Systems
Optimization
Laboratory

[redacted]

a
PILOT
publication

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

Department of Operations Research
Stanford University
Stanford, CA 94305

SYSTEMS OPTIMIZATION LABORATORY
DEPARTMENT OF OPERATIONS RESEARCH
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305-4022

USING THE PILOT MODEL TO STUDY THE EFFECTS OF TECHNOLOGICAL CHANGE

by
John C. Stone, Patrick H. McAllister and George B. Dantzig

TECHNICAL REPORT SOL 86-16

November 1986

This report will appear in **Strategic Planning in Energy and Natural Resources**, Proceedings of the 2nd Symposium on Analytic Techniques for Energy, Natural Resouces and Environmental Planning (B. Lev, J. Bloom, A. Gleit, F.Murphy, and C. Shoemaker, eds.), April 1986.

Research and reproduction of this report were partially supported by Electric Power Research Institute Contract RP 5006-01; the Center for Economic Policy Research at Stanford University; U.S. Department of Energy Contract DE-AA03-76SF000326, PA# DE-AS-03-76ER72018; National Science Foundation Grants DMS-8420623, ECS-8312142; and Office of Naval Research Contract N00014-85-K-0343.

USING THE PILOT MODEL TO STUDY THE EFFECTS OF TECHNOLOGICAL CHANGE

John C. Stone, Patrick H. McAllister and George B. Dantzig

Systems Optimization Laboratory, Department of Operations Research,
Stanford University, Stanford, California, 94305-4022, USA

PILOT is a large-scale dynamic model of the U.S. economy which synthesizes structural representations of all sectors of the economy in a general equilibrium context. PILOT's process-oriented representation of production synthesizes engineering-type data (or judgments) about sector-specific technological alternatives into a consistent overall picture of the long-run consequences of technological change and of government policy and foreign market conditions in the context of technological change. Ongoing studies focus on the effects of a "high-tech" (vs. a "low-tech") economy on aggregate and sectoral patterns of growth, employment, and energy use over the next 25 years.

1. INTRODUCTION

People making decisions in both the private sector and government are faced with many issues in which the long-run consequences of today's actions are the paramount consideration. In choosing among investment alternatives, research and development strategies, tax policies, energy policies, and in other areas, the consequences of actions taken now will not be fully known for many years. A dynamic long-term model of the economy can be a valuable tool in making these decisions, giving the decision-makers a way to generate internally consistent hypothetical scenarios of future events, to evaluate the effects of their actions under those hypotheses, and to choose among alternatives on the basis of measurable criteria. In order to be useful in such a context, a model must satisfy a stringent set of conditions. It must be a comprehensive representation of the major forces which will affect the development of the economy over the relevant time horizon, including technological innovation, changing consumer tastes, competition from other countries, and rising energy and natural resource prices. It must be able to represent a wide variety of possible futures, as determined by variations in government policies, world market conditions, and technological opportunities. Model scenarios must be consistent with reasonable beliefs about the behavior of economic agents. Finally, the model must admit to solution using current computation technology.

Consideration of these conditions has significantly influenced the current structure of the PILOT economic model (developed and maintained by the Systems Optimization Laboratory, Department of Operations Research, Stanford University). PILOT is a large-scale dynamic model of the U.S. economy which combines structural representations of all sectors of the economy in the context of a general equilibrium; that is, the model simulates economic interactions among sectors by determining market-clearing prices and quantities for all commodities over time. By conforming to this rigorous theoretical paradigm, PILOT implicitly embodies two central assumptions about economic behavior: all markets are perfectly competitive and firms behave so as to maximize the net present value of profits. Furthermore, we have simplified the general equilibrium framework by assuming that there is no uncertainty; all agents have perfect foresight. PILOT is thus a physical flow model which admits no role for financial instruments, including money. These characteristics have particular implications for the strengths and weaknesses of the model as a tool for technology assessment and scenario analysis.

While no one contends that the economy actually behaves in strict accordance with the above theoretical principles, it is widely accepted that the general equilibrium paradigm is the most plausible representation of the state of the economy in the absence of detailed information on the decision rules followed by individual agents. Such information is, of course, not available beyond the very immediate future. We accordingly believe that general equilibrium is a powerful and defensible modeling paradigm for analyzing long-run economic trends, particularly when addressing such significant structural changes in the economy that modifying a model without a rigorous and natural structure would be difficult at best. In addition to this theoretical plausibility, utilization of a general equilibrium formulation is supported by the substantial experience which has been gained in formulating economic equilibrium problems and computing solutions to them.

We do not consider PILOT to be a forecasting model in the sense in which this term is frequently misused. PILOT results, like those of any model, can be viewed as forecasts conditional upon the whole array of behavioral and technological assumptions inherent in model structure and parameterization. This conditioning is all too frequently overlooked or misunderstood in discussions and comparisons of model results. There are two reasons in particular why we do not deem it appropriate to view PILOT results as point forecasts. First, a given model scenario requires numerous exogenous assumptions about highly uncertain real-world magnitudes, such as world oil prices, rates of disembodied technological change, and import/export market conditions. This inherent uncertainty in model inputs is naturally inherited by model results, which cannot then be interpreted as unconditional forecasts. The proper mode of analysis is to assess the sensitivity of model results to important and uncertain input assumptions, and thereby ascertain whether particular results appear to be robust across various alternative futures.

Second, PILOT is not designed to model the short-term issues of the transition from a benchmark state to a long-term trajectory, but rather to capture the major economic and technological forces that determine the long-term trajectory. Because of departures in the real world from such paradigms as perfect competition and perfect look-ahead, we cannot expect the economy to behave as smoothly or efficiently through a transition as does a model like PILOT. So, again, a point forecast interpretation is inappropriate. What we can expect, however, is that the combination in PILOT of rigorous model structure and credible input data helps to ensure that differences across model scenarios are truly reflective of basic economic movements. That is, the model can be reliably and valuably used to obtain consistent comparative analyses of alternative long-run trajectories based on systematic alterations of key input assumptions.

PILOT's process-oriented representation of production allows the user to synthesize engineering-type data (or judgments) about sector-specific technological alternatives into a modeling structure which provides a coherent overall picture of the long-run consequences of technological change and of government policy and foreign market conditions (e.g., world oil price) in the context of technological change. In any model solution, productive investments select the most profitable technological alternatives over time, and, accordingly, the model can be used to assess the effects of different time paths of availability and/or technical characteristics of contemplated new technologies, with energy technologies being a special case. With respect to policy analysis, PILOT is best suited to addressing direct controls (such as import quotas or fuel use restrictions) and relatively simple output-based taxation (for example, import duties). Its ability to directly represent more complicated taxation schemes is limited, although these can sometimes be represented adequately by indirect means. The model is not designed to study very sector-specific or region-specific issues, but rather to synthesize the results of microeconomic analyses of such issues, arising from more detailed and narrowly focused models.

Current studies seek to utilize the unique capabilities of PILOT to study the effects of a "high-tech" (vs. a "low-tech") economy on aggregate and sectoral patterns of growth, employment, and energy use over the next 20-25 years. With respect to energy use in particular, while we may reasonably expect the direct effects of high technology to be somewhat energy-saving (though perhaps more electricity intensive), the indirect effects of higher economic growth, different import-export patterns, and different rates of growth in the various economic sectors are likely to be more important. An integrated, technologyoriented model such as PILOT can be profitably employed to evaluate the net energy effects of the whole array of economic forces at work. A broadly focused study of alternative energy/economic futures can provide a valuable perspective on general trends and magnitudes which would not be available from a more issue-specific analysis.

2. AN OVERVIEW OF PILOT

Since the model's beginnings in 1975, PILOT has been continually enhanced and expanded in accordance with the changing interests of model developers and sponsors. Three significant previous stages in model development (corresponding to 1977, 1980, and 1983) have been documented in [1], [2], and [3], respectively. The 1986 version of PILOT has not yet been documented and is briefly described in this section.

PILOT-1977 was based upon a 23-sector input/output model derived from the 1967 Department of Commerce table. (There was also a 12-sector aggregated version.) The model included some activity analysis detail corresponding to energy resource supplies and electricity generation, but little flexibility in the final demand for energy. Aggregate consumer demand was modeled as a linear function of consumption income, and the discounted sum of the stream of consumption income values was employed as an objective function.

PILOT-1980 incorporated the aggregated 12-sector input/output model from PILOT-1977. A reasonably detailed activity analysis representation was incorporated for oil, gas, coal, oil shale and uranium supplies, electricity generation, coal gasification/liquefaction, and petroleum refining. Considerable flexibility was also extended to energy demands through the addition of activity analysis models for energy end-use services (e.g., steam and space heat) in the residential and industrial sectors. Final consumer demand was endogenized in the form of an aggregate utility function. (A utility function is a mathematical construct used to represent a consumer's preferences among different commodities in terms of a single measure.) The specified function apportioned consumption between energy and nonenergy commodity aggregates in accordance with a so-called shifted constant elasticity of substitution functional form.

PILOT-1983 employed a new 23-sector aggregation scheme based on a 1976 table supplied by INFORUM (as updated from the 1972 Department of Commerce table). Model structure for nonenergy sectors and commodities advanced beyond traditional fixed-coefficient input/output analysis by defining multiple columns for each sector representing alternative production technologies for new investments. The model of industrial energy services was revised and enhanced to accompany the new input/output structure. A new model of energy end-use in commercial buildings was added. The mathematical structure of the energy resources supply model was revised. Modeling of consumer demand was generalized by incorporating a quadratic utility function (with diagonal Hessian) for 5 aggregate commodities and exogenous time trends for per capita consumption of 3 other commodity aggregates.

PILOT-1986 is an important step forward. While maintaining the energy detail inherited from previous model versions, the model significantly advances the efforts of PILOT-1983 in better representing technological change and final consumer demand. The 1986 model incorporates data from the 1977 Department of Commerce input/output table, which was released in 1984. The sectoral aggregation scheme has been expanded to 40 sectors, including 23 manufacturing sectors and 9 service sectors, selected with particular attention to isolating those industries which are likely to be most heavily affected by technological innovation relating to electronics and automation. (See Table 1.) Each of these sectors is modeled via multiple input/output columns which represent changing production alternatives over time. The productive capital stock is vintaged and unmalleable once in place. Domestic industries compete with imports (whose prices are given exogenously) and face a downward-sloping export demand schedule (also exogenous). The exchange rate is determined endogenously. Final demand is represented via a government input/output sector, endogenous investment activity in all sectors, and consumer demand for 13 aggregate commodities. Per capita demand for 5 of these consumption aggregates is specified exogenously. Demand for the other 8 is a function of prices and income, modeled via an aggregate quadratic utility function with non-diagonal Hessian (see Section 3.1).

The energy-producing sectors of the economy as well as energy-use decisions in manufacturing and in residential and commercial buildings are represented via modular process models. The results and assumptions of more detailed energy models are frequently used to adjust model calibration and to apply appropriate constraints so as to obtain energy results consistent with those of the more detailed models.

PILOT-1986 directly represents economic activities and relations in each of nine periods of five years in length, covering the time horizon 1975-2015. Consistent with the assumption of perfect look-ahead, the model is solved for all time periods simultaneously.

2.1. Aggregate input/output sectors

The 40 aggregate economic sectors in PILOT are defined in Table 1. Four of these aggregate sectors correspond to primary energy production and conversion, and have an expanded activity analysis representation (briefly described below). The remaining nonenergy sectors are represented by import and export activities and by one or more production activities, each of which is modeled by input/output relations defining the flows of goods and services into and out of that sector per unit of activity. An important enhancement over conventional input/output modeling is the incorporation of multiple columns for each sector, representing alternative technologies which could be adopted in the future. Many fundamental changes in the structure of the economy can be meaningfully represented as changes in the input/output relations of one or more economic sectors. Structural changes which can be represented in this manner include the overall improvement in factor productivity which results from technological innovation and price-driven substitution among inputs to production.

A given alternative technique is represented in PILOT via a particular input/output activity, with a preoperation investment requirement and a time stream of output and operating inputs (labor, energy services, commercial building services, and commodities from other sectors). The model embodies a "putty-clay" formulation: once a unit of capacity using a certain technique has been installed, that unit of capacity is restricted to using the chosen technique until it is retired. At equilibrium, a process alternative is utilized only if, at model-determined prices, the net present value of investment and the time stream of inputs and outputs is zero.

Process alternatives in the model may have quite different motivations and effects. Some are primarily related to energy conservation, including use of more efficient electric motors, more heat recovery or insulation, and Alcoa process aluminum production. Others are primarily labor-saving innovations, most notably factory and office automation. Still others, such as Rapson process papermaking, steel minimills, or continuous casting of metals, represent application-specific alternative processing chains, with pervasive effects on losses, productivity, and energy use.

The available alternatives for a given sector may change over time, reflecting technological change, but in most sectors a choice of two or three alternatives is available for new investments in each time period from 1985 onward. We believe that endogenously determined combinations of the alternative input/output columns reasonably span the alternative structures the U.S. economy might assume over the next 20-25 years.

Table 1
ECONOMIC SECTORS OF THE PILOT MODEL

	PILOT SECTORS	BEA SECTORS
1.	agriculture	1-4
2.	mining	5,6,9,10
3.	construction	11,12
4.	food and tobacco products	14,15
5.	textiles, apparel, and leather	16-19,33,34
6.	lumber and wood containers	20,21
7.	paper and allied products	24,25
8.	printing and publishing	26
9.	chemicals and paints	27,30
10.	plastics and synthetic materials	28
11.	drugs, cleaning and toilet preparations	29
12.	rubber and plastic products	32
13.	stone, clay, and glass products	35,36
14.	primary iron and steel	37
15.	primary non-ferrous metals	38
16.	metal products	39-42
17.	heavy machinery	43-46, 61
18.	precision machinery	47,50,62,63
19.	industrial machinery	48,49,53
20.	electrical appliances	52,54
21.	computers and office equipment	51
22.	radio, TV, and communications equipment	56
23.	electronic components	57
24.	motor vehicles and equipment	59
25.	aircraft and parts	60
26.	miscellaneous manufacturing	13,22,23,55,58,64
27.	transportation and warehousing	65
28.	communication common carriers	66,67
29.	trade	69
30.	finance and insurance	70
31.	real estate[1]	71
32.	miscellaneous services	72,75,76,78,79[2]
33.	business services	73
34.	eating and drinking places	74
35.	health, education, and social services	77
36.	coal	7
37.	crude oil and natural gas	8
38.	petroleum refining	31
39.	electric, gas and other utilities[3]	68,78.02,79.02
40.	residential housing	–

---

[1] Excludes rental value of buildings and land

[2] Excludes 78.02, 79.02

[3] Includes government utilities
Separate rows for electricity, gas, and all other

2.2. Energy supply sectors

Depletion of the U.S. stock of energy resources will be an important factor influencing conservation and technological choices in the future. PILOT represents, in physical terms, the increasing effort required to find and produce incremental units of oil, gas, coal, and uranium, as currently producing deposits become depleted and progressively more difficult deposits must be utilized. A primary effect of increasing the physical resources needed to produce a unit of these energy sources is to increase the market value of energy and energy-intensive commodities relative to those of other commodities, thus motivating changes to more energy-efficient technologies by the various sectors in the model.

Exploration for oil and gas in PILOT is characterized by a finding-rate curve, which links the amount of oil or gas found per foot drilled to cumulative drilling. (Exploratory drilling and development drilling are separated for oil but not for gas, as a consequence of differences in the data sources used for them.) Oil production is separated between primary and enhanced recovery, with different costs associated with each. Additional development drilling is needed if enhanced recovery of oil is to be implemented.

The coal module divides the United States into two regions, East and West, because of the substantial differences in the coal mining industries in these regions. Within each region, operating costs, manpower requirements per ton of coal mined, and investment costs for opening new coal mines are an increasing function of cumulative coal production. Since PILOT macro sectors are not regionalized, a simple time trend is specified to define the proportion of coal demand (on a Btu basis) occurring in each region. For simplicity we assume that western coal may be shipped to meet eastern demand, but not vice versa.

To bridge raw energy supplies and processed energy demands, PILOT incorporates straightforward process representations of electricity generation, natural gas processing, petroleum refining, and gas and electricity transmission. The usual complement of nuclear, fossil fuel, hydro, and unconventional electric power plants is provided. There is also some detail on the nuclear fuel cycle. Petroleum refining is greatly simplified, considering only homogeneous crude oil and an aggregate of all refined oil products. Such a simplification does not seriously bias long-run aggregate results.

2.3. Energy end use

Consumption of energy for most industrial, commercial, and residential uses, as well as for personal automobile transportation, is modeled by an activity analysis representation of the end-use conversion and conservation processes involved. In the manufacturing sector, consumption of various end-use services (e.g., steam, metal heating) is determined on the basis of output levels and technology choices in those sectors of the economy. These services are supplied by stocks of various alternative conversion devices distinguished by efficiency, fuel use, and other physical characteristics. The demand for commercial building space is determined as a function of output levels in the commercial sectors of the economy, while the associated demand for energy end-use services (e.g., space heat) is determined as a function of the building stock, which is differentiated by type, efficiency level, and location. These services are supplied by stocks of conversion devices, again defined in terms of fuel type, efficiency, and operating characteristics. The residential sector is modeled in a manner similar to the commercial sector, but with less detail. Finally, automobile travel for final consumers is treated as an energy end-use service, with a variety of automobiles, at varying fuel mileage ratings, available to supply this service. A substitution relationship is also defined to represent consumer choice between large and small automobiles. Transportation uses of energy in the rest of the economy are modeled through the input/output relations for each economic sector, and efficiency is assumed to improve at an exogenously specified rate.

2.4. Final demand

Final demands for goods and services in consumption, investment, and government activity are the driving forces behind the economy. Consumer use of each commodity in PILOT is determined on the basis of price-sensitive demand functions for 8 aggregate commodities: housing (including energy services), household operation, transportation, 2 recreation aggregates, clothing, personal care services, and personal care supplies. Per capita consumption of food, health care services, personal business services, private education, and foreign travel are specified exogenously. This commodity aggregation scheme reflects a blend of common sense and data analysis. The price-sensitive demand functions are estimated econometrically using a flexible functional form which embodies both own- and cross-price effects (see Section 3.1). Demand for each commodity resulting from investment activity is determined on the basis of the rate of capacity expansion taking place in each sector. Capacity expansion costs for each investment activity are first aggregated into a number of general expenditure types, e.g., buildings, industrial equipment, and computers and office equipment. A different fixed allocation of expenditures among commodities is then made for each aggregate. Finally, the government demands various commodities in fixed proportion to total government purchases of goods and services. The level of government expenditures is proportional to the levels of production and other final demand activities, using constants of proportionality which may be interpreted as tax rates.

3. MATHEMATICAL FORMULATION OF PILOT

As indicated above, the representation of the production sector in PILOT makes extensive use of the techniques of linear process modeling and input/output analysis (extended to encompass multiple columns for each sector). In addition a number of key nonlinear relationships are approximted by standard techniques of piecewise linearization. The resulting structure is then mathematically equivalent to that of an activity analysis or linear programming model. A further specialization of structure arises from the dynamic nature of the model and, in particular, from eschewing assumptions of exponential (technical) depreciation of productive capacity. An activity representing a long-lived investment may have coefficients in the relations of many (if not all) subsequent periods; it may also have coefficients in the relations of one or more previous periods to the extent that the investment requires a substantial construction lead time.

Since an equilibrium solution is to be calculated simultaneously across all time periods, the resulting linearized dynamic model of production is rather large, amounting to some 2000 relations and 4800 variables. The matrix of activity analysis coefficients is unusually dense for an economic model of this size, containing over 70000 nonzero elements. Data management and model generation is a laborious task, and extensive use is made of a conventional (mainframe) matrix generation and report-writing language (OMNI).

By adjoining an activity analysis model of production to a set of (smooth) consumer demand functions, a special (and well-studied) class of economic equilibrium systems can be constructed. The essential attributes of a competitive equilibrium solution in this case are as follows:

(a) the demand for all commodities must be less than or equal to supply;
(b) any excess supply must be accompanied by a zero price;
(c) the net present value of production activity must be nonpositive;
(d) only production activities with zero net present value can be operated.

With respect to (c) and (d), a normal rate of return is allowed; only profits in excess of this rate (called economic profits) are eliminated at equilibrium.

For general nonlinear demand functions, the above conditions define a special case of the so-called nonlinear complementarity problem. Model variables include both production and consumption activities and commodity prices. A feasible solution (or choice of activities and prices) corresponds to satisfaction of conditions (a) and (c) above. An equilibrium solution is a feasible solution which furthermore satisfies the complementarity conditions (b) and (d).

Solving an activity analysis equilibrium model with general demand functions can be a formidable task. Indeed, with the size of the production sector in PILOT, the corresponding complementarity problem contains some 6800 relations and 6800 variables. Such a formulation is well beyond the reach of current solution algorithms. If the richness of representation of the production sector is to be maintained, some sacrifice must be made in terms of selecting a more restricted class of demand functions (see below). In particular, resort is made to a class of so-called integrable demand functions, that is, a set of equations which could be derived from the optimality conditions for maximizing a known utility function. In the integrable case, an equilibrium solution can be computed by maximizing the associated utility function of consumption levels subject to the activity analysis production constraints. The feasibility and optimality conditions for this mathematical program are precisely the equilibrium conditions (a) through (d).

The significant computational advantage of imposing integrability is that well-developed techniques of large-scale mathematical programming can be applied to the equilibrium problem. In particular, PILOT is solved using MINOS, an efficient, FORTRAN-coded system for large-scale linear or nonlinear optimization, developed and maintained by the Systems Optimization Laboratory. We continue to experiment with iterative solution techniques for the nonintegrable case (which involve solving a sequence of integrable problems), but none is as yet sufficiently reliable and efficient to be routinely applied to PILOT.

3.1. Consumer demand functions

The consumer demand system employed in PILOT utilizes a reasonably flexible functional form (even with imposition of integrability conditions). Specifically, we denote by x and p the relevant vectors of consumption quantities and prices and by w the total consumption expenditure to be allocated among the commodities x. The demand system is then given by:

$$x = s - \left(\frac{s'p - w}{p'Mp}\right)Mp, \tag{1}$$

where s and M are a vector and matrix of estimated parameters. (The scaling and sign convention of M are not determined and can be set by any convenient normalization.) Note that this functional form is homogeneous of degree zero in (p, w) and that it ensures that $p'x = w$, a condition known as Walras' law.

No further restrictions are required in order for (1) to define a valid system of aggregate consumer demand functions, although it can be noted that demand is undefined for any prices such that $p'Mp = 0$. Imposition of the integrability condition amounts to requiring that the matrix M be symmetric. In this case system (1) represents the demand functions which are derived from maximization of the quadratic utility function $(s-x)'M^{-1}(s-x)$ subject to the budget constraint that $p'x = w$. This utility function satisfies the usually assumed concavity property only if the matrix M is further restricted to be negative definite.

As indicated above, owing to the large size of PILOT's production sector, computational considerations currently oblige us to utilize the restricted functional form (with M symmetric and negative definite). This permits the computation of an equilibrium solution by means of large-scale quadratic programming.

4. PRELIMINARY RESULTS ON THE EFFECTS OF TECHNOLOGICAL CHANGE

As stated near the outset, ongoing studies with the PILOT model address the relationship between the rate at which advanced new technologies become available and aggregate and sectoral patterns of growth, employment, and energy use over the next 20-25 years. As of this writing, we are still in the process of model calibration and scenario refinement. Nonetheless, it may be worthwhile to examine some preliminary results from two model scenarios. While certain flaws are apparent in the underlying model runs, we believe that the qualitative conclusions which can be drawn from a comparison of the two cases are valid and will be supported by more definitive model runs.

The intent of the two cases is to isolate a pure effect of delays in the availability of new technology. For convenience, we shall refer to one case as the Base Case and the other as the Delay Case. The only difference between the two cases is that technologies which are available in 1985-1990 in the Base Case are delayed five years in the Delay Case, while those available in 1995 and beyond in the Base Case are delayed ten years in the Delay Case. These delays effectively reduce the potential rates of growth in factor productivity on a sector-by-sector basis. In both scenarios the assumed rate of growth in productivity through disembodied technological change is minimal until 2005. After that the rate increases toward 1 percent per year, purely as a device to maintain a level of economic growth in the later periods of the model (for which lack of data or knowledgeable conjecture prevents at this time a meaningful specification of sector-specific new technologies). For purposes of the scenario comparison, the cause of the delays in technology availability is not important. Any number of technical or economic factors (external to PILOT) could delay the somewhat optimistic introduction dates hypothesized in the Base Case. The usefulness of PILOT is not in modeling how and why technical advances are made but in assessing the potential utilization of new technologies and the effects thereof on the economy as a whole.

Table 2 presents some simple measures of economic performance and energy utilization for the two scenarios. Since there are some subtle differences between the ways in which commodity prices, Gross National Product (GNP) and per capita consumption are computed in PILOT relative to standard statistics, the measures of economic variables are presented on an index number basis. The energy measures are reported in physical units (quadrillion Btu or quad) and correspond to the summary tabulations in, say, the *Annual Energy Review* from the U.S. Energy Information Administration. In particular, total energy production refers to primary energy. Energy consumption per unit of GNP is reported as a crude measure of the energy intensity of economic activity. Note that it includes both changes in the technical efficiency of energy use and changes in aggregate energy use arising from different patterns of sectoral outputs (e.g., a declining relative importance of energy-intensive industries).

Apart from certain curiosities in 1985 (a "projection" year in PILOT), the results are in line with prior expectations. Because PILOT does not reflect the business cycle and tends to be bullish in any event, both economic activity and energy measures are higher than actual for 1985 — GNP by some 20 percent and energy consumption by about 3 quad. These differences are not important in assessing the effects of the delays in technological innovation. The general upward trend in world oil price is an exogenous assumption (from early 1986), but the presence of upward-sloping imported oil supply curves in each period causes the attained price to vary in accordance with demand pressure. For this reason, the higher rate of economic growth in the Base Case induces higher oil prices (relative to the Delay Case) toward the end of the horizon.

Table 2
COMPARISON OF TWO PILOT SCENARIOS

	1985	1990	1995	2000	2005	2010
WORLD OIL PRICE (1976=1)						
Base Case	1.197	1.346	1.843	2.361	3.040	3.667
Delay Case	1.214	1.322	1.826	2.293	2.810	3.346
ECONOMIC ACTIVITY (1976 = 1)						
GROSS NATIONAL PRODUCT						
Base Case	1.426	1.702	2.036	2.443	2.768	3.137
Delay Case	1.404	1.656	1.974	2.288	2.585	2.961
PER CAPITA CONSUMPTION						
Base Case	1.273	1.456	1.649	1.825	2.071	2.180
Delay Case	1.293	1.431	1.640	1.787	1.964	2.072
ENERGY MEASURES (QUAD BTU)						
TOTAL PRODUCTION						
Base Case	68.143	74.107	77.142	85.876	95.092	107.150
Delay Case	68.149	73.181	76.419	84.313	92.843	104.952
NET IMPORTS						
Base Case	9.004	9.364	15.416	19.478	23.520	24.073
Delay Case	9.664	8.526	14.222	15.945	20.866	20.139
TOTAL CONSUMPTION						
Base Case	77.148	83.471	92.558	105.354	118.612	131.223
Delay Case	77.813	81.707	90.641	100.258	113.709	125.092
ENERGY CONS./GNP (1976=1)						
Base Case	0.747	0.677	0.627	0.595	0.591	0.577
Delay Case	0.765	0.681	0.634	0.605	0.607	0.584

The effects of the delays in technological innovation are just noticeable in 1985 and become more pronounced thereafter. Over the 1985-2010 horizon, GNP grows at an average annual rate of 3.2 percent in the Base Case, dropping to 3.0 percent in the Delay Case. Similarly, the annual rate of growth in per capita consumption falls from 2.2 percent to 1.9 percent. These small differences in rates compound to a divergence of 5-6 percent by 2010. Underlying these aggregate results in both scenarios is a typical trend of growing relative importance of the service sector and of declining importance within manufacturing of the basic or heavy industries, particularly metals.

Commensurate with the reduced rate of economic growth in the Delay Case is a reduction (after 1985, anyway) of energy production, net imports, and consumption. By 2000, energy consumption is some 5 quad lower in the Delay Case than in the Base Case, with this difference growing slightly to 6 quad in 2010. More than half of the reduction in consumption is allocated to a decline in net imports (and in oil imports, in particular). The technology delays also lead to a somewhat higher level of aggregate energy intensity, although the differences in this measure between cases are somewhat erratic in magnitude.

The notable declines in energy intensity in both scenarios are sufficient to slow the annual rate of growth in total energy consumption to about 2 percent. Interestingly, the levels of energy consumption in industrial uses are comparable in the two cases, which accounts in part for the somewhat higher level of energy intensity in the Delay Case. This also means that the difference in energy consumption between the two scenarios is almost entirely attributable to residential and commercial uses (including automobiles). A curious underlying result (which merits further study) is a modest declining trend in electricity intensity (consumption per unit GNP) until 2000, followed by a healthy upward trend for the rest of the horizon. Apparently, the reductions in electricity use that accompany falling production levels in the metals industries are sufficient in the early periods to outweigh the general electrification trends in the rest of the economy.

A wealth of more detailed information is available from PILOT scenarios, but the tentative nature of the cases described here does not justify an in-depth analysis. Available results include final consumption levels by commodity; industrial output, employment, and productivity levels by industry; import/export balances by commodity; and fuel-specific energy production and end-use patterns. We are in the process of refining the scenario comparison described above and hope to have final results in early 1987.

REFERENCES

[1] Dantzig, G.B., Connolly, T.J., and Parikh, S.C. **Stanford PILOT Energy-Economic Model.** EA-626, Volume 2, Research Project 652-1. Interim Report, May 1978. Electric Power Research Institute, 3412 Hillview Ave., Palo Alto, California, 94304.

[2] Dantzig, G.B., Avi-Itzhak, B., and Connolly, T.J. **PILOT-1980 Energy-Economic Model.** EA-2090, Volume 1, Research Project 652-1. Interim Report, November 1981. Electric Power Research Institute, 3412 Hillview Ave., Palo Alto, California, 94304.

[3] McAllister, P.H., Stone, J.C., Dantzig, G.B., and Avi-Itzhak, B. **The PILOT-1983 Model.** Technical Report SOL-85-12. July 1985. Systems Optimization Laboratory, Department of Operations Research, Stanford University, Stanford, California, 94305-4022.

R