups account for approximately 64% of total energy resources use and approximately 82% of water use in industry in the United States. Additionally, these industries process virtually 100% of the crude oil and natural gas used and supply almost all liquid and gaseous fuels (except for product imports and synthetic fuels), electricity, organic chemical intermediates, and petrochemical products used in the United States.

The model is formulated in a linear programming process analysis framework. This method allows for the evaluation and measurement of restrictions which limit process substitution possibilities, such as resource availabilities, output requirements, and effluent standards. For a given set of output requirements, supplies of raw material inputs, water effluent limitations and air emission restrictions, the model identifies a set of feasible processes. Efficient (cost-minimizing) process-substitution possibilities are substituted for others until the set of processes which satisfy the output requirements and production restrictions at minimum cost is found. This solution gives the most efficient use and maximizes the value of scarce resources.

The models which describe production in each of the eight industry groups are composed of four major parts which are described below.

The Production Sector

This sector identifies the important production possibilities for newly-designed plants and represents currently available technology. The process alternatives allow for choice among different technologies, raw material inputs, and use of by-products.

The Process Energy System

All heat, steam horsepower, and electrical energy are provided by this submodel. The primary fuel input can be chosen from any petroleum fuel (including by-products), natural gas, or several grades of coal. In addition, electricity can be purchased from a utility or generated internally. The power and process activities are fully integrated and allow heat from high temperature processes to be transferred to lower temperature processes. Devices modeled include fired heaters, waste heat boilers, steam boilers, gas turbines, back-pressure steam turbines, condensing steam turbines, electric motors, electric generators, and, in the electric power generation industry, a coal-gasification combined-cycle (CGCC) system.

The Water Treatment System

This component accounts for and treats all water used from withdrawal to discharge. With the exception of once-through cooling water, the water withdrawn for process use is clarified for solids removal. Boiler feed water is dimeralized by ion exchange. Clean steam condensate is recycled to the boilers. Treatment processes for other waste-water streams include sour-water stripping, API separation, air flotation, activated sludge bio-treatment, filtration, and carbon adsorption. A wet cooling tower becomes part of the waste treatment system if zero discharge is required. The wastewater pollutants accounted for are oil, suspended solids, BOD_5, COD, total dissolved solids, phenols, and ammonia. The system can satisfy any discharge limitation on these pollutants including zero discharge.

The Air Treatment System

Emissions of sulfur dioxide and particulates to the air are controlled by fuel substitutions or particulate removal and flue gas desulfurization systems.

The eight industry group models, each containing the above components, were combined into a single integrated economic model. The integration adds additional flexibility and realism by placing all industry groups in a common economic environment in which they compete for resources and investment capital. In addition the integration allows for (1) substitutions of fossil energy resources between energy and chemical uses, (2) the efficient use of the product of one industry as an input to another, and (3) the efficient use of the by-products or waste products of an industry as inputs to that industry or another industry. This allows for the efficient allocation of scarce resources, as this allocation is based on a complete economic evaluation of the alternative uses of the scarce resources.

Figure 3 is a schematic of the industry model used in this study, showing the major components and their interactions. A listing of the industry groups included and their Standard Industrial Classification (SIC) codes is given in Appendix C.

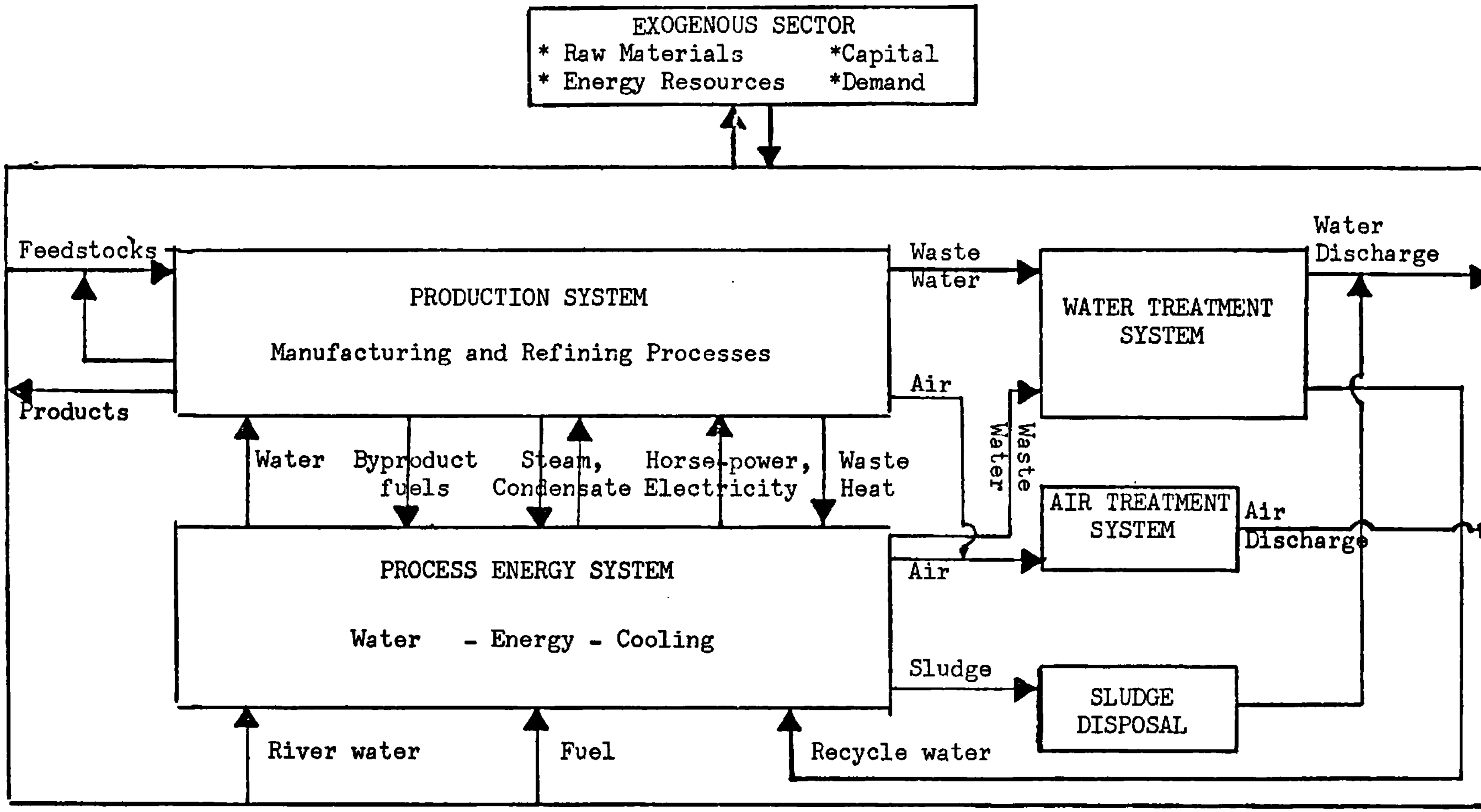

Figure 3. The University of Houston NSF (RANN) Industry Model [23,25]

AN ECONOMIC MODEL OF THE UNITED STATES ENERGY MARKET

The conceptual approach to the analysis of the energy-environment problem is to pose it in terms of a problem in scarce resource allocation. Posing the problem in this manner allows the use of the wealth of economic theory and analytical methods which have evolved over the last 40 - 50 years concerning the allocation of resources. Specifically, it allows the use of the theory of value, suggests the criteria for choosing among competing uses, and defines what constitutes an efficient allocation of scarce resources. If one energy resource is relatively scarcer than another, and if environmental quality considerations increase energy requirements in general and the demand for one (or more) energy source in particular (e.g., because it is cleaner, more convenient, or economically efficient), then the criterion and the method for allocation should explicitly indicate the relative values of different energy sources. Furthermore, separate analyses under increasingly restrictive environmental quality standards should indicate increasingly higher values of the environmentally desirable energy sources. Price theory gives a criterion for efficient allocation and the determination of value under the fundamental economic theorem that a pricing system can serve as a guide for the efficient allocation of scarce resources. The essential characteristics of the prices which correspond to an efficient allocation of resources are as follows [12]:

(1) They are non-negative.

(2) If the resources used by each activity are valued by these

prices, the value of each activity in an efficient allocation will be imputed completely to the resources absorbed.

(3) If the resources used by each activity are valued by these prices, there will exist no activity whose value is greater than the value of the resources it absorbs.

(4) These prices measure the marginal productivities of the scarce resources.

Thus the objective is to determine efficient allocations of scarce resources under different levels of environmental quality standards; the relative prices of the different energy resources will guide the search for this efficient point. It is necessary, then, to construct a model of the energy system which explicitly describes the response of the different components of the energy system (supply, conversion and intermediate use, final demand) to the prices of energy resources, and combines these components in a manner which makes use of economic theories of resource allocation and competitive market behavior. The sections below discuss the theoretical considerations utilized in the design of the model and the method by which the component models were synthesized into a model of the United States' Energy System.

Theoretical Considerations

The characteristics desired of the model which is to determine the economically efficient allocation of scarce resources are:

(1) It should have a criterion with which to identify an efficient allocation,

(2) it should provide an objective measure of the value of the scarce resources,

(3) the allocation obtained should comply with the economic definition of efficiency and be provably so,

(4) it should represent a competitive market,

(5) it should be able to arrive at a provable economic equilibrium,

(6) it should be solvable.

The widely used technique of linear programming can be shown to have the properties mentioned above. The sections which follow will discuss the relationships between linear programming and the economic theories of efficiency, resource allocation and valuation, competitive markets, and economic equilibrium. For a discussion of the mathematical properties of linear programming, see Spivey and Thrall [24] , Hadley [18], or Wagner [29].

Linear Programming and Economic Efficiency

In economics, efficiency in resource allocation is a property of production. In general, a production pattern is efficient if there is no way of increasing the output of some commodity without either decreasing some other outputs or increasing some resource inputs [12]. It is relatively simple to show that an optimal solution to a linear programming problem has this property and in fact makes use of analogous concepts to search for and identify an optimal solution. Suppose a linear programming production problem is to be solved with the objective of minimizing costs. Then the objective function depends positively on all the variables, which represent goods (or alternative methods of producing goods). Suppose we have a set of outputs X^* which represent an optimal (minimum cost) solution to the problem. Then, by the definition of optimality and by the method by which that solution has been found, increasing the output of any good without either decreasing the output of some other commodity or increasing some resource inputs will increase the value of the objective function, and the resulting set will not be optimal. Looking at the problem in another way, suppose a linear programming problem is to be solved with the objective of maximizing net profit from the production and sale of a set of goods with restrictions on the amount of available resources. The allocation of the scarce resources will be among those processes which form an efficient set, as follows:

Maximize: $p_1x_1 + p_2x_2 + \dots + p_nx_n$

Subject to:

$$\begin{array}{l} a_{11}x_{11} + a_{12}x_2 + \dots + a_{1n}x_n \leq S_1 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n \leq S_2 \\ x_i \geq 0 \ \forall \ i \end{array} \tag{8}$$

Where:

P_i = price of good i (or process i) per unit

a_{ij} = units of resource i input per unit of process j

x_j = level of process i (units produced)

S_i = supply of resource i

Suppose $X = (x_1 \dots x_n)$ is an optimal solution to the problem. Then X is an efficient point.

Proof: Suppose X is not efficient. Then there exists a feasible solution $U = (U_1 \dots U_n)$ such that $U_i \geq x_i$. Since $p_i \geq 0$ then $p_iu_i \geq p_ix_i \ \forall \ i$ and at least one

$p_i u_i > p_i x_i$, and $p_1 u_1 + \ldots + p_n u_n \geq p_1 x_1 + \ldots + p_n x_n$. But this is a contradiction, since X was an optimal solution to (8) and U cannot give a greater value to the objective function. Therefore, no such U can exist and X must be efficient.

Linear Programming and Resource Allocation and Valuation

As was shown above, linear programming yields a solution which can be shown to be economically efficient. Furthermore, we can clearly distinguish between efficient and inefficient allocations. If there were a solution in which all the inequalities in (8) were satisfied as strict inequalities, this would clearly be an inefficient solution, as more of any product could be produced without reducing the output of other products. In an efficient (optimal) solution, then at least one of the resources will be exhausted (i.e., one or more of the inequalities in (8) will be satisfied as an equality). This scarce resource constrains the maximum value of the objective function; after this resource is exhausted, the objective function can increase no more. This scarce resource, then, has economic value, for if more were available more output could be obtained, and a higher profit; similarly, if the availability of the resource were to be reduced by one unit, the corresponding optimal solution would yield a smaller net revenue. This difference in net revenues obtained from varying the availability of a scarce resource is a measure of the value of that scarce resource. In economic terms, it is the marginal revenue product of the scarce resource. The total value so imputed upon this scarce resource can be shown to completely absorb the value of the goods or processes to which this resource is an input. Suppose that the optimal solution to the linear program given by (8) consisted of the set $X = (x_1, \ldots x_l)$ where the x_i are the levels at which processes $x_1, x_2, \ldots x_n$ are operated. Let $\underline{A}$ be the matrix of coefficients $\underline{A} = a_{ij\,nn}$. Then $\underline{A}\,X = S$, where S is the vector of resource supplies. Now let k_i be the vector of process levels which uses one unit of resource i. This vector is the solution to $\underline{A}\,k_i = e_i$, where e_i is an n-element unit vector (with a 1 in ith position, zeros elsewhere). As $\underline{A}$ is nonsingular, $k_i = \underline{A}^{-1}e_i$. Let $P = (p_1 \ldots P_l)$ be the vector of values of included processes. Then the value of k_i is the sum of the values of its components, or $P'k_i = P'A^{-1}e_i$. We take this as the value of the ith resource, so $\pi_i = P'A^{-1}e_i$. Let Π be the vector of resource values. The matrix of the vectors e_i is the identity matrix I_n. Then $\Pi' = P'A^{-1}I = P'A^{-1}$. Post-multiplying by S, the vector of resource supplies, we obtain the total value of the resources, or $\Pi'S = P'A^{-1}S$. But since $\underline{A}\,X = S$ we have $X = \underline{A}^{-1}S$ and then $\Pi'S = P'X$, or total value of resources equals total value of output from the processes. It is seen, then, that an optimal solution to an allocation problem can just as well be conceived as an optimal solution to a resource valuation problem. The solution to the two problems is the same, and the values thus obtained for the resources ($P'k_i$ per unit) have the properties of the market prices which correspond to an efficient allocation of resources (these properties were given on page 53).

Linear Programming, Competition, and Economic Equilibrium

It has been shown that for a given set of resource supplies and prices, linear programming yields an efficient solution to the allocation problem, and, furthermore, this solution imputes a value to the scarce resources equal to the value of the output. This valuation of the scarce resources implies that if the scarce resources are valued at their marginal productivity, each process in the optimal set will have zero economic profits (the costs include a profit margin), and that any process not included in the optimal set will have negative economic profits. These are characteristics of a competitive market. In an economy-wide allocation of resources, the efficient point is the point where resources are valued such as to eliminate economic profits in each economic activity. Furthermore, in classical economic theory, the value of any resource and its compensation in a competitive economy are determined by its marginal productivity [9]. If solutions to linear programming problems, then, can be shown to have characteristics similar to those of a competitive economy, then it seems as if some relationships could be developed between linear programming and competitive equilibrium. The problem so far is that nothing has been mentioned concerning market supply functions for resources and demand functions for outputs. Nothing has been said which guarantees that the quantities and prices of outputs and the imputed value and the quantity of resource supplies in a linear program bear any relationship to the market supply and demand functions. A linear program of the type represented by (8) has a solution for any given set of positive p_i and S_j. Multiple solutions with different values for these p_i and S_j would result in multiple optimal solutions, all efficient and all with a corresponding value for the resources. Is there any way to determine if one of these solutions has a set of output prices and quantities and resource supplies and values which also satisfies the market supply and demand functions?

Dorfman, et al.[12] established that, under quite general conditions, such a point does exist, and it corresponds to a solution of a linear program. The values of scarce resources and their prices in a competitive economy have already been established. These are determined by their marginal productivity [9] . The scarce resources will have been completely exhausted in an optimal solution to a linear programming problem. Thus the supply of scarce resources equals the demand in an efficient solution, the supply and demand prices are equal, and the equilibrium exists on the supply side. To prove that an equilibrium exists on the demand side, Dorfman, et al. [12] assume that the demands depend, in some way, on the product prices and on the prices of resources. That is, there is a demand function of the form:

$$Q = F(P,V) \tag{9}$$

Where:

Q = Quantities demanded

P = Product prices

V = Resource prices

What must be shown is that there exists a set of product prices P and derived resource prices V such that the product quantities demanded Q equal the product quantities supplied, Q^1. This is done by starting with an arbitrary set of product prices P and related values V and deriving a set of demands Q through function (9). This set Q may not be a feasible production level, or, if feasible, may not be efficient (no resource is used up to capacity). What is done then is to adjust (increase or decrease) Q proportionately for all products until the resulting set kQ lies on the "efficiency frontier" defined by all possible solutions to the linear program (8). There can be found a set of prices p^1 which will correspond to kQ so that kQ will be an optimal solution to (8). This set of prices p^1 represents the prices at which the output quantity kQ will be supplied by the linear program, to be compared to the set of prices P used in the demand function (9). At this point, Dorfman, et al.[12] use Kakutani's Fixed Point Theorem, according to which (provided a number of conditions, which can be shown to hold in this case, are satisfied) there must be some P^* which is itself included among the sets of p^1 which it generates. It must now be shown that kQ satisfies the demand function (9) at this price P^*. Say Q satisfies (9), then the nature of the demand function is such that $P_i^*(Q_i) = S_iV_i$ (total expenditures equal total earnings to resources). From the linear program, an efficient output kQ is such that $P_i^*(kQ_i) = S_iV_i$, therefore $\Sigma P_i^*(kQ_i) = \Sigma P_i^* Q_i$, so k = 1 and Q = kQ. The demand function is satisfied, demands and supplies are equal and optimal; demand and supply prices are equal. Thus the competitive equilibrium exists.

An interesting feature of this proof is that nothing is assumed about the shape of the demand function (9). The reason for this is that nothing has been assumed or proven concerning the uniqueness of the equilibrium. It is possible to show that the presence of such factors as income may lead to such things as "upward-sloping demand curves" and multiple equilibria. Sufficiently strong downward slope assumptions (what the authors call "the weak axiom of revealed preference") do, however, prove uniqueness [12].

Model Synthesis

The synthesis of the economic models described in the previous section into an economic model of the energy market of the United States is accomplished through the linear programming industry model. This model provides the interface between the suppliers of primary resources and the final consumption sector.

The linear programming industry model is a large scale model of production in which the objective is to minimize production costs subject to the constraints of meeting output demands, plus other imposed or natural constraints on the system. The imposed constraints include limitations on waste discharges to the air and water; natural constraints include material balances, production capacities, and resource availabilities. Mathematically, the model may be defined as follows:

Minimize: $C'X$

Subject to:

$$
\begin{array}{lll}
\text{(a)} & A_eX \leq B_e & \text{Technical, Environmental Restrictions} \\
\text{(b)} & A_kX \leq K & \text{Production Capacity} \\
\text{(c)} & A_qX \leq Q & \text{Supply of non-energy inputs} \\
\text{(d)} & A_sX \leq S & \text{Supply of energy inputs} \\
\text{(e)} & A_dX \geq D & \text{Demand for outputs} \\
 & X \geq 0 &
\end{array}
\tag{10}
$$

The dual of this program is:

$$\text{Maximize:} \qquad -B'_e u - K'v - E'w - S'\pi_s + D'\pi_d$$

Subject to: (11)

$$\text{(f)} \quad -A'_e u - A'_k v - A'_q w - A'_s {}_s + A'_d {}_d \leq C$$

$$u,\ v,\ w,\ \pi_s,\ \pi_d \geq 0$$

Where:

C = Vector of costs of production processes, resources

A = Matrix of process input/output coefficients

X = Vector of process levels

The system (10) describes a program for minimizing the cost of production subject to the restrictions a - e. The system in (11) describes a program for maximizing the value of resources subject to the restriction that the total value of resources used in any process cannot exceed the costs of production.

The primal and dual programs determine the (shadow) prices π_s and π_d as functions of S and D respectively. Specifically, they determine the functions:

$\pi_s = F(S,M)$ - which can be interpreted as the vector function of demands for energy inputs. (12)

$\pi_d = G(D,Z)$ - which can be interpreted as the vector function of supply of outputs. (13)

Where:

π_s = shadow price (value of energy resource supplies)

S = supply of energy resources

M = other factors affecting the value of energy resources (e.g. production capacities, waste discharge restrictions, output requirements)

π_d = shadow price (cost of outputs)

D = demand for outputs of the industries in the linear model (fuels, chemicals, and other products)

Z = other factors affecting the cost of outputs (e.g. fuel prices, waste discharge restrictions)

Additionally, we have exogenous estimates of energy resource supply as a function of the prices of oil, natural gas and coal, and exogenous estimates of the final demand for energy as a function of the prices of oil, natural gas and coal (i.e., the other components discussed in the previous chapter). These can be represented by:

$S = H(P_s, E)$ - which is the vector function of the supply of oil, natural gas, and coal. (14)

$D = T(P_d, O)$ - which is the vector function of final demand for energy. (15)

Where:

S = Supply of oil, natural gas, coal

P_s = Prices of oil, natural gas, coal

E = Other factors affecting supply (e.g. technology, rates of return)

D = Demand for energy

P_d = Prices (delivered) of energy sources

O = Other factors affecting demand (e.g. population, income)

The objective is to find a set of prices P_s and P_d which satisfy the internal prices π_s and π_d generated by the linear programming model. By the considerations given in the first Section of this Chapter under Theoretical Considerations, for an equilibrium solution we must find a point on the supply and demand curves which is also a solution to the linear program, and, furthermore, this solution must be such that:

(1) There is no excess supply of demand for energy resources. This means that constraints (d) and (e) of (10) must be satisfied as equalities;

(2) Supply and demand prices must be equal, i.e.,

$$P_s = \pi_s$$
$$P_d = \pi_d$$

This means that the shadow prices from the linear model and the input prices for energy resources and products must be equal.

It must be made clear that the solution so defined is a partial equilibrium, as the only variables considered here are the supply and demand prices for energy. Other factors affecting the supply and demand for energy (the factors represented by M, Z, E, and O in equations 12 - 15) are assumed to remain constant.

Operation of the Model

The Solution Procedure

Figure 4 is a schematic representation of the solution procedure for the Energy Market Model discussed above. The slant-sided boxes represent data inputs to or outputs from a component model, the rectangles represent the component models, and the diamond represents a decision point. The iterations begin in 2 with a set of representative prices for oil, natural gas, and coal. These prices are input to the Supply Model in 3a and the price submodel in 3b. The Supply Model generates a set of 1985 supply quantities of crude petroleum and natural gas. The price submodel generates a set of delivered prices of fuels which are used as input to the Demand Model to generate a set of 1985 fuel demands by demand sector and fuel type. These supply prices and quantities and demand prices and quantities are input to the Industry Model as parameters in the cost and constraint equations, which already contain fixed parameters for all non-energy inputs and outputs. The Industry Model is then solved, yielding: (1) a cost-minimizing solution satisfying all of the input limitations, production capacities, output requirements, and water and air waste discharge restrictions, and (2) a set of computed (shadow) supply and demand prices for energy resources and products. This set of prices is examined and compared to the prices input in 2. If the input price for a particular energy resource exceeds its computed price, the input price is revised downward and the procedure starts anew in 2. Similarly, if the computed price of a particular energy resource exceeds its input price, the input price is revised upward and the procedure starts anew in 2. These iterations continue until the input prices are equal to the computed prices. This condition identifies the partial equilibrium solution, as the quantities of energy products supplied and demanded by the Industry Model will equal the supply and demand because of the nature of the linear programming solution.

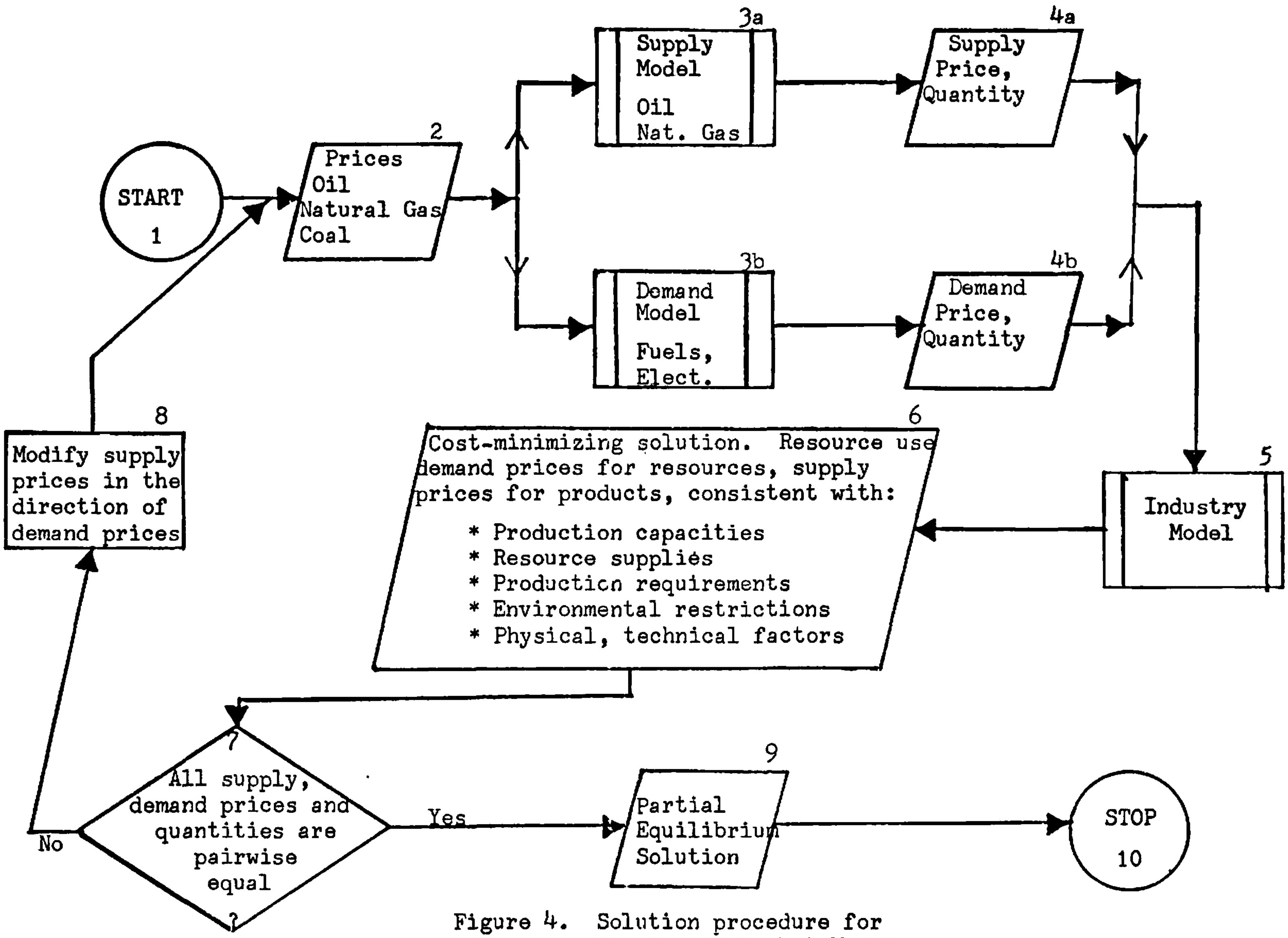

Figure 4. Solution procedure for The Energy Market Model

Computation

The iterative solution procedure described above was implemented for computation through the interfacing of the linear programming solution procedure of the UNIVAC 1108 Functional Mathematical Programming System (FMPS) with a user-supplied FORTAN subroutine. The computer program allows the user to operate the model on-line through a remote terminal. The FORTRAN subroutine: (1) accepts prices as inputs, (2) automatically operates the supply and demand models and revises the appropriate parameters of the Industry Model according to the results, (3) automatically displays the pertinent results from the solution to the Industry Model, and (4) saves the solution for use as a starting basis for the next iteration. The user may modify the data set manually through the terminal, and can stop the iterations at any point. A printout of the complete solution to the Industry Model occurs when called for by the user.

Operational Problems

The major operational problem is the difficulty of establishing the convergence properties of the model. This difficulty arises from the presence of own and cross-price elasticities in the demand functions. If all cross-price elasticities were zero, it would be a relatively simple matter to determine the magnitude and direction of the changes in demand quantities for a given change in the price of a particular fuel. With the presence of non-zero cross-price elasticities, however, the demand functions allocate fuel demands in response to the relative prices of all fuels, and it is possible for the demand for a particular fuel to increase along with an increase in its price. As the fuel prices change from iteration to iteration in the operation of the model, it is difficult to determine the magnitude and direction of the changes in advance.

This lack of knowledge concerning the general convergence properties of the model makes it impossible to establish optimal decision rules for systematically changing the prices in each iteration in a manner which will lead to convergence in a minimal number of iterations. There is significant motivation to decrease the number of iterations, as each lasts for 7 - 12 minutes of computer time depending on how many changes are made to the data set and the constraints placed on the Industry Model. The actual elapsed time may be considerably longer, depending on the load on the computer system, as the Industry Model is large (954 rows, 1698 columns) and requires 44K words of core storage on the UNIVAC 1108.

RESULTS OF THE ANALYSIS

Assumptions

Various assumptions had to be made concerning various uncertain factors the effects of which were not explicitly evaluated in this analysis. The major assumptions were:

1. No regulation of oil and natural gas prices.
2. The average delivered price of imported oil will be 13.00 per barrel (1974 dollars) in 1985.
3. Domestic oil and natural gas will be used to fulfill domestic needs exclusively (no exports).
4. Oil supply from Alaska, the Pacific Outer Continental Shelf, and the Atlantic Outer Continental Shelf will be 1.7 billion barrels in 1985 (4.7 millions barrels per day) as projected by the Federal Energy Administration[15]for a minimum price of $8 per barrel (1974 dollars).
5. At prices above $14 per ton, the supply of coal is elastic up to 2063 million tons in 1985 [15].
6. Supplies of synthetic fuels (gasified and liquefied coal) oil shale, and new energy sources (solar, geothermal, solid wastes) will be negligible in 1985.
7. Nuclear and hydroelectric sources will supply 25% of the total electric power generated in 1985. (9.55×10^{11} kwh in the base case)

8. Total crude oil capacity of domestic refineries will be 17.4 million barrels per day [28].
9. The demands for non-fuel products from the industries modeled (chemicals, chemical intermediates, fertilizers) will increase proportionately to income and population growth.
10. Exploration for and development of energy resources, industrial plant expansion and construction; and investment in efficient control equipment will not be constrained by capital availability or cost.

Cases Analyzed

The four cases analyzed assume different levels and combinations of environmental standards to be enforced in 1985. The cases chosen represent currently-announced national environmental policy as implemented by the Environmental Protection Agency. The environmental standards evaluated include the "Best Practical Technology" (BPT) standards due to be implemented by July, 1977, and the "Best Available Technology" (BAT) standards due to be implemented by July, 1983, the "Zero Discharge" standards due to be implemented by 1985, and currently-announced standards limiting the emission of particulates and sulfur oxides to the air.

The four cases analyzed are listed below:

Case I

This base case represents BPT water standards required by 1977 and assumes that no stricter standards will be required in 1985. No restrictions are placed on emissions to the air. Water treatment in the industries modeled is accomplished by what is termed secondary or Level 2 technology [25], which consists of API gravity separators, air flotation units, and activated sludge units. Once-through cooling is utilized.

Case II

This case represents BAT water standards required by 1983 and assumes that no stricter standards will be required in 1985. Maximum technologically-achievable removal of particulates and sulfur oxides from flue gases is required. Water treatment in the industries modeled is accomplished through tertiary or Level 3 technology, which consists of API gravity separators, air flotation units, activated sludge units, filtration units, and carbon adsorption units. These units accomplish up to 90% removal of BOD_5, COD, ammonia, sulfides and oil from wastewater streams. Cooling is through wet cooling towers. Control of air emissions is achieved through precipitators for particulate removal, and wet limestone flue-gas desulfurization units, by using clean fuels, or, in the electric power generation model, by coal-gasification combined-cycle (CGCC) units.

Case III

Zero discharge of pollutants to the water, the present national goal for 1985, is required in this case. No restrictions are placed on air emissions. Zero discharge is accomplished through a water treatment system composed of API separators, dissolved air flotation units, activated sludge units, carbon adsorption units, ion exchange demineralizers, and cooling towers with recycle to the carbon adsorption units.

Case IV

This is the most restrictive case, and the one which represents announced EPA implementation plans for 1985. Zero discharge of pollutants to the water and maximum reduction in particulate and sulfur oxide emissions to the air are required.

The Supply and Price of Fossil Energy

Summary of Results

The major results concerning the supply and price of domestic fossil energy resources are listed below. All prices are in 1974 dollars.

1. The values imputed on oil and natural gas resources are high enough in all cases analyzed to stimulate substantial supply response from producers.
2. The production of crude oil in the lower 48 states in 1985 would be 7% above 1974 levels.
3. The production of natural gas in the lower 48 states in 1985 would be 42% above 1974 levels.
4. The production of coal in the lower 48 states in 1985 would be between 61% and 76% above 1973 levels.
5. At prices of $8.95 per barrel or higher, the supply curve for crude oil is perfectly inelastic at a level of 11.225 million barrels per day in 1985.
6. At prices of $0.80 per thousand cubic feet or higher, the supply curve for natural gas is perfectly inelastic at a level of 29 trillion cubic feet per year in 1985.

7. Crude oil imports would not be required at oil prices above $10 - $13 per barrel, depending on the environmental restrictions imposed, if oil supply expectations from Alaska and the Outer Continental Shelf materialize.

The Results

Table 3 summarizes the results for the equilibrium supply of fossil energy resources. The supply of oil and natural gas shows no variation between cases because even the lowest equilibrium oil and gas prices ($10.85 per barrel for oil, $0.83 per smcf for natural gas--see Table 4) were sufficient to push the expansion capacity of the oil and gas industry up to the likely limits of the industry. A comparison of the supply results with 1972 figures indicates a 3.7% increase in oil supply from the lower 48 states, and a 3.6% decrease in overall oil supply. Even with this decrease in overall oil supply, however, the results indicate the elimination of crude oil imports because of the significant increases in natural gas (35.5% over 1972) and coal (up to 102% above 1972) supplies.

The equilibrium prices shown in Table 4 indicate the prices required to obtain the supply levels shown above and to balance supply and demand. These prices would have to exist now and continue through 1985. As the table shows, environmental standards do influence the prices of fossil energy resources. The prices increase monotonically as the environmental restrictions are made increasingly stricter. Natural gas, the environmentally cleanest fuel, shows the most marked increase in price, a 92.77% increase between the price in the least (Case I) and the price in the most (Case IV) restrictive cases. Oil

TABLE 3

SUPPLY OF FOSSIL ENERGY - 1985

	1972	CASE I	CASE II	CASE III	CASE IV
CRUDE OIL* (10^9 Bbl/yr)					
LOWER 48	3.950	4.097	4.097	4.097	4.097
ALASKA, OCS	0.000	1.695	1.695	1.698	1.693
IMPORTS	2.060	0.000	0.000	0.000	0.000
TOTAL OIL	6.010	5.792	5.792	5.795	5.790
NATURAL GAS (10^{12} cf/yr)	21.400	29.000	29.000	29.000	29.000
COAL (10^6 st/yr)	520.830	1010.380	966.890	1051.820	1028.200

*Includes all liquid hydrocarbons

TABLE 4

DOMESTIC PRICES FOR FOSSIL ENERGY SOURCES - 1985
(1974 Dollars)

	CASE I	CASE II	CASE III	CASE IV
CRUDE OIL[a]				
$/Bbl	10.85	12.37	11.32	12.73
$\$/10^6$ BTU	1.91	2.18	2.00	2.24
NATURAL GAS[b]				
$/smcf	0.83	1.41	1.03	1.60
$\$/10^6$ BTU	0.81	1.37	1.00	1.55
COAL[c]				
$/t	14.04	14.11	14.04	14.34
$\$/10^6$ BTU	0.58	0.76	0.58	0.76

[a]Well-head price

[b]Field price

[c]Mine mouth price

prices show a corresponding increase of 17.37% between the two cases, while coal price increases by only 2.14% The separate effects on price resulting from water and air standards are shown in Table 5. Increasing the water standards from Case I levels (BPT) to Case III levels (Zero Discharge) with no air emission restrictions increases the price of oil by 4.33% and the price of natural gas by 24.1%. Increasing the water standards from Case II levels (BAT) to Case IV levels (Zero Discharge) with air emission restrictions increases the price of oil by 2.91% and the price of natural gas by 13.5%. The effects of air emission standards are significantly greater, however, as oil price increases by 12.5% and the price of natural gas increases by 55.3% in going from Case III (Zero Discharge--no air emission restrictions) to Case IV (Zero Discharge--restrictions on particulate and sulfur dioxide emissions). The influence of restrictions on air emissions is also evidenced by the fact that the prices of all fossil energy resources could be rank-ordered by whether the case includes air restrictions. In Case III, which has maximum restrictions on waste discharges to the water, the prices of oil, natural gas, and coal are lower than in Case II, which has less restrictive water standards than Case III, but maximum air emission restrictions.

The Demand for and Price of Fossil Energy

Summary of Results

The overall results indicate the potential for adjustment to higher prices. Reduced growth rates in the use of oil and natural gas are compensated by the increased use of coal. The growth rate in total

TABLE 5

EFFECTS OF ENVIRONMENTAL STANDARDS ON ENERGY PRICES
(% Change)

	WATER STANDARDS		AIR STANDARDS
	CASE I TO III	CASE II TO IV	CASE III TO IV
OIL	4.33	2.91	12.46
NATURAL GAS	24.10	13.48	55.34
COAL	0.00	1.63	2.14

fossil energy demand is reduced from historical trends. The most important results are summarized below.

1. Strict environmental restrictions do not increase total fossil energy demand. The relatively large increase in the price of clean fuels counteracts any increased requirements for operating effluent and emission control and treatment equipment.
2. The growth rate in total fossil energy demand would be reduced from the historical growth rates of 3 - 4% per year to approximately 2% per year.
3. The growth rate in oil demand would be reduced from the historical growth rate of 3% per year to a zero growth rate.
4. The growth rate in natural gas demand would continue at or exceed the historical growth rate.
5. Electricity demand would continue to increase at the historical rates of 6 - 7% per year.
6. Coal would absorb most of the growth in total fossil energy demand.

The Results

Total Demand. The results shown in Table 6 indicate the potential for adjustment to higher oil and natural gas prices. In all cases the demand quantities are equal to the supply quantities shown in Table 3, as these are equilibrium results. The most interesting result is that total demands in the strict cases (Case II and Case IV) are not at higher levels than in the least strict cases (Cases I and III). Presumably, the need to operate control and treatment equipment to meet effluent and emission standards would raise energy requirements in the industrial sector. As shown in Table 6, however, Case II standards result in the lowest total demand, while Case IV standards--the strictest--result in a total demand less then 0.5% above those in Case I--the least strict. The reason for this is the increased price of environmentally clean fuels. With strict environmental standards, particularly for air emissions, the price of these fuels is bid upwards by the high value users--those for whom environmentally clean fuels provide a substitute for treatment and control equipment. The lower value users, for whom these fuels provide just energy needs, choose to substitute other energy sources and/or to curtail their energy use. As these lower value users release more of these fuels, more is available for the high value users, but at high prices. These high prices motivate the use of processes which reduce energy requirements. The net result of these adjustments is the apportionment of the available supply of environmentally clean fuels among those users who would have to pay the greatest penalty for clean fuel deficits, and to reduce total fossil energy demand.

TABLE 6

TOTAL FOSSIL ENERGY RESOURCE DEMAND - 1985
(Quadrillion BTU)

	1972	CASE I	CASE II	CASE III	CASE IV
OIL	32.97	32.84	32.84	32.84	32.84
NATURAL GAS	23.13	29.93	29.93	29.93	29.93
COAL	12.50	24.25	23.21	25.24	24.67
TOTAL	68.60	87.02	85.98	88.01	87.43

<u>The Demand for Oil and Natural Gas</u>. The demand for these energy sources does not vary between the cases analyzed because of supply limitations. As was mentioned in the previous section, the supply of domestic oil reaches its 1985 upper limit at a price of approximately $8.95 per barrel, and the supply of domestic natural gas reaches its 1985 upper limit at a price of approximately $0.80 per thousand cubic feet because of the limits on the expansion capacity of the oil and gas industry. As in each case the values imputed on these resources are in excess of the prices required for these maximum supplies, what occurs in each case is that the price is bid up until the demand is equal to the fixed supply. The prices required for this are higher in the strict environmental cases because of the environmental control value imputed on oil and natural gas.

<u>Energy Demand and Price by Sector</u>. More variation in demands is shown in Table 7, in which the sectoral demands for major fossil fuels are given for each of the cases analyzed. The 92.77% increase in the field price of natural gas between Cases I and IV influences a decrease in demand of 11.7% in the residential and commercial sector, and a 22.04% decrease in demand in the industrial sector. This is partially countered by corresponding increases in the demand for fuel oils, coal, and especially electricity, which do not show such a marked increase in price. The price of electricity (see Table 8) shows the smallest range of price changes, except for coal prices, which stay virtually constant across all cases. These interfuel substitutions do not make up the inital decrease in demand, however. The overall increase of 22.6% in the average delivered price of all energy sources between Cases I and

TABLE 7

FOSSIL FUELS AND ELECTRICITY DEMAND BY SECTOR*
(Quadrillion BTU)

	CASE I			CASE II			CASE III			CASE IV		
	RC	I	T	RC	I	T	RC	I	T	RC	I	T
DISTILLATE FUEL OIL	4.52	2.15	2.70	4.72	2.43	2.67	4.64	2.26	2.69	4.81	2.51	2.67
RESIDUAL FUEL OIL	0.87	1.05	1.29	0.92	1.16	1.29	0.90	1.12	1.29	0.94	1.23	1.28
NATURAL GAS	10.34	6.27	1.20	9.35	5.12	1.06	10.00	5.66	1.15	9.13	4.89	1.04
COAL	0.24	10.10		0.33	12.33		0.27	11.34		0.37	13.32	
ELECTRICITY	10.17	2.86	0.07	10.10	2.39	0.07	9.97	2.39	0.07	9.93	2.12	0.07
GASOLINE			14.58			13.87			14.35			13.71
TOTALS	26.14	22.43	19.84	25.42	23.43	18.96	25.78	22.77	19.55	25.18	24.07	18.77

*RC - Residential and Commercial

I - Industrial

T - Transportation

TABLE 8

DELIVERED PRICES FOR FOSSIL FUELS AND ELECTRICITY BY SECTOR

	CASE I			CASE II			CASE III			CASE IV		
	RC	I	T	RC	I	T	RC	I	T	RC	I	T
DISTILLATE FUEL OIL												
$/Bbl	13.29	11.90	11.90	14.81	13.42	13.42	13.76	12.37	12.37	15.17	13.78	13.78
$\$/10^6$ BTU	2.28	2.04	2.04	2.54	2.30	2.30	2.36	2.12	2.12	2.60	2.37	2.37
RESIDUAL FUEL OIL												
$/Bbl	11.88	11.78	11.78	13.40	13.30	13.30	12.35	12.25	12.25	13.76	13.66	13.66
$\$/10^6$ BTU	1.89	1.87	1.87	2.13	2.12	2.12	1.96	1.95	1.95	2.19	2.17	2.17
NATURAL GAS												
$/scmf	1.68	1.43	1.43	2.26	2.01	2.01	1.88	1.63	1.63	2.45	2.20	2.20
$\$/10^6$ BTU	1.63	1.39	1.39	2.19	1.95	1.95	1.83	1.58	1.58	2.38	2.14	2.14
ELECTRICITY												
¢/kwh	2.46	1.28	1.28	2.83	1.65	1.65	2.69	1.51	1.51	3.04	1.86	1.86
$\$/10^6$ BTU	7.20	3.75	3.75	8.29	4.83	4.83	7.88	4.42	4.42	8.91	5.45	5.45
COAL												
$/T	18.96	18.96		19.03	19.03		18.96	18.96		19.26	19.26	
$\$/10^6$ BTU	0.79	0.79		0.79	0.79		0.79	0.79		0.80	0.80	
GASOLINE (ALL GRADES)												
$/Bbl			20.58			22.10			21.05			22.46
$\$/10^6$ BTU			3.92			4.21			4.01			4.28
$/Gallon			0.44			0.53			0.50			0.54

IV influences a net decrease in demand of 3.7% in the residential and commercial sector, and of 5.4% in the transportation sector. The industrial sector, however, shows a 7.31% increase in demand in spite of the price increases. This is possibly because of increased energy requirements for the operation of control equipment. This issue will be discussed in the section which follows.

Energy Conversion and Intermediate Use

The results discussed in this section refer only to the operations of the industries included in the linear programming Industry Model. For a description of the model and its components, see the chapter on Economic Models and Appendix C.

The tables given in this section display the relative changes in various important variables in terms of percentage changes from Case I. As the levels of fuel use, waste discharges, and operating costs are dependent on output levels, which vary between cases, the raw figures were adjusted by production indices.

Summary of Results

The combined effects of waste discharge restrictions and higher prices for energy resources result in a significant changes in production processes in this sector. These changes affect the use of water, energy, and capital resources, and production costs. The major results are briefly summarized below.

1. Strict waste discharge restrictions do not result in significant increases in net fuel use.

2. Strict waste discharge restrictions result in significantly increased use of natural gas.
3. Strict waste discharge restrictions result in significant increases in the use of both internally generated and purchased electricity.
4. Strict waste discharge restrictions result in significantly increased water consumption.
5. Strict waste discharge restrictions, together with high oil and natural gas prices, result in significantly increased production costs.
6. Strict waste discharge restrictions result in significantly increased capital requirements.
7. The simultaneous imposition of water and air standards results in a great increase in solid waste discharges, which are diverted to the land.
8. Air emission restrictions have a greater effect on natural gas and electricity use, water consumption, and solid waste discharges than restrictions on waste discharges to the water.

Table 9 summarizes the results in terms of percentage changes from Case I. The values shown in the table have been adjusted for output levels to facilitate the comparison between cases.

Energy Use

The configuration of the process energy system for each of the industries included in the Industry Model is significantly affected by fuel prices and waste discharge restrictions.

TABLE 9

SUMMARY OF RESULTS
(% Change)

CASE I TO:	CASE II	CASE III	CASE IV
PRODUCTION	-4.03	-2.48	-4.23
ADJUSTED FUEL USE	-0.11	6.10	4.30
AVERAGE FUEL PRICE	45.30	12.10	59.00
ELECTRICITY			
IN-PLANT	21.60	180.80	65.60
PURCHASED	41.70	-15.50	47.00
WATER WITHDRAWALS	-96.31	-99.36	-98.83
WATER CONSUMPTION	145.52	88.08	248.40
PARTICULATE EMISSIONS	-97.32	0.48	-97.21
SULFUR DIOXIDE EMISSIONS	-96.58	5.89	-96.44
SOLID WASTES DISCHARGED	14,104.33	17.52	17,936.59
PRODUCTION COSTS	16.39	19.83	30.79
CAPITAL REQUIREMENTS	19.40	31.00	44.80

The major process changes occurring under increasingly restrictive waste discharge standards were: (1) the increased integration of the energy system within each industry for the efficient use of excess heat from high-temperature processes in low-temperature processes (2) the increased use of natural gas to fire heaters and boilers, (3) the increased use of electricity, generated internally and purchased, and (4) the use of gas turbines in combined-cycle operation with waste-heat boilers. The net effects of these changes on energy use are shown in Table 10. The numbers shown are actual percentage changes from Case I levels, before adjustment for output levels. All cases show increased use of natural gas and electricity, but both of these energy sources are particularly favored in Cases II and IV, which include air emission restrictions. Case III shows a large increase in the in-plant generation of electricity because the combination of relatively low fuel prices (compared to Cases II and IV) and increased electricity requirements for the operation of waste control and treatment equipment made it more advantageous to do so. The results indicate that the energy conservation activities motivated by higher fuel prices counteract any additional energy requirements for the operation of waste control and treatment equipment. The two cases with air emission restrictions (Cases II and IV), which result in the highest fuel prices, have also the lowest total fuel use on an unadjusted basis. Even after adjustment for output levels, Case II has the lowest fuel use, while fuel use in Case IV is only 4.3% above that in Case I, and 1.7% below that in Case IV.

TABLE 10

ENERGY USE SUMMARY
(% Change)

CASE I TO:	CASE II	CASE III	CASE IV
LIGHT FUEL OILS	-5.36	-5.37	-9.85
HEAVY FUEL OILS	-10.50	-0.38	-6.52
NATURAL GAS	23.52	8.57	28.09
COAL	-27.57	-0.41	-24.00
TOTAL FUELS	-4.13	3.47	-0.37
ELECTRICITY			
IN-PLANT	20.70	176.30	62.80
PURCHASED	40.00	-17.50	45.00
TOTAL	33.10	15.20	46.20

Water Use

Water withdrawals are substantially reduced as increasingly-restrictive water standards are imposed, first through partial and then through complete recycle of cooling water using cooling towers. This increased recycling, however, greatly increases water consumption through increased evaporation loses (see Table 9). The imposition of air emission restrictions in addition to strict water effluent standards increases both withdrawals and consumption. Table 11 summarizes the relative changes in the level of air and water standards imposed.

Solid Waste Discharges

The imposition of strict water standards do not influence a large change in solid waste disposal, as it increases by only 17.5% from Case I to Case III. Air emission standards, however, increase solid waste disposal dramatically. The increases in solid waste disposal for Cases II and IV are on the order of 140 and 180 times those of Case I, respectively. This great increase reflects the recovery of air pollutants (particulates and sulfur) from stack gas emission control equipment (See Tables 9 and 11).

Production Costs

The combined effects of strict restrictions on waste discharges to the water and air, and increased fuel prices significantly increase production costs. Increasing the restrictions from Case I standards to Case IV standards resulted in an increase in production costs of 30.79% (after adjustment for output levels); 64% of this increase resulted from water standards and fuel price increases; the balance from air

TABLE 11

SEPARATE EFFECTS OF AIR AND WATER STANDARDS
(% Change)

	WATER STANDARDS CASE I TO CASE III	AIR STANDARDS CASE III TO IV	WATER AND AIR STANDARDS CASE II TO IV
FUEL USE	6.10	-1.70	4.41
AVERAGE FUEL PRICE	12.10	41.80	9.40
ELECTRICITY USE	15.60	32.10	10.10
WATER WITHDRAWAL	-99.36	82.81	-68.29
WATER CONSUMPTION	88.08	85.24	41.90
PARTICULATE EMISSIONS	0.48	-97.22	4.11
SULFUR DIOXIDE EMISSIONS	5.89	-96.64	4.10
SOLID WASTES DISCHARGED	17.52	15,247.48	27.20
PRODUCTION COSTS	19.83	9.15	12.37
CAPITAL REQUIREMENTS	31.00	10.50	21.30

standards and fuel price increases. A calculation of average fuel prices per million BTU's for both cases shows that average fuel prices increased by 59% between Cases I and IV (see Table 9). A comparison of actual production Costs for Case IV to production costs for Case IV after subtraction of fuel price increases from Case I levels reveals that 63% of the increase in production costs result from the imposition of strict water and air standards; 37% of the increase results from increased fuel prices.

Capital Requirements

The availability of capital at reasonable cost is a crucial issue for the achievement of environmental and energy objectives, as it is capital which makes it possible to substitute processes which reduce energy use and/or pollutants, and to obtain control and treatment equipment. As was to be expected, increasing the level of control required increases the capital requirements. Achieving Zero Discharge of pollutants to the water (Case IV) increases capital requirements by 31% from Case I levels. The achievement of Zero Discharge plus maximum control of particulates and sulfur dioxide increases capital requirements by 44.8% from Case I levels. Water standards contribute 69% of this increase; the balance is the result of air standards.

Comparison With Other Studies

Comparisons between studies are often difficult because of the different objectives and emphasis of different studies. It is nevertheless illustrative to make such comparisons, if only to show the sensitivity of the results to different objectives, assumptions, and methodology. The results of the studies chosen here are to be compared to those from Cases I and IV in this study. The Ford Foundation Study [16] developed three scenarios for analysis: the Historical Growth scenario, a Technical Fix scenario, and the Zero Growth scenario. The Technical Fix scenario is the one which most closely compares with the assumptions of the study developed in this paper, as the effects of increasing energy prices are explicitly included. Adjustments are also made in this scenario for environmental standards. The second study included is the Project Independence Report [15], of the Federal Energy Administration. The scenario chosen for comparison is the "Business-as-usual With Conservation, $11.00 Oil", again as the scenario which most nearly conforms with the assumptions of this study. The third study included is by Dupree and West [13], of the Bureau of Mines. This study included only one scenario; it is included merely to illustrate the changes which have occurred in energy forecasting since 1972. Whenever necessary and possible, the figures shown in Table 13 have been adjusted to conform to the conversion factors for physical energy units to BTU's used in this study. These are given in Table 12.

Allowing for differences in assumed levels of economic activity, demographic factors, energy use efficiencies, environmental standards, and demand responses to price, the results of the FEA and Ford Studies are quite similar to the results of this study in terms of total energy use. The major differences are in the estimates of natural gas, coal, and nuclear energy use. The difference in natural gas use arises from the use of a normative supply model which shows substantial responses to price, but is constrained in its rate of output expansion. The

TABLE 12

CONVERSION FACTORS

ENERGY SOURCE	UNITS	BTU's per UNIT
OIL	1 42-gallon barrel	5.67 million
NATURAL GAS	1 standard cubic foot	1,032
COAL	1 short ton	24 million
ELECTRICITY	1 kilowatt-hour	3,413

TABLE 13

COMPARISON OF 1985 ENERGY CONSUMPTION ESTIMATES*

	DW	CASE I	CASE IV	FEA	FORD
OIL	50.70	32.84	32.84	33.51	30.87
NATURAL GAS	28.39	29.93	29.93	23.68	32.39
COAL	21.47	24.25	24.67	19.67	14.62
NUCLEAR & OTHER	16.07	9.49	8.74	17.31	14.62
TOTAL	116.63	96.51	96.18	94.17	94.56

*DW - Dupree and West [13].

CASE I - This Study

CASE IV - This Study

FEA - Business-as Usual, $11 Oil, With Conservation [15].

FORD - Technical Fix [16].

differences in coal and nuclear use are somewhat related. This study assumed low rates of expansion in nuclear and hydroelectric capacity, and high rates of expansion in coal production capacity. Consequently, nuclear and hydroelectric sources were assumed to contribute 25% of the total generation of electricity. The slack was taken up by fossil fuels, mostly coal.

The results of the DW study differ by more than 20% from the others in total energy use, and more than 50% in oil use. This is an indication of the changing outlook on domestic energy prices, and the demand response to those prices which has taken place since the pre-embargo days when the DW study was completed. The OPEC oil embargo, combined with higher costs of producing domestic oil and natural gas, have led to higher prices for those fuels. At the same time, there has been an increase in the awareness of the social and environmental costs of energy production and use. These factors, together with occasional physical shortages, have led to the realization that energy could be saved in many activities without great loss of comfort or service. Increased insulation in homes and buildings, smaller automobiles, integrated energy systems in industry--all allow for energy saving at little, if any, loss in service.

Conclusion

The major conclusions devived from the results of this study are briefly summarized below.

1. The overall results indicate that if crude oil and natural gas were priced at their inputed values, supply and demand equilibrium could be achieved at any level of environmental quality

standards likely to be imposed by 1985 at prices similar to those being paid today for "new" oil and deregulated (intrastate) natural gas. Sufficient adjustments are made in the long run by both producers and consumers at those prices to allow virtually zero growth in oil consumption, a reduced growth rate in total energy consumption, and the elimination of oil imports. At lower prices than those indicated, demand would exceed domestic supplies of oil and natural gas. At higher prices, domestic supplies would exceed demand.

2. Industrial waste discharges to the water and air could be reduced to insignificant levels at substantial cost to the industries involved and the public at large. The public benefit to be derived from clean water and air, however, is also large. Additionally, the increased prices of energy and energy products resulting from the imposition of strict water and air standards would promote energy conservation and reduce United States' dependence on foreign energy sources.

3. The value imputed on oil and natural gas results from the effectiveness of these fuels to substitute for air emission control equipment. The development of reliable, efficient, and less expensive air emission control equipment would lessen the demand pressure on oil and natural gas, and reduce their value.

SUGGESTIONS FOR FURTHER RESEARCH

An attempt has been made in this study to design an analytical method for studying the energy market. In any enterprise of this kind, the most difficult task is to attempt to isolate the variables which have the greatest effect on the system under study. Indeed, this task is often the objective of the study. When studying a system such as the energy system in which so many economic, technological, and social factors interact, one must necessarily ignore some factors which one knows to be important; lack of time, data, or conceptual grasp preclude their inclusion. Such has been the case here. A discussion of the major economic, technical, and environmental factors which were not explicitly included in this study follow.

Economic Factors

Macroeconomic Effects

The major economic factor not explicitly included is the effect of the energy prices resulting in this study on the economy at large. Although demand and output were based on a macroeconomic scenario, the prices found may not be quite compatible with that scenario and could alter it significantly, requiring yet another iteration through the energy market model developed here. Ideally, one would iterate back and forth between a macroeconomic model and the energy market model until a macroeconomic equilibrium was obtained in which gross national product, personal income, supply, demand and prices of all products were all in equilibrium. Such an enterprise was beyond the scope of this study.

Regional Factors

Another major exclusion was the lack of spatial dimensions in any of the models. This is an important factor, as 70 - 80% of the delivered price of some fuels such as natural gas and coal is due to transportation and distribution cost. In order to keep the models down to a manageable size, a choice had to be made between geographical detail and technological detail in the industry model. As that model is already of good size (954 rows, 1698 columns), expansion in the geographical dimension would have had to be at the expense of industrial detail.

The Availability of Capital

This study assumed the availability of investment capital at a reasonable price. The industries modeled were assumed to be able to obtain the capital necessary (within broad limits) to make major investments in waste control equipment, new production processes, and new capacity. It is well known that the high cost of capital has been one of the major factors which has made it difficult for some industries, particularly the electric power industry, to comply with environmental restrictions. No upper limit on capital availability was included in the industry model, so the value of this capital could not be considered. It is possible that lowering or raising the level of this constraint would change the equilibrium prices found in this study. It would be reasonably simple to analyze the value of capital, but it was considered difficult to evaluate in the presence of so many other factors which were varied in this study.

World Oil Prices

In this study, world oil prices were assumed to remain at their present high levels in real terms through 1985, and domestic oil and natural gas producers were assumed to be insensitive to this price. In particular, it was assumed that the domestic production was exclusively for domestic consumption, and if the domestic prices of oil and natural gas fell below world prices owners of domestic resources would be impeded from engaging in world trade. Whether these are strong assumptions is a matter which lends itself to much speculation. The issue of world oil prices has become a political rather than an economic question, and speculating on the future actions of OPEC would presume a knowledge of their objectives. In any case, if present desires for a greater level of United States energy independence continue, one could assume that the price of imports will either stay at its high present levels, or that appropriate tariffs will be assessed on imports to maintain the high prices. Similarly, it would seem unreasonable for the United States to achieve greater levels of domestic oil and natural gas production and energy independence, and then allow this oil and gas to be consumed in the world market.

Demand for Non-Fuel Products From Oil and Natural Gas

Fourteen of the forty-five end-products of the industries modeled are fuels. The remaining products are chemicals, lubricants, fertilizers, and rubber. These products all use oil and/or natural gas derivatives as raw materials. It would be a logical extension of the model developed here to include demand responses to the prices of these products in the evaluation of the supply, demand, and price of fossil energy sources. The difficulty in doing so is that many of these products are intermediates which are used in the manufacture of hundreds of end-products. Estimating demand functions for these, and then estimating the derived demand for the intermediates would be a major task in itself.

Environmental Factors

The Effect of Environmental Restrictions on Energy Supply

The supplies of oil, natural gas, and coal projected for 1985 in this study imply massive exploration and development activities in all potential producing regions. Many of these regions are relatively uninhabited and unspoiled. The fear of the potential degradation of these regions by extensive exploration and development could result in severe restrictions on these activities by the Department of the Interior or the Environmental Protection Agency. At present, severe opposition to the development of off-shore oil and gas regions exists in some states, notably on the East Coast. Opposition to the development of new coal regions also exists. The effects of these restrictions on energy supply could be very severe. Oil and natural gas prices would probably be much higher than those found in this study, and oil imports would be a necessity.

The Effects on Industries Not Modeled

Although this study did take into account the energy demands by industry groups not included in the industry model, the alternatives which these industries have for adjusting to higher energy prices and strict environmental standards were not included. Plans exist at present for the inclusion of two more large fuel and water using industries, pulp and paper and iron and steel; to the industry model. When this addition is completed, a more precise analysis of the type done in this study can be made.

The Effects on Non-Industrial Sectors

Energy use in the residential and commercial sector has a relatively small impact on water and air quality. Environmentally clean energy sources (oil, natural gas, electricity) account for 98% of the energy used in this sector. Energy use in the transportation sector is a major source of air pollutants, accounting for 77% of the carbon monoxide and 71% of the hydrocarbon emissions directly attributable to energy use [10]. The uncertainty regarding the measures for transportation control announced by the Environmental Protection Agency for 38 metropolitan areas [10] precluded the inclusion of environmental restrictions on energy use in this sector.

Mathematical Considerations

Mathematically, the problem discussed in this study consists of a search for a fixed point, which is guaranteed to exist in case certain conditions hold. In order to further develop the model and formalize the procedure for the mathematical programming problem stated in the chapter An Economic Model of the United States' Energy Market, it would be beneficial to: (1) develop the conditions for the existence of this fixed point mathematically, (2) derive a set of convergence conditions mathematically, and (3) develop optimal rules for the iterativo procedure.

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APPENDIX A

SUPPLY MODEL PARAMETERS

SUPPLY MODEL PARAMETERS

Exploration and Development--Oil

Lag time between finds and development: 3 years.

Investment Cost per well: $88,571

Operating Cost per well-year: $3,012

Required rate of discount: 0.15

Exploration and Development--Natural Gas

Lag time between finds and development: 3 years.

Investment cost per well: $214,559

Operating cost per well-year: $3,012

Required rate of discount: 0.15

APPENDIX B

DEMAND MODEL PARAMETERS

DEMAND MODEL PARAMETERS

Price Submodel

Variable Names

Sectors

RC - Residential and Commercial

I - Industrial

T - Transportation

Fuels

DFO - Distillate fuel oil

KER - Kerosene

RFO - Residual fuel oil

NG - Natural Gas

CLS - Coal, low-sulfur

CHS - Coal, high-sulfur

EL - Electricity

GSL - Gasoline

Resource Prices

POIL - Price of crude oil in $/Bbl.

PNG - Price of Natural gas in $/mcf

PCLS - Price of low-sulfur coal in $/ton

PCHS - Price of high-sulfur coal in $/ton

PEL - Price of electricity in $/kwh

Price Equations

The delivered price for each energy source is calculated as the sum of the resource cost and estimates of transportation, distribution, and tax costs derived from Foster [17]. The prices are in the same units as the resource prices shown above. The price variable names are formed by placing a P before the name of the fuel and the appropriate sector symbol as a suffix.

PDFORC = POIL + 2.44

PDFOI = POIL + 1.05

PDFOT = POIL + 1.05

PRFORC = POIL + 1.03

PRFOI = POIL + 0.93

PRFOT = POIL + 0.93

PNGRC = PNG + 0.85

PNGI = PNG + 0.60

PNGT = PNG + 0.60

PELRC = PEL + 0.0154

PELI = PEL + 0.0036

PCLSRC = PCLS + 4.92

PCLSI = PCLS + 4.92

PCHSI = PCHS + 3.48

PGSLT = POIL + 9.73

Demand Model

Price Elasticities

For $\$4 \leq \text{POIL} < \$7$

Sector RC

	PDFORC	PRFORC	PNGRC	PELRC	PCLSRC
DFORC	-0.666		0.361	0.110	0.004
RFORC		-0.378	0.327	0.097	0.004
NGRC			-0.462	0.133	0.005
ELRC	0.088	0.059	0.161	-0.436	0.264
CLSRC			1.110	0.335	-0.271

Sector I

	PDFOI	PRFOI	PNGI	PELI	PCLSI	PCHSI
DFOI	-1.398		0.860	0.007	0.228	0.228
RFOI		-1.860	0.870	0.007	0.600	0.600
NGI	0.035	0.090	-1.160	0.288	0.068	0.068
ELI	0,068	0.136	0.218	-1.204	0.151	0.151
CLSI			0.605	0.007	-0.600	1.000
CHSI			0.605	0.007	1.00	-0.600

Sector T.

Sector T has only one PE matrix, for POIL $\$4$.

	PDFOI	PRFOI	PNGI	PGSLT
DFOT	-0.069			
RFOT	0.191	-0.191		
NGT			-0.355	
GSLT				-0.756

For $\$7 \leq POIL < \$11$

Sector RC

	PDFORC	PRFORC	PNGRC	PELRC	PCLSRC
DFORC	-0.629		0.344	0.110	0.007
RFORC		-0.347	0.312	0.099	0.007
NGRC			-0.438	0.135	0.009
ELRC	0.083	0.054	0.152	-0.443	0.502
CLSRC			1.060	0.341	-0.515

Sector I

	PDFOI	PRFOI	PNGI	PELI	PCLSI	PCHSI
DFOI	-1.268		1.181	0.008	0.262	0.262
RFOI		-1.819	1.190	0.008	0.690	0.690
NGI	0.032	0.090	-1.530	0.319	0.078	0.078
ELI	0.062	0.137	0.300	-1.336	0.174	0.174
CLSI			0.830	0.008	-0.691	1.000
CHSI			0.830	0.008	1.000	-0.691

For $POIL \geq \$11$

Sector RC

	PDFORC	PRFORC	PNGRC	PELRC	PCLSRC
DFORC	-0.638		0.289	0.110	0.009
RFORC		-0.345	0.262	0.099	0.008
NGRC			-0.368	0.135	0.011
ELRC	0.084	0.054	0.128	-0.444	0.602
CLSRC			0.888	0.341	-0.618

Sector I

	PDFOI	PRFOI	PNGI	PELI	PCLSI	PCHSI
DFOI	-1.147		1.158	0.008	0.225	0.225
RFOI		-1.697	1.176	0.008	0.593	0.593
NGI	0.029	0.085	-1.506	0.324	0.067	0.067
ELI	0.056	0.128	0.294	-1.356	0.149	0.149
CLSI			0.816	0.008	-0.593	1.000
CHSI			0.816	0.008	1.000	-0.593

Base Demand Quantities

Sector RC

DFORC : 1.0029 $X10^9$ bbls

RFORC : 0.1593 $X10^9$ bbls

NGRC : 11.1700 $X10^{12}$ cf

ELRC : 2.4700 $X10^{12}$ kwh

CLSRC : 7.9200 $X10^6$ t

Sector I (Includes only industries exogenous to the Industry Model)

DFOI : 0.3118 $X10^9$ bbls

RFOI : 0.219 $X10^9$ bbls

NGI : 8.090 $X10^{12}$ cf

ELI : 0.663 $X10^{12}$ kwh

CLSI : 140.000 $X10^6$ t

CHSI : 135.250 $X10^6$ t

Sector T

DFOT : 0.486×10^{9} bbls

RFOT : 0.205×10^{9} bbls

NGT : 1.320×10^{12} cf

GSLT : 3.529×10^{9} bbls

Macroeconomic and Demographic Paremeters

Gross National Product (billion in 1958 dollars): 1279.

Personal disposable income (billion 1958 dollars): 921.4

Population (millions): 235.5

APPENDIX C

DESCRIPTION OF INDUSTRY MODELS

DESCRIPTION OF INDUSTRY MODELS

The integrated industry model is a linear programming model reflecting national operation of eight specific industries--petroleum refining, organic chemicals, inorganic chemicals, cyclics, alkalies and chlorine, fertilizers, rubber, and electric power--in direct competition for the nation's supply of energy and feedstock resources [25]. The product boundaries for each industry are determined by the specific four-digit standard industrial classification code for the industry. Both inter-industry and intra-industry product transfers are made at cost with no transportation charges. Product costs, however, do include a margin of profit.

The integrated industry model evolved in three separate steps. Models of large modern plants at the design stage were developed first. Next, the plant models were combined into SIC code models. Finally, the industry models were linked together with product and energy flows to create the final integrated model. Control of the model is affected through specification of a set of final demands for the products produced by the model. Given this set of demands, an optimal cost-minimizing solution to the model yields (1) the process configuration of the production complex, (2) the level of operation of each activity, and (3) the marginal value of scarce resources.

Each industrial segment of the integrated model is composed of four parts: (1) a production sector containing processes for the processing of productive inputs and the manufacture of selected products; (2) a process energy system to provide the necessary heat, steam, and electric energy inputs; (3) a water treatment system designed to handle all uses of water for cooling or process purposes from the withdrawal to the discharge stage; and (4) an air treatment system designed to reduce stack emissions of air pollutants whenever restrictions are placed on discharges to the air. Each industry has available to it a number of fuel sources, including natural gas, petroleum-derived liquids, and coal. The model calculates distribution of fuel use by type for each industry as well as total fuel consumption. Water withdrawals and consumption are also calculated by industry as are waste discharges by type. Further detail on each of the model's component parts is provided below.

Exogenous Sector

The model contains an exogenous sector which does not represent any particular industry but serves to supply the model with various inputs not produced by the model itself. These inputs include such materials as crude oil, natural gas and natural gas liquids, coal, bauxite, limestone, sulfur, hydrochloric acid, and lead. The inputs are supplied at their estimated market prices; both price and availability can be varied to allow determination of the impact of such a change on the industries included in the model.

Petroleum Refining (SIC 2911)

The petroleum refinery comprises the largest sub-unit of the industry model. The unit is basically an updated and modified version of the Russell refinery model, sufficiently detailed to interface with other components of the industry model. The refinery section contains vectors representing most of the refinery processes that are in commercial operation today, and the processes produce an extensive slate of final and intermediate products, including gasoline, residual and distillate fuel oils, kerosene, butanes, naphthas, LPG, petroleum coke, asphalt, lubricating oil, grease, and wax.

Organic Chemicals (SIC 2869)

The major component of the organic chemicals section is ethylene manufacture. The model produces ethylene by thermal cracking of any of five possible feedstocks (ethane, propane, butane, light naphtha, and gas oil). By-products of the ethylene processes include propylene, butene-butylene, and pyrolysis gasoline. Also included in the organics section are production of isobutylene and butadiene.

Cyclic Crudes and Intermediates (SIC 2865)

The cyclics section of the model is a highly interrelated set of processes acting primarily to extract various aromatic chemicals from basic feedstocks and convert or combine these chemicals into later generation products. Central to the operation of this section are the production of benzene, ethyl-benzene, and o-m-p xylenes. Marketable products include the xylenes, toluene, styrene, cyclohexane and phthallic anhydride.

Synthetic Rubber (SIC 2822)

The synthetic rubber section of the model is designed to produce styrene-butadiene rubber by either the emulsion or suspension process. Provision is also made for the production of SBR latex and for oil and black extension of the basic product.

Inorganic Chemicals (SIC 2819)

The primary component of the inorganic chemicals section is the production of sulfuric acid, either from elemental sulfur or spent acid. Elemental sulfur can be purchased exogenously or produced in a claus plant. Other components of the section are the production of aluminum sulfate hydrate (alum), hydrogen production, and an air plant.

Alkalies and Chlorine (SIC 2812)

The alkali-chlorine section of the model incorporates an extensive model of the production of chlorine and caustic sode (NAOH). The production process modeled is electrolytic separation of purified brine using diaphragm cells of varying current density. Cooling and purification of cell products are modeled explicitly, with hydrogen being produced as a by-product. Also included in this section of the model is the production of lime by thermal conversion of limestone.

Fertilizers (SIC 287)

The fertilizer section of the model incorporates a stand-alone model of ammonia production. Natural gas or naphtha serve as alternative feedstock inputs to a steam-reforming production process.

Electric Power (SIC 4911)

Each industry has the capacity to generate its own electricity from excess process steam or by producing steam at offsite facilities. A stand-alone linear model of utility electric power generation has also been added to the overall model, both to service the industries within the model (where cost-optimal) and to provide estimated final demands for electricity by users not included in the model. The utility model is composed of vectors representing power plants differentiated by age (old-new) and fuel type (coal, natural gas, or fuel oil), and provision is specifically made for coal gasification and combined cycle operation. Nuclear and hydroelectric power generation are not explicitly modelled but are included in the form of an exogenous "input" whose cost and availability can be varied as appropriate.