Center for Advanced Computation

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ON DECOUPLING ENERGY AND GNP GROWTH

by

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ABSTRACT

This paper presents an energy demand model for the U. S. which involves four classes of variables: population, per capita GNP, life-style, and technology. The model is implemented on a computer with an interactive graphics terminal. This allows a user to describe future scenarios in terms of the four parameters and to immediately see the resulting energy implications. It is a structural, not a predictive, model which is intended to demonstrate the sensitivity of energy demand to each of these parameters.

INTRODUCTION

The historical growth of energy productivity in the United States has slowed dramatically. In fact, the last two decades have been characterized by almost zero growth. As a consequence, our growing economy has required a matching growth in energy demand (see Fig. 1).

During this same 20 year period, the United States has become increasingly unable to meet this growing energy demand from domestic resources. For a time, oil import quotas helped hold the line until the early 1970's when they were removed. About that same time, domestic oil production peaked and has continued to decrease in spite of higher prices during the post-embargo period.

The decline in domestic oil production was predicted by Hubbert (1962) using a Malthusian resource scarcity argument. Moreover, the political, economic and environmental costs of sustaining an exponential growth in domestic energy resource extraction have continued to increase.

These trends present a dilemma for those who advocate continued growth of the U. S. gross national product on a limited energy budget. Steady increases in energy productivity would be required to support such GNP growth. In this paper we shall set aside the questions relating to the merits of GNP as a social welfare criterion, for that subject has been well covered elsewhere.*

Since growth in energy productivity has been stagnant for nearly 20 years, it is apparent that substantial changes may be needed if

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*See for example Daly, (ed.) (1974) and Nordhaus and Tobin (1975).

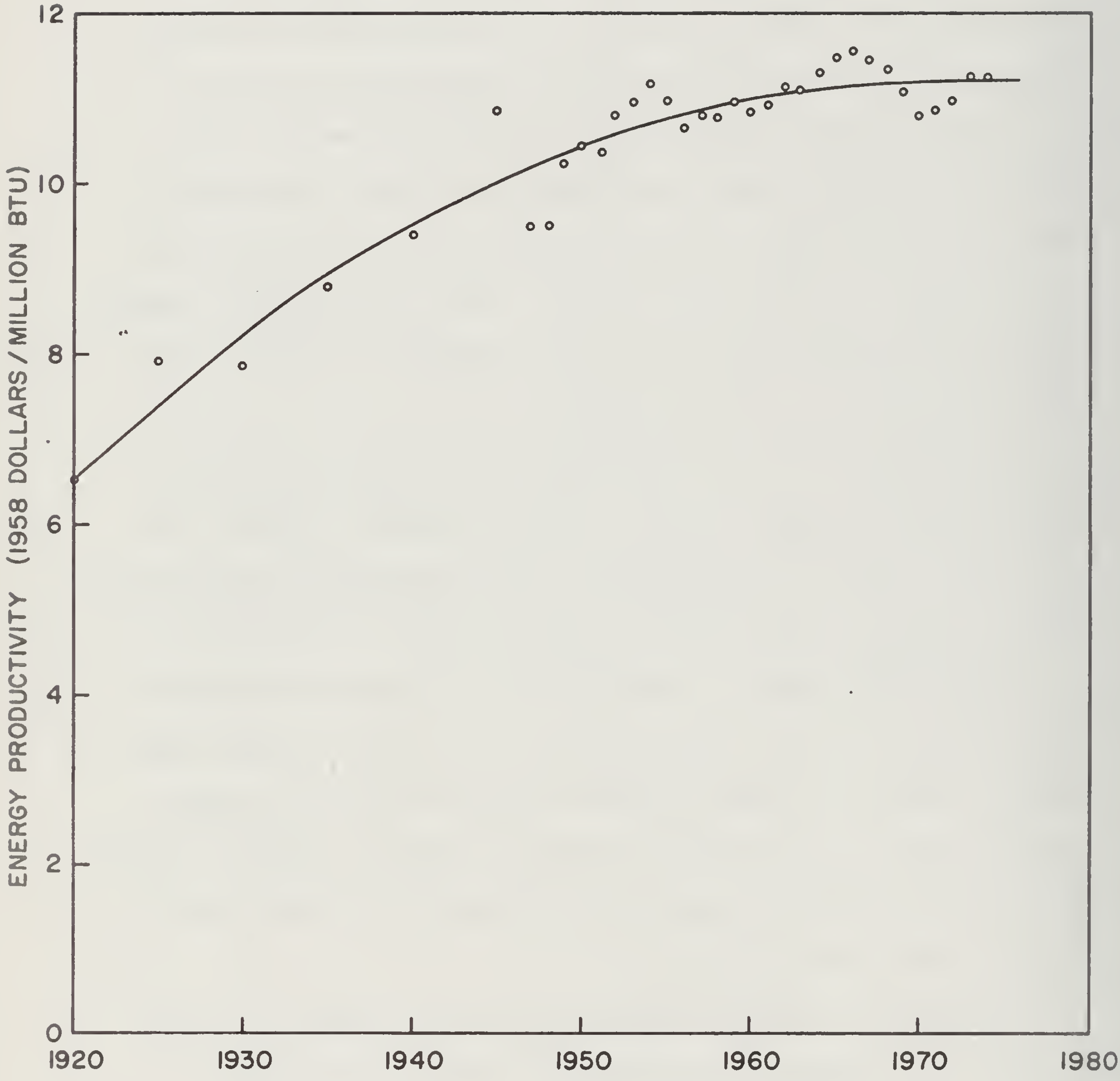

Figure 1. Energy Productivity Since 1920.

energy and economic growth are to be decoupled. The purpose of this paper is to demonstrate the sensitivity of U. S. energy demand to changes in key variables.

ELEMENTS OF ENERGY DEMAND

For purposes of this investigation, we shall express energy demand as the product of the four variables:

1) Population
2) Per capita GNP
3) Lifestyle: the mix of goods and services making up the GNP
4) Technology: the energy required to produce various goods and services

Our purpose here is to analyze the effects of changes in these four variables on total U. S. energy demand. Since the product of the first two variables equals the GNP, the energy productivity of the economic system depends only on lifestyle and technology. As Figure 1 indicates, the cumulative effect of these two variables has been negligible during the last two decades. This, together with the exponential growth in population and per capita GNP, explains the exponential growth of energy demand in the United States.

In an attempt to explore energy choices for the future, the Ford Foundation* (1974) presented three scenarios for energy demand in the

*See Freeman, (1974).

period 1975-2000. The three scenarios shared approximately the same exponential growth in GNP, but displayed radically different total energy requirements. The first scenario was essentially an extrapolation of historical exponential growth. The second included "technical fixes" which decoupled energy and GNP growth by reducing the energy required to produce various goods and services. The third, "zero energy growth" scenario, combined technological and lifestyle changes to level the growth in energy demand by the turn of the century. Thus by transient improvements in energy productivity, it was shown that energy demand could be reduced from that of the historical growth scenario without substantially affecting the GNP.

What the Ford report did not emphasize, however, was that these effects are indeed transitory and exponential energy growth would resume after the year 2000 unless more technological and lifestyle changes were made beyond that time. Figure 2 illustrates what the Ford Foundation's scenarios would imply if the prescribed changes saturated the potential for conservation: The exponential growth in GNP would dominate, and the net effect of switching to smaller cars, changing life-styles, etc., would only be to shift the demand curve to the right. The dilemma is not unlike a dieter wishing to limit calories while increasing the total quantity of food eaten. The calorie intake can be slowed for only a short period while the composition of the diet is being changed.

The greatest shortcoming of the Ford study is that it leans heavily on a model of the U. S. economic system that is highly aggregated. In

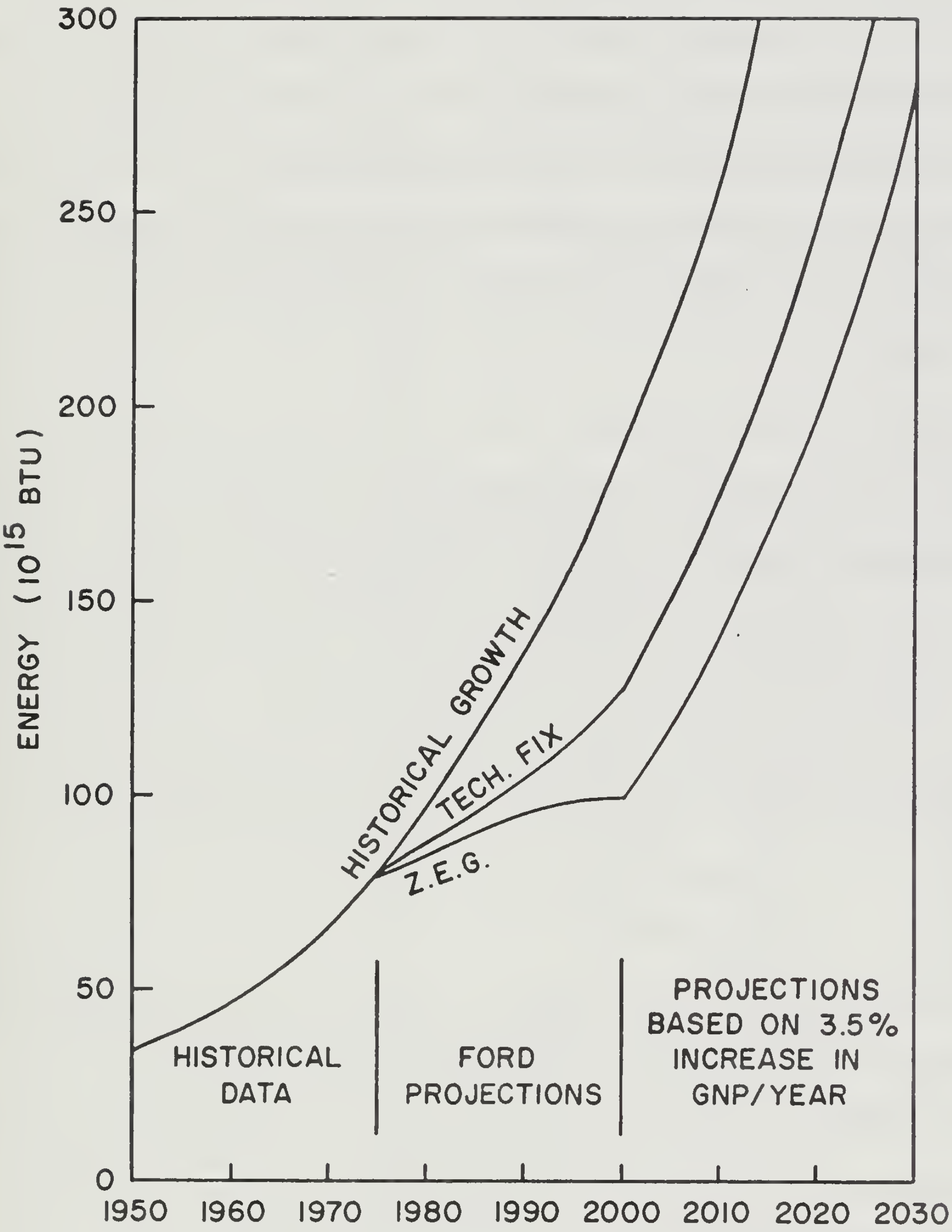

Figure 2. Extension of Ford Foundation's Projections.

fact, it represents only nine sectors, five of which are energy sectors. With such coarse descriptors as "durable goods" and "services" it is impossible to accurately measure the energy impact of substituting one type of goods for another, substitutions among various services, or of certain goods for services. The model's parameters are too aggregated to reflect real options for technological or lifestyle changes. For this study we have used a similar but much more detailed model of the U. S. economy.

THE MODEL

The model employed for this analysis is the linear Leontief input-output model of the U. S. economy. Let X_j represent the total output from sector j, and let Y_j be that portion delivered for final consumption. (The sum of the dollar value of the elements of Y_j equals the gross national product.) The output distribution equation (in matrix notation) is:

$$(\underline{\underline{I}} - \underline{\underline{A}})\,\underline{X} = \underline{Y}$$

where the element A_{ij} is the amount of sector i's output needed as an intermediate input by sector j, per unit output of sector j. The parameter matrix A describes the technology of the economic system. The energy required directly and indirectly to produce a unit of any product for final consumption depends only on the matrix of technological cooefficients A. Specifically, the energy sector row of the matrix $(I-A)^{-1}$ is the so-called vector of energy intensities, measured in Btu/unit of each product.

These energy intensities have been calculated for the U. S. economy in the year 1967 using a model at the 360 sector level of detail (see Bullard and Herendeen, 1975). At this level of disaggregation, it is possible to see wide variations in the energy costs of various goods and services, and individual elements of the technological coefficients matrix correspond quite well to real technological options (e.g. the amount of steel purchased by the automobile industry per unit car produced).

The total energy output of the U.S. economic system can be calculated from eq. (1) given the U.S. population, P, the per capita consumption*, g, and a lifestyle vector, $\underline{y}$, representing the composition of the market basket of final goods and services purchased.

$$E = \underline{\varepsilon}\underline{y}gP$$

where $\underline{\varepsilon}$ is the energy sector row of $(I-A)^{-1}$ and the total final demand is expressed as the product of the last three terms.

IMPLEMENTATION

To help a wide variety of users understand the relative quantitative importance of the technology, life style, income and population variables in the above equation, the model was implemented on a Data General Nova 1200 mini-computer running under RDOS (Real Time Disk Operating System). The program

*Approximately equal to per capita GNP.

is run from an interactive terminal with graphics capability. In principle, the model could be implemented at the 360 sector level of detail, but for the present example it was aggregated to 106 sectors to accommodate constraints imposed by this particular mini-computer.

Initially the four parameters are set to portray historical growth. This base case assumes a continuation of GNP/capita growth of 2% per year and population growth of 1.5% per year. The lifestyle and technology parameters are assumed to remain constant at their 1967 values. A plot of the energy demand vs. time shows an increase from 59 quads (1 quad = 10^{15} BTU) in 1967 to 185 quads in year 2000, or an increase of more than 200%. This is not meant to be a realistic projection considering the scarcity of future energy supplies, but is based on the same unrestricted growth in the future as has been experienced in the past. The user may change any or all of the parameters and compare this new projection with the base case. Changes are made gradually over a specified number of years.

To give the model greater flexibility, the lifestyle parameter is divided into several parts. Because the final demands for the different categories differ greatly, the user has the option of changing the fraction of GNP made up of personal consumption expenditures, government expenditures and/or private investment. The relative size of these categories can be adjusted and then changes in the actual sector mix can be made for personal and government expenditures. The number of goods and services is aggregated to about 30 for each of these two categories to simplify the modifications. Tables 1 and 2 list these categories for personal consumption and government "lifestyles."

Table 1. Personal Consumption Lifestyle Coefficients

Sector Names

ENERGY PRODUCTS

1. Space Heat
2. Water Heat
3. Gasoline
4. Electric Lighting & Power
5. Cooking Heat
6. Air Conditioning

TRANSPORTATION

7. Air Transportation
8. Train Transportation
9. Bus Transportation
10. Truck Freight Transportation

MANUFACTURED PRODUCTS

11. Chemical & Plastic Products
12. Rubber, Paper, Glass, Stone & Paints
13. Fabricated Metal Products
14. Automobiles, Trucks & Parts
15. Textile Products
16. Agricultural Products
17. Drugs & Cosmetics
18. Machinery
19. Food & Tobacco
20. Furniture & Fixtures
21. Books, Newspapers & Magazines
22. Clothing
23. Radios & T.V.'s

SERVICES

24. Water & Sanitary Services
25. Hotel & Repair Services
26. Medical & Educational Services
27. Amusements & Business Services
28. Banking & Insurance
29. Telephone
30. Housing

Table 2. Government Expenditure Lifestyle Coefficients

Sector Names

ENERGY PRODUCTS

1. Space Heat
2. Misc. Heat
3. Water Heat
4. Jet & Motor Fuel
5. Air Conditioning
6. Lighting & Electric Power

TRANSPORTATION

7. Water Transportation
8. Air Transportation
9. Train Transportation
10. Bus Transportation
11. Truck Transportation

MANUFACTURED PRODUCTS

12. Chemical Products
13. Metal Products
14. Rubber, Paper, Glass & Stone
15. Motor Vehicles & Trans. Equipment
16. Food & Agricultural Products
17. Machinery
18. Military Hardware (Ordinance)
19. Furniture, Office & Scientific Eq.
20. Aircraft
21. Communication Equipment

SERVICES

22. New Construction
23. Maintenance & Repair Construction
24. Medical & Educational Services
25. Business Services
26. Banking, Insurance & Real Estate
27. Telephone
28. Government Wages

Technology changes are more difficult to specify. To make a technology change requires altering the A matrix which in this case is a 106 order matrix.* The matrix must then be subtracted from the identity matrix and then inverted and aggregated. Because of the limited memory size of the mini-computer used, this task would be greatly complicated. As a result, the time required to do such a calculation exceeds that which is satisfactory in an interactive mode.

To greatly simplify the problem, the user is given the choice of leaving the technology coefficients unchanged, or to specify a period of time over which they would change gradually to values prescribed by the Ford Foundation's Technical Fix Scenario.** Briefly, these are energy saving technology changes which are economically feasible based on current energy prices. The changes include more efficient cars and industrial processes, and the shifting of transportation modes to save fuel. These changes are based on implementing existing technology and are not dependent on future technological developments.

The user may make any number of changes in each pass through the program. Each time a plot of the new energy demand is generated and overlayed on the historical growth curve and curves corresponding to previous changes. Figure 3 is a flowchart of the program.

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*The model is described by Bullard and Sebald (1975) and in Appendix A. The computer code is documented in Foster (1976).

**For a detailed description of these changes, see Appendix B.

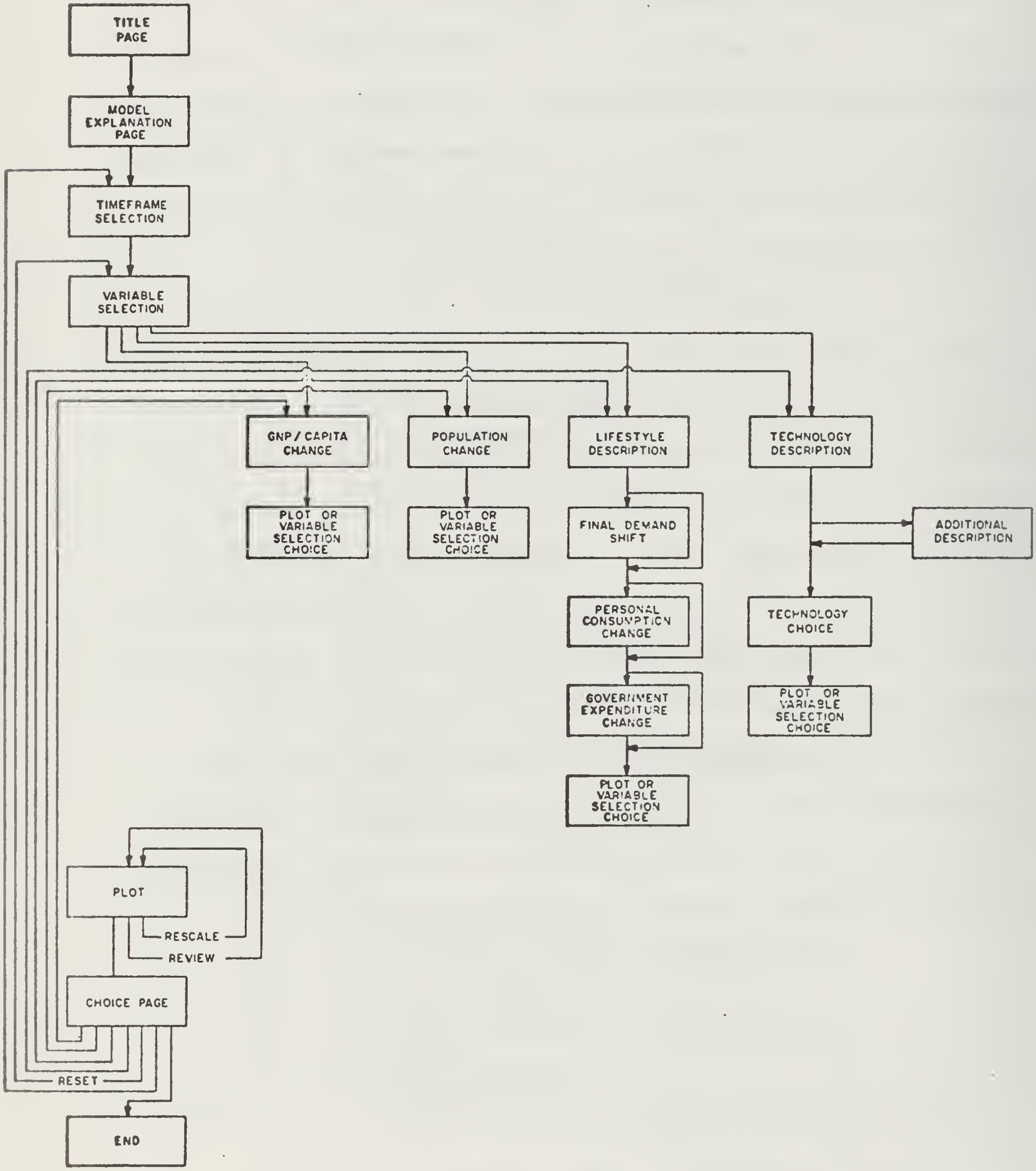

Figure 3. Flowchart of Energy Demand Model

EXAMPLE

The following examples demonstrate the types of changes that can be made and show how a user would interact with the computer. The model permits the changes to be made cumulatively so that the results of a particular change are dependent on changes previously made.* A 25-year planning horizon is chosen for this example.

Technology. The most likely change to make would be to assume that post-embargo energy prices hold and induce changes in the technology of producing all goods and services. The Ford Foundation assumed these changes would be economic at current prices and could be accomplished by 1985. Figure 4 shows how this change would be specified. The user may now see the effect of this change by plotting the results as in Figure 5. The new curve is compared with a base curve which represents an extrapolation of historical trends. As can be seen from the graph, the energy demand in year 2000 has dropped from 168 to 147 quads, but has still more than doubled during the 25 year period.

Lifestyle. For this example, we shall hold constant the distribution of GNP among individuals, government, and investment expenditures. We shall, however, specify changes in the composition of the personal and government expenditure dollars.

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*For example, technological changes affect the energy intensity of all goods and services, and hence the energy impact of subsequent lifestyle changes involving substitution of goods and services. Marginal impacts from any datum may also be calculated, and such results are presented later in Table 3.

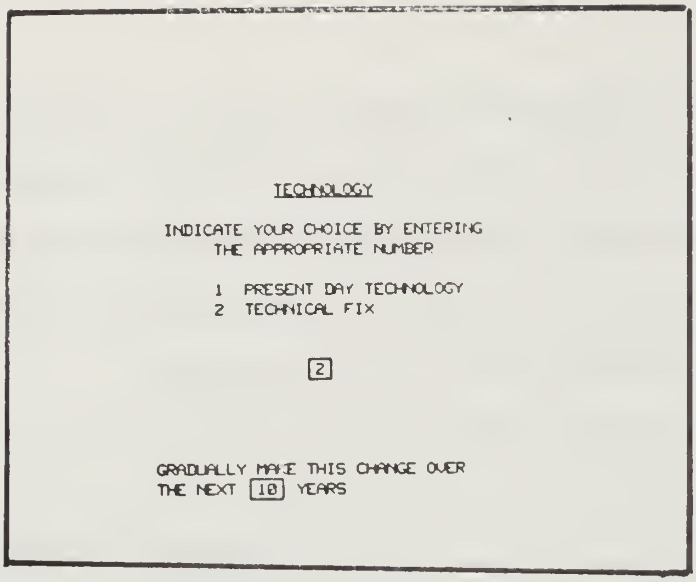
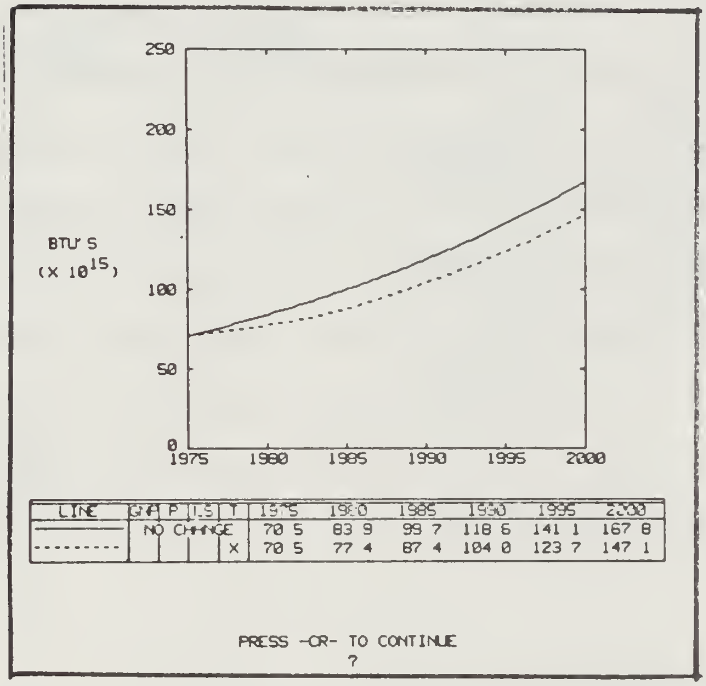


Figure 4. Technology Change*



LINE	G/A	P	I.S	T	1975	1980	1985	1990	1995	2000
————	NO CHANGE				70 5	83 9	99 7	118 6	141 1	167 8
- - - - -				X	70 5	77 4	87 4	104 0	123 7	147 1

Figure 5. Plot of Energy Demand Projection With and Without the Technology Change.

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*The numbers in the boxes were entered by the user.

The first personal lifestyle change involves a nationwide home insulation program where space heating requirements would be reduced one-third and the money spent on insulation. Next, gasoline expenditures are cut in half and the savings split between bus and rail mass transit. These changes do not necessarily imply a reduction in personal travel; only a modal shift and, perhaps, a shift to smaller economy cars. To reflect the reduction in automobile use, a little less than half the money now spent for the purchase of cars is shifted to educational and medical expenses.* Another energy-saving transportation modal shift was accomplished by shifting half the airline transportation to train transportation. Because of the pricing difference, only three-fourths of the money taken from the airline sector need be spent on train fare to travel the same number of miles. The additional money saved is spent on entertainment. Finally, a shift away from energy-intensive commodities and packaging was simulated by reducing those expenditures 25% and spending the money on better housing. The amount of air conditioning was left unchanged to represent use by more people, but with more efficient units. Figure 6 shows how the first of these changes is made, and Figure 7 shows the computer terminal screen after all these changes have been completed.

The composition of government expenditures was also changed. Space heat and air travel changes were the same as those noted above for

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*Note that the range of lifestyle choices is not restricted; the shifts need not be among "substitutable" commodities providing similar services.

PERSONAL CONSUMPTION

	SECTOR	ORIGINAL DISTRIBUTION (CENTS/DOLLAR)	NEW DISTRIBUTION
	ENERGY PRODUCTS		
1	SPACE HEAT	1 89	1 26
2	WATER HEAT	0 51	
3	GASOLINE	3 58	
4	ELECTRIC LIGHTING & POWER	0 83	
5	COOKING HEAT	0 27	
6	AIR CONDITIONING	0 18	
	TRANSPORTATION		
7	AIR TRANS	0 48	
8	TRAIN TRANS	0 10	
9	BUS TRANS	0 58	
10	TRUCK FREIGHT TRANS	0 16	
	MANUFACTURED PRODUCTS		
11	CHEMICAL & PLASTIC PRODUCTS	0 18	
12	RUBBER PAPER GLASS, STONE, & PAINTS	1 77	2 40
13	FABRICATED METAL PRODUCTS	0 49	
14	AUTOMOBILES, TRUCKS, & PARTS	4 47	
15	TEXTILE PRODUCTS	1 71	
16	AGRICULTURAL PRODUCTS	2 40	
17	DRUGS & COSMETICS	2 70	
18	MACHINERY	0 50	
19	FOOD & TOBACCO	22 51	
20	FURNITURE & FIXTURES	5 76	
21	BOOKS, NEWSPAPERS, & MAGAZINES	1 35	
22	CLOTHING	7 33	
23	RADIOS & T V 'S	1 34	
	SERVICES		
24	WATER & SANITARY SERV	0 39	
25	HOTEL & REPAIR SERV	5 07	
26	MEDICAL & EDUCATIONAL SERV	0 86	
27	AMUSEMENTS & BUSINESS SERV	2 19	
28	BANKING & INSURANCE	5 44	
29	TELEPHONE	1 69	
30	HOUSING	15 27	

TAKE [0 63] FROM SECTOR NUMBER [1]
AND ADD IT TO SECTOR [12]

Figure 6. Example Of How Lifestyle Changes Are Made.*

PERSONAL CONSUMPTION

	SECTOR	ORIGINAL DISTRIBUTION (CENTS/DOLLAR)	NEW DISTRIBUTION
	ENERGY PRODUCTS		
1	SPACE HEAT	1 89	1 26
2	WATER HEAT	0 51	
3	GASOLINE	3 58	1 78
4	ELECTRIC LIGHTING & POWER	0 83	
5	COOKING HEAT	0 27	
6	AIR CONDITIONING	0 18	
	TRANSPORTATION		
7	AIR TRANS	0 48	0 24
8	TRAIN TRANS	0 10	1 00
9	BUS TRANS	0 58	1 48
10	TRUCK FREIGHT TRANS	0 16	
	MANUFACTURED PRODUCTS		
11	CHEMICAL & PLASTIC PRODUCTS	0 18	0 13
12	RUBBER PAPER GLASS, STONE, & PAINTS	1 77	1 96
13	FABRICATED METAL PRODUCTS	0 49	0 37
14	AUTOMOBILES TRUCKS, & PARTS	4 47	2 47
15	TEXTILE PRODUCTS	1 71	
16	AGRICULTURAL PRODUCTS	2 40	
17	DRUGS & COSMETICS	2 70	
18	MACHINERY	0 50	
19	FOOD & TOBACCO	22 51	
20	FURNITURE & FIXTURES	5 76	
21	BOOKS, NEWSPAPERS, & MAGAZINES	1 35	
22	CLOTHING	7 33	
23	RADIOS & T V 'S	1 34	
	SERVICES		
24	WATER & SANITARY SERV	0 39	
25	HOTEL & REPAIR SERV	5 07	
26	MEDICAL & EDUCATIONAL SERV	0 86	10 06
27	AMUSEMENTS & BUSINESS SERV	2 19	2 35
28	BANKING & INSURANCE	5 44	
29	TELEPHONE	1 69	
30	HOUSING	15 27	15 00

DO YOU WISH TO MAKE ANOTHER CHANGE ?
INDICATE YOUR CHOICE BY ENTERING -N- OR -Y-
?

Figure 7. Changes Made to the Personal Consumption Lifestyle

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*The numbers in the boxes were entered by the user.

households,* while a third of the money spent on new construction was moved to maintenance and repair. Figure 8 shows these changes.

These personal and government lifestyle changes are effected gradually, and completed by 1982. The effect on the year 2000 energy demand is a further reduction to 126 quads, as seen in Figure 9. This figure represents the combined effect of changes in both technology and lifestyle, and shows that energy demand still increases by more than 75% over the 1975-2000 period.

Population. To determine the energy impact of the expected decline in the population growth rate, it is necessary to specify only two parameters: the lower growth rate and the length of the transition period. For this example, we used the slowest growth scenario published by the U. S. Census Bureau. It projects a zero population growth by the year 2030. The model assumes a linear decrease in growth rate from the present level of 1.5% to zero over the 55 year period. Figure 10 shows how the user would specify this change.

Adding this to the technology and lifestyle changes prescribed above, energy demand is reduced an additional 10 quads to 116 quads by the year 2000. This can be seen by plotting the results after this change (see Fig. 11). Note that the previous plots are automatically retained for comparison purposes.

GNP/capita. This parameter is changed in the same manner as the population variable, and is reduced from the historical growth rate of

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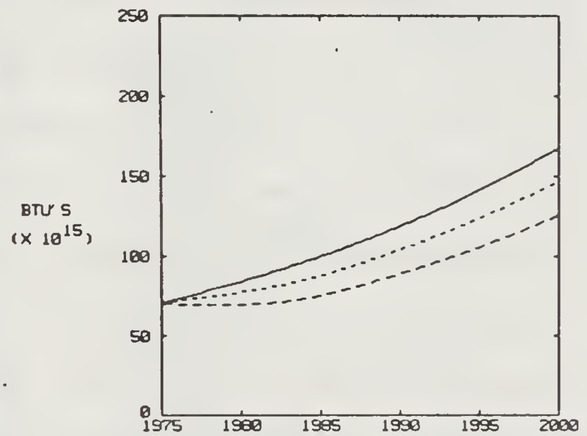
*The money saved by shifting from planes to trains is spent on medical and educational services.

GOVERNMENT PURCHASES

	SECTOR	ORIGINAL DISTRIBUTION (CENTS/DOLLAR)	NEW DISTRIBUTION
	ENERGY PRODUCTS		
1	SPACE HEAT	0 66	0 44
2	MISC HEAT	0 01	
3	WATER HEAT	0 07	
4	JET & MOTOR FUEL	0 68	
5	AIR CONDITIONING	0 08	
6	LIGHTING & ELECTRIC POWER	0 76	
	TRANSPORTATION		
7	WATER TRANS	0 47	
8	AIR TRANS	0 62	0 31
9	TRAIN TRANS	0 13	0 23
10	BUS TRANS	0 29	
11	TRUCK TRANS	0 62	
	MANUFACTURED PRODUCTS		
12	CHEMICAL PRODUCTS	1 21	
13	METAL PRODUCTS	0 86	
14	RUBBER PAPER GLASS, & STONE	0 68	0 90
15	MOTOR VEHICLES & TRANS EQUIP	2 02	
16	FOOD & AGRICULTURAL PRODUCTS	1 86	
17	MACHINERY	2 12	
18	MILITARY HARDWARE (ORDINANCE)	4 91	
19	FURNITURE, OFFICE & SCIENTIFIC EQ	1 73	
20	AIRCRAFT	5 03	
21	COMMUNICATION EQUIP	3 96	
	SERVICES		
22	NEW CONSTRUCTION	14 81	9 07
23	MAINTENANCE & REPAIR CONSTRUCION	3 30	0 24
24	MEDICAL & EDUCATIONAL SERV	2 73	2 94
25	BUSINESS SERV	2 46	
26	BANKING, INSURANCE & REAL ESTATE	0 79	
27	TELEPHONE	0 59	
28	GOVERNMENT WAGES	47 34	

DO YOU WISH TO MAKE ANOTHER CHANGE ?
INDICATE YOUR CHOICE BY ENTERING -N- OR -Y-
?

Figure 8. Changes Made To The Government Purchases "Lifestyle"



LINE	GNP	P	LS	T	1975	1980	1985	1990	1995	2000
————	NO CHANGE				70 5	83 9	93 7	110 6	141 1	167 0
·········				X	70 5	77 4	87 4	104 0	123 7	147 1
- - - - - -			X	X	70 5	69 7	74 6	88 8	105 6	125 6

PRESS -CR- TO CONTINUE   ENTER -S- TO RESCALE PLOT

?

Figure 9. Plot Of The Original, Technology Change, and Technology Plus Lifestyle Change Projections.

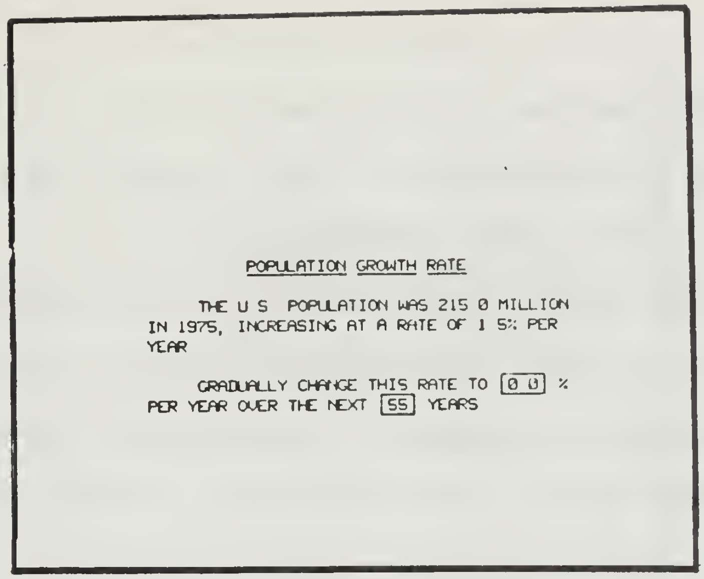
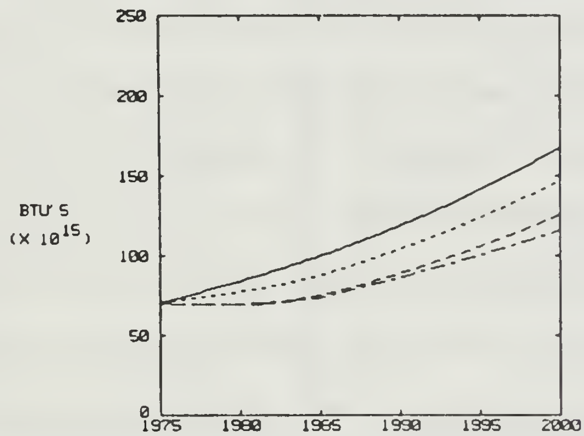


Figure 10. Change To The Population Growth Rate.*



LINE	GNP	P	LS	T	1975	1980	1985	1990	1995	2000
————	NO CHANGE				70 5	83 9	99 7	118 6	141 1	167 8
········				X	70 5	77 4	87 4	104 0	123 7	147 1
- - - - -			X	X	70 5	69 7	74 6	88 8	105 6	125 6
-·-·-·-		X	X	X	70 5	69 5	73 7	86 2	100 2	115 6

PRESS -CR- TO CONTINUE ENTER -S- TO RESCALE PLOT

?

Figure 11. Plot Of Population Growth Rate Change In Addition To The Previous Changes.

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*The numbers in the boxes were entered by the user.

2% to 0.5% by 1980 (see Fig. 13). This has a dramatic effect on energy demand, resulting in a requirement for only 83 quads in year 2000 as shown in Figure 13. The growth rate during the 1975-2000 transition period averages only about 0.7% per year if all changes are implemented. It should also be noted that the energy demand actually decreases slightly until about 1985. Compared to the historical growth trend, the year 2000 energy demand is cut in half by the changes outlined above.

As another example, consider the same changes as made earlier but instead of a stabilizing economy, the GNP/capita was changed to a growth rate of 4% per year. This essentially means a pay increase of 4%/year (in real terms) for everyone.* The result is shown in Figure 14. This single change more than neutralizes all the energy savings effected through changes in technology, lifestyle, and population growth rate.

Summary of results. Only after the exponential growth rates in population and GNP/capita are reduced, do the curves start to flatten out. The results emphasize that technology and lifestyle changes can only reduce energy growth rate during limited transition periods.

The incremental savings due to each change depend, of course, on changes made earlier. To compare the relative impact of each type of change, their effect on the base case (historical growth) was calculated. Results presented in Table 3 show that, all other things being equal, U. S. energy demand was most sensitive to the GNP/capita.

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*Note that this increase is above any needed to compensate for inflation.

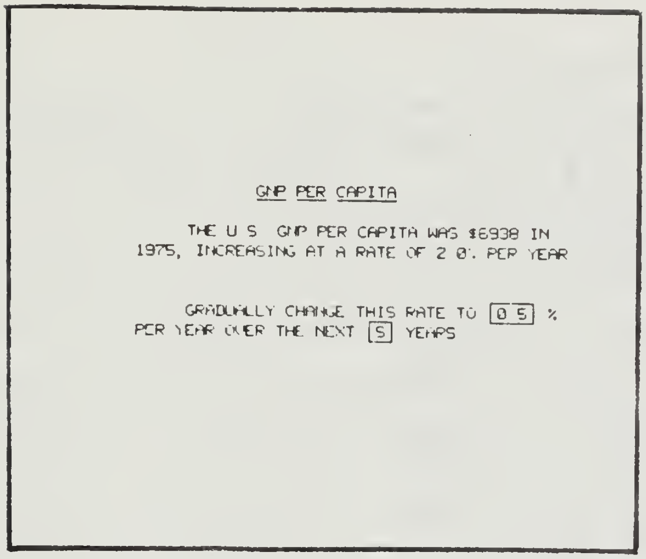

Figure 12. Change Made To GNP/Capita Growth Rate.*

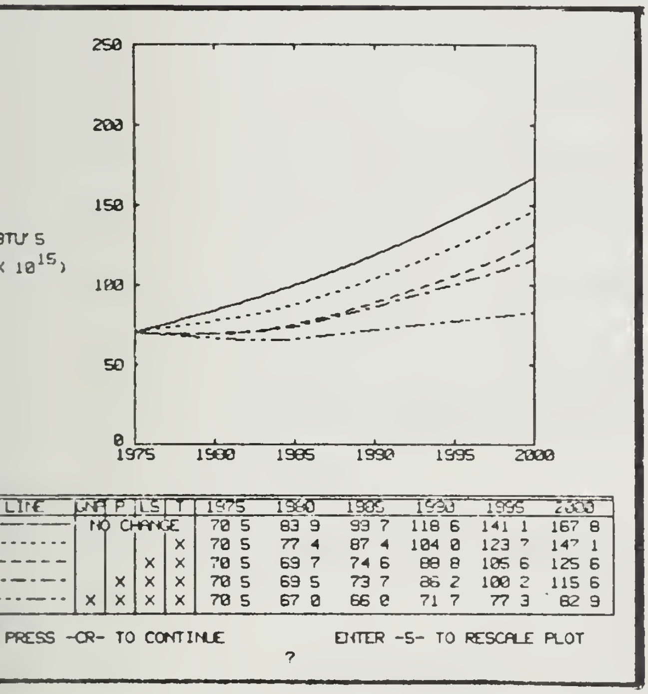

Figure 13. Plot of GNP/Capita Change In Addition To Previous Changes.

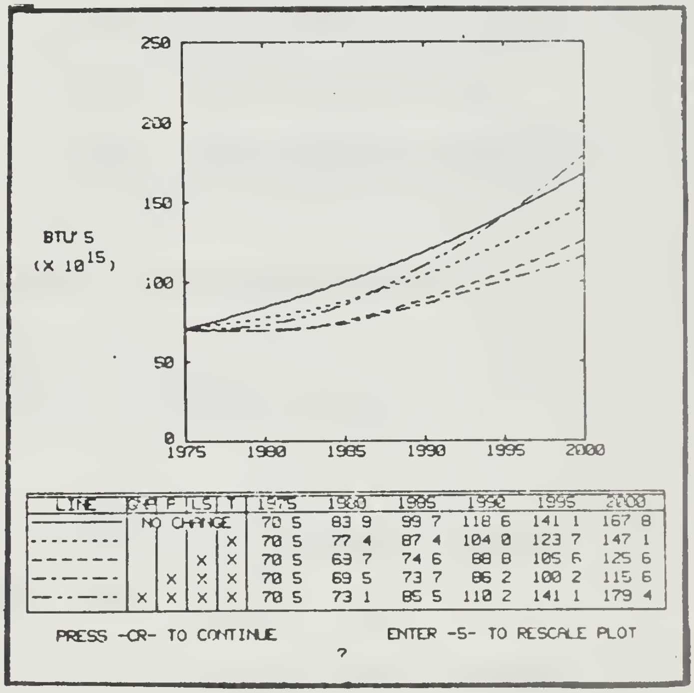

Figure 14. Result Of A GNP/Capita Growth Rate Of 4% In Addition To The Other Changes.

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*The number in the boxes were entered by the user.

Variable Changed	Year 2000 Energy Demand	Savings Compared to Historical Growth
No Change (historical growth)	167.8	----
Technology	147.1	20.7
Lifestyle	146.0	21.8
Population	154.6	13.2
GNP/capita	120.3	47.5

Table 3. Marginal Impact of Variable Changes (10^{15} Btu)

CONCLUSIONS

The model was designed and implemented with the simple, interactive user interface to enable persons to see first-hand the impacts of his or her own "solution" to the energy crisis. It is tailored specifically to the user with little or no previous exposure to computer models. Of particular importance are the educational values of: (1) dramatically emphasing the dangers of projecting exponential growth trends far into the future*; and 2) quantifying the extent to which energy and GNP growth can be decoupled through what the user feels are "feasible or acceptable" changes in technology and lifestyle. It encourages probing for the upper and lower limits to energy demand in the future.

The 106-sector detail built into the model is necessary to permit the user to specify "real" changes in lifestyle and technology, and quantify their impacts with the model. Despite the constraints imposed by the minicomputer used here,** the user is afforded considerable latitude for the specification of alternative lifestyle patterns. Future work will provide similar latitude with the technology variables through a planned telephone line interface with larger computers on the ARPA network.

When interpreting results from the present model, one must be aware of its limitations: it does not predict the future; the user must specify all parameters. The base case "historical growth" scenario

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*The user may select a planning horizon up to 100 years.

**This was chosen because it is portable enough to be moved from its home at the Congressional Office of Technology Assessment to other offices and conference sites in Washington.

is for reference purposes only. The model's greatest usefulness is that it allows a wide variety of users to determine the sensitivity of U.S. energy demand to an even wider variety of possible variations in future technologies, lifestyles, and population and economic growth.

REFERENCES

Bullard, C. W., "Energy Conservation Through Taxation," Document No. 95, Center for Advanced Computation, University of Illinois, Urbana, Illinois, February 5, 1974.

Bullard, C. W., "An Input-Output Model for Energy Demand Analysis," Document No. 146, Center for Advanced Computation, University of Illinois, Urbana, Illinois, January 1975.

Bullard, C. W. and Herendeen, R., "Energy Cost of Consumer Goods 1963/67," Document No. 140, Center for Advanced Computation, University of Illinois, Urbana, Illinois, November 1974. Also in Energy Policy, December 1975.

Bullard, C. W. and Herendeen, R., "Energy Impact of Consumption Decisions," Proceedings of the IEEE, Vol. 63, No. 3, pp. 484-493, March 1975.

Bullard, C. W. and Sebald, A. V. "A Model for Analyzing Energy Impact of Technological Change," Proceedings of the AICHE-AMS-ISA-SCI-SHARE Summer Computer Simulation Conference, San Francisco, July 1975.

The Commission on Population Growth and the American Future, Population, Resources, and the Environment, 1972.

Daly, H. E. (editor), Toward a Steady-State Economy, W. H. Freeman and Company, San Francisco, California, 1973.

Foster, C. Z., "U.S. Energy Demand Computer Model," Technical Memo No. 71, Center for Advanced Computation, University of Illinois, Urbana, Illinois, March 1976.

Freeman, D. S., "A Time to Choose," Ford Foundation Energy Policy Project, Ballinger Press, Cambridge Massachusetts, 1974.

Hannon, B. M., "Energy, Employment and Transportation," Document No. 142, Center for Advanced Computation, University of Illinois, Urbana, Illinois, December 1974; Reprinted in World Resources: The Forensic Quarterly, Vol. 49, September 1975.

Herendeen, R. A., "An Energy Input-Output Matrix for the United States, 1963: User's Guide," Document No. 69, Center for Advanced Computation, University of Illinois, Urbana, Illinois, March 1973.

Hubbert, M. K., "Energy Resources, A report to the Committee on Natural Resources," National Academy of Sciences - National Research Council Publ. 1000-D, Washington, D. C. 1962.

Knecht, R. and Bullard, C. W., "End Uses of Energy in U.S. Economy, 1967," Document No. 145, Center for Advanced Computation, University of Illinois, Urbana, Illinois, September 1975.

Noh, K. and Sameh, A., "Computational Techniques for Input-Output Econometric Models," Document No. 134, Center for Advancec Computation, University of Illinois, Urbana, Illinois, September 1974.

Nordhaus, W. and Tobin, J., "Is Growth Obsolete?" National Bureau of Economic Research Colloquim, December 1970.

U.S. Department of Commerce, Bureau of Economic Analysis, Input-Output Structure of the U.S. Economy, 1967, Vols. 1-3, Washington, D. C., 1974.

U.S. Department of Commerce, Statistical Abstract, 92nd Annual Edition, Washington, D. C., 1971.

APPENDIX A

DERIVATION OF DATA

The lifestyle data are for three classifications of final demand: personal consumption, government expenditures and private investment. The data portray the relative importance of each of the various goods and services based on the percentage of the total expenditures spent by the three components of the final demand sector.

The technology data gives the total (direct plus indirect) energy cost per dollar's worth of goods purchased by final demand. Because of pricing differences, separate technology vectors are required for each of the three components of final demand.

The sum of these vector products of the lifestyle coefficients and the technology coefficients times the total U.S. national consumption yields the total U.S. energy demand. (As described in a later section, total national consumption is similar to, but not the same as, GNP.)

The data used in this model are derived from three data bases. The three data bases contain essentially the same information but in different forms using different units. The first is the 97-order data which is a direct aggregation of the 368-order data published by the Bureau of Economic Analysis. These data are exclusively in dollar units. The second is a 90-order data set which essentially corresponds, sector by sector, to the 97-order data except that the energy sectors are expressed in Btu's rather than dollars. The sector orders are changed so that the energy sectors appear first and several "dummy" sectors are deleted. For details, see Bullard and Herendeen (1975).

The third data set is based on 101 sectors. It differs from the 90-order data in the addition of eight energy products and three additional energy supply sectors, all of which are expressed in Btu's. The energy supply sectors sell only to other energy sectors. A detailed description is given by Bullard and Sebald (1975). The correspondence between the three data sets is given in Table A1.

The information contained in the 101-order data is most of that required for the model, but, in some cases, there are problems with the units. The information not included in the 101 data base, but needed for the model, correspond to the five "dummy sectors" used to account for "paper transactions" in the National Income and Product Accounts. The final demands for these five sectors are taken directly from the 97-order data. Because of the nature of these dummy sectors, their energy intensities are defined as zero.

The numbers corresponding to the energy sectors are in physical units (Btu's) rather than dollar units as are the other sectors. This facilitates calculating energy intensities and energy demands for the majority of the sectors, but presents some problems with the energy sectors. The model requires that all final demands (lifestyle coefficients) be in dollar values rather than Btu's, and that all energy intensities (technology coefficients) be expressed in Btu's/$ and not Btu's/Btu as occurs in the energy sectors.

Lifestyle

This section describes construction of the base year (1967) lifestyle vectors in terms of 1967 purchaser's prices. In the case of the final demands, a conversion factor is required for each of the

Table A1. Sector Correspondence

106 Order	97 Order	90 Order	Sector Name	106 Order	97 Order	90 Order	Sector Name
1	7	1	Coal Mining	54	41	43	Metal Containers
2	8	2	Crude Petro, Gas	55	42	44	Heating, Plumbing
3	--	--	Converted Coal	56	43	45	Screw Mach Prod
4	31	3	Petro Refin Prod	57	44	46	Fab Metal Prod
5	77	5	Gas Utilities	58	45	47	Engines, Turbines
6	76	4	Electric Util	59	46	48	Farm Machinery
7			Nuclear Elect	60	47	49	Const, Mining Eq
8			Renewable Elect	61	48	50	Mat Handling Eq
9	--	--	Coke	62	49	51	Metalworking Eq
10	--	--	Other Feedstocks	63	50	52	Spec Ind Mach
11	--	--	Motive Power	64	51	53	Gen Ind Mach
12	--	--	Misc Thermal	65	52	54	Mach Shop Prod
13	--	--	Water Heat	66	53	55	Ofc, Comput Mach
14	--	--	Space Heat	67	54	56	Service Ind Mach
15	--	--	Air Conditioning	68	55	57	Elec Ind Apparat
16	--	--	Electric Power	69	56	58	H'Hold Appliance
17	1	6	Livestock	70	57	59	Elec Light Eq
18	2	7	Misc Ag Products	71	58	60	R-TV Commun Eq
19	3	8	Forest Fish Prod	72	59	61	Electronic Comp
20	4	9	Ag For, Fish Ser	73	60	62	Electrical Equip
21	5	10	Iron Ore Mining	74	61	63	Motor Veh & Eq
22	6	11	Nonferr Mining	75	62	64	Aircraft & Parts
23	9	12	Stone Clay Min	76	63	65	Transport Equip
24	10	13	Chem Mineral Min	77	64	66	Prof Scient Supp
25	11	14	New Construction	78	65	67	Optical Supplies
26	12	15	Maint, Rep Const	79	66	68	Misc Manufact
27	13	16	Ordnance	80	67	69	Railroad
28	14	17	Food	81	68	70	Local Transport
29	15	18	Tobacco	82	69	71	Motor Fgt Transp
30	16	19	Fabric & Mills	83	70	72	Water Fransport
31	17	20	Textile Goods	84	71	73	Air Transport
32	18	21	Apparel	85	72	74	Pipeline Transp
33	19	22	Fab Textile Prod	86	73	75	Transp Services
34	20	23	Wood Products	87	74	76	Communications
35	21	24	Wood Containers	88	75	77	R-TV Broadcast
36	22	25	H'Hold Furniture	89	78	78	Water, Sanit Ser
37	23	26	Furn, Fixtures	90	79	79	Whole, Retail Tr
38	24	27	Paper Products	91	80	80	Finance Insur
39	25	28	Paperboard Cont	92	81	81	Real Estate
40	26	29	Printing, Publ	93	82	82	Hotels, Pers Ser
41	27	30	Chem Products	94	83	83	Business Service
42	28	31	Plastics	95	84	84	Auto Repair
43	29	32	Drugs, Toil Prep	96	85	85	Amusements
44	30	33	Paints	97	86	86	Med, Educ Ser
45	32	34	Paving	98	87	87	Fed Govt Enterp
46	33	35	Asphalt	99	88	88	St, Loc Govt Ent
47	34	36	Rubber Prod	100	91	89	Business, Travel
48	35	37	Leather Products	101	92	90	Office Supplies
49	36	38	Footwear	102	93	--	Scrap
50	37	39	Glass Products	103	94	--	Govt Industry
51	38	40	Stone Clay Prod	104	95	--	World Industry
52	39	41	Prim Ir, Stl Manu	105	96	--	H'Hold Industry
53	40	42	Prim Nonfer Met	106	97	--	Inventory Adjust

energy sectors to convert Btu's to dollars. This corresponds to the price of a single Btu of energy supply or product bought by that sector. Because by definition, energy supplies are not sold to final demand, the final demands for these sectors are zero, hence no conversion is required.

Three effects must be considered to arrive at the energy cost of the various energy products: how much of which energy supply sectors goes into a particular energy product sector; the cost per Btu of the energy supply; and the efficiency of converting these energy supplies to the energy products. The cost per Btu of the energy supplies is found by taking the ratio of the final demands of the energy sectors at the 90-order level to the same final demands at the 97-order level, the 90-order level being in physical units and the 97-order data being in dollar units. The remaining two effects are included in the E_{kpj} matrix as described by Knecht and Bullard (1975). An element in this matrix represents the amount of fuel (in 10^6 Btu's) from sector k used to produce energy product p for consumption in sector j; its size is 5x8x111. In the Knecht and Bullard model, there are 101 "industries" and 10 categories of final demand resulting in 111 possible consumers of an energy product. This leads to the following equations for the dollar values of the final demands of the energy product sectors:

$$Y_{pj} = \sum_{k=1}^{5} E_{kpj} P_{kj} \qquad (A.1)$$

Y_{pj} is the final demand for energy product sector p consumed by final demand category j.

P_{kj} is the price/10^6 Btu of energy supply k which is required to produce the various energy products consumed by final demand j. Energy product p is dependent on the final demand category j because of the pricing system used by the various utilities and suppliers which give discounts to large consumers (e.g., government), but not to individuals who make up the personal consumption category of final demand. The various "mark ups" which account for these pricing differences are called margins and are given in the 101x8x3 order matrix M_{kxj}. Index k corresponds to the 101 sectors, j corresponds to the three categories of final demand and x corresponds to the eight margins: railroad transportation, pipeline transportation, truck transportation, water transportation, airline transportation, insurance, retail trade, and wholesale trade. P_{kj} is given by the following equation:

$$P_{kj} = \frac{DAFD_{kj} + \sum_{x=1}^{8} M_{kxj}}{FDC_{kj}} \qquad (A.2)$$

$DAFD_{kj}$ is the cost of purchases from sector k made by final demand j at the 97 level. In this case, k corresponds to the energy supply sectors 1-5. $DAFD_{kj}$ is in producer's prices, that is to say, it does not include margins. Adding the margins to DAFD converts the numerator to purchaser's prices.

FDC_{kj} is the total amount of energy purchased (in Btu's). This means that P_{kj} has units of \$/Btu which is needed to get Y_{pj} in \$'s ($Y(\$) = E(Btu) \times P(\frac{\$}{Btu})$). Combining these two equations gives:

$$Y_{pj} = \sum_{k=1}^{5} \frac{E_{kpj}}{FDC_{kj}} (DAFD + \sum_{x=1}^{8} M_{kxj}) \qquad (A.3)$$

The remaining final demands for sectors 17-106 are given by:

$$Y_{kj} = DAFD_{k'j} + \sum_{x=1}^{8} M_{k'xj} \qquad (A.4)$$

where k goes from 17 to 106 as k' goes from 1-97 excluding k' = 7, 8, 31, 76, 77, 89, 90 due to the different organization of the two data bases. This can be seen by examining Table A1.

The lifestyle coefficients used in this model are an aggregation of the normalized final demands. Because the magnitudes are relatively small, the results are multiplied by 100¢/$. Normalized final demands for each category of final demand (j = 1-3) are given by:

$$Y_{k'j} = \frac{Y_{kj}}{\sum_{k=1}^{100} Y_{kj}} \times 100 \qquad (A.5)$$

The aggregation is done by adding together the appropriate normalized final demands. It is not necessary to make the same aggregation for the different final demand categories. These aggregations for personal consumption and government expenditures are shown in Tables A2 and A3. Because of the nature of the investment category, it was aggregated into only one sector.

The 31 personal consumption sectors and 29 government expenditure sectors are given in Tables A4 and A5 with their corresponding lifestyle coefficients for the 1967 base year.

Table A2. Aggregation from 106 to 31 Sectors for Personal Consumption Expenditures

1. Space Heat
   14 Space Heat

2. Water Heat
   13 Water Heat

3. Gasoline
   11 Motive Power

4. Electric Lighting and Power
   16 Electric Power

5. Cooking Heat
   12 Misc Thermal

6. Air Conditioning
   15 Air Conditioning

7. Air Trans
   84 Air Transport

8. Train Trans
   80 Railroad

9. Bus Trans
   81 Local Transport

10. Truck Freight Trans
    82 Motor Fgt Transp
    86 Transp Services

11. Chemical & Plastic Products
    24 Chem Mineral Min
    41 Chem Products
    42 Plastics

12. Rubber, Paper, Glass, Stone & Paints
    23 Stone Clay Min
    38 Paper Products
    39 Paperboard Cont
    44 Paints
    47 Rubber Prod
    50 Glass Products
    51 Stone Clay Prod

13. Fabricated Metal Products
    52 Prim Ir, Stl Manu
    53 Prim Nonfer Met
    55 Heating, Plumbing
    56 Screw Mach Prod
    57 Fab Metal Prod
    65 Mach Shop Prod

14. Automobiles, Trucks & Parts
    74 Motor Veh & Eq
    76 Transport Equip

15. Textile Products
    30 Fabric & Mills
    31 Textile Goods
    33 Fab Textile Prod

16. Agricultural Products
    17 Livestock
    18 Misc Ag Products
    19 Forest Fish Prod
    20 Ag For, Fish Ser

17. Drugs & Cosmetics
    43 Drugs, Toil Prep

18. Machinery
    27 Ordnance
    34 Wood Products
    58 Engines, Turbines
    59 Farm Machinery
    62 Metalworking Eq
    63 Spec Ind Mach
    66 Ofc, Comput Mach
    67 Service Ind Mach
    68 Elec Ind Apparat

19. Food & Tobacco
    28 Food
    29 Tobacco

20. Furniture & Fixtures
    36 H'Hold Furniture
    37 Furn, Fixtures
    69 H'Hold Appliance
    70 Elec Light Eq
    73 Electrical Equip
    77 Prof Scient Supp
    78 Optical Supplies
    79 Misc Manufact

21. Books, Newspapers & Magazines
    40 Printing, Publ

22. Clothing
    32 Apparel
    49 Footwear

23. Radios & T.V.'s
    71 R-TV Commun Eq
    72 Electronic Comp

24. Water & Sanitary Serv
    89 Water, Sanit Ser

25. Hotel & Repair Serv.
    93 Hotels, Pers Ser
    95 Auto Repair

26. Medical & Educational Serv.
    97 Med, Educ Ser

27. Amusements & Business Serv.
    94 Business Service
    96 Amusements

28. Banking & Insurance
    91 Finance Insur

29. Telephone
    87 Communications

30. Housing
    92 Real Estate

31. Misc.
    1 Coal Mining
    2 Crude Petro, Gas
    3 Converted Coal
    4 Petro Refin Prod
    5 Gas Utilities
    6 Electric Util
    7 Nuclear Elect
    8 Renewable Elect
    9 Coke
    10 Other Feedstocks
    21 Iron Ore Mining
    22 Nonferr Mining
    25 New Construction
    26 Maint, Rep Const
    35 Wood containers
    45 Paving
    46 Asphalt
    48 Leather Products
    54 Metal Containers
    60 Const, Mining Eq
    61 Mat Handling Eq
    64 Gen Ind Mach
    75 Aircraft & Parts
    83 Water Transport
    85 Pipeline Transport
    88 R-TV Broadcast
    90 Whole, Retail Tr
    98 Fed Govt Enterp
    99 St, Loc Govt Ent
    100 Business, Travel
    101 Office Supplies
    102 Scrap
    103 Govt Industry
    104 World Industry
    105 H'Hold Industry
    106 Inventory Adjust

Table A3. Aggregation from 106 to 29 Sectors for Government Expenditures

1. Space Heat
   14 Space Heat

2. Misc. Heat
   12 Misc Thermal

3. Water Heat
   13 Water Heat

4. Jet & Motor Fuel
   11 Motive Power

5. Air Conditioning
   15 Air Conditioning

6. Lighting & Electrical Power
   16 Electric Power

7. Water Trans.
   83 Air Transport

8. Air Trans.
   84 Air Transport

9. Trans Trans.
   80 Railroad

10. Bus Trans.
    81 Local Transport

11. Truck Trans.
    82 Motor Fgt Transp

12. Chemical Products
    24 Chem Mineral Mining
    41 Chem Products
    42 Plastics

13. Metal Products
    22 Nonferr Mining
    52 Prim Ir, Stl Manu
    53 Prim Nonfer Met
    54 Metal Containers
    55 Heating, Plumbing
    56 Screw Mach Prod
    57 Fab Metal Prod
    65 Mach Shop Prod

14. Rubber, Paper, Glass & Stone
    38 Paper Products
    39 Paperboard Cont
    44 Paints
    47 Rubber Prod
    50 Glass Products
    51 Stone Clay Prod

15. Motor Vehicles & Trans. Equip.
    74 Motor Veh & Eq
    76 Transport Equip

16. Food & Agricultural Products
    17 Livestock
    20 Ag For, Fish Ser
    28 Food
    43 Drugs, Toil Prep

17. Machinery
    34 Wood Products
    35 Wood Containers
    58 Engines, Turbines
    59 Farm Machinery
    60 Const, Mining Eq
    61 Mat Handling Eq
    62 Metalworking Eq
    63 Spec Ind Mach
    67 Service Ind Mach
    68 Elec Ind Apparat

18. Military Hardware (Ordinance)
    27 Ordnance

19. Furniture, Office & Scientific Eq
    36 H'Hold Furniture
    37 Furn, Fixtures
    69 H'Hold Appliance
    70 Elec Light Eq
    73 Electrical Equip
    77 Prof Scient Supp
    78 Optical Supplies
    79 Misc Manufact

20. Aircraft
    75 Aircraft & Parts

21. Communication Equip.
    71 R-TV Commun Eq
    72 Electronic Comp

22. New Construction
    75 New Construction

23. Maintenance & Repair Construction
    26 Maint, Rep Const

24. Medical & Educational Serv.
    97 Med, Educ Ser

25. Business Serv.
    94 Business Service

26. Banking, Insurance & Real Estate
    91 Finance Insur
    92 Real Estate

27. Telephone
    87 Communications

28. Government Wages
    103 Govt Industry

29. Misc.
    1 Coal Mining
    2 Crude Petro, Gas
    3 Converted Coal
    4 Petro Refin Prod
    5 Gas Utilities
    6 Electric Util
    7 Nuclear Elect
    8 Coke
    10 Other Feedstocks
    18 Misc Ag Products
    19 Forest Fish Prod
    21 Iron Ore Mining
    23 Stone Clay Min
    29 Tobacco
    30 Fabric & Mills
    31 Textile Goods
    32 Apparel
    33 Fab Textile Prod
    40 Printing, Publ
    45 Paving
    46 Asphalt
    48 Leather Products
    49 Footwear
    85 Pipeline Transp
    86 Transp Services
    88 R-TV Broadcast
    89 Water, Sanit Ser
    90 Whole, Retail Tr
    93 Hotels, Pers Ser
    95 Auto Repair
    96 Amusements
    98 Fed Govt Enterp
    99 St, Loc Govt Ent
    100 Business, Travel
    101 Office Supplies
    102 Scrap
    104 World Industry
    105 H'Hold Industry
    106 Inventory Adjust

Table A4. Personal Consumption Lifestyle Coefficients

Sector Names	Cents/Dollar
ENERGY PRODUCTS	
1. Space Heat	1.89
2. Water Heat	.51
3. Gasoline	3.58
4. Electric Lighting & Power	.83
5. Cooking Heat	.27
6. Air Conditioning	.18
TRANSPORTATION	
7. Air Transportation	.48
8. Train Transportation	.10
9. Bus Transportation	.58
10. Truck Freight Transportation	.16
MANUFACTURED PRODUCTS	
11. Chemical & Plastic Products	.18
12. Rubber, Paper, Glass, Stone & Paints	1.77
13. Fabricated Metal Products	.49
14. Automobiles, Trucks & Parts	4.47
15. Textile Products	1.71
16. Agricultural Products	2.40
17. Drugs & Cosmetics	2.70
18. Machinery	.50
19. Food & Tobacco	22.51
20. Furniture & Fixtures	5.76
21. Books, Newspapers & Magazines	1.35
22. Clothing	7.33
23. Radios & T.V.'s	1.34
SERVICES	
24. Water & Sanitary Services	.39
25. Hotel & Repair Services	5.07
26. Medical & Educational Services	8.86
27. Amusements & Business Services	2.19
28. Banking & Insurance	5.44
29. Telephone	1.69
30. Housing	15.27

Table A5. Government Expenditure Lifestyle Coefficients

Sector Names	Cents/Dollar
ENERGY PRODUCTS	
1. Space Heat	.66
2. Misc. Heat	.01
3. Water Heat	.07
4. Jet & Motor Fuel	.68
5. Air Conditioning	.08
6. Lighting & Electric Power	.75
TRANSPORTATION	
7. Water Transportation	.47
8. Air Transportation	.62
9. Train Transportation	.13
10. Bus Transportation	.29
11. Truck Transportation	.62
MANUFACTURED PRODUCTS	
12. Chemical Products	1.21
13. Metal Products	.85
14. Rubber, Paper, Glass & Stone	.68
15. Motor Vehicles & Trans. Equipment	2.02
16. Food & Agricultural Products	1.25
17. Machinery	2.12
18. Military Hardware (Ordinance)	4.90
19. Furniture, Office & Scientific Eq.	1.74
20. Aircraft	5.02
21. Communication Equipment	3.95
SERVICES	
22. New Construction	14.78
23. Maintenance & Repair Construction	3.30
24. Medical & Educational Services	2.72
25. Business Services	2.45
26. Banking, Insurance & Real Estate	.79
27. Telephone	.59
28. Government Wages	47.25

Technology

The derivation of the 106 energy intensities for both the base case and for the technical fix scenario requires unit conversion similar to those done for the final demands.

Energy intensities are defined by the expression:

$$\underline{\varepsilon} = (\underline{\underline{I}}-\underline{\underline{A}})^{-1}_{\text{coal}} + (\underline{\underline{I}}-\underline{\underline{A}})^{-1}_{\substack{\text{crude}\\\text{oil}}} + 3.2511\ (\underline{\underline{I}}-\underline{\underline{A}})^{-1}_{\substack{\text{non-fossil}\\\text{electric}}} \qquad (A.6)$$

as shown by Bullard in CAC Document 146.

The energy intensities for the technical fix scenario are determined as above, but using a modified A matrix as described in Appendix B. As with the final demands, the energy intensities in CAC 146 are for producers' (not purchasers') prices, so the margins must be added in.

Due to the arrangement of units in the A matrix, the energy intensities of the energy sectors (1-16) have the units Btu/Btu rather than the Btu/$ units required by the model. This means a Btu/$ conversion factor is required for these energy sectors. This task is simplified by the fact that final demands for the first eight sectors (the energy supply sectors) are zero. This makes the value of the energy intensities for these sectors immaterial. For this reason, the energy intensities for the first eight sectors is arbitrarily set to zero.

The following equation converts the energy intensities to Btu/$ units and adds the effects of the margins for the energy product sectors:

$$\varepsilon'_{pj} = \frac{\varepsilon_p \, FD_{pj} + \sum_{k=1}^{5} \frac{E_{kpj}}{FDC_{kj}} \sum_{x=1}^{8} M_{kxj} \, \varepsilon_{x'}}{Y_{pj}} \qquad (A.7)$$

where:

FD_p is the amount of energy product p purchased by final demand j expressed in Btu's (producers' prices)

x' is the sector correspondence to margin x. As x goes from 1 to 8, x' = 80,85,82,83,84,91,90,90

In this equation the numerator is the total energy (in Btu's) purchased from energy product p by final demand j. It can be separated into two parts: $\varepsilon_p \, FD_{pj}$ is the energy purchased directly; while

$\sum_{k=1}^{8} \frac{E_{kpj}}{FDC_{kj}} \sum_{x=1}^{8} M_{kxj} \, \varepsilon_{x'}$ is the additional energy due to the margins.

The denominator is the total amount (in dollars) spent on that sector by final demand j (from equation A.3), so that ε'_{pj} has units of Btu/$.

The remaining energy intensities $\varepsilon'_{(17\text{-}101)j}$ (recall that $\varepsilon'_{(102\text{-}106)j} \equiv 0$) are determined by:

$$\varepsilon'_{kj} = \frac{\varepsilon_k \, DAFD_{kj} + \sum_{x=1}^{8} M_{kxj} \, \varepsilon_{x'}}{Y_{kj}} \qquad (A.8)$$

These energy intensities may now be aggregated into vectors of technology coefficients which correspond to the aggregations of the final demands. The aggregation is a weighted summation given in the following expression:

$$\varepsilon'_{ij} = \frac{\sum_k \varepsilon'_{kj} \, Y'_{kj}}{\sum_k Y'_{kj}} \qquad (A.9)$$

Tables A6 and A7 list the technology coefficients for both the 1967 base year and the Technical Fix Scenario for personal consumption and government categories.

Table A6. Personal Consumption Technology Coefficients

Sector Names	1967 (Btu's/Dollar)	Technical Fix Scenario (Btu's/Dollar)
ENERGY PRODUCTS		
1. Space Heat	782433	777483
2. Water Heat	719744	715919
3. Gasoline	596496	590771
4. Electric Lighting & Power	582788	578875
5. Cooking Heat	526794	524116
6. Air Conditioning	458582	455547
TRANSPORTATION		
7. Air Transportation	191482	130410
8. Train Transportation	78714	71289
9. Bus Transportation	67107	63166
10. Truck Freight Transportation	41872	32779
MANUFACTURED PRODUCTS		
11. Chemical & Plastic Products	174809	145143
12. Rubber, Paper, Glass, Stone & Paints	82245	55360
13. Fabricated Metal Products	65581	50230
14. Automobiles, Trucks & Parts	63564	48474
15. Textile Products	60249	46637
16. Agricultural Products	54536	46589
17. Drugs & Cosmetics	54375	43041
18. Machinery	51576	39438
19. Food & Tobacco	51315	41489
20. Furniture & Fixtures	48857	37011
21. Books, Newspapers & Magazines	46510	30711
22. Clothing	45349	34540
23. Radios & T.V.'s	36853	27160
SERVICES		
24. Water & Sanitary Services	113025	91944
25. Hotel & Repair Services	65344	52467
26. Medical & Educational Services	44502	36205
27. Amusements & Business Services	28567	21811
28. Banking & Insurance	23200	17544
29. Telephone	17623	13927
30. Housing	15738	12772

Table A7. Government Expenditure Technology Coefficients

Sector Names	(Btu's/Dollar) 1967	Technical Fix Scenario
ENERGY PRODUCTS		
1. Space Heat	1.60876E+06	1.59858E+06
2. Miscellaneous Heat	1.49142E+06	1.48384E+06
3. Water Heat	1.45396E+06	1.44624E+06
4. Jet & Motor Fuel	1.06623E+06	1.05599E+06
5. Air Conditioning	857007	851336
6. Lighting & Electric Power	717160	712346
TRANSPORTATION		
7. Water Transportation	226096	216110
8. Air Transportation	191482	130410
9. Train Transportation	78714	71289
10. Bus Transportation	67107	63166
11. Truck Transportation	46191	36169
MANUFACTURED PRODUCTS		
12. Chemical Products	236568	196996
13. Metal Products	111023	84665
14. Rubber, Paper, Glass & Stone	105943	70074
15. Motor Vehicles & Trans. Equipment	69216	52521
16. Food & Agricultural Products	60510	48738
17. Machinery	57844	42880
18. Military Hardware (Ordinance)	55264	41498
19. Furniture, Office & Scientific Equip	51188	38085
20. Aircraft	43338	30791
21. Communication Equipment	38066	26961
SERVICES		
22. New Construction	70592	56343
23. Maintenance & Repair Construction	54176	45508
24. Medical & Educational Services	44502	36205
25. Business Services	30780	22245
26. Banking, Insurance & Real Estate	18228	14364
27. Telephone	17623	13927
28. Government Wages	0	0

POPULATION

The historical population growth rate used in this model is based on the Series B projection of the Bureau of Census. This projection assumes a continuation of an average family size of about three children per family. It also includes an increase of 400,000 per year due to immigration resulting in a population of 277.3 million in 1990, corresponding to a growth rate of abcut 1.5% per year. Figure A1 compares this growth rate with the population levels since 1950 and shows that this projection in fact does correspond to historical growth.

GNP

GNP/capita is a measure of how much each consumer buys both directly and indirectly (indirectly meaning such things as government consumption supported by the consumer's taxes, etc.). This can be thought of as the gross national product divided by the number of consumers.

The total domestic consumption and gross national product differ only slightly. The calculation of the GNP includes inventory changes--that is to say, GNP counts goods sold to the consumer as well as those put into inventory. The total national consumption counts the goods brought from industry as well as those bought from inventory. Over a long period of time, the amount of goods put into inventory for all practical purposes equals the amount of goods sold from inventory.

The other basic difference between GNP and total consumption is how foreign trade is handled. The GNP includes exports as part of the domestic production and excludes imports because they are produced elsewhere. Total domestic consumption is just the opposite; exports

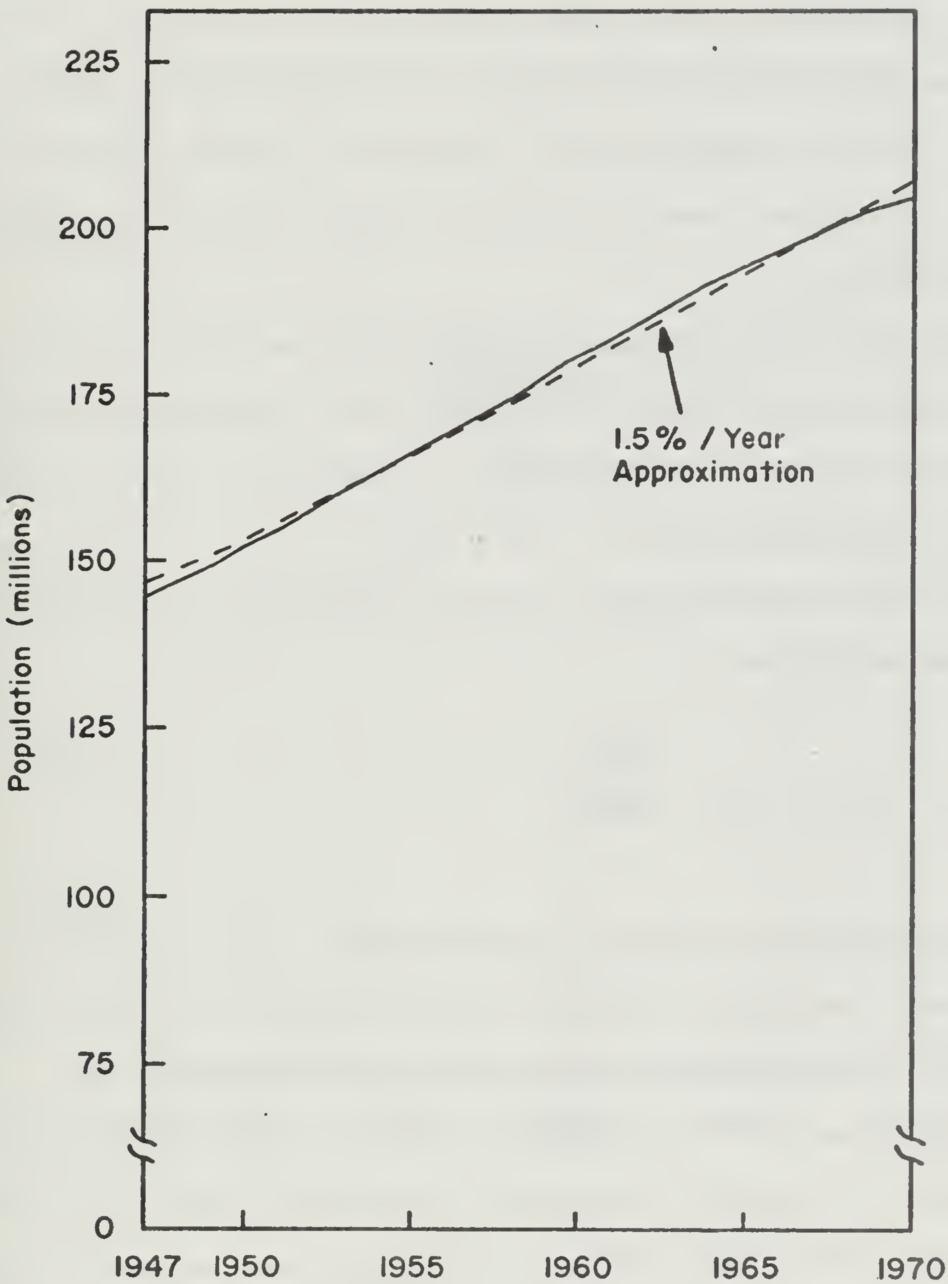

Figure A1. Correspondence Between U.S. Population and a 1.5%/year Growth Rate Approximation are excluded because they are consumed elsewhere and imports are included because they are consumed domestically. This means that the energy demand described by this model is not the energy "burned" in the U.S., but the energy required to support the American lifestyle. Though these two are numerically about the same, they are conceptually quite different.

These differences between consumption and production are small when comparing dollar values, particularly over a long period of time. The value of imports is about the same as exports and the net inventory change is approximately zero.

The total consumption (TC) base value (1975) is derived from the 1967 value as follows:

$$TC_{70} = TC_{67} * \frac{GNP_{75}}{GNP_{67}}$$

where all numbers are expressed in 1967 dollars. TC_{67} is the sum of all final demands excluding inventory change and exports. The rate of historical growth is approximately 2% per year as shown in Figure A2.

Updating the 1967 total consumption to that of 1975 by multiplying by the ratio of the GNP's is the only change made to 1967 data. In other words, the lifestyle and technology coefficients were assumed to remain constant. This assumption is not entirely true. In the late sixties, energy intensities increased due mainly to cheap energy prices during that period. The energy intensities have, however, returned to approximately those of 1967 as energy prices have increased recently. The model gives 72.7 quads as the 1974 energy demand, which nearly equals the published value of 73.1 quads.

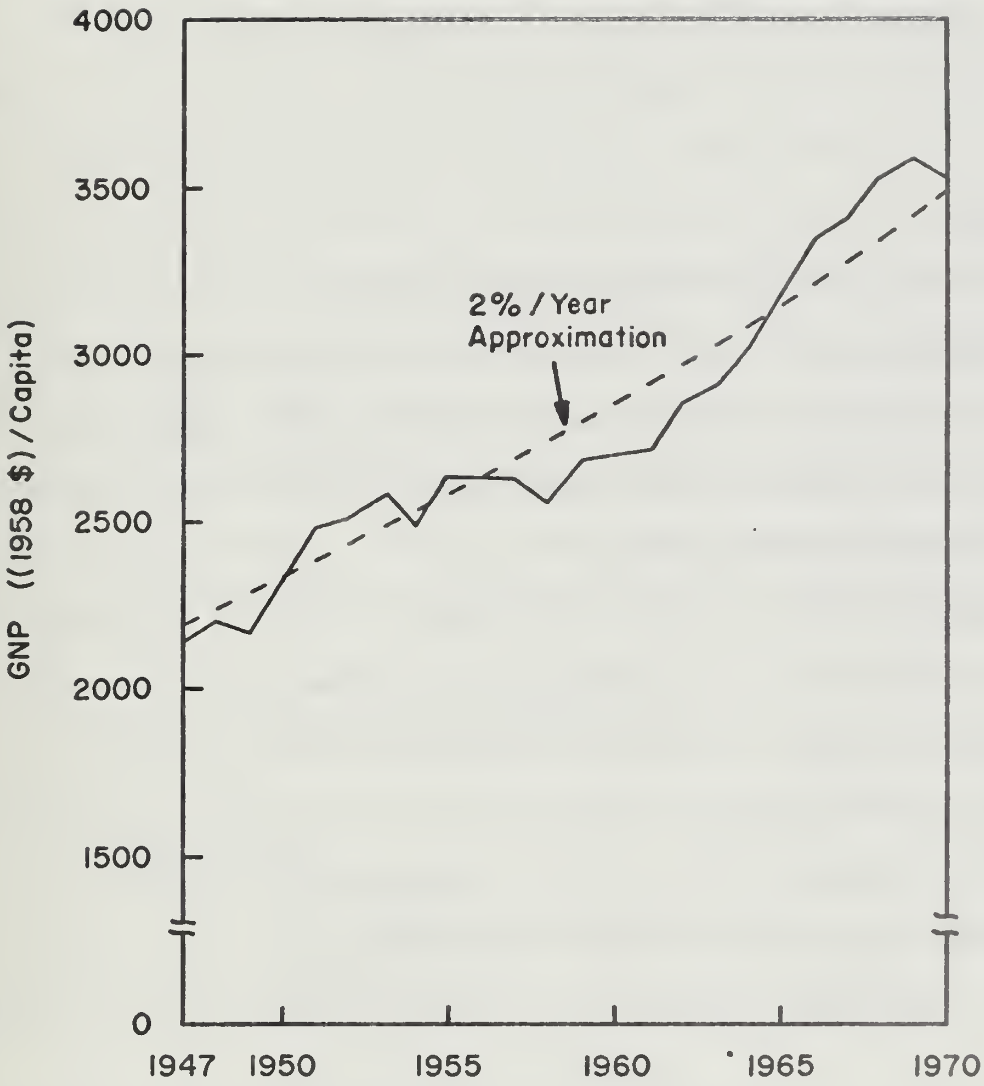

Figure A2. Correspondence Between GNP/Capita (in Constant Dollars) and a 2%/year Growth Rate Approximation

APPENDIX B

TRANSLATION OF FORD FOUNDATION TECHNICAL FIX

SCENARIO TO CHANGES IN THE CAC TECHNOLOGY MATRIX

Introduction

In late 1971 the Ford Foundation organized a group to look into the U.S. energy needs. Their final report is a book entitled, *A Time to Choose.* In this book three scenarios are presented to illustrate (not predict) the domestic energy requirements of three possible paths the U.S. may take up to year 2000.

The scenarios are: 1) Historical Growth, which is an extrapolation into the future of the increasing rate of energy consumption seen over the past 20 years; 2) Technical Fix, which reflects an effort to use energy more efficiently by putting to use the practical, economical, energy-saving technology that is either available now or soon will be; 3) Zero Energy Growth, which includes those changes made in the Technical Fix scenario plus a shift towards a less energy intensive, service oriented economy.

The reduction in energy requirements seen in the Technical Fix and Zero Energy Growth scenarios are achieved by energy-saving technological advances, a change in the mix of goods and services purchased, and by a general cutback in output seen as a reduction in the GNP. Of these, only the technological changes will be discussed here.

Description of Technology Matrix

The type of technological changes described in *A Time to Choose* can be readily transformed into changes in the coefficients of the technology matrix of the form described by Knecht and Bullard (1975). The technology matrix used here is a 101 order square matrix, where coefficient A_{ij} is the amount sector j purchases from sector i per unit output of sector j. Because the energy sectors (1-16) are in Btu's rather than dollars as are the rest of the sectors, there is a mixture of units ($\frac{Btu}{Btu}$, $\frac{\$}{Btu}$, $\frac{Btu}{\$}$, and $\frac{\$}{\$}$) in the A matrix. Of the sixteen energy sectors, the first eight are energy supplies and the second eight (9-16) are energy products. Table B1 lists these first 16 sectors.

Table B1. Energy Sectors

Supply Sectors

1. Coal mining
2. Crude Petroleum and Natural Gas
3. Converted Coal
4. Petroleum refining and related products
5. Gas utilities
6. Fossil electric utilities
7. Nuclear electric utilities
8. Renewable electric utilities

Product Sectors

9. Coke (ore-reduction) feedstocks
10. Other feedstocks
11. Motive power
12. Miscellaneous thermal
13. Water Heat
14. Space Heat
15. Air Conditioning
16. Electric Power

By definition, the non-energy sectors buy energy exclusively from the energy product sectors and the energy product sectors buy energy exclusively from the energy supply sectors. In other words, the eight energy product sectors were added as an energy accounting scheme. This technology matrix is diagrammed in Figure B1 as shown by Bullard (1975).

The energy intensity of each of the 101 sectors as given by Herendeen (1973) is:

$$\varepsilon_{ij} = \varepsilon_{\text{coal},j} + \varepsilon_{\text{crude oil and gas},\,j} + 3.2511 \times \varepsilon_{\text{non-fossil electric},j}$$

where $\varepsilon_{ij} = (\underline{\underline{I}}-\underline{\underline{A}})^{-1}_{ij}$, $\underline{\underline{A}}$ being the technology matrix.

	Energy Supply Sectors	Energy Product Sectors	Non-Energy Sectors
Energy Supply Sectors	$\frac{\text{Btu}}{\text{Btu}}$	$\frac{\text{Btu}}{\text{Btu}}$	0
Energy Product Sectors	$\frac{\text{Btu}}{\text{Btu}}$	0	$\frac{\text{Btu}}{\$}$
Non-Energy Sectors	$\frac{\$}{\text{Btu}}$	0	$\frac{\$}{\$}$

Figure B1. Distribution of Units in the Technology Matrix

Changes in the Technology Matrix for Technical Fix Scenario

The technological coefficient changes in this section correspond to the various assumptions described in *A Time to Choose.*

There are basically two types of changes made to the technology matrix. The first is a change in the energy product rows. This indicates a change in efficiency of the corresponding sectors. For example, a reduction of the coefficients in the electric power row indicate that the sectors which buy electric power can produce the same output with less electricity (an increase in efficiency). The other type of change is to shift some of one row to another row, ideally to a less energy intensive row. Specifically, this happens in the transportation sectors. For example air freight and passenger transportation are shifted to the less energy intensive truck and railroad transportation sectors.

The first change made is to the space heat and air conditioning rows. By improving building insulation, construction techniques, and also improving the design of furnaces and air conditioners, an increase in efficiency of 20 percent for space heat and 44 percent for air conditioning is possible. These changes are made to the technology matrix by multiplying the space heat row (14) by 0.80 and the air conditioning row (15) by 0.56.

In a similar manner, the amount of electric power used for lighting and small miscellaneous uses is reduced by 9 percent due to conservation and better design of equipment. This change, however, does not apply to industrial sectors whose main use of electricity is for industrial processes or to power heavy machinery. The industrial sectors will be handled separately later. This increase in efficiency is taken care of by multiplying the non-industrial columns (5-8, 17-20, 25-26, 80-101) of the electric power row (16) by a factor of 0.91.

The efficiency of automobile transportation was increased from an average of 13.6 mpg to 25 mpg which corresponds to a 45.6 percent reduction in fuel requirements. As before, this change in the motive power row does not apply to all the sectors, but only to those whose purchase of motive power is primarily for automobile transportation. This excludes the commercial transportation sectors, which are taken care of individually and the agricultural and construction sectors which are left unchanged. This leaves columns 5-8, 21-24, 27-79 and 87-101 of the motive power row (11) to be multiplied by 0.544.

The efficiency of air transportation is increased by both increasing the load factor and reducing flight speed to save fuel. This reduces the need for fuel by 32.5 percent. This means the motive power to air transportation coefficient (A(11,82)) is reduced by a factor of 0.675. Changes similar to these also apply for railroad transportation: coefficient (A(11,80)) is multiplied by a factor of 0.96. The efficiency of truck transportation is increased by converting all trucks which are gas powered to diesel fuel. Diesel powered trucks are about 30 percent more efficient than gas powered ones. This change reduces the motive power to truck transportation coefficient (A(11,82)) by 0.785.

In addition to the improvement in the transportation efficiencies described, there is also a shifting of transportation modes to conserve energy. Airline passengers traveling less than 400 miles are shifted to trains. This accounts for 10 percent of the airline passenger miles. The only place in the technology matrix where purchases from the air transportation transport row (84) are for passenger travel rather than air freight is the air transport to business travel coefficient (A(84,101)). This number is reduced by 10 percent and the railroad transport to business travel (A(80,101)) is increased by that same amount times a conversion factor of 0.76 to compensate for the lower price per mile of the railroad sector.[1] In a similar manner air freight traveling less than 250 miles (3.8 percent of all air freight) is shifted to trucks and air freight traveling less than 400 but more than 250 miles (6 percent of all air freight) is shifted to trains. These changes apply to the entire row except for the business travel column which buys no freight. Each element of the air transport row (84) (except business travel) is reduced by 9.8 percent and the corresponding amounts added to the elements of the truck (82) and railroad (80) rows times the appropriate conversion factors. The conversion factor of air ton miles per dollar to truck ton miles per dollar is 0.54 which not only compensates for the difference in price per mile but also for the additional distance that the freight must travel on trucks. The corresponding conversion factor for air to trains is 0.0871.

The final shift in transportation modes is to shift the long haul freight (more than 250 miles) which is now on trucks to trains. This accounts for about 27 percent of the truck freight. This change is accomplished by multiplying the truck transport row (82) (except business

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1. The transportation pricing and circuity data are given by Hannon (1974).

travel) by 0.73 and adding that amount times a conversion factor of 0.16 to the railroad transport row (80).

The industrial sectors are grouped together except for five energy intensive industries which are considered in detail. For the most part the industrial sectors primarily use process heat and electric power as energy products. Increased efficiencies are obtained by reducing processing losses, the cogeneration of electricity and steam, and the use of heat recuperators and regenerators.

The five industries which were dealt with separately are, paper (38), aluminum (53), steel (52), plastics (42), and cement (51). The reduced requirements for process heat for these five are: 50 percent for paper, 35 percent for aluminum, 47 percent for steel, 13 percent for plastics, and 45 percent for cement. The reduced requirements for electric power are: 100 percent for paper, 30 percent for aluminum, 48 percent for steel, 100 percent for plastic, and 31 percent for cement. The process heat requirements for the other industries (1-4, 21-24, 27-37, 39-41, 43-50, 54-79) are reduced by 0.2 percent while the electric power requirements are reduced by 54 percent.

Table B2 lists the energy intensities for a 101 order economy, both with and without the Technical Fix Scenario.

Table B2. Energy Intensities With and Without the Technical Fix Scenario

	SECTOR	ENERGY INTENSITIES 1967 (BTU/BTU)	TECH. FIX (BTU/BTU)
1	COAL MINING	1.0069	1.0057
2	CRUDE PETRO, NATURAL GAS	1.0563	1.0532
3	CONVERTED COAL	0.2264	0.2228
4	PETROLEUM REFINING,RELATED PROD	1.2052	1.1937
5	GAS UTILITIES	1.1005	1.0959
6	FOSSIL ELECTRIC UTILITIES	3.8193	3.7929
7	NUCLEAR ELECTRIC UTILITIES	4.0084	3.9300
8	RENEWABLE ELECTRIC UTILITIES	3.6271	3.6139
9	COKE (ORE-REDUCTION) FEEDSTOCKS	1.5028	1.5010
10	OTHER FEEDSTOCKS	1.1845	1.1748
11	MOTIVE POWER	6.0260	5.9683
12	MISCELLANEOUS THERMAL	1.7244	1.7157
13	WATER HEAT	2.1699	2.1586
14	SPACE HEAT	1.5728	1.5629
15	AIR CONDITIONING	1.4087	1.3998
16	ELECTRIC POWER	3.7854	3.7611
		(BTU/$)	(BTU/$)
17	LIVESTOCK & LIVESTOCK PRODS	63700	54162
18	OTHER AGRIC PRODS	69175	62054
19	FORESTRY & FISHERY PRODS	64796	57277
20	AG,FOR, & FISH SERVICES	34386	28737
21	IRON & FERRO ORES MINING	126147	96311
22	NONFERROUS METAL ORES MNG	127047	92506
23	STONE & CLAY MNG	103358	82205
24	CHEM & FERT MINERAL MNG	198830	169539
25	NEW CONSTRUCTION	78611	56364
26	MAINT & REPAIR CONSTRUCT	54603	45871
27	ORDNANCE & ACCESSORIES	55480	41592
28	FOOD & KINDRED PRODS	62148	50625
29	TOBACCO MANUFACTURES	31354	25591
30	FABRICS	101205	77290
31	TEXTILE PRODS	95798	75050
32	APPAREL	53986	40434
33	MISC TEXTILE PRODS	71632	54228
34	LUMBER & WOOD PRODS	64103	51046
35	WOODEN CONTAINERS	50826	39229
36	HOUSEHOLD FURNITURE	51854	38856
37	OTHER FURNITURE	60864	46358
38	PAPER & ALLIED PRODS	159629	80219
39	PAPERBOARD CONTAINERS	97277	57822
40	PRINTING & PUBLISHING	51114	31357
41	CHEMICALS, SELECTED PRODS	251549	209631
42	PLASTICS & SYNTHETICS	201281	160352
43	DRUGS & COSMETICS	67440	53477
44	PAINT & ALLIED PRODS	115678	95427
45	PAVING MIXTURES AND BLOCKS	558357	542873
46	ASPHALT FELTS AND COATINGS	472317	446655
47	RUBBER, MISC PLASTICS	89470	69076
48	LEATHER TANNING & PRODS	55419	46775
49	FOOTWEAR, LEATHER PRODS	43009	32571
50	GLASS & GLASS PRODS	121223	101547

Table B2 (continued)

	SECTOR	ENERGY INTENSITIES 1967 (BTU/$)	TECH. FIX (BTU/$)
51	STONE & CLAY PRODS	171333	106387
52	PRIMARY IRON, STEEL MFG	222583	172493
53	PRIMARY NONFERROUS MFG	144857	101907
54	METAL CONTAINERS	117591	89914
55	FABRICATED METAL PRODS	97071	73906
56	SCREW MACHINE PRODS, ETC	91182	68752
57	OTHER FABRIC METAL PRODS	87370	66685
58	ENGINES & TURBINES	73076	55155
59	FARM MACHINERY & EQUIPMENT	76644	59440
60	CONSTRUCTION MACH & EQUIP	75983	57909
61	MATERIALS HAND MACH & EQUIP	63543	47879
62	METALWORKING MACH & EQUIP	54131	40026
63	SPECIAL MACH & EQUIP	57231	42862
64	GENERAL MACH & EQUIP	66319	49565
65	MACHINE SHOP PRODS	55432	40571
66	OFFICE, COMPUTING MACHINES	37359	26421
67	SERVICE INDUSTRY MACHINES	65985	49120
68	ELECTRIC TRANSMISSION EQUIP	59204	42486
69	HOUSEHOLD APPLIANCES	71864	53864
70	ELECTRIC LIGHTING EQUIP	63990	47454
71	RADIO, TV, ETC EQUIP	36230	25573
72	ELECTRONIC COMPONENTS	52767	37567
73	MISC ELECTRICAL MACH	65988	48717
74	MOTOR VEHICLES, EQUIP	69058	52369
75	AIRCRAFT & PARTS	43300	30759
76	OTHER TRANSPORT EQUIP	72644	54888
77	PROFESSIONAL, SCIENT EQUIP	48506	35168
78	MEDICAL, PHOTOG EQUIP	45453	33727
79	MISC MANUFACTURING	56252	40961
80	RAILROADS AND RELATED SERVICES	79164	71696
81	LOCAL/SUBURBAN/INTERURBAN PASS.	67105	63168
82	MOTOR FREIGHT TRANS./WAREHOUSE	46274	36236
83	WATER TRANSPORTATION	226533	216535
84	AIR TRANSPORTATION	191495	130421
85	PIPELINE TRANSPORTATION	94232	83289
86	TRANSPORTATION SERVICES	6945	5367
87	COMMUNIC, EXCL BROADCASTING	17646	13946
88	RADIO & TV BROADCASTING	28864	23179
89	WATER AND SANITARY SERVICES	112885	91839
90	WHOLESALE & RETAIL TRADE	35549	27930
91	FINANCE & INSURANCE	23215	17556
92	REAL ESTATE & RENTAL	15771	12801
93	HOTELS, REPAIR SVC/EXC AUTO	74225	60185
94	BUSINESS SERVICES	30844	22295
95	AUTO REPAIR & SERVICES	48380	37733
96	AMUSEMENTS	26756	21467
97	MED, ED SERV., NONPROF ORGAN	44504	36211
98	FEDERAL GOVT ENTERPRIZES	37157	28933
99	STATE & LOCAL GOVT ENTERPZE	107211	87261
100	BUS TRAVEL, ENTERTAIN, FIGT	98427	71514
101	OFFICE SUPPLIES	75122	44274