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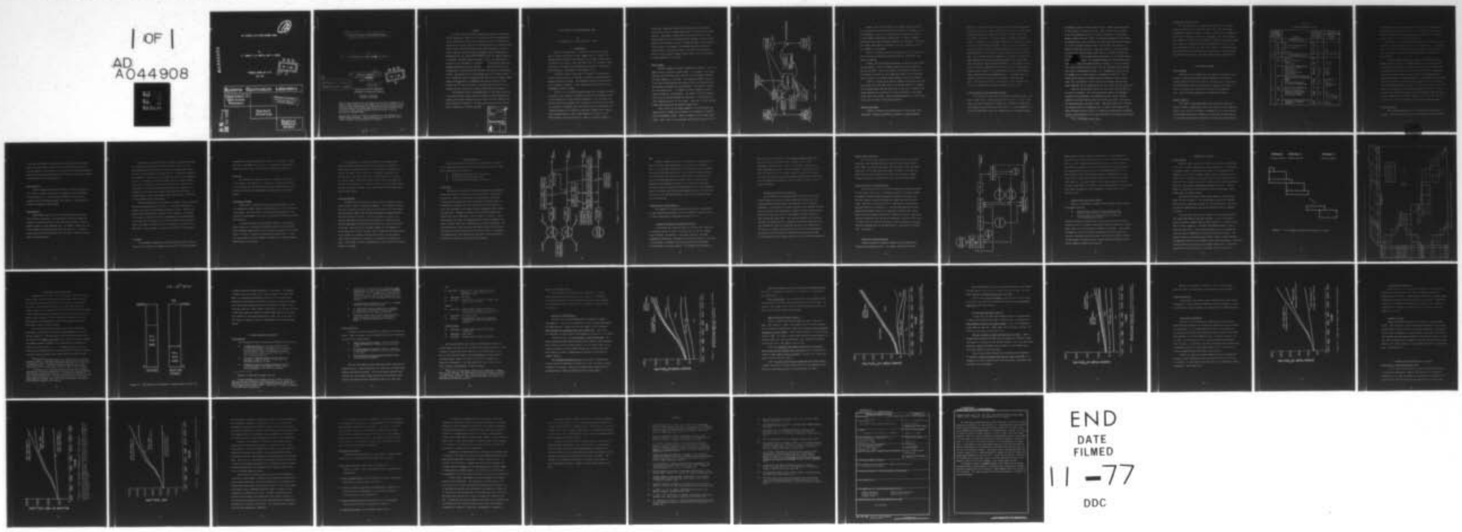

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BY

T.J. CONNOLLY, G.B. DANTZIG, AND S.C. PARIKH

TECHNICAL REPORT SOL 77-19

JULY 1977

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⑩ T.J. Connolly, G.B. Dantzig, and S.C. Parikh

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Abstract

The PILOT Energy Modeling Project, being conducted at Stanford's Systems Optimization Laboratory, is concerned with: (1) performing modeling and methodology research dealing with construction and solution of reasonably large scale mathematical programming models of energy/economic systems; 2 (ii) using ~~the~~ modeling research towards analysis of some of today's important energy questions; and 3 ~~(iii)~~ using the modeling and methodology work ~~for construction of~~ to construct better models for improved analysis of tomorrow's important energy questions. At the core of this ~~the~~ project activity is the development of a multisec[illegible] intertemporal linear programming modeling system that describes [illegible]ysical terms many of the technological interactions within and across the sectors of the American economy. The general aim of the modeling effort is to permit studies to asses (1) ~~(i) to assess~~ how specific energy policies will affect the energy supply/demand picture, and (2) ~~(ii) to assess~~ how the physical capacity of the economy over the next 30-35 years to provide goods and services to its populace could be affected by changes in ~~the~~ energy supply picture.

Intertemporal linear programming models of the energy sector and the economy provide a unique medium for exploring future energy policy options. This paper presents the first version of PILOT together with three illustrative scenarios. The model deficiencies and new developments in progress are briefly discussed.

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1. Introduction

PILOT is a target model. It does not predict what the path into the future will be but, rather, suggests what it could be. It assumes that the purpose of the economy is to provide a high standard of living for the people. Thus, what PILOT does is to provide a trajectory which, if followed, would maximize the standard of living over a given time span. This maximum is the target or goal.

Our model is only a first step. In general, a target model to be fully useful requires, in addition, a comparison between actions in progress and those targeted. The differences between them plus incentives considered necessary to close the gap permit identification and development of policy changes.

PILOT is a U.S. national energy/economic model designed to measure the impact on the standard of living of various policy decisions, such as the scheduling of various energy technologies to be built and used, pollution abatement equipment to be installed, the nature and the extent of conversion to equipment types that use energy more efficiently, the required expansion of the general economy and foreign trade to supply an increasing population with a high standard of living, etc. [1]. PILOT reflects certain assumptions or scenarios regarding changes in life-styles, embargoes, feasibility of proposed new technologies, restrictions on use of certain technologies, and availability of raw reserves. The growth of population, the available workforce, and labor productivity are key assumptions that provide a setting for the growth of the standard of living. Another important class of assumptions relates to the amounts of raw energy resources available at various levels of extraction effort, or available through imports which, in turn, depend on import limits, prices, and the availability of export markets for U.S. goods.

Main Linkages

The main linkages in PILOT are displayed in Figure 1. The energy supply sector is modeled in great detail. It is linked to raw energy sources, on the one hand, and to the rest of the economy, including the final consumer, on the other. The economy is linked to the rest of the world through imports and exports, which are limited by available markets and balance-of-trade relations. The economy is modeled in a less detailed way. It consists of various industrial sectors, capacity formation, and government. The payoff is the bill-of-goods vector that the economy supplies the population. The population, in turn, supplies man hours to the economy. There are four main linkages between the economy and the detailed energy sector:

First, there are the energy demands of the economy upon the energy sector for industrial processing, for consumers, for exports, and for governmental needs. These are supplied in five final energy forms: coal, crude oil, oil products, gas products, and electricity.

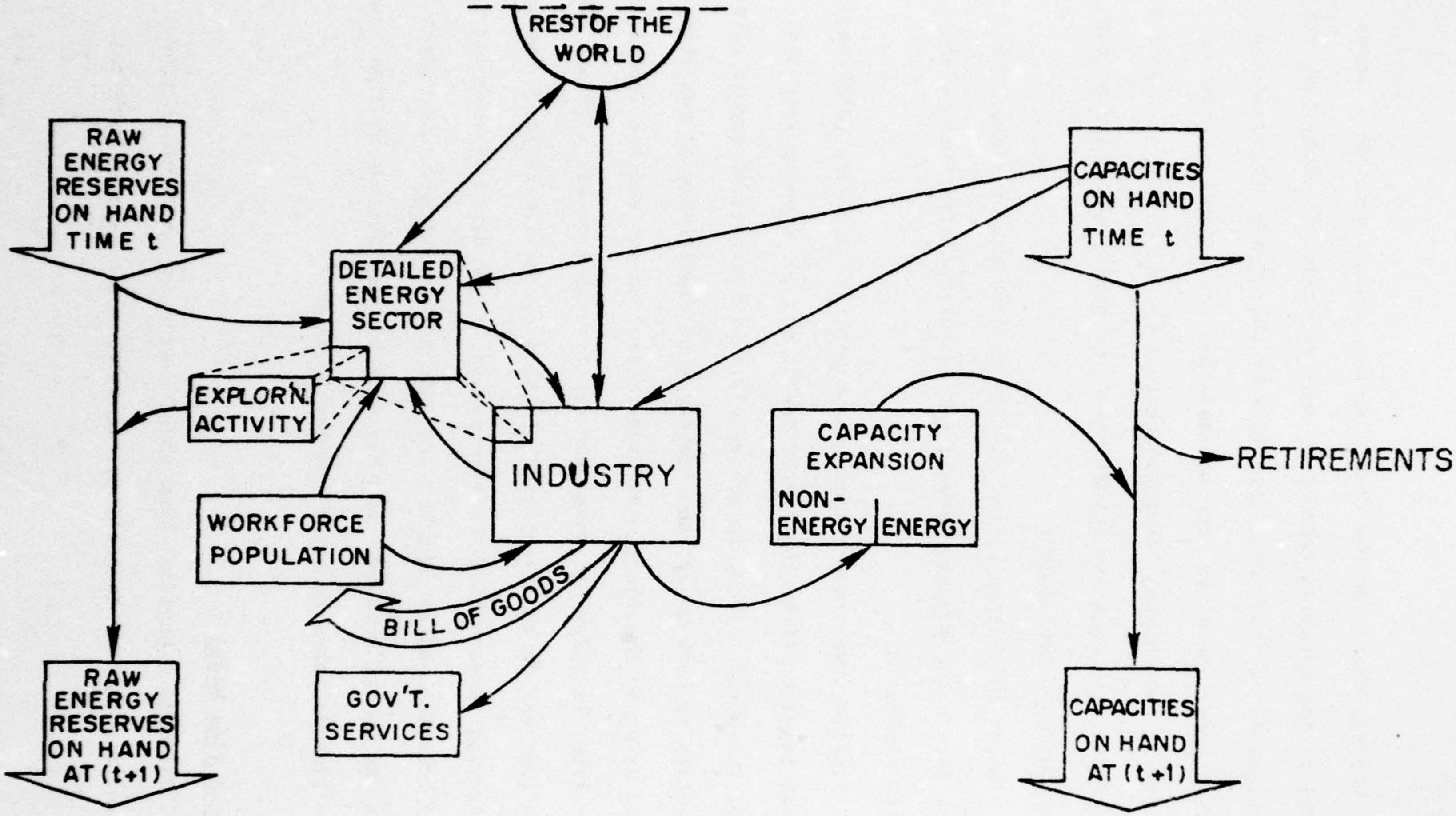

Figure 1. Main Linkages of the PILOT Model

Second, there are the energy sector demands upon the economy for capital and material resources, such as crude oil pipelines, railroad shipments of coal, etc. (provided by the transportation sector of the economy); machinery and construction for capacity expansion (provided by the capital formation sectors of the economy). The latter must compete with capacity formation of the other industrial sectors for expansion or replacement.

Third, the energy sector and the economy use the same workforce pool to obtain the manpower needed for operation, maintenance, and capacity expansion.

Finally, the trade balance constraint, by matching total exports to total imports, links the energy sector and the economy with the rest of the world. Thus, in the model, if the crude oil import price or quantity or both go up, the economy must export more of something else to bring in the foreign exchange needed to pay for the imports.

PILOT is a dynamic model and the linkages through time are shown on the left and on the right side of the diagram (Figure 1) -- namely, the carrying forward from one time period to the next of remaining raw energy reserves and of capacity of various facilities in the energy sector and in the economy. Another link between periods is that caused by the time it takes to build new facilities.

Physical Flow Model

PILOT is a physical flow model except for the foreign trade constraint. Insofar as possible, we endeavor to express material balances of various input and output items into the various processes in physical units, for example, BTU's of coal or oil, etc. The several sectors of the general economy each produces a characteristic item. For example, the sector -- Textiles, Leather, Clothing, and Shoes -- produces a composite item, abbreviated TEX, which is made up of a large variety of textile related products. It is, of course, impossible to treat this composite except in some aggregated way. This is done by applying weights to the vector of various quantities produced and summing. It is assumed that this industry in the future can produce the same aggregated output using the same aggregated inputs from other industries and the same aggregated facilities. This suggests that the vector of products aggregated into TEX either occurs in the same proportions in the future or that substitutions can occur among them as long as they preserve their aggregated total. The weights most convenient to use are the prices of the products in the base year 1967. Thus, the unit of TEX is the quantity of that composite item (vector of outputs) that could be purchased for $1 in 1967.

Utility Function, Linear Consumption Vector

The standard of living also is expressed in physical terms. The bill-of-goods vector is what the population receives. On a per capita basis, the sum of components of this vector represents the take home or consumption income measured in 1967 dollars. As the consumption income of an individual rises, his consumption vector undergoes changes.

For example, people of higher income allocate a higher percentage share of their income to service type items. What the PILOT model requires is not the consumption vector of a typical individual at a given consumption income level but, rather, the average consumption vector formed by weighting the various vectors by the percentage distribution of people at various consumption income levels. In the future the average consumption income will increase -- implying, therefore, that the distribution will shift towards higher income levels. We assume in PILOT that the distribution in the future will be the same as it is currently except translated to the right. This assumption means that lower income people would get a greater percentage increase in income. It turns out empirically, under fixed base year prices, that the resulting average consumption vector is approximately linear, i.e., consumption of each item can be assumed to be a linear function of consumption income [2]. Since future prices as well as average income are expected to vary, we have under test a hierarchical utility function that permits substitutions among components of the consumption vector for a given level of utility [3].

There are many possible choices for the utility function that can be used as a maximand. Up to now we have been using as our maximand a standard-of-living measure, the consumption income, in 1967 dollars, summed for each year from the start of the plan, say 1975, to the end of the planning horizon, say 2010 or 2075. The model permits one to specify any discount factor in forming the sum. In many of our studies we have used a discount factor of unity.[1] In addition, we assume that consumption income in any time period is not less than that of the previous time period.

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[1] i.e., an interest rate of zero.

Time Horizon, End Conditions

The time horizon of our model has been 40 years in five year periods centered at 1975, 1980, 1985, 1990, 1995, 2000, 2005, 2010. In addition to initial conditions, it also is necessary to provide end conditions at 2010 that reflect post 2010 needs. We do this by means of a variant of the PILOT model (called the "variable time period" model) which allows us to aggregate several time periods into one. For the same computational effort, we solve such a model up to 2075 and extract from the solution the facilities and stocks on hand at end of 2010 and pass these data off-line to the regular PILOT model [4, Appendix H].

2. The General Economy

The I/O Tableau

The source of our economic data of industrial processes is the 87 Sector Leontief Input/Output Table, published by the Bureau of Economic Analysis for the year 1967 [5]. Because of our limited human and computational resources, we have had to aggregate this down to 23 sectors for regular runs and down to 12 sectors for Sigma Mode runs. These industrial aggregations are displayed in Table 1.

Capital Formation

The dynamic linear programming model formulation allows the modeled economy to endogenously select the allocation of the industrial output to two types of activities: consumption in the current period that provides the country's standard of living, and capital formation in the current period that will provide the future production capacity

Table 1

SECTORAL AGGREGATIONS OF PILOT

SIGMA MODE (12 SECTORS)			STANDARD MODE (23 SECTORS)		BEA SECTORS (87 INDSTRL. SECTORS)
LINE COUNT	SECTOR CODE	SECTORS	SECTOR CODE	LINE COUNT	INDUSTRY NUMBER
		MACROENERGY SECTORS			
1	COL	Coal	COL	1	7
2	CRO	Crude Oil and Crude Natural Gas	CRO	2	8
3	ROP	Refined Oil Products	ROP	3	31
4	GAS	Gas	GAS	4	68.02
5	ELE	Electricity	ELE	5	68.01,78.02,79.02
		MACRO NONENERGY SECTORS			
6	AGR	Agriculture	AGR	6	1-4
7	MNG	Mining and Construction			
		Mining	MNG	7	5,6,9,10
		Construction	CON	8	11,12,55
8	EIM	Energy Intensive Manufacturing			
		Chemicals and Plastics	CMP	9	27-30,32
		Foodstuffs	FDS	10	14,15
		Paper Products	PPP	11	24,25
		Stone, Clay, and Glass	SCG	12	35,36
		Primary Metals	MET	13	37,38
9	ENM	Energy Nonintensive Manufacturing			
		Textiles, Leather, Clothing, and Shoes	TEX	14	16-19,33,34
		Lumber	LUM	15	20
		Furniture and Appliances	FAP	16	21-23,54
		Miscellaneous Manufacturing	MFG	17	13,26,39-42,56,57,62-64
10	TAW	Transportation and Warehousing	TAW	18	65
11	TRD	Trade and Other Services			
		Wholesale and Retail Trade	TRD	19	69
		Finance and Real Estate	FIN	20	70,71
		Miscellaneous Services	SVS	21	66,67,68.03,72,73,75-79 (except 78.02,79.02),81-87
12	MAC	Machinery and Transportation Equip.			
		Transportation Equipment	TRE	22	59-61
		Machinery	MAC	23	45-53,58

by replacement of old equipment and structures as well as building of new additional equipment and structures. The capital formation activities, of course, provide the economy with a vehicle for achieving a better standard of living in future years [6].

The PILOT model distinguishes and keeps separate account of the capacities of the 18 nonenergy sectors (7 in Sigma Mode). In any given period, the model allows the building of additional capacity for any sector provided, of course, the industrial output is available for such addition.

In order to keep the initial version of the model relatively simple, the input profile to produce \$1 increase in capacity per year for each individual sector is assumed to be the same as the input profile averaged over all sectors. The profile used is the distribution of the total capital formation inputs in the 1967 Input/Output Data Base of the Bureau of Economic Analysis [5]. A provision has been made for later inclusion of a detailed capital matrix by sector of destination, developed by Battelle Institute, 1971 [6], which will allow a more realistic description of the capital equipment and structures. Hence at some later stage of development it will be possible either to incorporate such detail directly into the model or to use such data indirectly to check and correct the assumed profiles and then rerun the model.

Construction Lags

For the nonenergy sectors, a construction lag of two years is assumed. This means that 20% of the total capacity addition initiated in any five year period is completed and becomes available for production in the same five year period and the remaining 80% in the next five year period. The construction lags (after the planning and approval stage) for energy facilities typically are three years except for nuclear. For the latter, we use a seven year lag.

Discard Factors

Discard (depreciation) factors used for the general economy are 4.5%, which is slightly lower than that suggested in the 1976 Report of the President [7]. For the energy facilities we have adopted a convention used in Brookhaven studies [8], namely, no depreciation for 30 years, followed by a 100% discard.

Imports/Exports

PILOT assumes that the U.S. has a favorable balance of trade over each five year period. Its import/export activities permit the economy to trade with the rest of the world and to adjust the mix of domestic output to a more desirable one. For example, imports of crude oil and exports of agricultural products allow the U.S. to trade its excess output from the agriculture sector in order to reduce its shortages in the energy sector.

Preliminary runs indicate that the solution is sensitive to what is assumed about import/export markets available to the U.S. Our import/export functions are based on studies by Clopper Almon and his students at the University of Maryland [9, 10]. Noncompetitive imports are assumed to be proportional to the domestic output of the respective industry. All imports by the final demand sectors, personal consumption, capital formation, and government services, are treated as noncompetitive. On the other hand, nonenergy competitive imports are allowed in the base case to be chosen freely within broad limits. In certain scenarios total energy imports have been limited to a fraction of total domestic energy consumption.

The nonenergy exports in the model are assumed to be in accordance with the decreasing returns to scale, i.e., the higher the amount of exports, the lower the average price received per unit. Finally, the growth of the world markets available for U.S. exports, if we choose to use them, is assumed to follow an exogenously given growth profile. In the base case of the model, a 4% per year growth of this potential market is assumed. Imports and exports of energy are accounted for in BTU terms. They are bought or sold at prices assumed by the scenario.

Government

The government expenditures, including state and local, are provided for in the model by assuming that the vector of future government consumption is in fixed proportions to what it is currently. In the base case of the model, the total level of government expenditures is assumed to be 34% of the total personal consumption expenditures.

Population

The population is assumed to grow in accordance with Series II of the Bureau of the Census [11]. The workforce assumption is based on the estimates for 1975-1990 by the Bureau of Labor Statistics [12] and what we believe to be reasonable extrapolations for the period beyond.

Technological Change

Turning now to technological change, new technologies, such as coal synthetics, nuclear reactors, solar energy, etc., are all included in the model. The actual choice of the mix and the intensity of the processes are determined by the model consistent with available resources and facilities.

An important measure of technological change is the growth in labor productivity. An explicit provision is made in the model that allows exogenous specification of the productivity growth profile (which needs not follow a constant percentage growth through time). In the base case scenario, we have assumed a constant rate of growth in labor productivity of 2% per year.

By specifying the technology available in the energy sector and by specifying the labor productivity in the general economy, we believe that a significant portion of the technological change is captured in the model. What is left out, of course, is the effect of new processes in all sectors that are not known today but will affect the capital, labor, and material inputs for the future production, and the effect of nonenergy sector processes, some of which are known today, that will bring about changes in the capital, labor, and material input ratios in the future.

Pollution Abatement

The model includes exogenously given pollution abatement requirements related to level of industrial expansion. Our assumptions concerning these are based on 10 year projections developed by the Environmental Protection Agency (EPA) using the SEAS (Strategic Environmental Assessment System) Model, 1975 [13]. Using its reference scenario 1, the capital, operating, and maintenance expenditures for abatement equipment are approximately 200 billion 1975 dollars over the 10 year period of 1975-85. The base case of our model assumes the environmental related expenditures to be of the same order of magnitude and spread across the 12 sectors in accordance with the 1967 profile for gross private fixed capital formation as recorded in the input/output transactions table. Beyond 1985, a level of expenditures of 22.5 billion 1975 dollars annually is assumed.

3. Energy Conversion

The detailed energy sector includes technological description of the raw material extraction and energy conversion processes. Technical coefficients are defined for

- exploration and production of oil and gas,
- extraction of natural uranium, and
- 18 other energy technologies. See Figure 2.

Fossil Fuels

The fossil fuel portion of the model includes various technical options with respect to oil, gas, coal, and oil shale. Exploration drilling for either oil or gas results in additions to the proven reserves of these raw energy forms. The level of drilling effort is endogenously determined, and the resulting oil-in-place and gas reserves are determined in accordance with the exogenously given finding rate functions. Expensive secondary and tertiary developments are options that can be undertaken to add to proven oil reserves. An oil shale mining, retorting, and upgrading activity also is defined in the model to provide shale oil to complement the crude oil production. Oil and gas production, and coal mining activities provide the raw fossil fuels which are next processed into final energy forms. Oil refining, coal gasification, coal liquefaction, and electric power generation processes are defined in the model for this purpose.

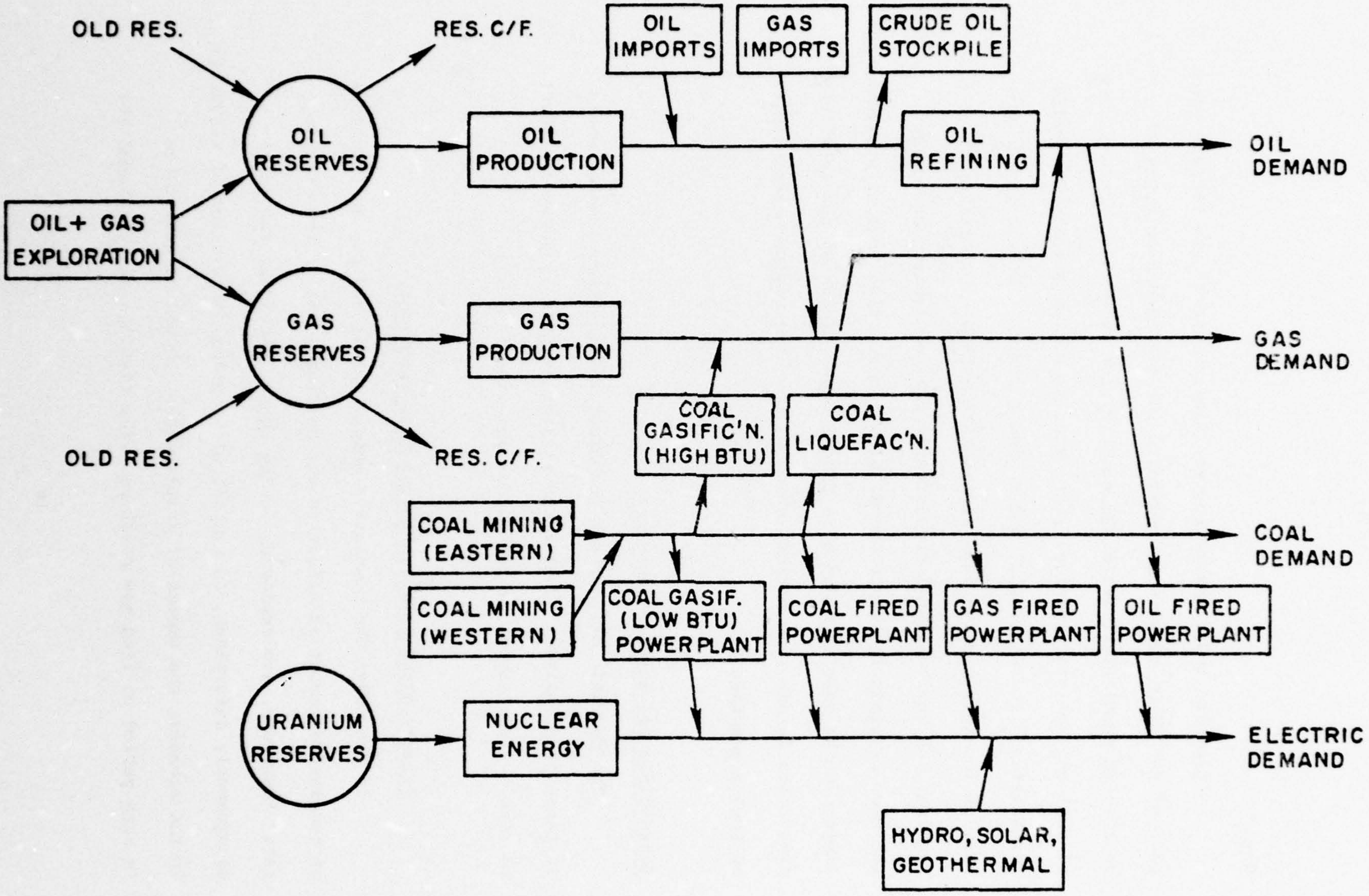

Figure 2. The Energy Sector of PILOT

Coal

Steps are under way to correct limitations of the present version of the PILOT model with regard to the mining and shipping of coal -- in particular, reclamation activities related to strip mining of coal and pollution control gear, such as sulfur scrubbers, needed for burning high sulfur coal and in power plants. We are in the process of investigating various alternative ways of formulating the regional and environmental economics of coal extraction and usage. For now, we limit the western coal mine construction to some exogenous limits in the base case and have placed upper limits on the total coal production in any time period, which we dub "the environmental limit on coal production".

Exhaustible Oil and Gas Resources

The domestic oil and gas resources have reached a point where it takes progressively greater and greater amounts of physical effort to find a given amount of additional reserves [14, 15].

Primary Oil Recovery, Finding Rate Functions

In the model the cumulative supply of oil and gas as functions of cumulative amount of effort to extract them, called the "finding rate" functions, are employed. Using these functions, the model endogenously determines, consistent with optimal allocation of resources in the economy, the amount of drilling that should be undertaken in each period to find new reserves. The finding rate functions are consistent with the estimates in the National Energy Outlook, 1976 [15], and the U.S. Geological Survey Circular 725 of the U.S. Department of Interior [14]. There is, of course, a great deal of doubt regarding the accuracy of these estimates. The approach of the model is flexible in that it allows one who is interested to assess the effect of this uncertainty by assuming different finding rate functions and measuring how sensitive the key economic indicators are to their differences.

Secondary and Tertiary Oil Recovery

As new reserves become progressively more difficult to find, it also becomes attractive to develop additional reserves from the existing unproven reserve base by secondary and tertiary recovery techniques. In any period, the model determines total unproven reserves that are available for development by advanced recovery techniques and within these limits the extent of development undertaken depends on other options and their costs -- not only with respect to oil and gas but also coal synthetics, etc., taking into account the short and long term interactions with the economy and the rest of the energy sector. The numerical estimates were derived with the aid of data developed by the National Petroleum Council, Federal Energy Administration (FEA) for the Business-As-Usual (BAU) Scenario, and by the Bechtel Corporation.

Electric Power Generation

For electric power generation, the model includes the following activities: LWR (enriched uranium operation), LWR (plutonium operation), LMFBR, coal fired power plant, gas fired power plant, oil fired power plant, low BTU gas fired power plant (coupled to a low BTU coal gasification process), hydroelectric power plant (coupled to pumped storage facilities), geothermal power plant, and solar power plant.

Nuclear Fuel Cycle, Uranium Resources

The nuclear portion of the model includes the following processes for the nuclear fuel cycle: the mining and milling of natural uranium, enrichment of natural uranium by gaseous diffusion, fabrication into the fuel elements, electricity generation using light water reactors (LWR). The spent fuel may be stored, or reprocessed to recover plutonium and uranium for recycling, i.e., the recycled uranium may be converted and enriched for use in the light water reactors; also, plutonium can be used together with natural uranium as a fuel for light water reactors dedicated to this mixed oxide operation. Finally, a fast breeder reactor also is defined in the model in which plutonium and tailings from the enrichment unit can be fabricated into the cores for its operation. See Figure 3.

Exhaustible Uranium Resources

Limited reserves of uranium are known to be recoverable with relatively low physical effort. For example, 200 thousand tons of

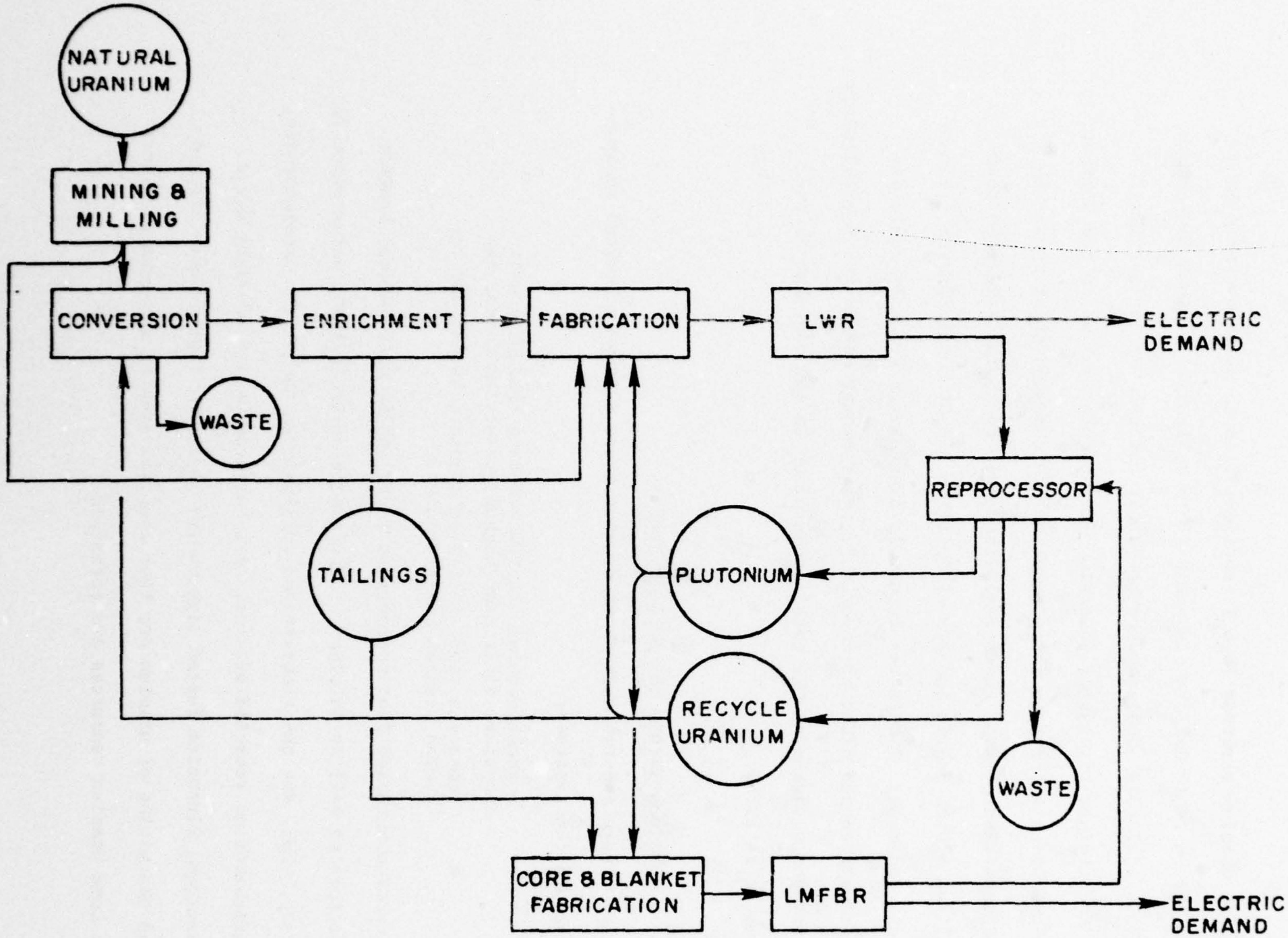

Figure 3. LWR and FBR Technology in the Energy Sector of PILOT

proven uranium reserves (U_3O_8) are identified to be recoverable at a cost of up to 10 dollars per pound (1975 dollars). See BNL Sourcebook, 1975, p. 37 [8]. Undiscovered potential reserves at various levels of uncertainty (probable, possible, and speculative) would add another 530 thousand short tons for a total of 730 thousand short tons. In BTU equivalent terms, these reserves amount to approximately 60 quadrillion BTU of proven and 220 quadrillion BTU of total (proven + potential) reserves. The latter amount in light water reactors could produce only enough BTU's to cover U.S. total energy demand for approximately three years (assuming the total consumption in any one year is the same as in 1975).

Options Within the Nuclear Sector

There are two methods to augment these extremely limited inexpensive uranium reserves:

- augment natural uranium reserves through greater physical effort and higher production costs, and
- reprocess spent fuel from reactors to recover recycled uranium and plutonium.

Plutonium obtained from reprocessed fuels can be used in fast breeder reactors as well as in place of enriched uranium in light water reactors. These, then, are the alternatives available in the model: reprocessing, enrichment of recycled uranium, enriched uranium fueled light water reactors, plutonium fueled light water reactors, fast breeder reactors, and the mining of uranium ore that requires greater and greater effort as more uranium resources are extracted.

4. Mathematical Structure

Solution Method

The PILOT model consists of a number of mass balance constraints in the form of linear equations and linear inequalities. The variables are unknown levels of various processes which are constrained to be nonnegative since these activities cannot operate at negative levels. Certain of the relations are nonlinear, such as the finding rate functions for oil or export revenues as a function of the amount physically exported. These we have approximated by broken line fits. The net result is a mathematical system called a linear program which can be solved using the simplex method.

The matrix structure for the linear program for eight periods takes the form of Figure 4. The coefficients outside the "staircase" blocks are zero (with the exception of a few coefficients). The staircase blocks themselves have an internal structure which is displayed in Figure 5.

The full eight period 40 year model with 23 industrial sectors has roughly 800 equations and 2000 variables. We use the Stanford Linear Accelerator Computer System, which consists of a system of three IBM 370 series computers. The Wylbur Text Editing System is used to input and modify data. The relations defining the linear program are inputted using the MAGEN matrix generator developed by Haverly. The optimal solution is obtained using the MPS3 software system developed by Management Sciences and the MINOS software system developed at Stanford's Systems Optimization Laboratory by Michael Saunders [16]. A detailed specification of the relations of the model can be found in [17].

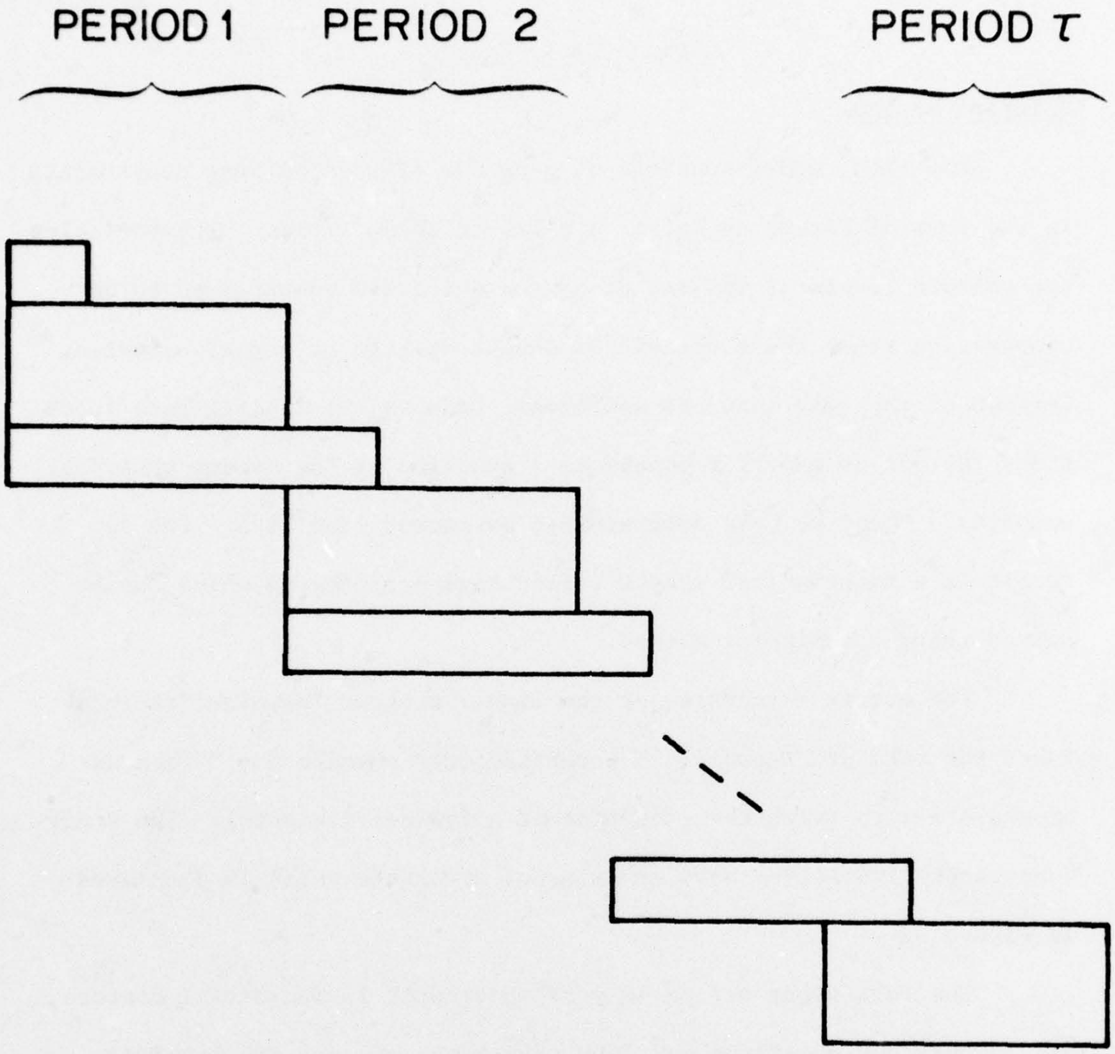

Figure 4. The Dynamic Staircase Structure of PILOT

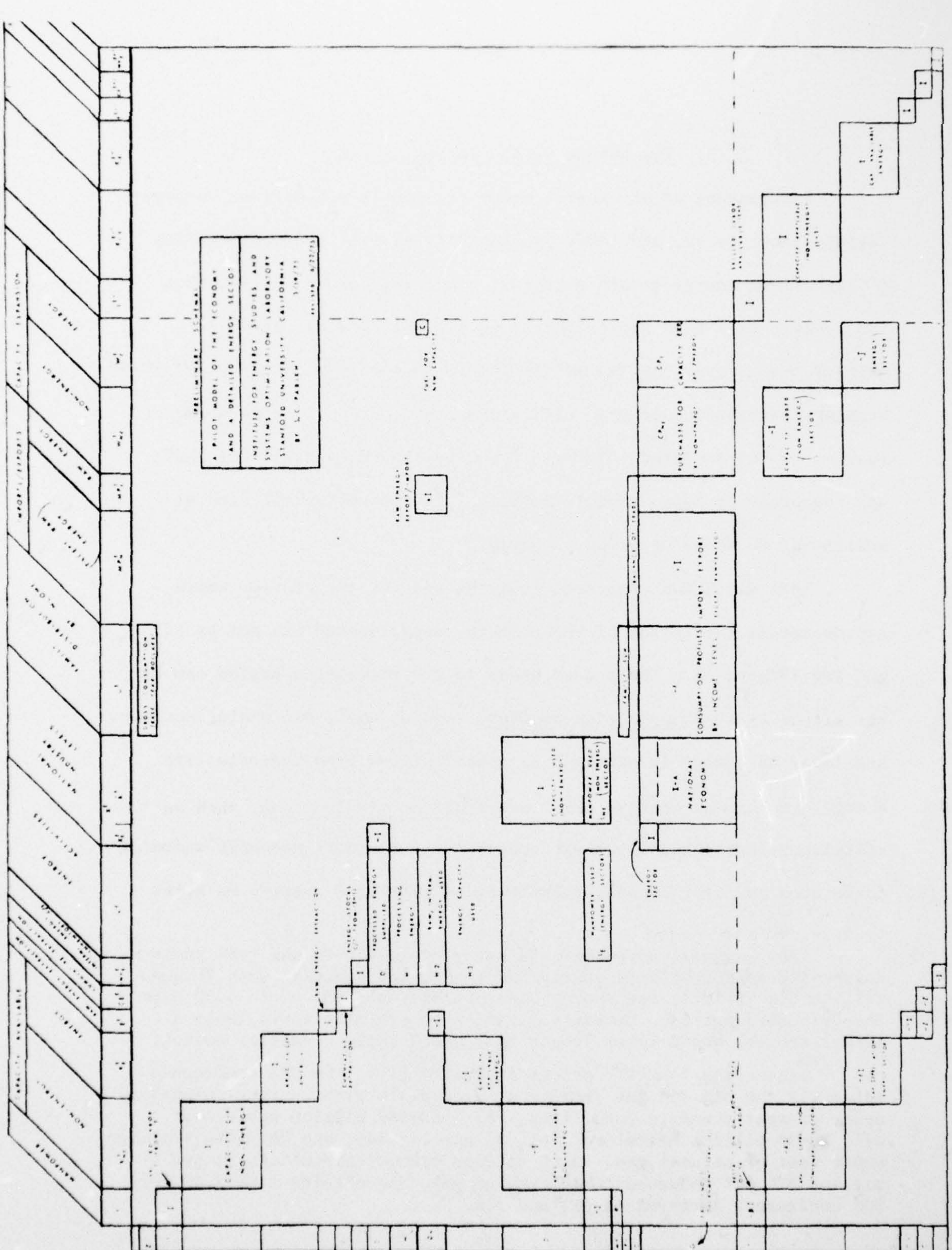

Figure 5. Matrix Structure of Two Successive Periods of PILOT

5. The Nature of the Energy Crisis

Independent of any model, under reasonable assumptions on population, labor force, and labor productivity growth, and continuation of historical energy growth patterns, one easily can calculate that the country will need approximately 6Q (1Q = 10^{18} BTU) units[2] of primary energy over the transition period of the next 40 years for which a major contribution from an ultimate energy source, such as solar or fusion, is not expected. Further, assuming the recoverable oil and gas resources of approximately 2Q units[3], the country will need an additional 4Q units of primary energy.

This situation contrasts from the one for the sixties where approximately two-thirds of the primary energy demand was met by oil and gas (Figure 6). The energy needs in the transition period can be met either by the supply side options, such as coal, oil shale, nuclear, and imported energy in addition to contributions from hydroelectric energy, geothermal energy, etc., or by demand side options, such as efficiency improvements through redesign and retrofit measures reducing conversion and heat losses, substitutions away from energy, as well

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[2] For example, assuming a 3% per year growth in the real gross national product, a fixed energy/GNP ratio, and starting with 76 quadrillion BTU in 1976, the energy consumption would add up to 5.9Q over the 1976-2015 period. Commercialization of synfuels would imply a larger amount, and a lower growth rate would imply a smaller amount.

[3] According to U.S. Geological Survey [14], the 90% confidence intervals for oil and gas resources recoverable with current technology under present economic conditions are: 112-189 billion barrels of oil, 23-34 billion barrels of natural gas liquids, and 761-1094 trillion cubic feet of natural gas. At 6 million BTU per barrel of oil and 1 million BTU per thousand cubic feet of gas, one obtains 1.6Q-2.4Q for 90% confidence interval on oil and gas.

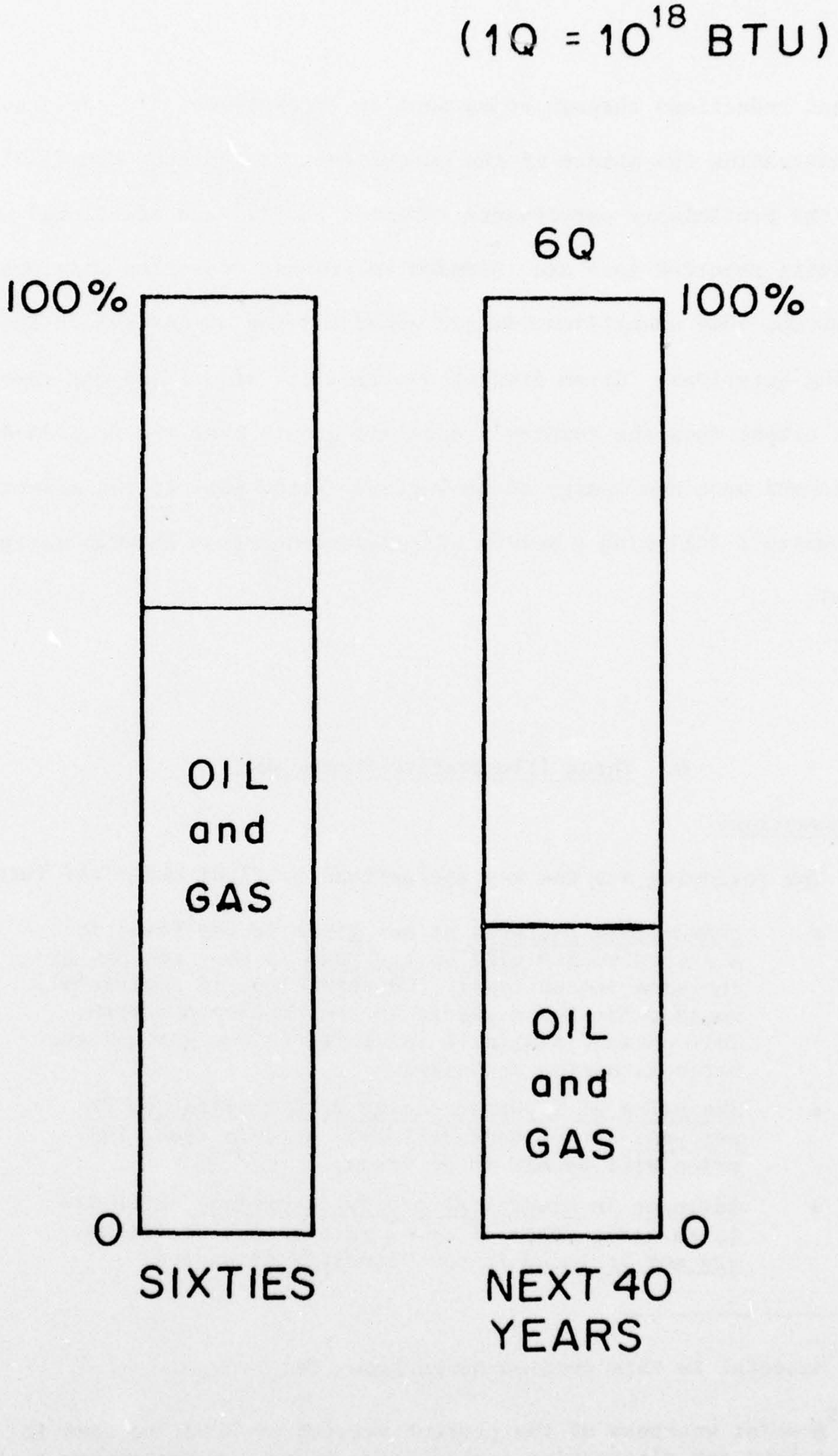

Figure 6. The Transition Problem of Energy Needs in the U.S.

as demand reductions through adjustment in life-styles. In addition to demonstrating the nature of the output information from the PILOT model, the preliminary experiments reported in [17] and additional experiments reported here are intended to provide scenarios that would help towards some quantification and understanding of answers to the following questions: Given limited availability of oil and gas resources, to what extent does the country's economic growth over the next 35-40 years depend upon new energy technologies? Also, what is the effect of this country's following a policy of independence from foreign energy sources?

6. Three Illustrative Scenarios[4]

Key Assumptions

The following are the key assumptions in PILOT about the future.

- Consumption patterns at any given income level in a future period will be the same as they are now at the same income level. Conservation, if successful, would represent a change in consumption patterns. This option, available in PILOT, is not part of the three scenarios presented.[5]
- The price of imported energy will increase by 2% per year in constant dollars. At this rate, the price will double in 36 years.
- Advances in electrical energy technology which are in an early stage of development, such as fusion, are not included in the scenarios presented.

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[4] Material in this section drawn from [18].

[5] A major weakness of the present version of PILOT is that it does not have any alternative technologies except in the energy sector. Nor does it reflect the full range of possible substitutions by the final consumer due to higher prices. See Section 7 for work in progress to overcome these deficiencies.

- Availability of nonconventional alternative energy systems (AES) for nonelectric purposes is permitted after 1990. This is a catchall for unspecified new technologies. It is assumed that no more than 10 quads of energy per year, at an average cost of $6 per million BTU, can be developed by 2010 from these sources.
- Oil shale will be available after 1995 at a maximum level of 6 quads per year in 2010.
- The fast breeder reactor (FBR) will be available for commercial use by 2000. Its use, however, is excluded in one of the scenarios presented.
- Assumptions about fossil fuel and uranium reserves, population growth, productivity, environmental needs, and government spending are included in PILOT.

Policy Constraints

In addition, several constraints are imposed in all three scenarios. These constraints reflect assumptions about the acceptability of certain policy implications:

- Imports cannot exceed exports. The U.S. must have a favorable balance of trade over each five year period.
- An upward mobility constraint prevents a decrease in the standard of living from one five year period to the next.
- Nuclear electricity cannot exceed one-half of the total electrical production.

The base case imposes certain additional policy constraints on imports and coal. These restrictions are removed for the high energy resource availability scenario. For the low energy resource availability case, even tighter policy restrictions are placed on coal, nuclear, and imported energy availability than in the base case:

Coal

- Base Case -- Overall limits are specified on coal development. These limits are not too restrictive however.
- High Case -- No limits.
- Low Case -- Overall limits are set at a lower level than in the base case.

Imports

- Base Case -- Energy imports cannot exceed 20% of total energy consumption, to keep dependence on foreign sources moderate.
- High Case -- No restrictions.[6]
- Low Case -- An additional constraint is imposed: energy imports cannot exceed 20 quads per year.

Nuclear Energy

- Base Case -- Nuclear cannot exceed 50% of total electricity.
- High Case -- Same limit.
- Low Case -- No new nuclear plants can be built.

The low availability case reflects restrictions on the use of nuclear energy (due, let us say, to fears about plutonium theft or nuclear accident), restrictions on the expansion of coal mining (due, let us say, to fears about the effect on the environment), and restrictions on foreign energy imports (in order, let us say, to maintain our political independence). The high availability case, by way of contrast, reflects the deemphasis of these concerns.

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[6] There are two intermediate limits on the quantities of energy which can be imported. The importing of refined oil products is limited to a maximum of 7 quads per year. Natural gas imports are restricted to below 5 quads per year. These policy constraints also apply to the high energy availability scenario.

Analysis of Scenario Results

The following sections describe the optimum mix of energy sources and conversion activities for each scenario. A comparison of the impact which each scenario would have on total energy consumption, the gross national product, and the standard of living follows this section.

Base Case Scenario Results

The base case is a constrained energy availability scenario. (See Figure 7.) Since coal is economical to use, its production reaches the limits imposed. Despite the lag time needed to build new mines, twice as much coal is produced per year by 1990 as now. Use of coal for conversion to pipeline gas becomes moderately economical in the 1990's.

In the base case, the nuclear power is heavily developed. The policy constraint which prevents nuclear power production from exceeding 50% of total electricity becomes binding. Use of nuclear power to this extent is achieved in this scenario through use of conventional light water reactors as well as reprocessing of nuclear fuel and the fast breeder reactors.

Oil consumption doubles by 2010 with the use of secondary and tertiary recovery techniques, the extraction of oil from shale, Alaskan production, and imports. Much of the growing energy demand is met by increased imports, which are limited to 20% of total energy.

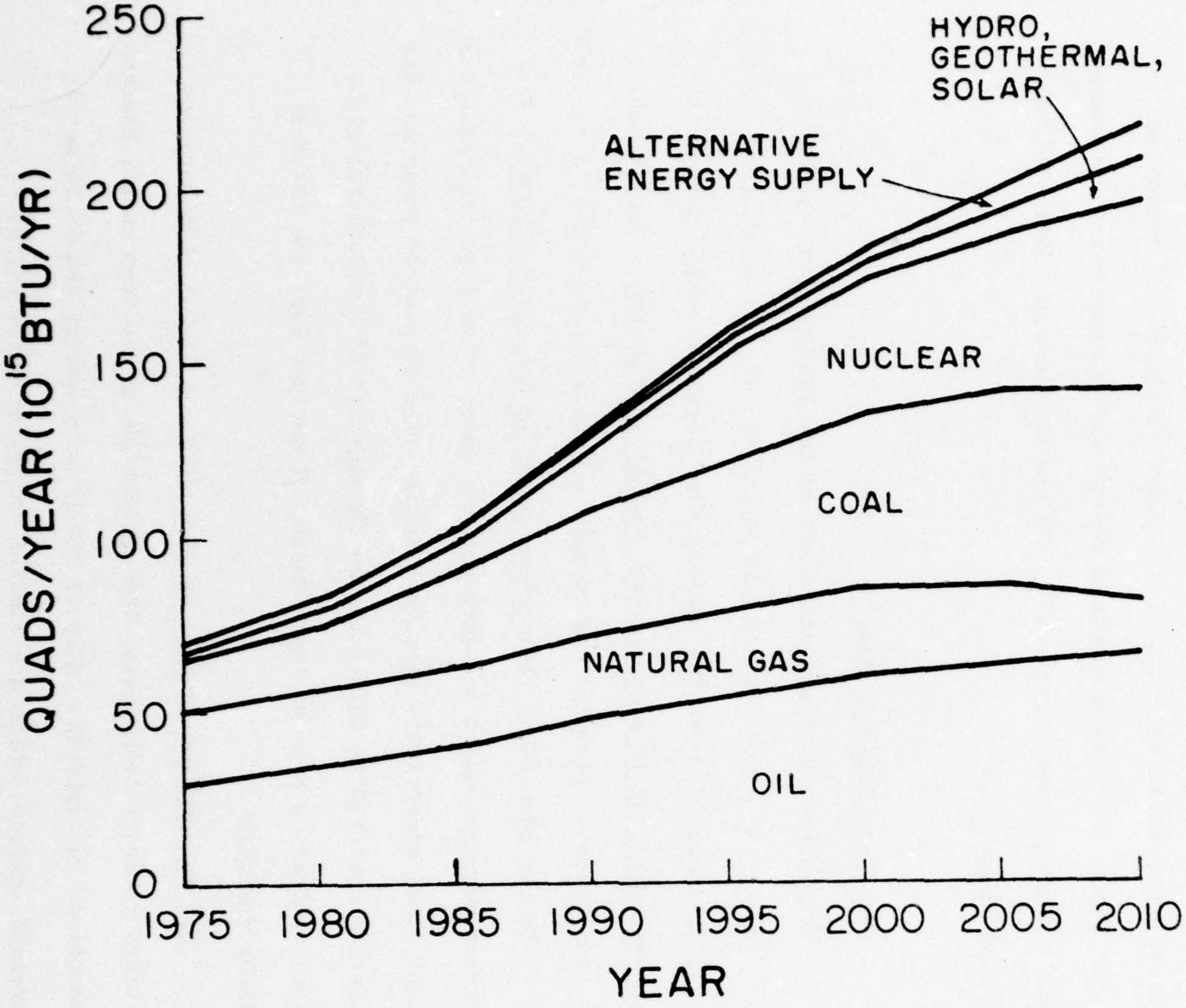

Figure 7. Optimal Energy Supply Mix to Maximize the Standard of Living under Base Case Conditions

Natural gas production is fairly even over the planning horizon, with rise in consumption compensated by a slight rise in imports and coal gasification.

Other technologies, such as hydroelectric and geothermal energy, are developed at the same exogenously specified rate in all cases. In addition, some energy in the base case comes from central station solar plants and alternative energy systems (AES).

High Availability Scenario Results

The key feature of the high availability case is the use of coal. (See Figure 8.) After a substantial period in which investment in coal mines and infrastructure takes place, the use of coal skyrockets beginning in the late 1980's. Coal production grows to 12 times present levels by 2000. As a result, total energy production grows dramatically, nuclear power is not used as extensively, coal conversion activities are very attractive, and imports cease by 1995.

Total oil consumption and domestic production are similar to that in the base case through 2000, after which the unrestrained availability of coal causes oil use to decline. The use of oil fired power plants ceases in the late 1990's.

Since only 14% of electricity is generated from nuclear plants in 2000, the need for the fast breeder reactor is precluded and installation of reprocessing capacity is delayed beyond the 2000's.

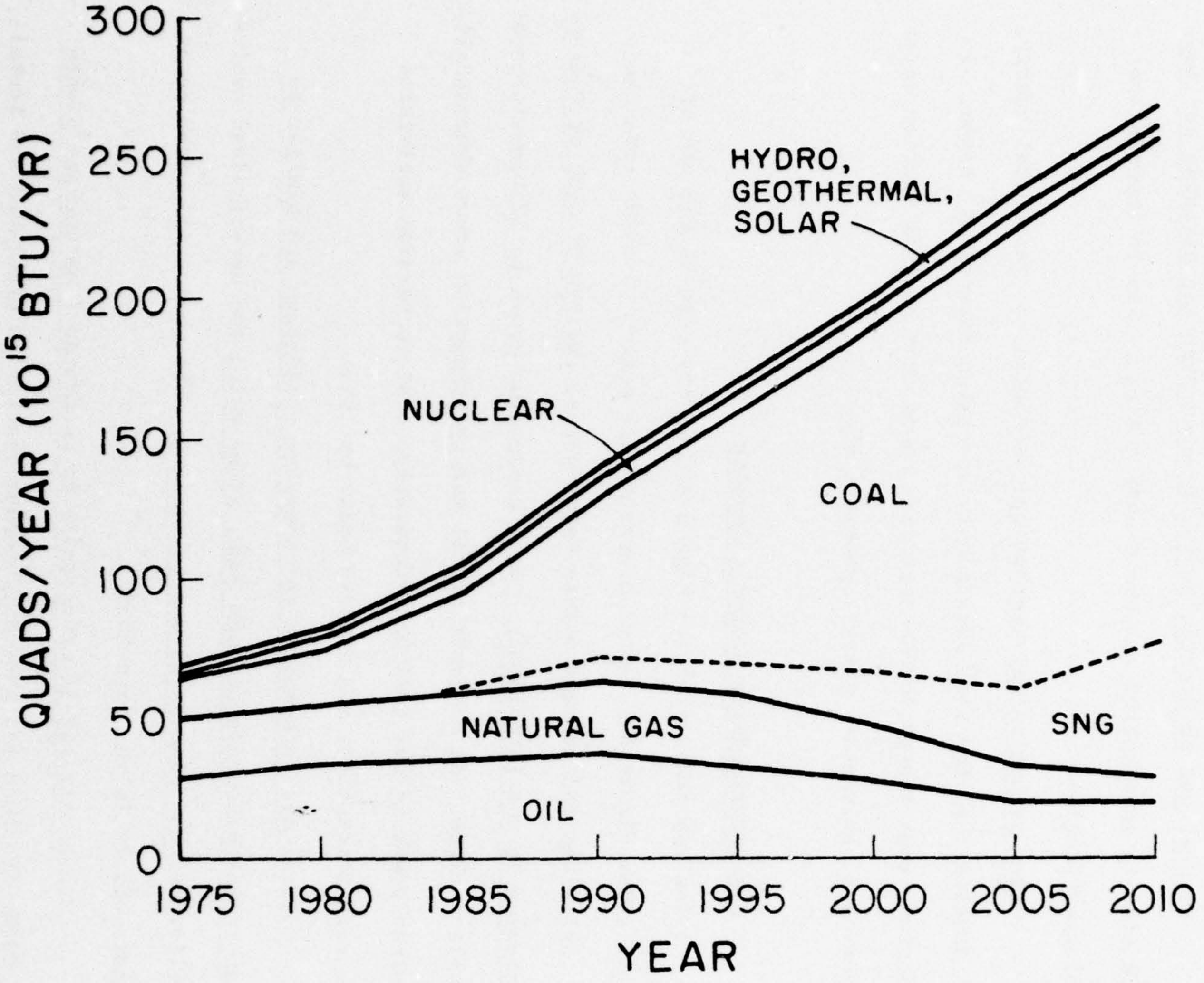

Figure 8. Optimal Energy Supply Mix to Maximize the Standard of Living under High Availability of Energy Resources

The permissibility of the unrestrained development of coal makes synthetic gas even less costly to produce than natural gas. For this reason, <u>the use of natural gas declines after 1985</u>.

Use of costly <u>other technologies</u>, such as central station solar electricity plants and alternative energy systems, <u>is not economically competitive</u> under this scenario.

<u>Low Availability Scenario Results</u>

In this case, the three major energy sources are tightened down to levels significantly below that of the base case. (See Figure 9.) <u>Coal production grows to the limits allowed</u> -- at a rate considerably slower than the base case. These limits are low enough to prevent coal synfuels from playing a significant role.

<u>Oil use is similar to that in the base case scenario</u>. Imports increase more rapidly until 1990, when the additional constraint limiting imports to 20 quads per year becomes binding. Since coal and nuclear energy are tightly restrained, twice as many oil fired power plants are used in 2000 as in the base case.

Since nuclear plants already under construction are allowed to be completed, <u>growth in nuclear power does not cease until 1985</u>. By assumption, the fast breeder reactor and reprocessing technologies also are absent in this scenario.

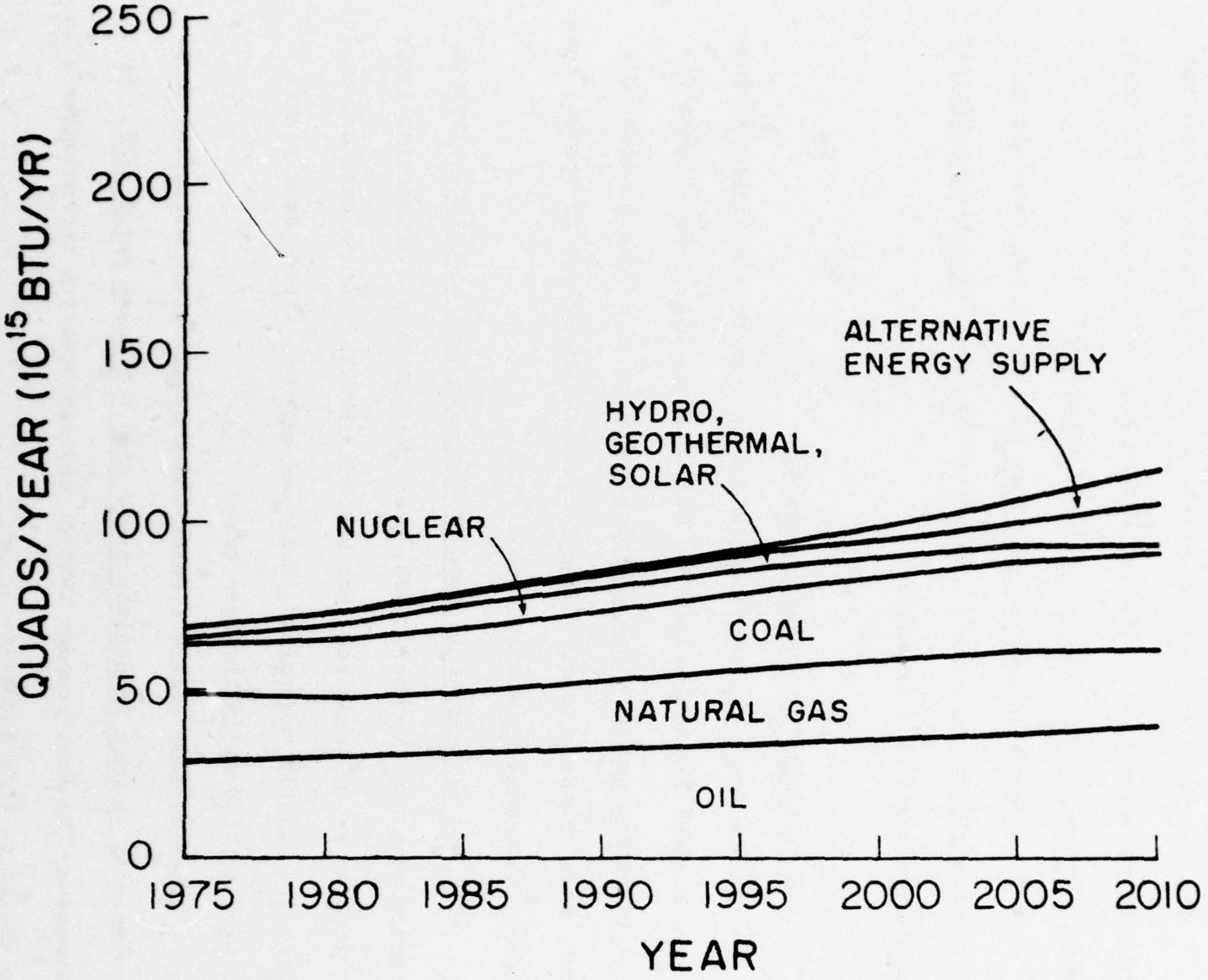

Figure 9. Optimal Energy Supply Mix to Maximize the Standard of Living under Low Availability of Energy Resources

Natural gas production is similar to that in the base case. Also, the lower coal limits make coal gasification less desirable.

Scenario Comparisons

As mentioned at the outset, supply policies affect total energy consumption, the gross national consumption, and the standard of living. The differences between scenarios are displayed by the following graphs.

Total Energy Consumption

The base case is energy supply oriented in the sense that no demand reduction measures are assumed to be implemented by the consumers and the industry. It is found that growth of the total energy flow in the base case parallels the historical growth scenario of the Energy Policy Project of the Ford Foundation [19]. The growth is about 3.3% per year. At this rate, total U.S. energy consumption would double every 21 years. In comparison, the high availability case allows energy consumption to grow at a considerably faster rate of 3.9% per year. Energy consumption would then double every 18 years.

Despite the very strict limits imposed on the low availability scenario, energy consumption still would grow but only 1.5% per year. At this rate, it would take 46 years for the U.S. to double its current consumption. (See Figure 10.)

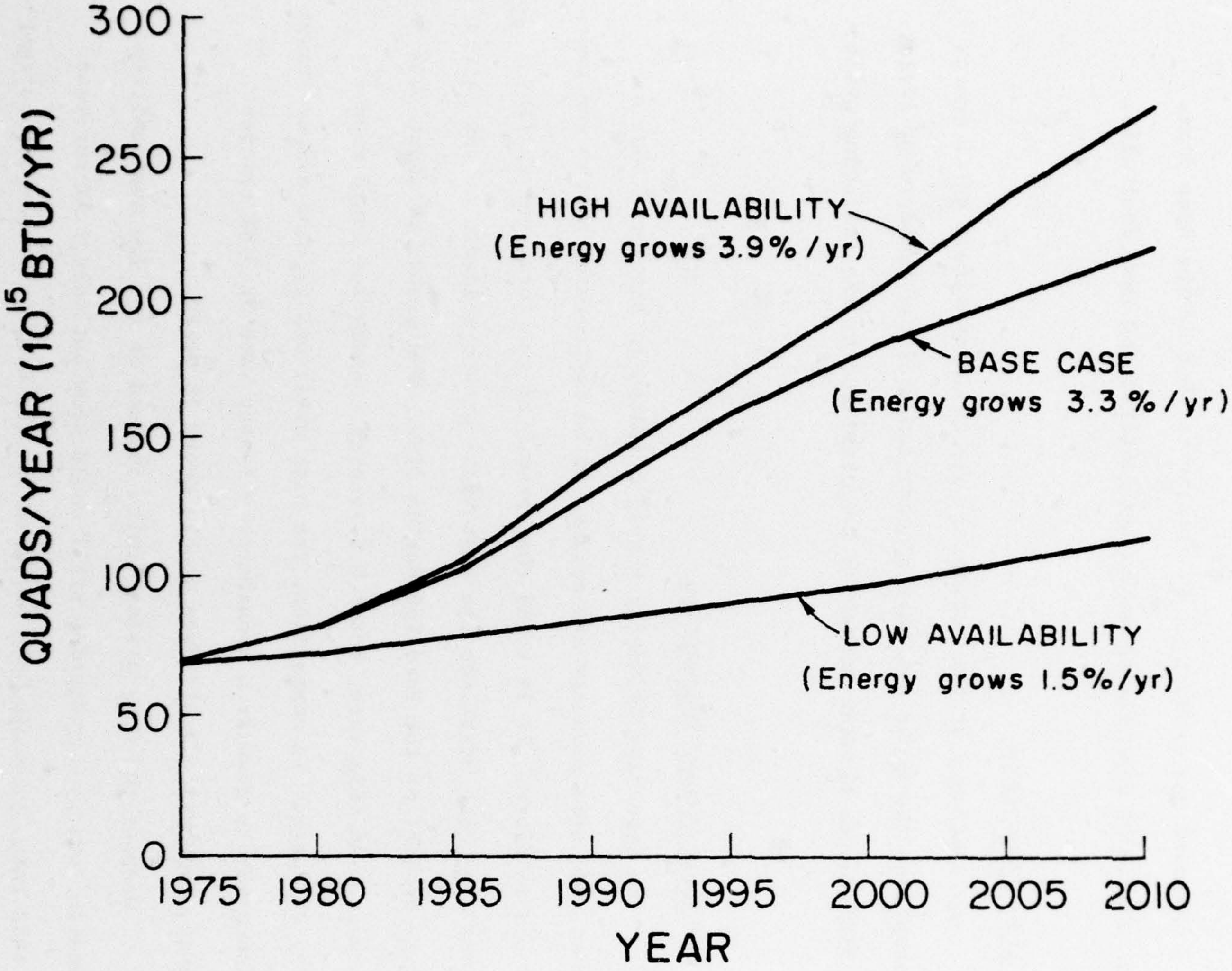

Figure 10. Comparison of Energy Supply for Three Scenarios

Gross National Consumption

Growth in the U.S. gross national consumption in the base case parallels the growth in the total energy consumption (Figure 11). Energy growth is related to economic growth since these scenarios assume traditional consumption patterns will hold for the future. Conservation measures, if successful in improving the efficiency of our energy use, would permit GNC to grow at a faster rate, or energy use to grow at a slower rate, or both.

Standard of Living

Energy availability can have a great impact on the standard of living. This effect will not be noticed until 1985 when today's energy choices begin to affect the level of personal consumption. Some growth in the personal consumption is achieved under all scenarios but the contrast between the high energy availability case and the low one is striking. The consumption level attained by 2000 under the high energy availability case is twice as much as that attained under the low availability case. (See Figure 12.)

7. Drawbacks and Development Work in Progress

Deficiencies in Mid-1976 Version of PILOT

In its present form the model includes: detailed description of the energy technologies, explicit description of the exhaustion processes for oil, gas, and uranium, the dynamics of the capital formation and the resource extraction that explicitly take into account

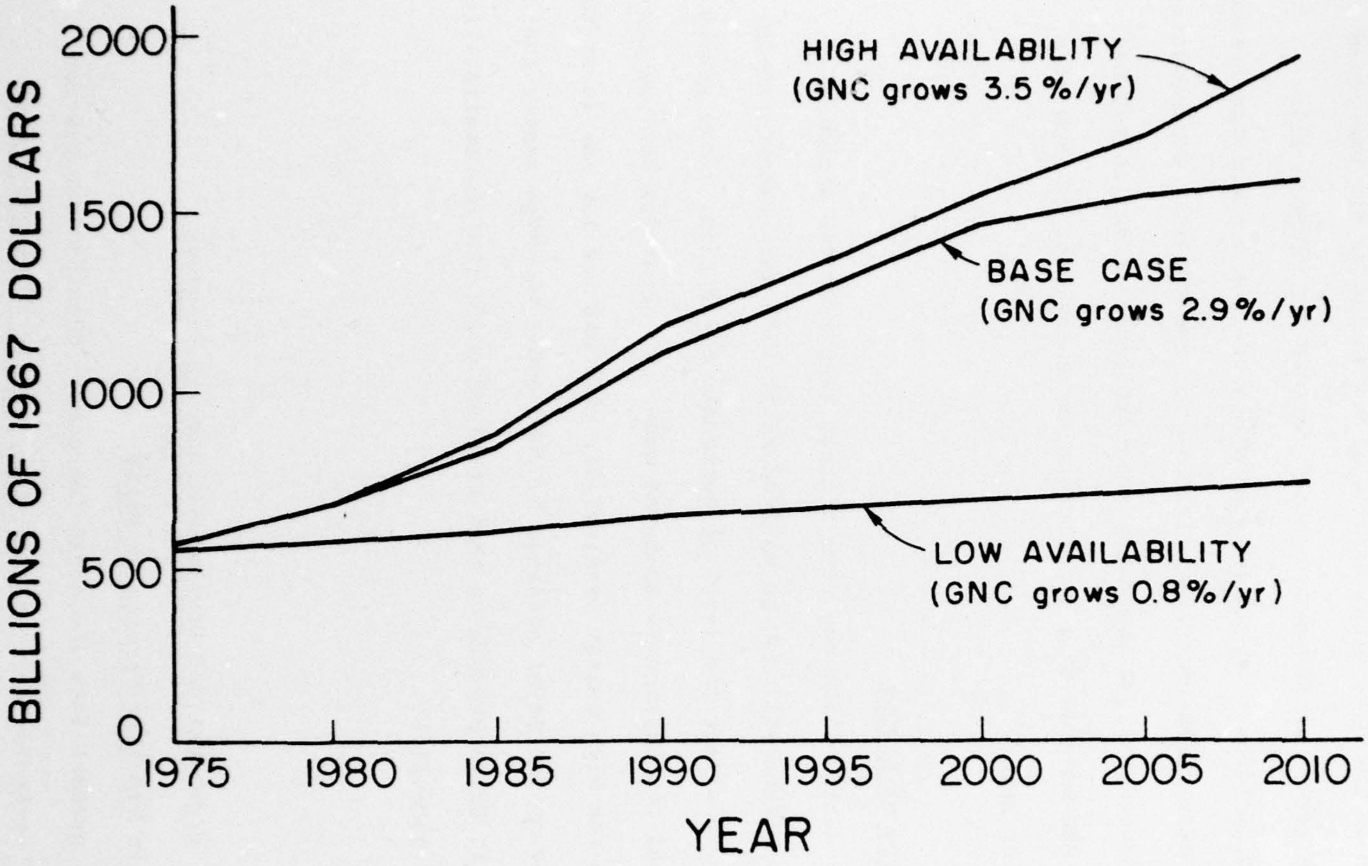

Figure 11. Gross National Consumption for Three Scenarios

A fuller range of substitution possibilities by the final consumer will be included in future PILOT runs. The estimates above on the gross national consumption attained are conservative, especially in the low energy availability case.

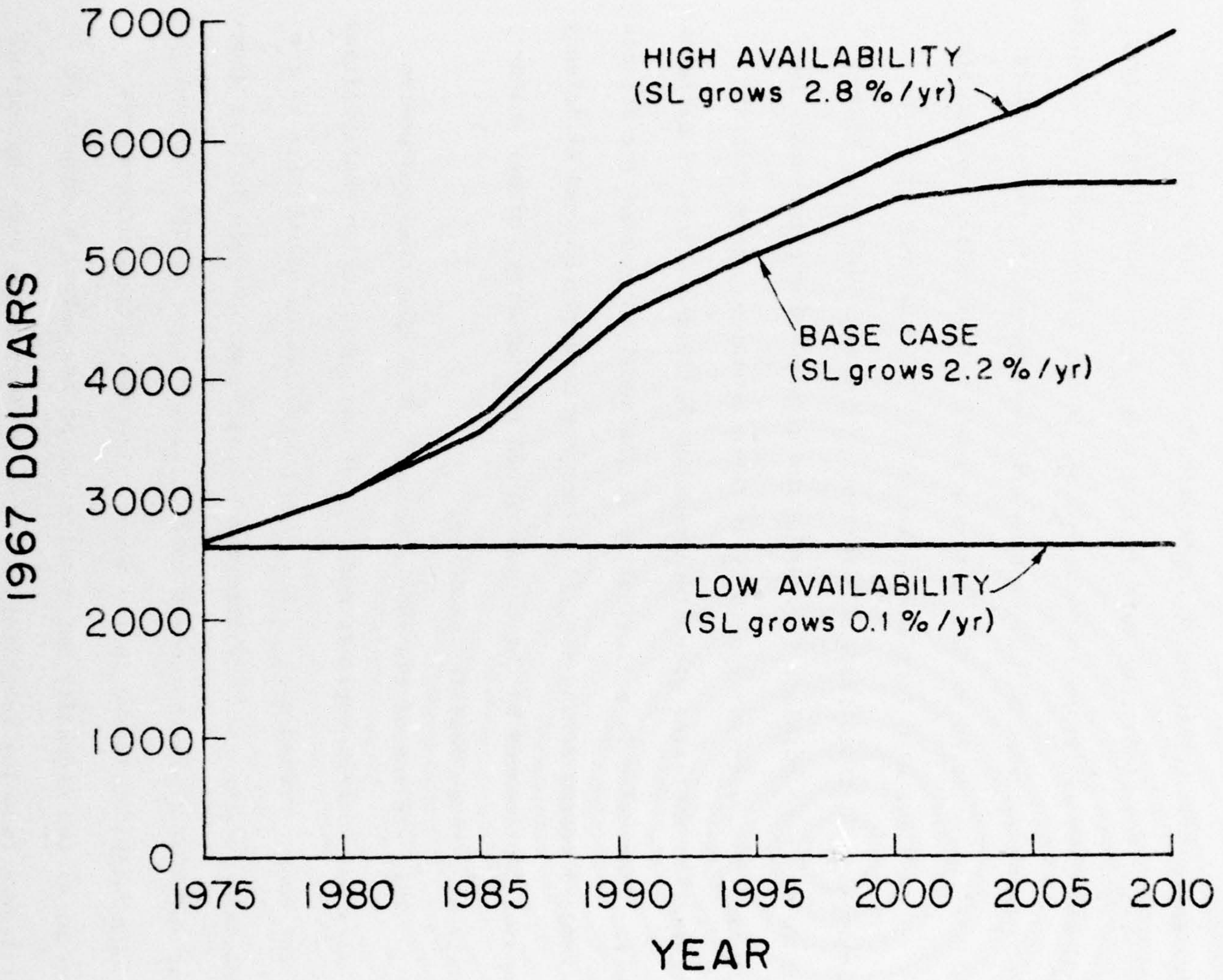

Figure 12. Comparison of Standard of Living (Average Per Capita Consumption) for Three Scenarios

the intertemporal tradeoffs, nonmalleable capital, variable construction lags, endogenous treatment of trade with the rest of the world, and consumption functions that were derived using a procedure that assumes equal absolute additions to income of all income groups and that describe the changing patterns of consumption with the changes in the standard of living as measured by the aggregate level of per capita consumption.

The model also contains a flexibility to experiment with the exogenously specified temporal profiles of consumer fuel mix. This feature makes it possible to examine the effects of the interfuel substitution by consumers especially in those scenarios where initial optimization indicates wide dispersion in the shadow prices of different fuels. There also is a flexibility in the model to examine the effects of reduced energy demand resulting from the conservation and efficiency measures implemented by the consumers and the industry, either voluntarily or through legislative means.

This version of the model, however, does have some weaknesses. It does not contain explicit modeling of the substitution possibilities on the energy demand side. Thus, the possibilities of switches by the consumers and the industry from the scarce forms of fuels to more abundant forms of fuels, nonenergy materials, labor, or capital are not endogenously considered in the model. The main disadvantages here consist of the necessity for examination of the solution outputs for bottleneck reducing substitutions, and reoptimization with appropriate adjustments in the matrix coefficients. Such reoptimizations, however, could be time consuming and cumbersome.

On the energy supply side, a weakness in the model is an absence of the endogenous descriptions of the requirements for the environmental related hardware particularly with respect to coal usage. The total coal production, therefore, is essentially exogenous in the model. Also, the 40 year planning horizon of the model is not long enough for certain decisions related to energy. Two examples worthy of mention in this regard are the decisions related to the fast breeder reactor and the central station solar technologies.

Main Model Developments

The main model developments are listed below. Naturally, most of them deal with overcoming the deficiencies just outlined.

- Coal Module--Physical Supply Curve of Delivered Coal (factors included: water, environment, changing transportation requirements).
- Longer Planning Horizon--100 Year Model with Variable Time Period Aggregation for Computational Efficiency.
- Potential Interfuel and Capital Fuel Substitution Module--Incorporates Efficiency Improvements and Constraints Imposed by Existing Stocks of Utilizing Devices.
- Welfare Equilibrium Variant--Comprehensive but More Aggregate Substitution Functions for Consumers and Industry.
- Financial Flow Model--To Study Market Imperfections.

A coal module is being prepared that takes into account the following considerations related to significant increases in the coal production: water availability constraints, environmental considerations related particularly to high sulfur coal, and shifts as well as increases in transportation requirements related to anticipated increases in the market share of western coal. While it is true that the supply curve of coal at mine mouth is relatively flat, a more meaningful treatment of coal must take into account the above economic and environmental considerations [4, Appendix D].

An approach is being developed for extending the planning horizon to 100 years. The staircase structure of the PILOT model with 20 five-year periods would take a significantly longer computation time. To overcome this difficulty, a computer program has been developed and is being tested to aggregate the 20 time periods into a smaller number of time periods of variable length. The length of any time period in the aggregation can be any desired multiple of five years [4, Appendix H].

A major area of development deals with modeling of the substitutions on the demand side. Two approaches are being pursued. The first one concerns process analysis based modeling of the limited area of interfuel and capital fuel substitution, the objective of which is to facilitate studies dealing with the determination of potential substitutions away from the scarce forms of energy that explicitly take into account the fact that the demand in the short run is "locked" into the existing stock of utilizing devices, and either retrofitting or replacement is required to bring forth adjustments [4, Appendix G].

The second approach concerns modeling of a much more comprehensive set of substitutions in the consumer and industrial demand but on a highly aggregated scale. Implementation of substitutions is achieved through a hierarchy of pairwise substitutions. "Hierarchical homothetic functions" are used to mathematically express the choice making behavior and technological substitutions [3].

Finally, some basic research is being conducted in the area of modeling market imperfections. The key idea here is an observation that the shadow prices from linear programming are marginal prices and do not reflect market prices which may be affected in part by institutional factors (e.g., salaries, taxes, profits, subsidies). The purpose of the Financial Flow Model is to derive a modified set of dual variables which reflect a number of these institutional factors [20].

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Technical Report SOL 77-19, July 1977, "The Stanford PILOT Energy/Economic Model", by T.J. Connolly, G.B. Dantzig, and S.C. Parikh

The PILOT Energy Modeling Project being conducted at Stanford's Systems Optimization Laboratory is concerned with (i) performing modeling and methodology research dealing with construction and solution of reasonably large scale mathematical programming models of energy/economic systems, (ii) using the modeling research towards analysis of some of today's important energy questions, and (iii) using the modeling and methodology work for construction of better models for improved analysis of tomorrow's important energy questions. At the core of the project activity is the development of a multisector, intertemporal linear programming modeling system that describes in physical terms many of the technological interactions within and across the sectors of the American economy. The general aim of the modeling effort is to permit studies (i) to assess how specific energy policies will affect the energy supply/demand picture, and (ii) to assess how the physical capacity of the economy over the next 30-35 years to provide goods and services to its populace could be affected by changes in the energy supply picture.

Intertemporal linear programming models of the energy sector and the economy provide a unique medium for exploring future energy policy options. This paper presents the first version of PILOT together with three illustrative scenarios. The model deficiencies and new developments in progress are briefly discussed.