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Stanford Pilot Energy/Economic Model

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NOTE

This report on the Stanford PILOT Energy/Economic Model has been issued in two volumes. Volume 1 is a description and demonstration of the Stanford PILOT Energy/Economic Model. Volume 2 contains Volume 1 and appendixes. See Contents, beginning on page x, for a listing of the latter.

Readers who are interested in receiving Volume 2 should write to the Department of Operations Research, Systems Optimization Laboratory, Stanford University, Stanford, California 94305.

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ABSTRACT

The Stanford PILOT Energy/Economic Model

PILOT is a U.S. national energy/economic model that compares various policy decisions by measuring their impact on the standard of living. Through its dynamic linear programming formulation, the modeled economy allocates industrial output to consumption and to capital formation in the current period to achieve the highest standard of living over the planning period. The "take home" or consumption income is used to measure the standard of living.

The model consists of a detailed description of energy technologies and a less detailed description of other economic sectors, investments, government, and final consumption. In particular, there is an explicit representation of the exploration and extraction processes for oil, gas, and uranium; there is an accounting over time of reserves and capital formation. Foreign trade balance is treated endogenously. Final consumption is represented by consumption vectors that vary with increasing level of income.

Three sets of input conditions are used to illustrate the behavior and capabilities of the model. The assumptions for the base case and two variations were developed in consultation with EPRI staff. One of the cases assumes a higher and another a lower availability of primary energy than that assumed for the base case.

The general conclusion on the supply side is that the availability of primary energy can have an important effect on the future standard of living. On the demand side, successful implementation of conservation measures can significantly increase the standard of living for the same amount of energy made available to the general economy. The model outputs are schedules of economic activity, imports and exports, raw energy extraction, new construction, and production of various conversion processes.

ACKNOWLEDGMENTS

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The PILOT project has been influenced by the ideas of William P. Drews of Exxon, William W. Hogan, Alan S. Manne, and James Sweeney of Stanford, and Chauncey Starr and Martin Greenberger of EPRI. We also appreciate their advice and encouragement.

The authors of various parts and supporting appendixes are listed in the Table of Contents. Dorothy B. Sheffield served as editor and coordinator. Arvind Jain and John Riddell have played a crucial role in the development of the model software and the running of scenarios.

Special thanks are due to Gail Lemmond, who took charge of all processing arrangements needed to keep the report preparation on schedule and for her relentless drive for perfection, and to Lynda Schrotenboer for excellent typing of the report.

EPRI PERSPECTIVE

Project Description

There is growing concern that the rising cost and dwindling supply of energy may have significant implications for the economy and the electric utility industry. To help the industry understand this important issue, EPRI's Systems Program has contributed to several research efforts which study the links between the energy sector and the rest of the economy. One of the most ambitious attempts to model these energy-economy interactions is the PILOT Model (RP652). It is being used along with ETA-MACRO (RP1014), the Wharton Energy Model (RP440), and the Hudson-Jorgenson Model (RP1152) to assess the effect of U.S. energy policies on the nation's standard of living. This interim report documents the development of the model and presents the results of a preliminary study which was designed to illustrate the behavior and capabilities of the model. Subsequent reports will present the findings of a series of cost/benefit analyses currently being performed for EPRI's Planning Staff.

Project Objective

The primary goal of this three-year project is to develop a capability for assessing the impacts of energy policy decisions on the U.S. economy. This is accomplished by linking an input-output matrix of the economy's industrial processes to a detailed linear programming submodel of the energy sector. The PILOT Model will be used to generate physically feasible economic and energy scenarios for EPRI's R&D planning use and for the industry's more general use.

Conclusions and Recommendations

To date much of the work has involved model development. For example, a dynamic physical flow model of the U.S. economy with a 40-year time horizon has been created. It includes both a 23-sector input-output matrix and a 12-sector input-output matrix. EPRI staff from the Systems Program, with advice from members of the utility industry, believes that the model can now be brought to bear on selected problems of importance to EPRI's Planning Staff and the industry. These include such questions as:

- Are we consuming domestic energy resources too quickly?
- Are we making sufficient investment now so that new energy technologies can come into commercial operation if needed in the future?
- Will we have sufficient physical capacity to build new plants and equipment in the energy and nonenergy sectors so that the growth in consumer consumption will not be seriously hampered?
- What are the feasible energy options under different patterns of crude oil import prices?
- What will be the short- and long-term impacts if oil and gas discoveries in the U.S. are fewer and/or less productive than predicted?

At the same time, continued model refinement is recommended. Areas of particular importance include the need for more detailed modeling on the energy demand side of substitution possibilities and a more explicit and detailed treatment of coal, pollution abatement, and regional factors.

George Dantzig, Thomas Connolly, and Shailendrah Parikh are principal investigators for the project. A highly qualified staff at Stanford and visitors from other universities and industry work with them. This provides the project with a broad range of expertise and experience which is integrated in the PILOT Model.

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EXECUTIVE SUMMARY

The Stanford PILOT Energy/Economic Model

The energy transition problem of the next 40 years is evident to anyone who compares recoverable oil and gas resources to our primary energy needs. Roughly two-thirds of the required energy will have to come from sources other than domestic oil and gas. This contrasts with the situation of the seventies in which about two-thirds of the primary energy demand is being supplied from these sources. The PILOT model has been developed by Stanford's Systems Optimization Laboratory to analyze this transition.

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 the time span studied.

The model is exercised by providing it with certain assumptions and proposed policies that are varied from one run to the next. The output information helps one quantify and understand answers to such questions as the following: 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? What is the effect of the U. S. following a policy of independence from foreign energy sources?

PILOT was one of six models chosen by the EPRI sponsored Energy Modeling Forum for its study, "Energy and the Economy." This report is an overview of a somewhat later version of the model (mid-1977). To demonstrate its behavior and its capabilities, the results of three runs are presented--a base case and two variations, one of which assumes a higher availability and another a lower availability of primary energy than that of the base case.

PILOT is a national energy/economic model. It compares various possible policy decisions by measuring their impact on the standard of living. The "take home" or consumption income is used to measure the standard of living. Through its dynamic linear programming formulation, the modeled economy allocates industrial output to consumption and to capital formation in each period in order to achieve the highest per capita consumption over all the periods studied. It analyzes the required expansion of the general economy and of foreign trade to supply an increasing population with a higher consumption income.

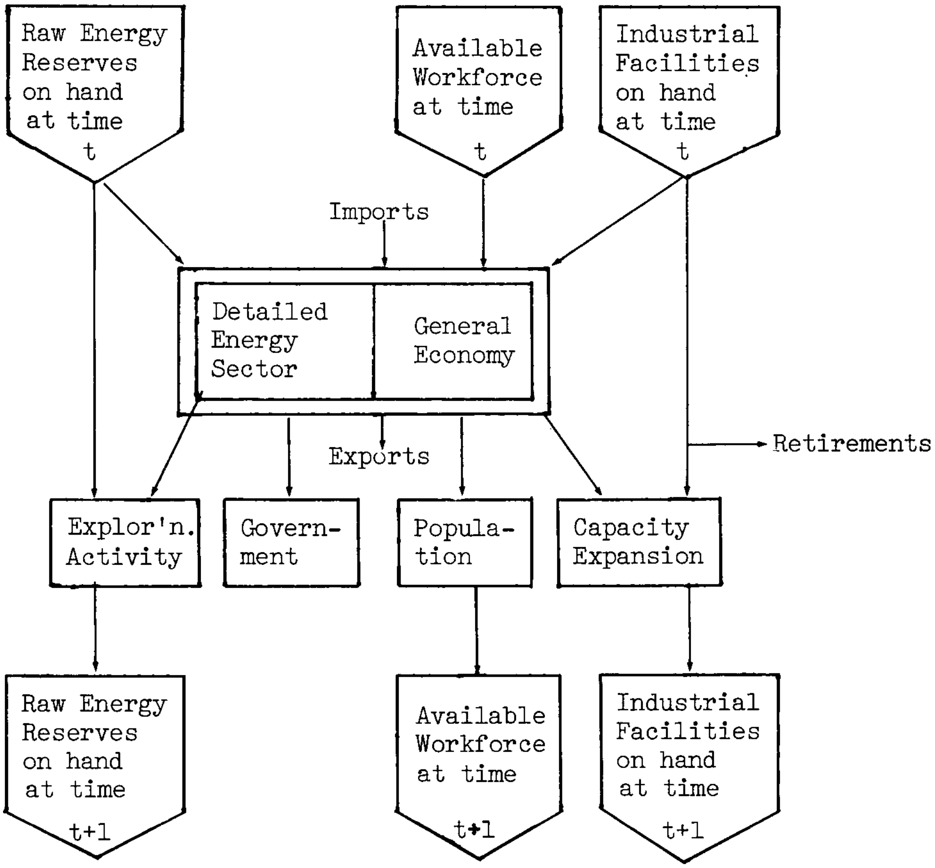
The model requires as input certain scenario assumptions, such as changes in lifestyles, dates when proposed new technologies could become commercially feasible, restrictions on the use of certain technologies and foreign imports, estimates of amounts of raw reserves. The growth of population, the available workforce, and labor productivity also are key assumptions that affect the growth in the standard of living. Other more detailed assumptions concern 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.

The outputs of a scenario run of the model are schedules of economic activity, imports, exports, raw energy extraction, and the expansion and production of various energy conversion processes.

The model consists of

- a detailed description of energy conversion technologies and a less detailed description of other economic sectors, investment, government, and final consumption;
- an explicit description of extraction processes for oil, gas, and uranium, and the exploration for new reserves;
- an accounting over time of reserves and capital formation;
- consumption vectors that vary with increasing income level.

The main linkages over time are:



Nonenergy Sectors. The model distinguishes and keeps account of the capacities of 18 nonenergy sectors, usually summarized in 7 classes: Agriculture, Mining and Construction, Energy Intensive Manufacturing, Energy Nonintensive Manufacturing, Transportation and Warehousing, Trade and Other Services, Machinery and Transportation Equipment.

In any given period, the model allows the building of additional capacity, providing, of course, that there is industrial capability to build this capacity while supplying other needs.

Energy Conversion. The detailed energy sector includes a technological description of the extraction of raw energy and conversion. Input/output coefficients are defined for

- exploration and production of gas and oil;
- extraction of uranium ore;
- 18 other energy technologies, such as: Eastern and Western coal mining, coal gasification and liquefaction, and electricity production from oil, gas, coal, nuclear, solar, hydro.

Nuclear Energy. The nuclear portion of the model includes the following processes:

- mining and milling of uranium ore,
- enrichment by gaseous diffusion,
- fabrication into fuel elements for LWR,
- fabrication into core and blanket for LMFBR,
- reprocessing of spent fuels,
- LWR and LMFBR electricity generation.

Primary Energy Limits Imposed by a Scenario. Depending on the scenario, the use of nuclear energy may or may not be restricted. The same is true for other sources of energy, coal, and imports of fossil fuels.

The mid-1977 version is a 40 year, eight period model with 23 industrial sectors. The eight periods are centered at five year intervals from 1975 to 2010. The facilities and stocks required to be on hand at the end of 2010 are estimated by a "variable time period" variant of the model which aggregates several time periods into one and solves the model up to 2075.

Three sets of input conditions are used to illustrate the behavior and capabilities of the model. The assumptions for the base case and two variations were developed in consultation with EPRI staff. One of the cases assumes a higher and another assumes a lower availability of primary energy than the base case.

Scenario Assumptions. The following are examples of assumptions made for the three scenarios:

- The price of imported energy in fixed dollars will increase by 2% per year.
- Oil shale will be available after 1995 at a maximum level of 4.3 quads by 2010.

- The fast breeder will be available for commercial use by 2000.
- The social discount factor of future consumption versus present consumption in fixed dollars is 5%.
- The amount of discoverable oil and gas is 20% higher in the high availability case and 20% lower in the low availability case than the base case.
- The amount of uranium ore available at different prices depends on the scenario. (See Table 2 of report.)
- The amount of coal mineable in any five year period depends on the scenario. (See Table 2 of report.)

Thus, the principal ways the three cases are made to differ from one another are through the constraints imposed on coal production and the assumptions on the amounts of oil and gas resources and on the costs of mining uranium ore. In addition to assumptions about population growth, future workforce, and productivity, several assumptions are motivated by policy considerations and are imposed on all scenarios.

- 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.

Effect of Conservation. The base case and low availability scenarios are formulated in two variants, a conservation variant and a nonconservation variant. The conservation variant assumes that appropriate measures by consumers and industry will gradually reduce the energy demands (to produce a unit of output) by 0.7% in 1980 to 15% in 2010. These reductions were deemed to be sufficiently mild that they could be achieved with negligible additional inputs of capital and labor. A comparison of the base case with and without conservation shows that the demands for energy supply over time are practically the same, whereas conservation yields the following significant growth in the average per capita consumption per year:

BASE CASE (Constant 1967 Dollars)

Year	Without Conservation	With Conservation
1980	$3002	$3005
1990	4269	4628
2000	4288	5155

Effect of Availability of Primary Energy. The per capita consumption (standard of living) rises an average of 1.7% per year in the base case with conservation. In the high energy availability scenario, it rises faster and attains a 17% higher consumption level by 2010. In the low availability scenario with conservation, it rises slower and attains 28% lower consumption levels by 2010 than the base case. The comparative per capita consumption is as follows:

	SCENARIO (Constant 1967 Dollars)		
Year	Low Availability	Base Case	High Availability
1980	$3093	$3005	$2989
1990	3701	4628	4750
2000	3701	5155	5710
2010	3701	5155	6023

Some Results of Base Case Run. The outputs of various scenario runs are schedules of various economic and energy activities. For example, the electric power generation (expressed in trillions of kilowatt-hours) by source for the base case with conservation is as follows:

	Trillion Kilowatt-hours per Year		
	1985	1995	2005
Coal Fired	1.24	1.75	2.38
Oil and Gas Fired	.17	.08	-
LWR (Uranium Enriched)	.74	1.28	2.15
LWR (Plutonium Enriched)	-	.98	.72
Fast Breeder	-	-	.18
Solar	-	-	.18
Hydro, Geothermal, etc.	.36	.42	.49

The overall U.S. energy supply picture generated by PILOT under the conditions of the base case is one of increasing oil imports (13 quads in 1975 to 20 quads by 2010); rapidly decreasing natural gas production (after 1990) and oil production (after 2010); strongly increasing coal and nuclear electric production. These shifts in the supply mix are summarized below in terms of quads (10^{15} Btu):

U.S. ENERGY SUPPLY MIX (Base Case)

	1985		1995		2005	
	Quads	Percent	Quads	Percent	Quads	Percent
Oil*	39.4	(39.8)	45.6	(34.3)	50.5	(32.9)
Natural Gas*	24.1	(24.4)	26.4	(19.8)	19.9	(13.0)
Coal	23.4	(23.7)	31.4	(23.6)	38.2	(24.9)
Nuclear	7.7	(7.8)	23.3	(17.5)	31.4	(20.4)
Hydro, Geo., Solar	3.8	(3.8)	4.4	(3.3)	7.0	(4.6)
Other	.5	(.5)	2.0	(1.5)	6.5	(4.2)
TOTAL	98.9	(100%)	133.1	(100%)	153.5	(100%)

*Includes imports and some oil from shale after 1990.

The general conclusions are these:

- On the supply side, policies and techniques that can result in a high availability of primary energy can have an important effect on the future standard of living.
- On the demand side, successful implementation of conservation measures could significantly increase the standard of living for the same amount of energy made available to the general economy.

Using the Model as a Tool. The values assumed in the PILOT model for computing energy costs are displayed in the report so that the reader may compare them with those in the other studies. Their values may be changed by relatively simple user instructions. Moreover, alternative estimates of future finding of oil as a function of a level of exploration may be used instead to measure how sensitive the key economic indicators are to their values. The model may be used as a tool to experiment with specified temporal profiles of consumer fuel mix. Thus, it is possible to examine the effects of the interfuel substitution by consumers, especially in those scenarios that exhibit wide differences in the implicit prices of different fuels when compared to their traditional prices. One can examine the effects of reduced energy demand resulting from the lower use of energy or from the implementation of other efficiency measures by consumers and industry, either voluntarily or through legislative means.

Model Improvements Under Way. Most of the future model developments of PILOT seek to overcome certain limitations. The mid-1977 version, for example, lacks explicit modeling of the full range of substitution possibilities on the energy demand side that might come into use as a result of higher prices for energy. On the supply side, there is a need for more explicit detail with regard to coal, pollution abatement, modes of transportation, and regional considerations (such as the availability in certain regions of water for oil shale development or sunlight for solar power development).

A DESCRIPTION AND DEMONSTRATION OF THE STANFORD PILOT ENERGY/ECONOMIC MODEL

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

Section 1

DESCRIPTION OF THE MODEL

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 lifestyles, 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:

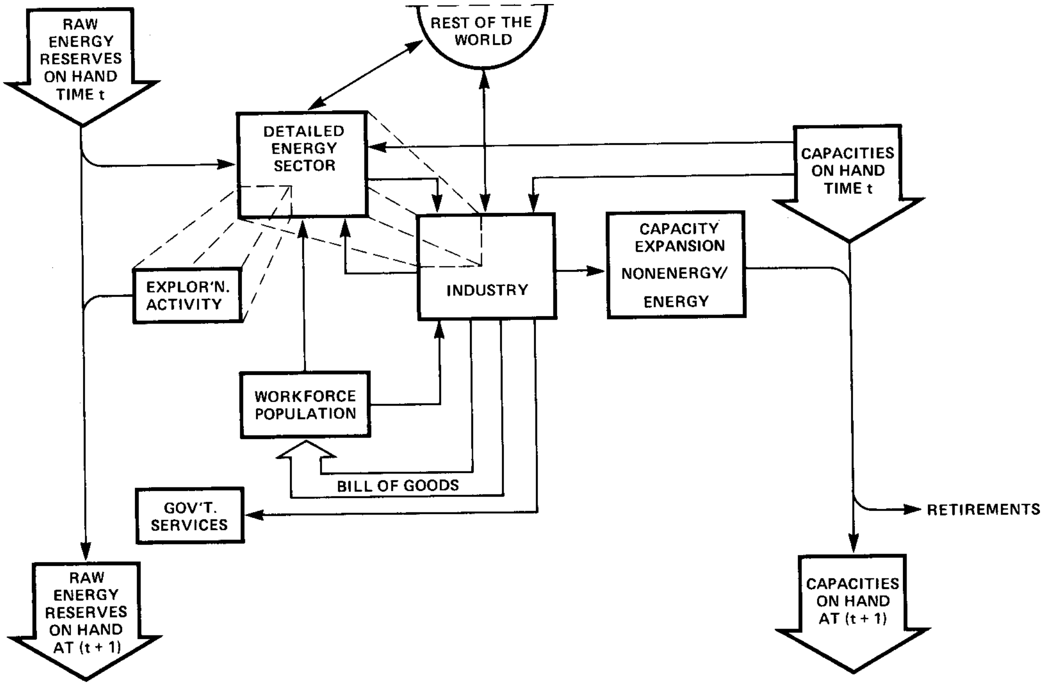


Figure 1. Main Linkages of the PILOT Model

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

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 and to deplete old 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 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.[†] In addition, we assume that consumption income in any time period is not less than that of the previous time period.

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 [Appendix H].

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 [4]. Because of our limited human and computational resources, we have had to aggregate this to 23 sectors for regular runs and 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 uses: 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 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 [5].

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.

[†] i.e., an interest rate of zero.

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

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 [4]. A provision has been made for later inclusion of a detailed capital matrix by sector of destination, developed by Battelle Institute, 1971 [5], 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 [6]. For the energy facilities we have adopted a convention used in Brookhaven studies [7], 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 [8,9].

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, 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 [10]. The workforce assumption is based on the estimates for 1975-1990 by the Bureau of Labor Statistics [11] 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 need 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 [12]. 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.

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

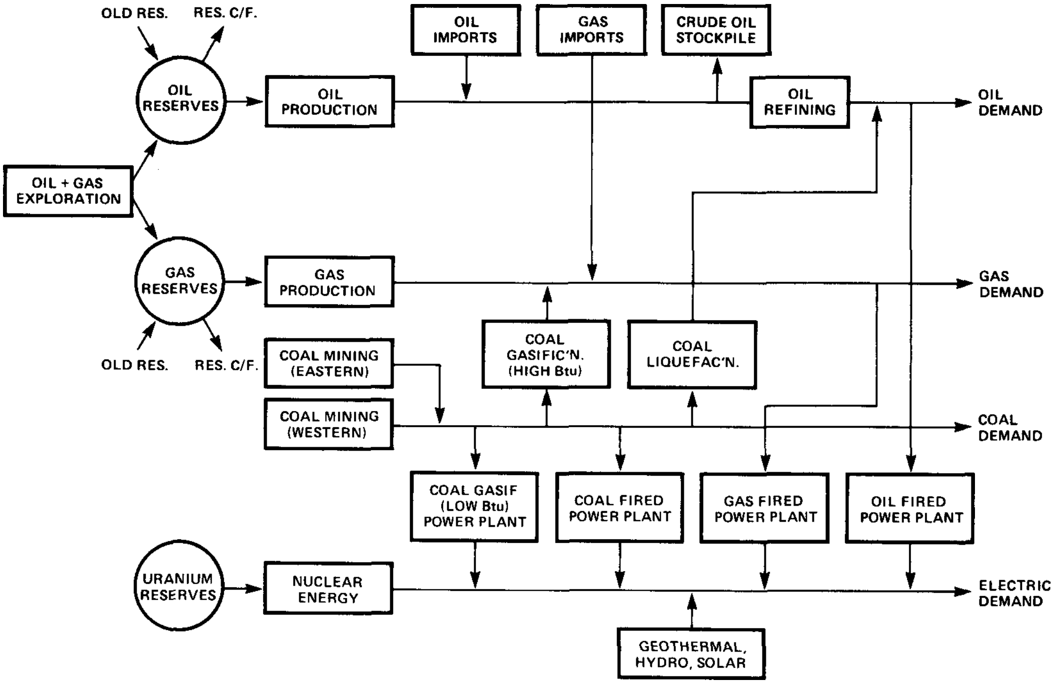


Figure 2. The Energy Sector of PILOT

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.

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 [13,14].

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 [14], and the U.S. Geological Survey Circular 725 of the U.S. Department of Interior [13]. 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.

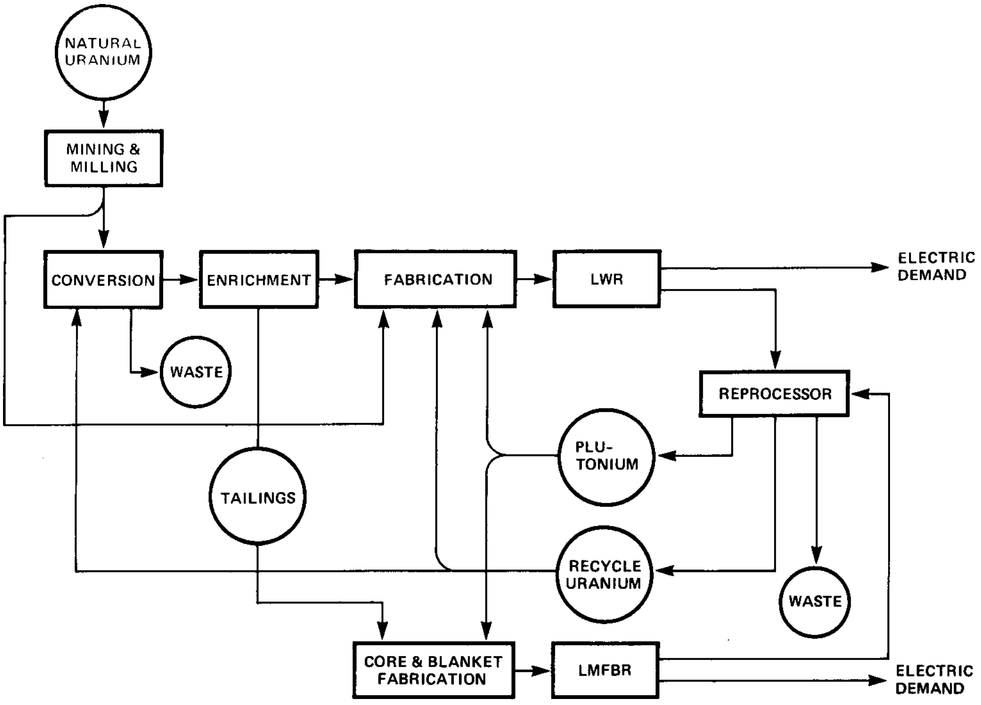


Figure 3. LWR and FBR Technology in the Energy Sector of PILOT

Exhaustible Uranium Resources. Limited reserves of uranium are known to be recoverable with relatively low physical effort. For example, 200 thousand tons of 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 [7]. 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 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.

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 may be taken advantage of at a later date to speed up the computations.

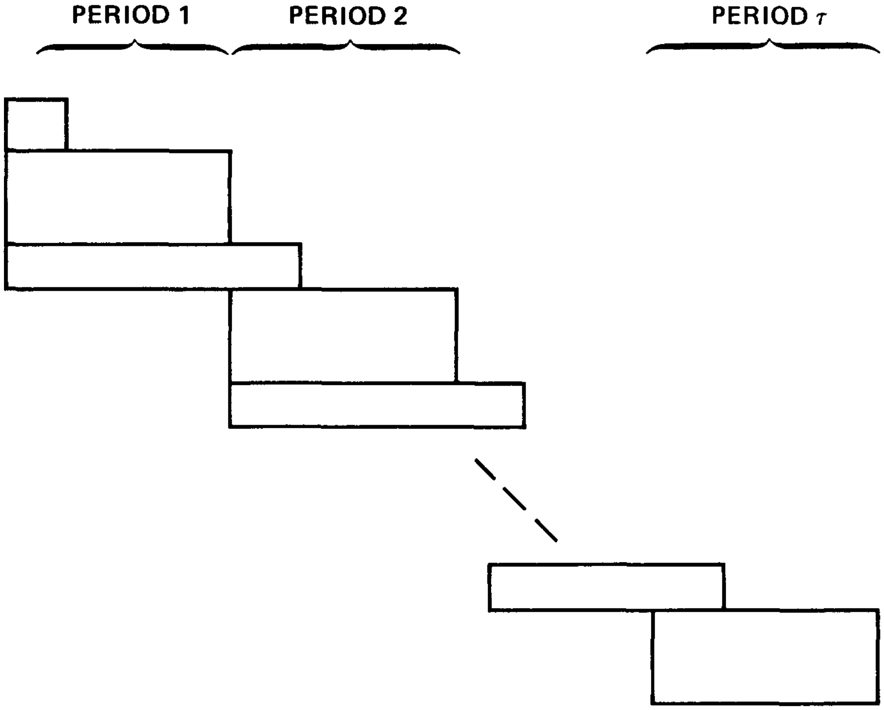


Figure 4. The Dynamic Staircase Structure of PILOT

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 Bruce Murtagh and Michael Saunders [15]. A detailed specification of the relations of the model can be found in [16].

Section 2

DEVELOPMENT WORK IN PROGRESS

SUMMARY OF MID-1977 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 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; and
- 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 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 [Appendix C].

An approach has been 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 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 [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 [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 [17].

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 [18].

Section 3

DEMONSTRATION SCENARIO RUNS ON PILOT

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 = 1000 quads) units[†] 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,[*] the country will need an additional 4Q units of primary energy.

This situation contrasts from the one for the seventies where about two-thirds of the primary energy demand is met by oil and gas (Figure 5). 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 as demand reductions through adjustment in lifestyles. In addition to demonstrating the nature of the output information from the PILOT model, the preliminary experiments reported in [16] 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?

[†] 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.

[*] According to U.S. Geological Survey [13], 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.

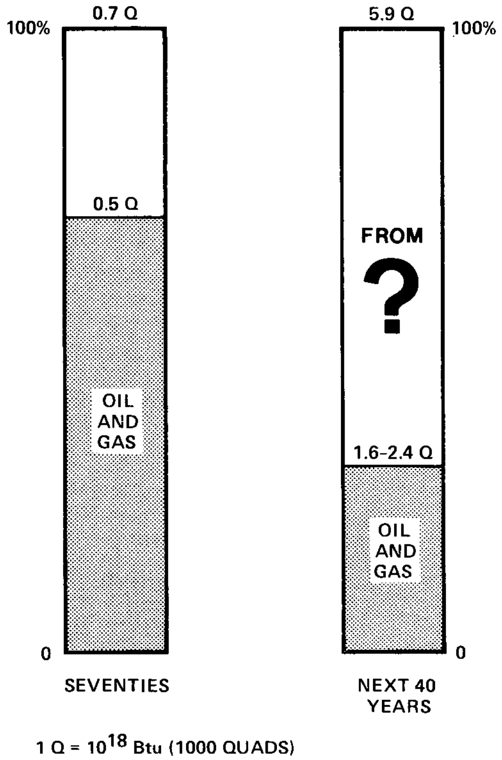


Figure 5. The Transition Problem of Energy Needs in the U. S.

THREE ILLUSTRATIVE SCENARIOS[†]

To illustrate the behavior and capabilities of PILOT, we have chosen three sets of input conditions or three scenarios. These include a base case, scenario S-B, and two variations--S-H, which assumes a higher availability, and S-L, which assumes a lower availability, of primary energy. The most important constraints are those imposed on coal production and those assumed concerning oil and gas resources and uranium costs.

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 part of the S-B and S-L scenarios presented.[*]

[†] Some material in this section is from [19].

[*] 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 earlier discussions of work in progress to overcome these deficiencies.

- 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.
- Availability of nonconventional alternative energy systems (AES) for nonelectric purposes is permitted after 1990. This is a catch-all 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 4.3 quads per year in 2010.
- The fast breeder reactor (FBR) will be available for commercial use by 2000.
- Assumptions about fossil fuel and uranium reserves, population growth, productivity, environmental needs, and government spending are included in PILOT.
- Scenario assumption: The total oil and gas discoverable in the U. S. is 20% higher in the S-H case and 20% lower in the S-L case than in the S-B case.

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. Some of 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. S-B case--overall limits are specified on coal development by years.
S-H case--higher limits that eventually are 50% higher than in the S-B case.
S-L case--overall limits are set at a lower level than in the S-B case, eventually 25% less.

Imports. Energy imports cannot exceed 15% of total energy consumption, to keep dependence on foreign sources moderate.

Nuclear Energy. S-B case--nuclear cannot exceed 50% of total electricity. S-H case--same limit but the cost of uranium ore is lower. S-L case--same limit but the cost of uranium ore is higher.

The set of exogenously specified conditions which characterize each scenario is given in Table 2.

Energy Costs in PILOT

The data base contains the "capital cost" estimate,† lifetime estimate, capacity factor, etc., of the various facilities. Operating costs assumed for energy product outputs are not given explicitly but can be inferred; these costs do not include taxes, scarcity rents, and profits. For the electric generating stations, the following capital cost values are those in the model for the scenarios of this report:

	\$/kWe (1975 \$)
Coal fired plant (ex scrubber)	450
Light water reactor	710
Fast breeder reactor	940
Solar thermal electric	2050

Each cost can be converted to unit capital cost using levelized capital recovery, a rate of interest, plant lifetime, and average capacity factor. Operating and maintenance costs can also be inferred from the data of the 1967 I/O table. The following costs underlie the present PILOT data base when various costs are aggregated using a 10% interest rate.

	(1975 \$)
Coal from eastern mines	\$ 0.39/MM Btu
Coal from western mines	0.33/MM Btu
High Btu gas from coal	1.94/MM Btu
Syncrude from oil shale	0.84/MM Btu
Syncrude from coal	1.93/MM Btu
Uranium	12.50/lb U_3O_8

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† In PILOT, associated with each unit of "capital cost" is a vector of physical goods required to build new capacity. If a facility has a capital cost c, this vector is multiplied by c to find the physical goods required to build the capacity.

Table 2

SCENARIO CONSTRAINTS AND ASSUMPTIONS

SUPPLY/PRODUCTION CONSTRAINTS

	All Scenarios
Maximum Rate of Growth of New Technologies after Initial Availability	40%/yr, first five years 30%/yr, second five years 20%/yr, third five years 10%/yr, thereafter

Year of Commercial Availability	Year
Fast Breeder Reactor	2000
Coal Liquefaction	1980
Low Btu Coal Gas	1980
High Btu Coal Gas	1980
Solar Power Complex	2000

Scenario Adjustment to Inferred Costs (1975 dollars) of PILOT Data Base	Cost/MM Btu
Oil Shale ($0.84/[Adjusted Capacity/Data Base Capacity])	$2.50
High Btu Coal Gas ($1.94/[Adjusted Capacity/Data Base Capacity])	$3.00

Limit on Nuclear Electricity: No more than 50% of total electricity.

	Year	Quads/Yr
Limit on Alternate Energy Sources (AES)	1985	0.12
	1990	1.00
	2000	3.73
	2010	10.00
Limit on Oil Shale Production	1995	0.5
	2000	2.0
	2010	4.3

Limit on Oil Fired Electric Plants: No new construction after 1975.

(continued)

Table 2
(continued)

SUPPLY/PRODUCTION CONSTRAINTS (continued)

		PILOT Scenario		
		S-B	S-H	S-L
	Year		Quads/Yr	
Limit on Coal Production	1975	15.8	15.8	15.8
	1980	19.5	21.4	17.7
	1985	23.4	28.0	19.6
	1990	27.5	35.4	21.4
	1995	31.4	42.9	23.3
	2000	35.0	50.0	25.0
	2005	38.2	56.2	26.6
	2010	40.8	61.3	28.1
	∞	50.0	75.0	37.5

RESOURCE LIMITS

	PILOT Scenario		
Uranium (million tons U_3O_8) Cumulative to:	S-B	S-H	S-L
	Million Tons U_3O_8		
\$15/lb U_3O_8	0.5	0.5	0.5
\$30/lb U_3O_8	1.8	2.5	1.1
\$100/lb U_3O_8	2.5	5.5	1.8
\$300/lb U_3O_8	10.0	20.0	3.5
\$1000/lb U_3O_8	99.0	99.0	99.0
Petroleum and Natural Gas			
40 year total quads available	2500	3000	2000

IMPORT/EXPORT CONSTRAINTS

Oil Import Price is \$13.50/bbl in 1975 and Rises at 2%/yr thereafter. (Prices in constant 1975 dollars.)

Oil and Gas Imports Combined are Limited to 15% of Total Energy Consumption.

ECONOMIC ASSUMPTIONS

For Objective Function Computation, Personal Consumption is Discounted at 5%/yr.

These values are given here so that the reader may compare with other sources. The PILOT Model itself does not generate such calculations.

Any of these values can be changed by relatively simple user instructions. In the scenarios for this report, for example, the inferred cost of high Btu gas from coal was adjusted to $3.00 per million Btu and that of syncrude from oil shale adjusted to $2.50 per million Btu (see Table 2). The cost of mined uranium also is adjusted according to the stepwise supply curves defined in Table 2.

Scenario S-B Results

The U.S. energy supply mix generated by PILOT under conditions of S-B is shown in Figure 6. The average annual rate for each five year period is plotted at the midpoint of the period. The U.S. energy supply by periods also is given in Table 3. Although a detailed discussion of the individual supply sectors is deferred, the overall supply picture may be described as one of declining indigenous oil and natural gas supplies, of increasing oil imports, of strongly increasing coal production,

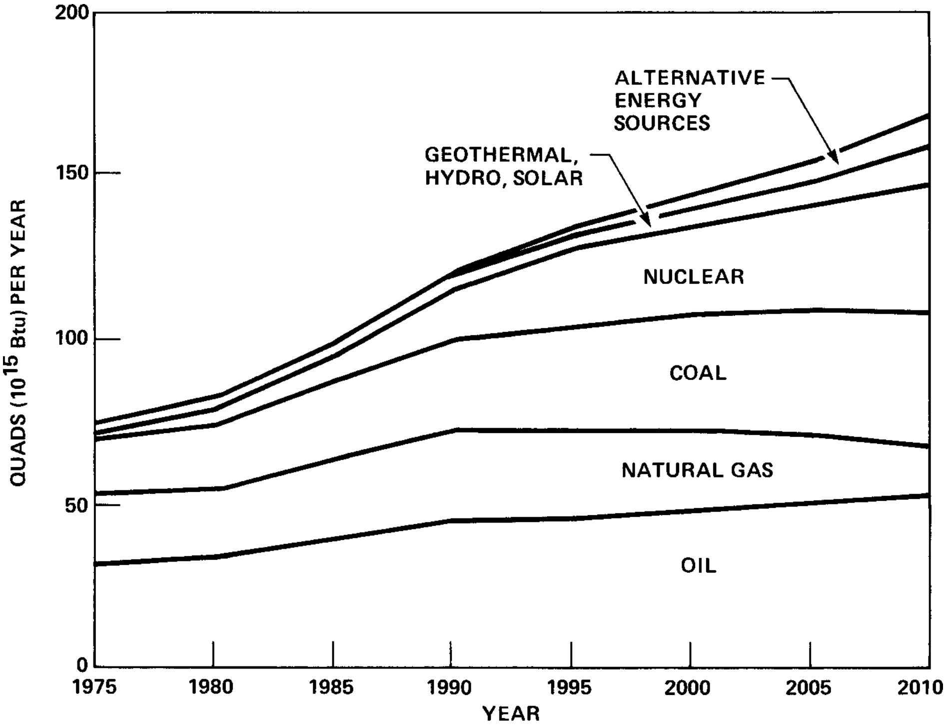

Figure 6. Sources of U. S. Energy Supply: PILOT Scenario S-B (Base Case)

Table 3

U.S. TOTAL ENERGY SUPPLY MIX
PILOT SCENARIO S-B (BASE CASE)

	QUADS PER YEAR							
SOURCE	1975	1980	1985	1990	1995	2000	2005	2010
Oil	31.7	33.9	39.4	44.6	45.6	48.3	50.5	52.8
Natural Gas	21.4	20.8	24.1	27.2	26.4	23.7	19.9	14.1
Coal	15.8	19.2	23.4	27.5	31.4	35.0	38.2	40.8
Nuclear	1.8	4.4	7.7	15.0	23.3	27.0	31.4	38.6
Geothermal Hydro Solar	2.9	3.3	3.8	4.1	4.4	5.1	7.0	12.5
Alternative Energy Sources	0.1	0.2	0.5	1.0	2.0	3.7	6.5	10.0
TOTAL	73.7	81.8	98.9	119.4	133.1	142.8	153.5	168.8

and of increasing nuclear electricity. Both coal and nuclear are produced up to the limits prescribed by the constraint sets (Table 2). Table 4 compares the S-B total energy consumption values with some projections by others published in the last few years.

Conservation

The S-B scenario is formulated in two variants, a conservation variant and a nonconservation one. The nonconservation variant assumes that effective conservation efforts are absent and, accordingly, energy inputs per unit output for all sectors are fixed throughout the 40 year span. The conservation variant assumes that appropriate measures by consumers and industry will gradually reduce the energy demands (per person in the private sector, and per unit output in the other sectors) by the following uniform percentages:

Year:	1975	1980	1985	1990	1995	2000	2005	2010
Percent Reduction in Energy Demands:	0%	0.7%	2%	3.7%	6.5%	10%	13%	15%

Table 4

A COMPARISON OF U.S. TOTAL ENERGY CONSUMPTION PROJECTIONS

	QUADS PER YEAR		
	1985	1990	2000
PILOT Scenario S-B (Base Case)	99	119	143
Ford Foundation Energy Policy Project (1974) [20]			
Historical Growth	116	†	187
Technical Fix	91	†	124
Zero Energy Growth	88	†	100
U.S. Department of Interior (1976) [21]	103.5	†	163.4
National Energy Outlook (FEA, 1976) [14]	98.9	†	†
EXXON (1977) [22]	102	119	†

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†Data not available.

Scenario S-L assumes the same conservation as in the conservation variant of S-B. S-H is a nonconservation scenario, in view of the high energy availability.

A comparison of the two variants of S-B shows that energy supply temporal profiles came out to be practically identical for the two variants, whereas, as expected, a significant difference is manifested in the growth rate of average per capita consumption. The comparison is given in Table 5. This comparison indicates that economic growth may significantly depend upon the economy's ability to conserve and substitute energy. The PILOT version used for these scenario runs does not allow interfuel capital, and labor substitution on the demand side. Therefore, a rather mild conservation level has been selected, so that the assumption that negligible capital and labor spendings are required to achieve it seems plausible.

Table 5

A COMPARISON OF U.S. TOTAL ENERGY CONSUMPTION AND AVERAGE PER CAPITA CONSUMPTION PROJECTIONS

PILOT SCENARIO S-B (BASE CASE)				
	NONCONSERVATION VARIANT		CONSERVATION VARIANT	
YEAR	TOTAL U.S. ENERGY SUPPLY (Quads/Yr)	AVERAGE PER CAPITA CONSUMPTION (1967 Dollars)	TOTAL U.S. ENERGY SUPPLY (Quads/Yr)	AVERAGE PER CAPITA CONSUMPTION (1967 Dollars)
1980	82	3002	82	3005
1985	99	3603	100	3768
1990	119	4269	122	4628
1995	133	4288	140	5155
2000	143	4288	145	5155
2005	153	4288	151	5155
2010	169	4288	164	5155

Figure 7 shows the sources of the U.S. electricity supply for scenario S-B. In year 2000, the total U.S. electricity production has reached 5×10^{12} kWh (5TkWh) per year which represents an average annual increase of over 4%.

A Comparison of the Three Scenarios

A summary comparison of the three scenarios is given in Tables 6 and 7 and Figure 8. The tables show the U.S. total energy and electricity supply for the year 2000. Figure 8 shows by period the per capita annual consumption before discount of goods and services in terms of constant 1967 dollars. The objective function in PILOT is to maximize the 40 year sum of these values, discounted or not as set by the user. In these scenarios the annual per capita consumption is discounted at 5% per year. The energy/economy interaction as seen by PILOT is fairly obvious. In scenario S-H, the final per capita consumption is 17% higher than in S-B; in scenario S-L, it is 28% lower. In scenario S-B, the standard of living rises an average of 1.7% per year.

Table 6

U.S. TOTAL ENERGY SUPPLY MIX
YEAR 2000

SOURCE	PILOT SCENARIO		
	S-B	S-H	S-L
	Quads		
Oil	48	58	40
Natural Gas	24	27	20
Coal	35	50	25
Nuclear	27	37	20
Geothermal Hydro Solar	5	5	5
Alternate Energy Sources	4	4	4
TOTAL	143	181	114

Table 7

U.S. TOTAL ELECTRICITY SUPPLY MIX
YEAR 2000

SOURCE	PILOT SCENARIO		
	S-B	S-H	S-L
	Terakilowatt-hours		
Geothermal Hydro	0.5	0.5	0.5
Coal	2.1	3.1	1.4
Oil	0.0	0.0	0.0
Gas	0.0	0.0	0.0
Nuclear	2.6	3.5	1.9
Solar	0.0	0.0	0.0
TOTAL	5.2	7.1	3.8

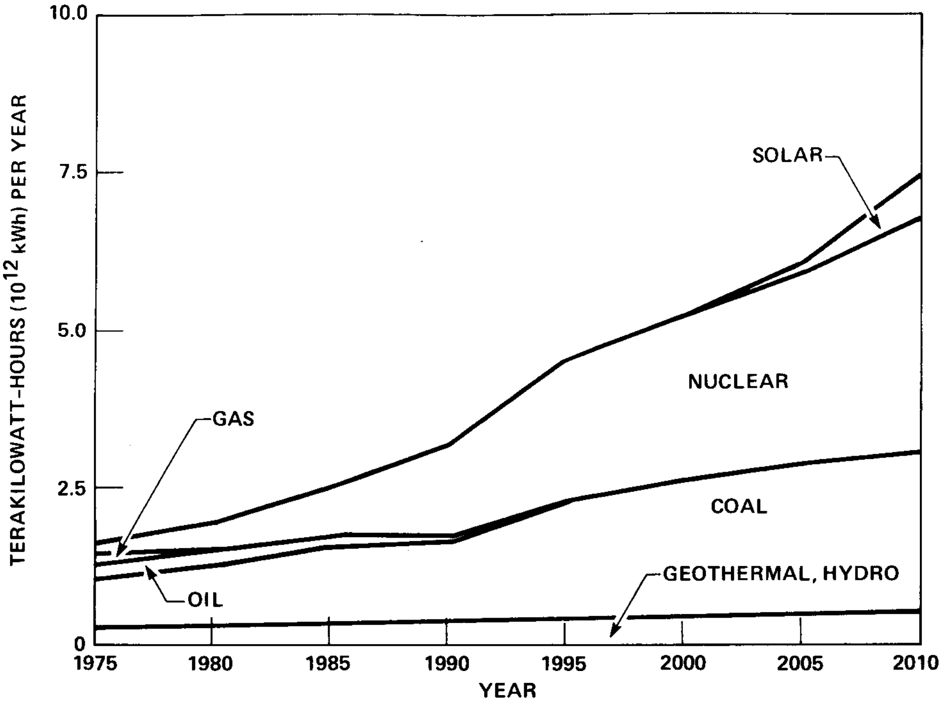

Figure 7. Sources of U. S. Electricity Supply: PILOT Scenario S-B (Base Case)

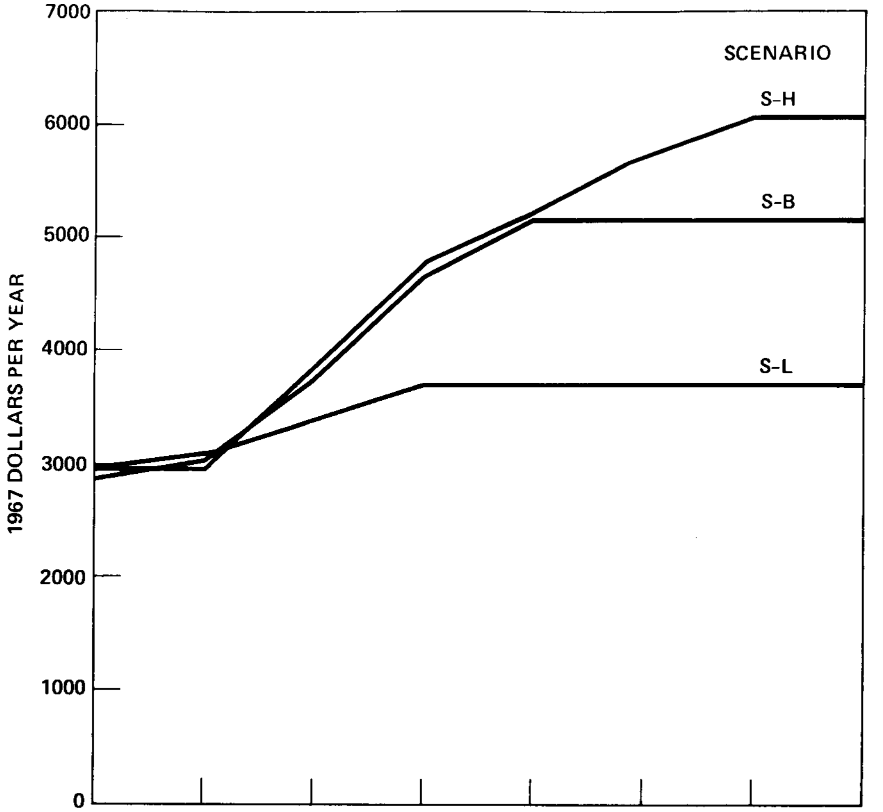

Figure 8. Comparison of U.S. Per Capita Consumption of Goods and Services Attained Under PILOT Base Case, High Availability and Low Availability of Primary Energy

One of the constraints used in PILOT is that the annual per capita consumption must not decrease. This constraint works counter to a positive discount which favors present consumption over future consumption. In these runs, the combination accounts for the absence of growth in the later periods and indicates that an even higher growth in earlier periods could have been achieved if the level in later periods were allowed to drop.

Oil Industry Activities: S-B

The U.S. oil supply is given in Figure 9. It is seen to increase throughout the 40 year span. The U.S. crude production, which includes natural gas liquids, is fairly level over this period, averaging around 10 million barrels per day. The indicated production from the Alaska North Slope is specified exogenously. The total quantity from that source is 16 billion barrels. The remainder of the U.S. production is modeled on the basis of decreasing marginal additions to reserves per foot of drilling, i.e., expenditure of physical effort. PILOT specifies the drilling effort in each time period. This activity adds to reserves an amount which depends on the position on the finding-rate curve. The annual production rate in any time period is limited to 1/12 of the proven reserve at the beginning of that time period. The option to produce oil by more expensive enhanced-recovery techniques also is provided. These become economic, as additions to reserves become progressively more expensive. The drilling activity and reserve status are given in Figure 10. The proven reserves shown represent a reserve-to-production ratio around 8.3 years because annual oil production in PILOT is not to exceed 1/12 of reserves.

In scenario S-B, some 89% of the total recoverable oil is extracted by the end of the 2010 time period. It is interesting that this production is so evenly distributed up to 2010 since it must necessarily decline rapidly after that time. This intertemporal distribution does not follow the pattern proposed by M. King Hubbert. In spite of declining crude oil production, the total oil supply is increased somewhat by the introduction of oil from shale (one million barrels per day in 2000), but mostly by steadily increasing imports. These reach 8.8 million barrels per day in 2000.

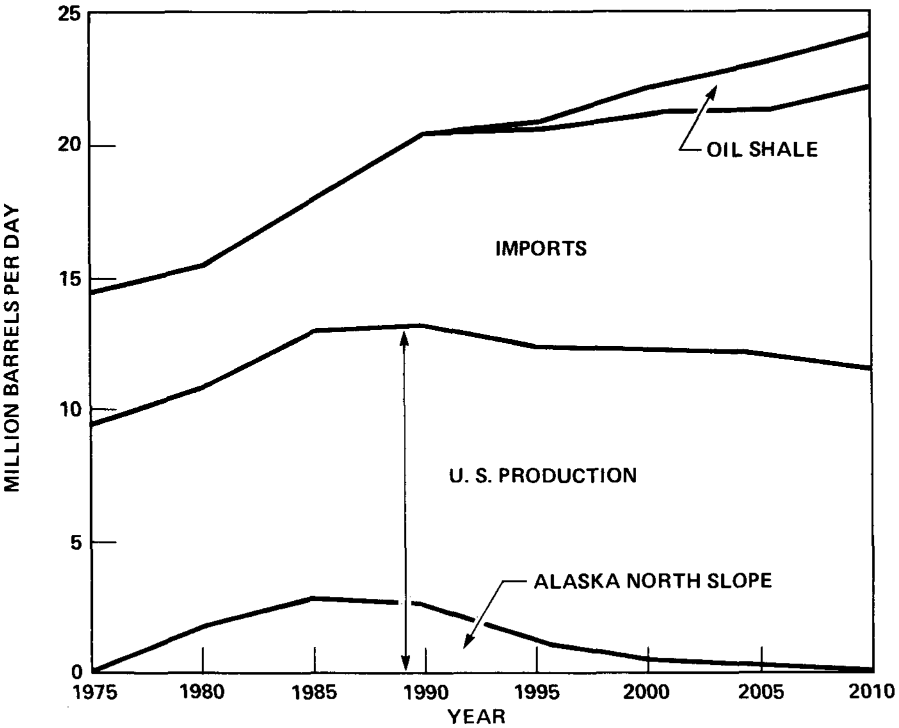

Figure 9. Sources of U. S. Oil Supply: PILOT Scenario S-B (Base Case)

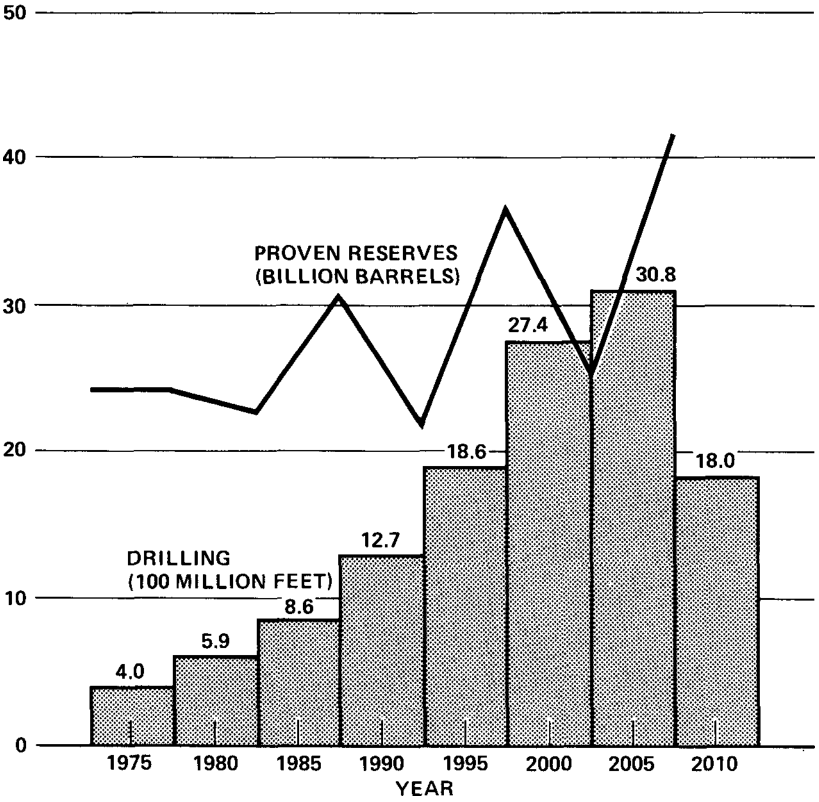

Figure 10. U. S. Crude Oil Production: PILOT Scenario S-B (Base Case)

It must be stressed that this scenario is no indication of the wisdom of such an import policy, nor of its feasibility. It simply says that if oil is available on the world market at a price of $13.50 (1975 dollars) per barrel in 1975 and increases at a real rate of 2% per year ($27 per barrel, or $330 per million Btu in 2010), then it is advantageous to import it in the amount shown. In S-B, the import constraint of 15% of total energy consumption is active.

Natural Gas Production Activities: S-B

The U.S. gas supply is given in Figure 11. It consists of domestic production, imports, and high Btu gas for coal (SNG). The imports are constrained to 2 quads/ yr (2 TCF/yr). If this gas all came in as LNG, a fleet of some 40 refrigerated tankers (3 billion scf capacity each) each making 17 trips per year would be required. No provision is made in PILOT for building this fleet in the U. S. Its capital formation is included in the import price which results in exports to balance the imports. The SNG production is seen (Figure 11) to rise 1.4 quads/yr in the 1990 time period and then drop to zero by 2000. This result is discussed in the section on general observations.

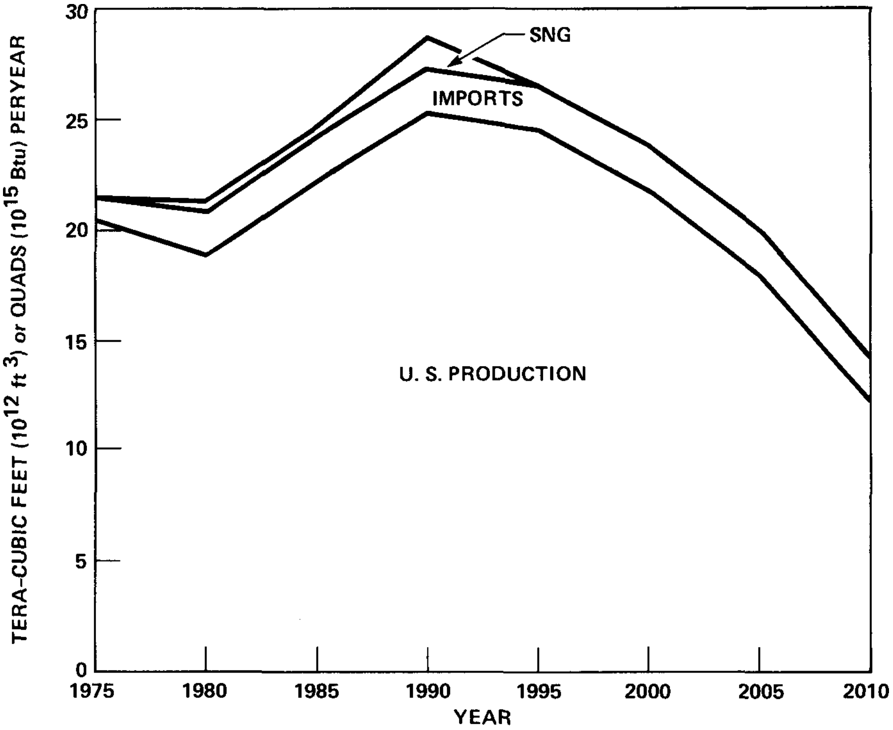

Figure 11. Sources of U. S. Gas Supply: PILOT Scenario S-B (Base Case)

The algorithm in PILOT for natural gas exploration and production is similar to that for crude petroleum with a few exceptions (e.g., no secondary or tertiary recovery). The results of natural gas production activity are presented in Figure 12. As with crude oil, the reserve-to-production ratio is constrained to be about 8.3 years. At the end of the 40 years, some 91% of recoverable gas has been extracted.

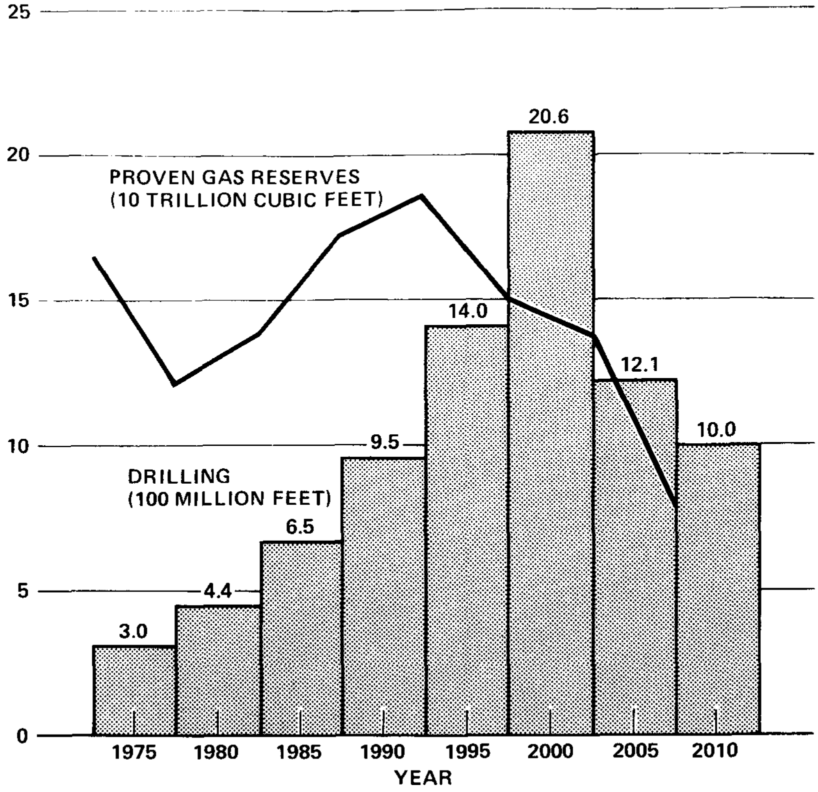

Figure 12. U. S. Natural Gas Production: PILOT Scenario S-B (Base Case)

Coal Production: S-B

As previously discussed (see Table 2), the energy obtainable from coal in the scenarios has an exogenously specified series of upper bounds. These constraints are active almost from the beginning of the scenario. In millions of tons per year, the following are the production rates in scenario S-B:

Year	MM Tons/Yr
1975	655
1980	848
1985	1051
1990	1258
1995	1459
2000	1592
2005	1707
2010	1707

This coal is a mix of eastern (25.8 million Btu/ton) and western (16 million Btu/ton) U.S. production. The cumulative 40 year production called for is 51 billion tons. This large increase in coal production could give rise to many well recognized physical and institutional problems. These include problems of transportation, water availability, environmental degradation, etc. At the present time, none of these is represented explicitly in PILOT although work is under way to include them (see Appendix C).

Figure 13 shows the schedule of mine construction starts required in this scenario. A lag of three years between construction start and production start is modeled by deferring the addition of the mine capacity to the national capacity until the time period following the construction start. The actual capacity in any time period is equal to the production figures listed above since there is no unused coal mine capacity in this scenario. Also shown in Figure 13 is the cumulative coal reserve commitment represented by the mine openings. Coal mines are assumed to operate for 20 years at their nominal capacity. The reserve commitment is simply 20 times the capacity. No allowance is made for improvements in recovery efficiency.

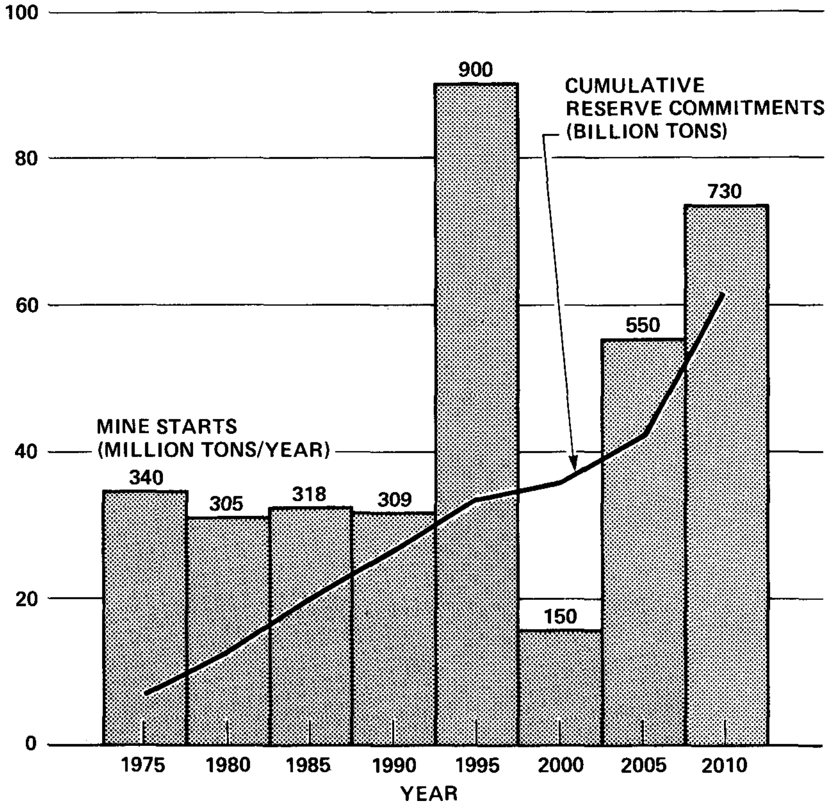

Figure 13. Coal Mine Construction: PILOT Scenario S-B (Base Case)

The Nuclear Industry: S-B

In this scenario, nuclear energy plays an important role in electrical generation. Nuclear electricity is constrained not to exceed 50% of total electrical generation. In the PILOT data base nuclear electricity is competitive with coal electricity, but coal has several uses whereas uranium can only produce electricity. Consequently, nuclear electricity is produced up to the 50% limit (see Figure 7). The nuclear electric plant installation schedule is shown in Figure 14. The LWR installations rise to a peak of 635 MWe (577 1100-MWe reference plants) in the 2005 time period. A small number of fast breeder reactors is introduced in the 2000 time period. The nuclear power activity described in PILOT includes spent fuel reprocessing and recycle of uranium and plutonium. PILOT is not required to reprocess spent fuel but in this case it finds it economic to do so. As a result, a number of the LWRs which are built operate on recycled plutonium.

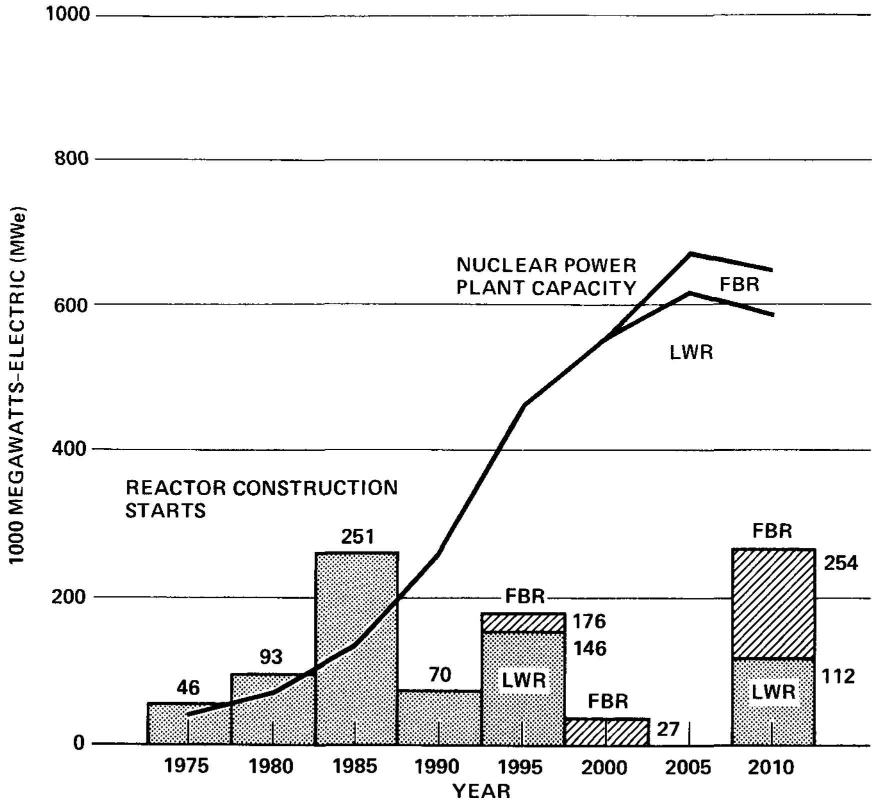

Figure 14. Nuclear Electric Plant Schedule: PILOT Scenario S-B (Base Case)

One of the differences in the three scenarios is the different uranium supply curves (Table 2). The PILOT results in terms of uranium consumption in each scenario are shown in Figure 15. In scenario S-B, about 2 million tons of U_3O_8 is consumed by the end of period 2010. The quantities in S-H and S-L are higher and lower, respectively. In each case, the level of production reaches the $100/lb U_3O_8 ore by 2000 or shortly thereafter. In order to look at longer term implications for uranium resource consumption, the 100 year variable time period version of PILOT was run. The uranium consumption profile in the first 40 years followed the curves of Figure 15 very closely. Natural uranium consumption is indicated to drop to a zero rate about 2040. The breeder is then supplying all of the nuclear electricity. The cumulative uranium consumption in scenario S-B reached 4.4 million tons of U_3O_8.

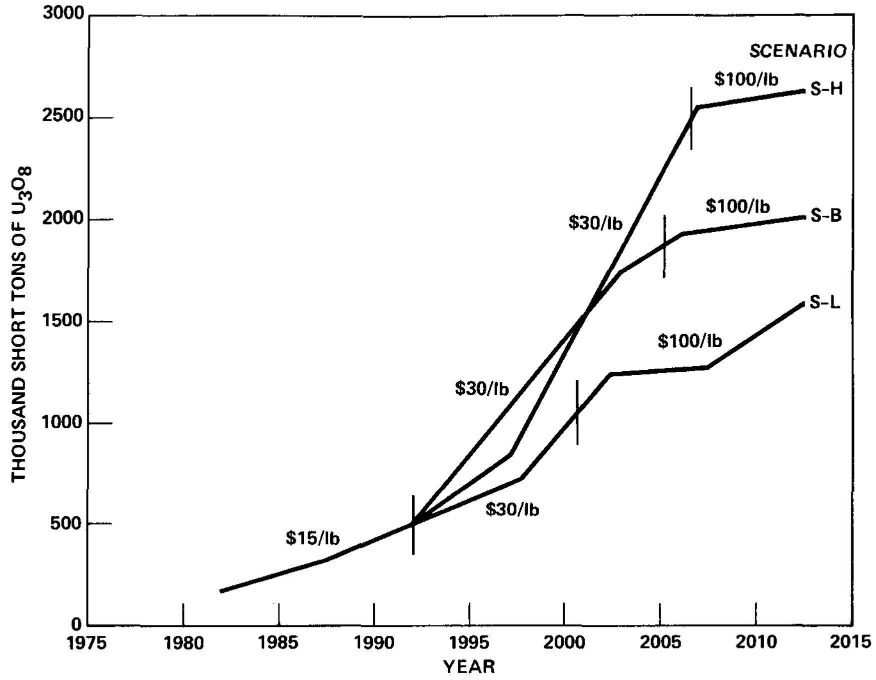

Figure 15. Comparison of Natural Uranium (U_3O_8) Consumption Under PILOT Base Case, High Availability and Low Availability of Primary Energy

Uranium enrichment requirements are shown in Figure 16. Construction of 29 million kilograms per year separative work units (SWU) capacity is called for. For comparison, the U. S. has at present about 17 million kg SWU/year capacity and is increasing the capacity of the present plants. PILOT does not take into account any foreign commitments for separative work. The enrichment technology is the gaseous diffusion process. In the S-B scenario, there is a sharp decline in enrichment in the 2010 period. This occurs because PILOT adopts a strategy of building up a large inventory of enrichment uranium and then uses it in the last two time periods.

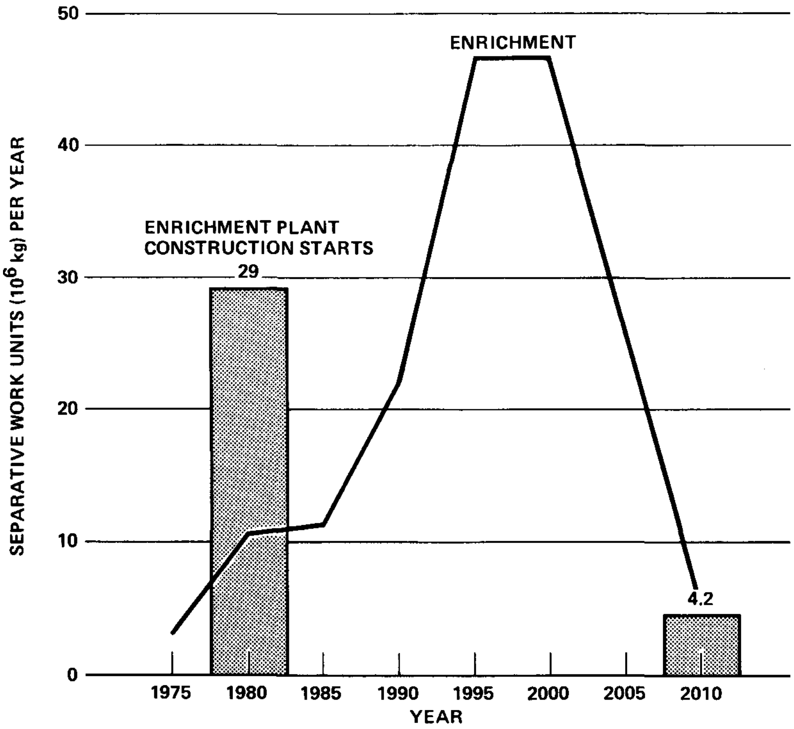

Figure 16. Uranium Enrichment Activity: PILOT Scenario S-B (Base Case)

PILOT closes the fuel cycle by constructing reprocessing plants which operate for the first time in the 1990 time period (Figure 17). The reprocessing capacity shown is sufficient to process all the spent fuel produced over the 40 year span, i.e., the closing spent fuel inventory is zero. Likewise, the separated plutonium produced is all used either in LWRs or the fast breeder reactors which are just getting under way at the end of the scenario. The large construction of reprocessing plants in the last time period is an endogenous result of the 100 year variable time period version of PILOT, which is run for the purpose of establishing some end conditions for the 40 year span.

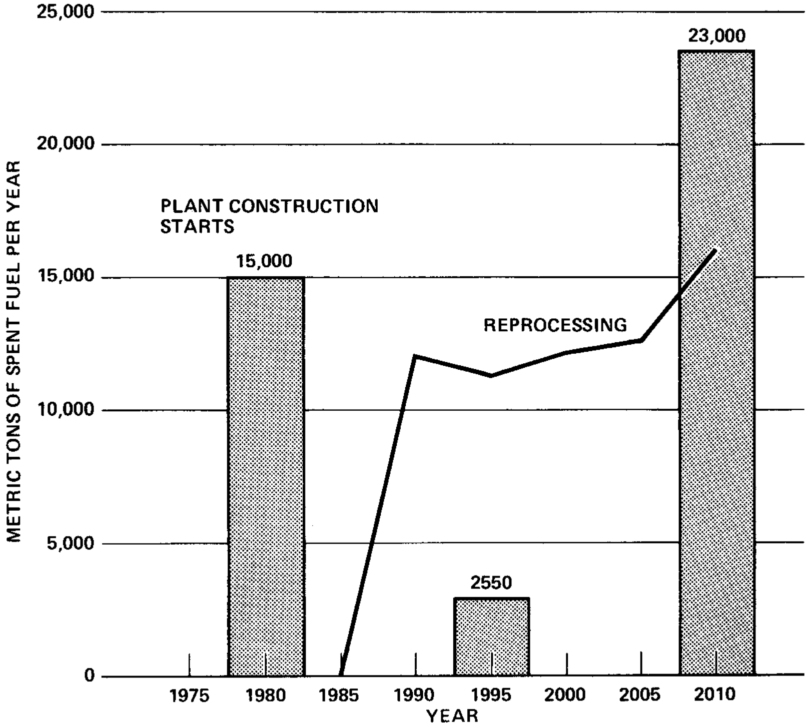

Figure 17. Nuclear Fuel Reprocessing: PILOT Scenario S-B (Base Case)

Some General Observations

The description of the various scenarios affords a good opportunity to display the capabilities of PILOT and the kinds of policy guidance which it offers. It is true that such scenarios often tell us more about the model than they do about the future. The present case is no exception. It is clear, for example, that PILOT must have a better description of coal production. Work is under way to evaluate the rising real cost of coal production, considering such mining variables as seam thickness, seam depth, etc., as well as transportation, water availability, and environmental protection costs. There is no doubt that the cumulative production of 48 billion tons in scenario S-B will cause real increases in all of these component costs.

A word should be said about the end-effect problem and the way it has been handled in PILOT. The end-effect problem refers to the fact that PILOT does not "see" beyond its time horizon and therefore does not "worry" about the state of the world beyond that time. In particular, it has no reason to invest capital in projects whose benefits will only be obtained beyond its time horizon. We have attempted to correct this problem by first solving a PILOT scenario with a 100 year time horizon (using an aggregation of several time periods to reduce computation) and then using the results to establish capital formation at the end of 40 years for the runs reported here.

It is clear that in these demonstration runs not every result meets a test of reasonableness. The limited introduction and then rapid retirement of SNG plants (Figure 11) is a case in point. Faced with the given set of constraints and a high demand for electricity, PILOT decides that coal can better be used under boilers than converted to gas. Likewise, PILOT's construction of large numbers of a given kind of facility (e.g., uranium enrichment plants) in a single five year period with none built in the adjacent time periods is not reasonable scheduling in the real world. In the use of PILOT for policy analysis, it is necessary for the analyst to exercise his judgment and to "smooth" some of these "bumps" by hand. Usually this can be done without destroying the logic and consistency of the information and the insights which the model has to offer. However, if there are doubts about the results obtained in this manner, the model always can be rerun with additional conditions.

The problem of achieving consistency at a useful level of detail has been and continues to be nontrivial and challenging. In the course of running various versions of the model, we have been able to test various parts by comparing our results with those obtained from other models built for other purposes using different approaches. Such comparisons are essential and mutually beneficial; they are perhaps the only guarantee that we have that no gross errors were made in the assembly of the model. We believe the initial version of PILOT has met these tests.

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