Chapter 5

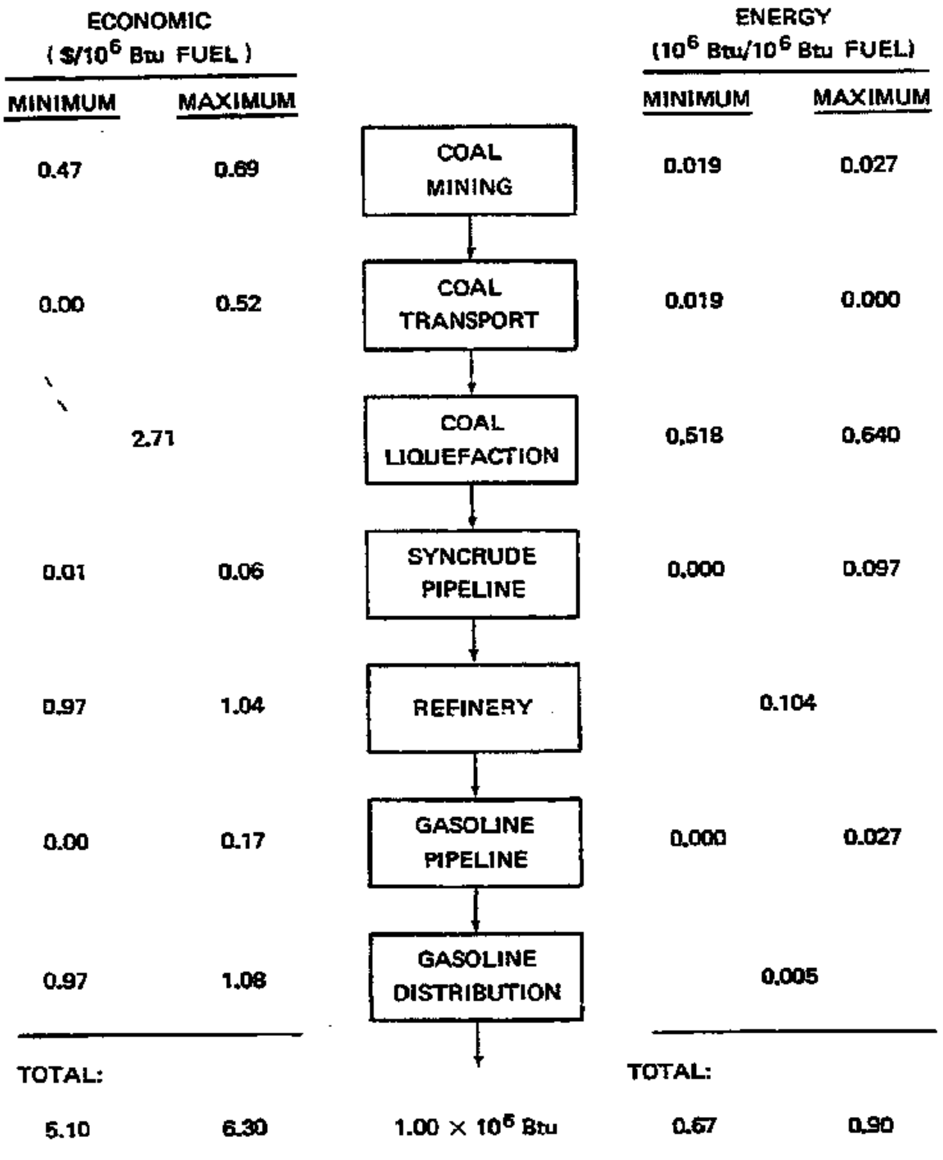
COMPARISON OF ENERGY AND ECONOMIC RESULTS

A. Summary of Results

To facilitate comparisons of the fuel costs and energy consumption calculated in the two previous chapters, the results of the eight systems analyzed have been displayed in parallel in Figures 5-1 to 5-8. The dollar costs at the left of each figure are shown on a "value added" basis. The cost of each system component is referred to the unit (10^6 Btu) of delivered energy. When there is a range of costs, the number on the left refers to the minimum (total) cost case, as determined by the computer model calculations, and the number on the right refers to the maximum (total) cost case. The component costs are added to give the total minimum and maximum automotive energy costs shown on the bottom line.

On the right of the figures, the results of the calculations of energy consumption are shown. These numbers are analogous to the dollar cost figures in terms of the maximum and minimum cases, and in terms of the additive nature of the component energy consumption values. Unlike Figures 4-1a through 4-1c, however, in which direct energy flows and ancillary energy consumption were displayed independently, only the total energy consumption at each stage is displayed in Figures 5-1 through 5-8. The total energy consumption equals the ancillary energy consumption, plus the energy conversion loss for that component. Both figures are referred to 10^6 Btu of delivered automotive fuel.

Note that the system pathways for which energy consumption figures are shown are not necessarily the same as those for which dollar costs are shown. In general, the pathways resulting in minimum or maximum cost have differed from those that lead to minimum or maximum energy consumption.



ECONOMIC ($/$10^6$ Btu FUEL) MINIMUM	ECONOMIC ($/$10^6$ Btu FUEL) MAXIMUM		ENERGY (10^6 Btu/10^6 Btu FUEL) MINIMUM	ENERGY (10^6 Btu/10^6 Btu FUEL) MAXIMUM
0.47	0.69	COAL MINING	0.019	0.027
0.00	0.52	COAL TRANSPORT	0.019	0.000
2.71		COAL LIQUEFACTION	0.518	0.640
0.01	0.06	SYNCRUDE PIPELINE	0.000	0.097
0.97	1.04	REFINERY	0.104	
0.00	0.17	GASOLINE PIPELINE	0.000	0.027
0.97	1.08	GASOLINE DISTRIBUTION	0.005	
TOTAL:			TOTAL:	
5.10	6.30	1.00 × 10^6 Btu	0.67	0.90

FIGURE 5-1. ENERGY—ECONOMIC COMPARISON: SYNCRUDE/GASOLINE

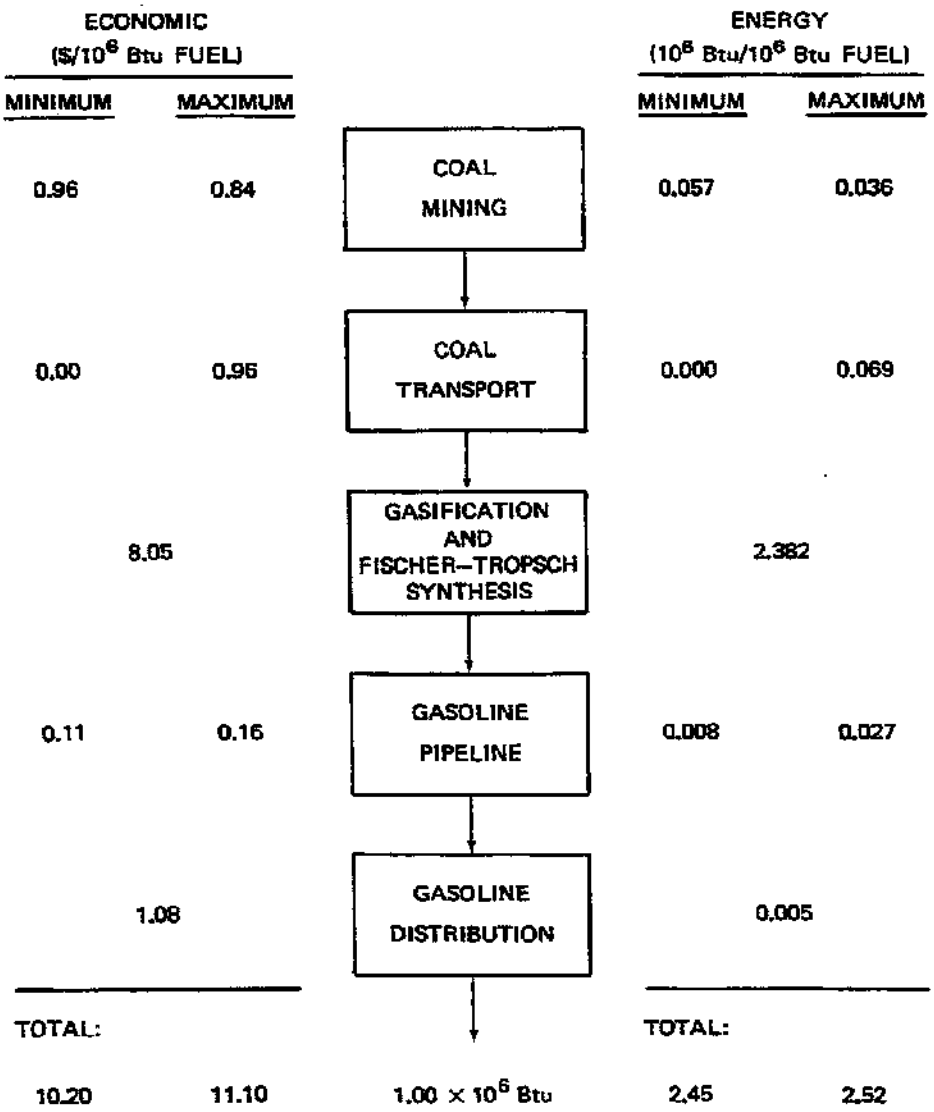


FIGURE 5-2. ENERGY–ECONOMIC COMPARISON: FISCHER–TROPSCH GASOLINE

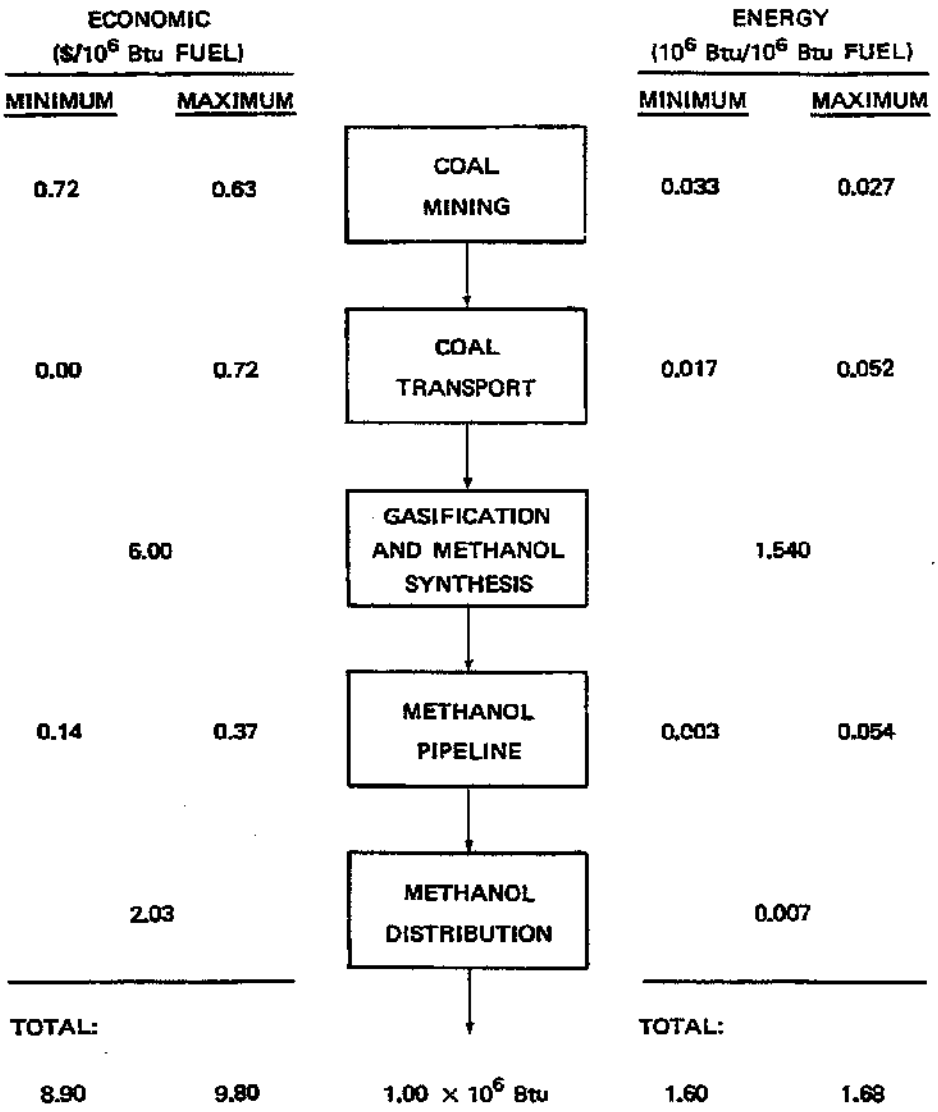


FIGURE 5-3. ENERGY—ECONOMIC COMPARISON: METHANOL

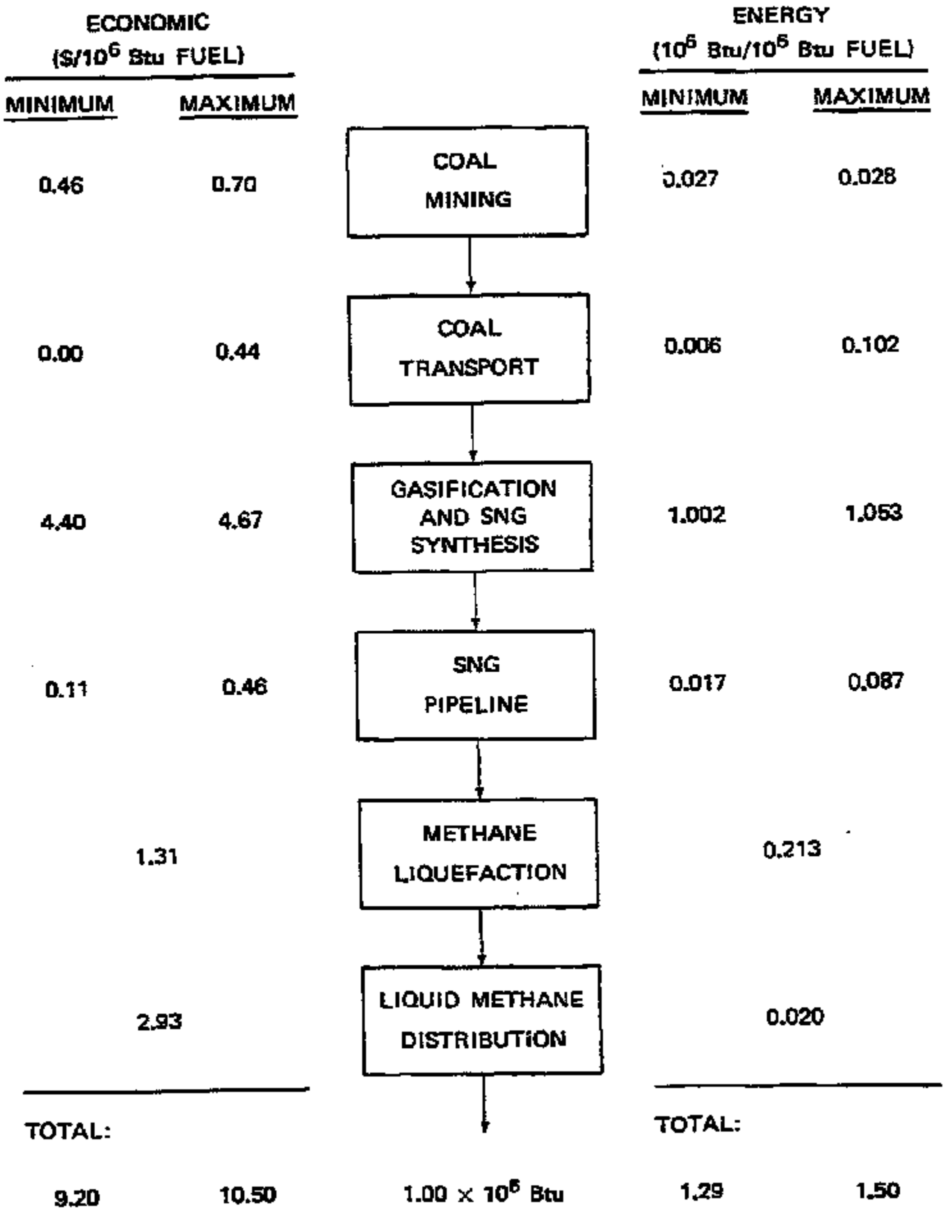


FIGURE 5-4. ENERGY—ECONOMIC COMPARISON: METHANE

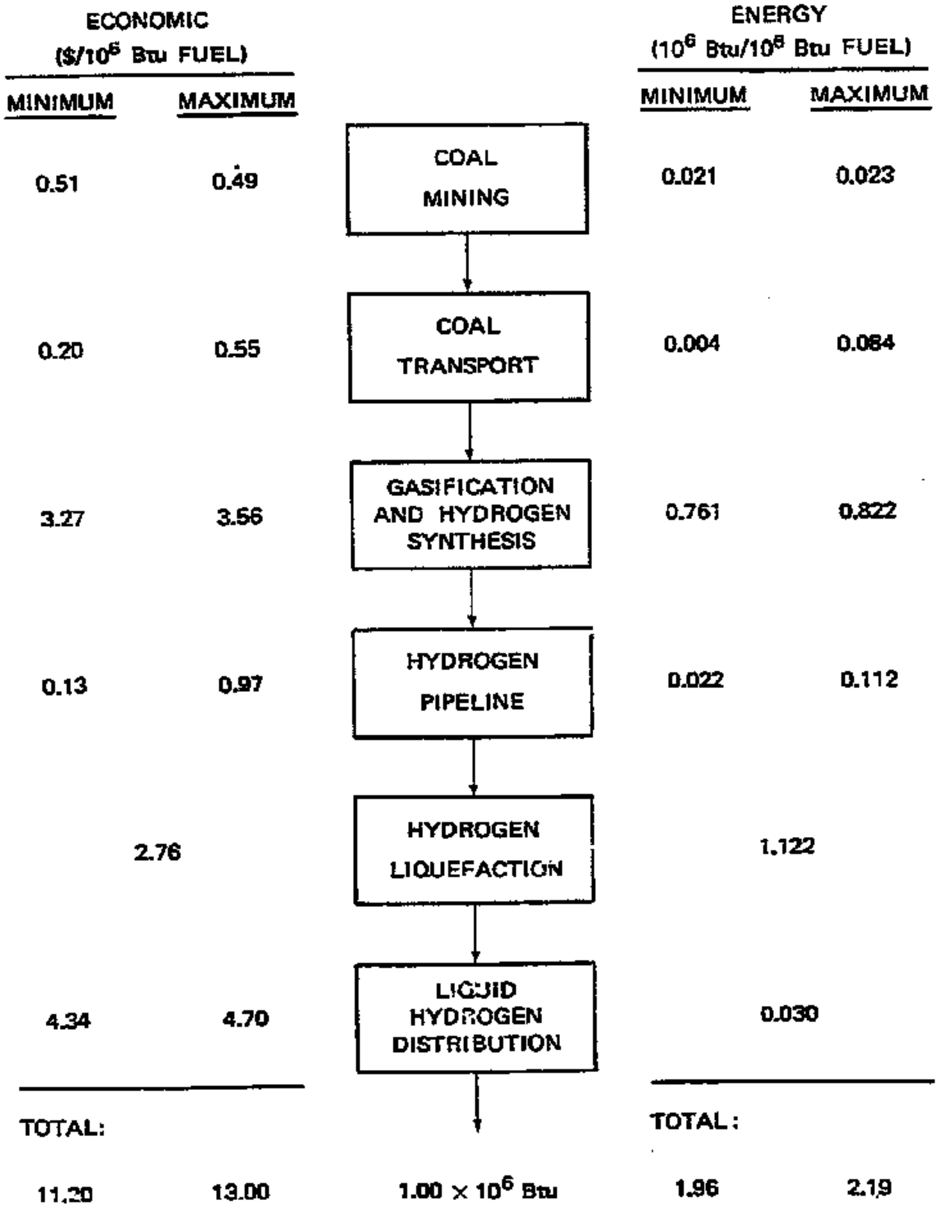


FIGURE 5-5. ENERGY–ECONOMIC COMPARISON: HYDROGEN

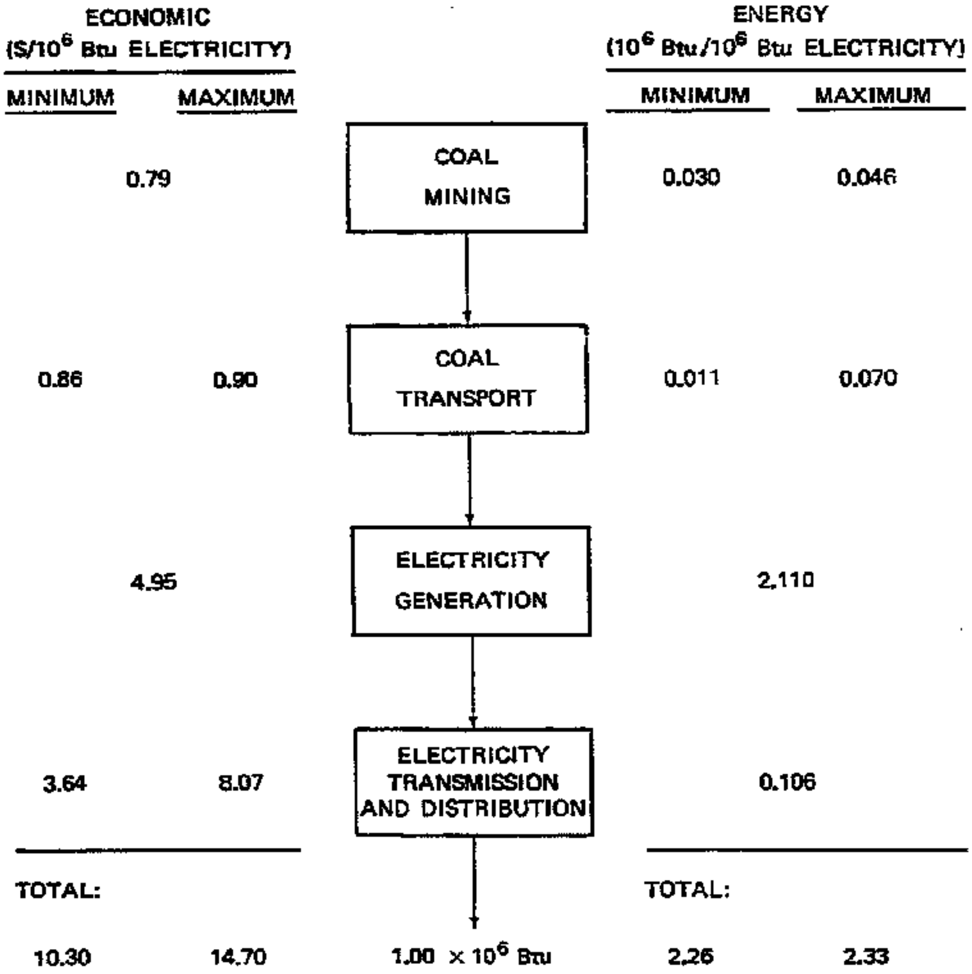


FIGURE 5-6. ENERGY—ECONOMIC COMPARISON: ELECTRICITY

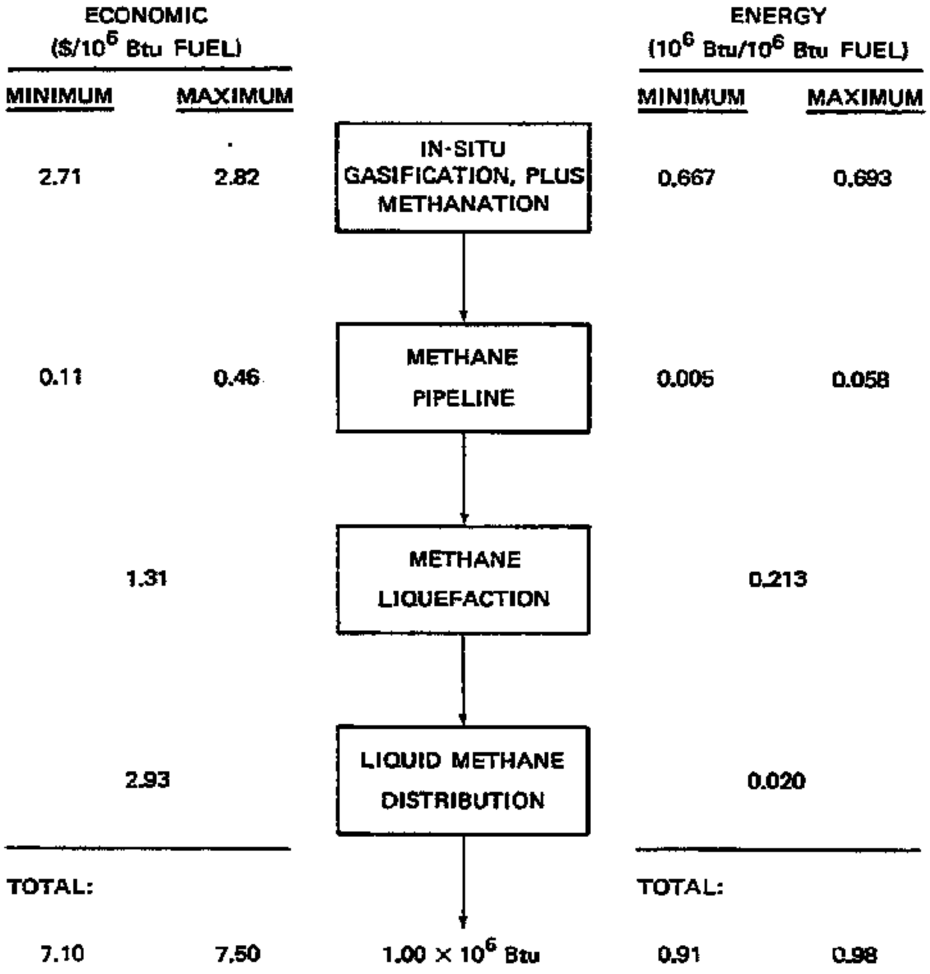


FIGURE 5-7. ENERGY—ECONOMIC COMPARISON: IN-SITU METHANE

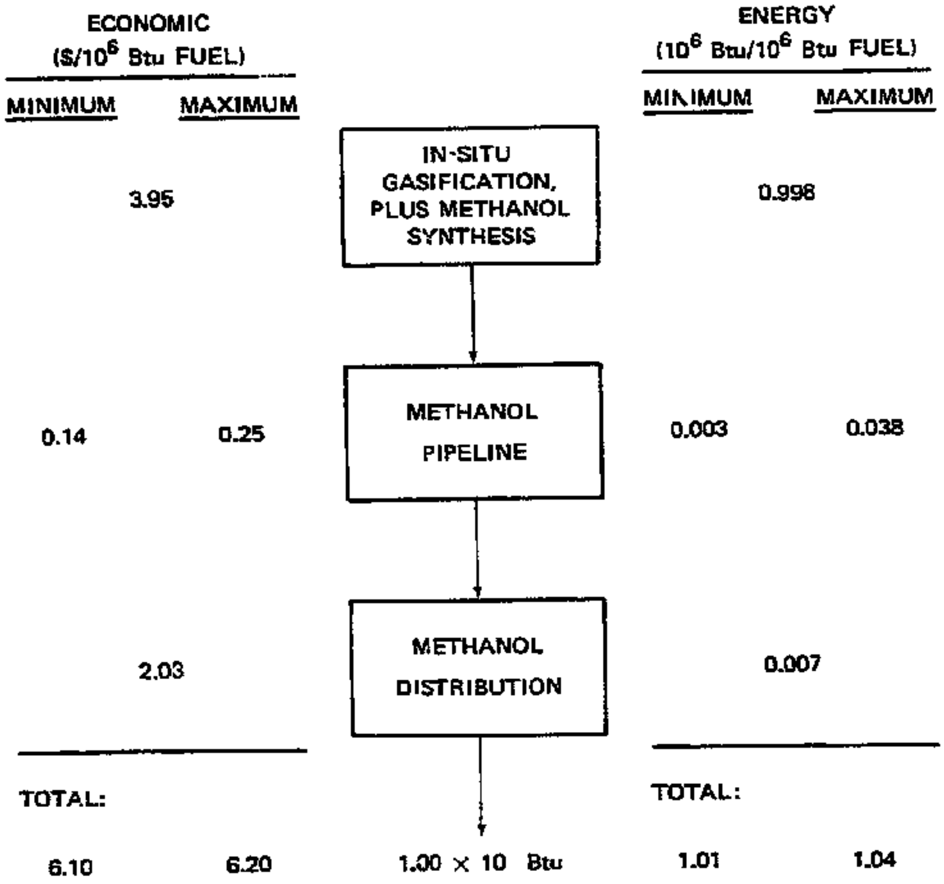


FIGURE 5-8. ENERGY—ECONOMIC COMPARISON: IN-SITU METHANOL

Examination of Figures 5-1 through 5-8 reveals interesting parallels between the consumption of energy by various system components and the corresponding costs associated with those components. In general, the most energy-consumptive system components are those that are also the most costly. For example, in the syncrude/gasoline system, two components--coal liquefaction and refining--contribute 60 to 72% of the delivered fuel cost; in terms of total energy consumption, these same components contribute 83 to 93%. Similar conclusions hold true for the other systems. The major exceptions are the fuel distribution components for which the costs are enormously out of proportion to the energy consumption.

Components that consume large amounts of energy do so because the energy form undergoes severe chemical or physical transformation as in gasifying coal, refining crude petroleum, or liquefying gaseous hydrogen. In terms of costs, these processes require large amounts of sophisticated equipment with high capital and operating costs. It is not surprising, therefore, that those system components that are the costliest also tend to consume the most energy.

For the exceptional case of fuel distribution, the high cost results from the large degree of handling required. The total costs include bulk fuel storage and transfer, delivery by truck, and dispensing the fuel at filling stations, as well as associated marketing costs such as advertising. Many of these activities are labor-intensive, and often expensive equipment is involved (such as that required for handling liquid methane or hydrogen). However, extreme physical or chemical transformations that require the expenditure of large quantities of energy are never involved.

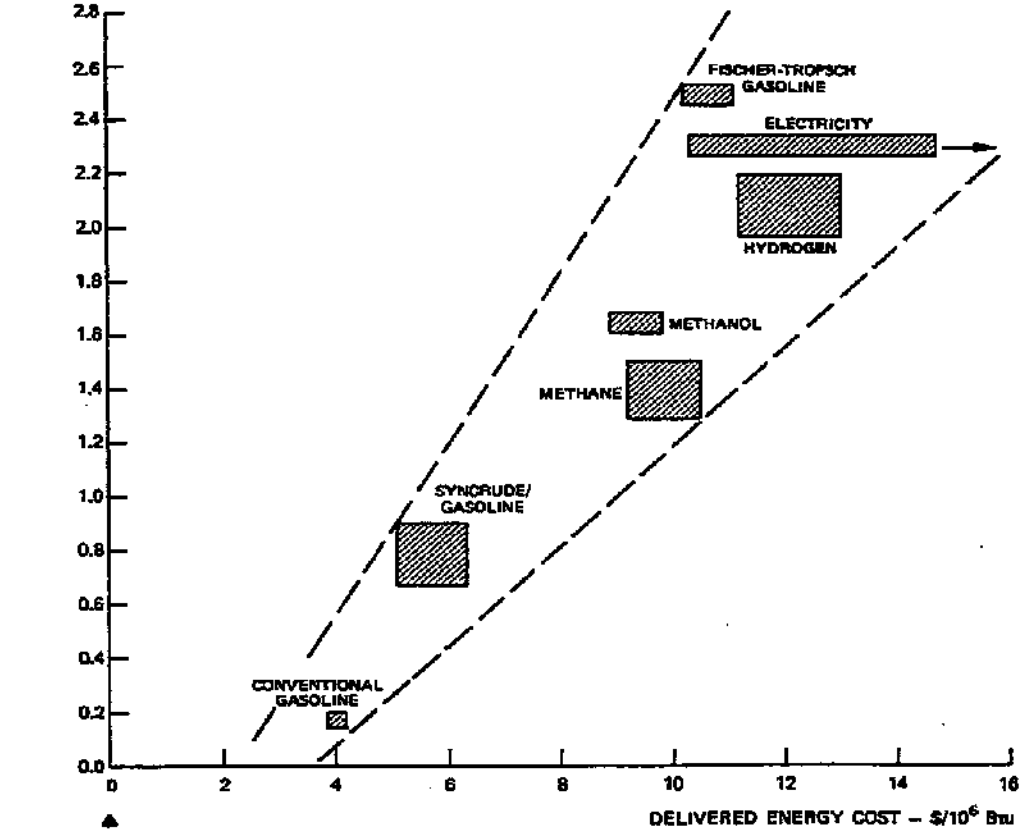
Looking at other system components reveals similar trends. Coal mining, for example, a much more labor-intensive activity than coal conversion, contributes about 5 to 10% to the total cost, whereas the corresponding energy consumption figures are 1 to 3%. However, in this and other cases (with the exception of distribution) when cost and energy consumption are out of proportion to one another, the overall contributions tend to be modest. The overwhelming tendency is for the overall system cost and energy consumption to go hand-in-hand.

B. Comparison of Costs and Energy Consumption

The preceding statement can be tested by plotting energy consumption versus cost for each energy system under consideration. Figure 5-9 displays such a plot. As a comparison case, the conventional gasoline-from-crude petroleum system is included. The coal-to-electricity system is shown with an arrow pointing to the right to indicate that this system is the only one not based on private Discounted Cash Flow (DCF) financing. Rather, it is based on utility economics, for which the recovery rate of capital is considerably less than for privately financed systems, based on about a 15% DCF rate of return. It would be fairly straightforward to calculate the electrical generation cost, based on private DCF financing, because the capital and operating costs have been specified. However, the costs of electricity transmission and distribution were taken from published information that did not break down specific capital and operating costs by region. However, based on the capital-intensive nature of both the generation and distribution portions of the system, the electricity costs shown in Figure 5-9 can be conservatively estimated to increase by at least 50% if private DCF financing were applied.

Results pictured in Figure 5-9 reinforce the notion that energy consumption tends to follow cost for synthetic automotive fuel systems. Although the variation of energy consumption with cost is not precisely a monotonically increasing function, the trend is certainly evident. When deviations from the trend (e.g., electricity and hydrogen) occur, it is generally because these systems have high-cost components—primarily distribution—that are significantly out of proportion in regard to the energy consumed. These high-cost components result from the special handling requirements of the energy form.

It would be tempting to apply the inferences present in Figure 5-9 to all types of energy systems. Such application would be futile, however, because the energy systems examined here have unique characteristics:



ARROW NEXT TO ELECTRICITY INDICATES THAT USE OF INDUSTRIAL DCF FINANCING RATHER THAN THE ASSUMED UTILITY FINANCING WOULD INCREASE ITS COST

FIGURE 5-9. ENERGY CONSUMPTION VS. COST FOR AUTOMOTIVE ENERGY SUPPLY SYSTEMS

ARROW NEXT TO ELECTRICITY INDICATES THAT USE OF INDUSTRIAL DCF FINANCING RATHER THAN THE ASSUMED UTILITY FINANCING WOULD INCREASE ITS COST

Specifically, they are both capital-intensive and energy-intensive; these two characteristics derive from the severe chemical and physical processing required to convert coal into a clean, storable, high-density energy form suitable for automotive use. Other systems more heavily dependent on other types of inputs--labor, nonenergy resources, and the like--may follow totally different patterns of cost and energy consumption. Possibly, they may follow no general pattern at all. Thus, extrapolation of the trends observed in Figure 5-9 to other types of systems without careful analysis could be misleading.

C. Conclusions

The analysis in this study has pointed out the trends in costs and energy consumption for several coal-based automotive energy alternatives. The many possible variations in coal conversion sites, and in transportation and distribution pathways have been considered. The varying efficiencies with which automobiles use the energy forms have been shown to be important in judging the relative costs and energy requirements for automotive transportation.

If we were to choose the single most attractive option, the syncrude/gasoline option would rank first as the energy supply of choice for conventional automobiles. If the successful development of advanced batteries for electric cars is assumed, the electricity option appears even more attractive. However, such a choice can never be so simple, and a host of other considerations such as automobile performance, automobile cost, refueling capability, and the like, must be brought to bear before actually choosing between one automotive option and another.

We reemphasize that narrow considerations of cost and energy consumption can never be the sole basis for public and private decisions regarding future energy systems. However, for transportation decision-makers who attempt to weigh these two parameters, among others, it appears that a decision based on low cost will tend to be an energy-conservative decision as well. Thus, a transportation decision-maker concerned primarily with energy conservation need not worry that the systems he tends to promote will be significantly more costly than others that consume more energy--at least for the capital- and energy-intensive systems considered here. Of course, systems that depend considerably less on capital and energy will have to be considered as separate instances.

APPENDICES

Appendix A

AN ALTERNATIVE APPROACH TO ENERGY ANALYSIS FOR SYNTHETIC LIQUID FUELS

A. Introduction

The calculation of energy resource consumption by energy conversion processes has usually been carried out by considering these processes in isolation from the existing energy supply network. The impacts of new processes on the energy flows through this network are never explicitly accounted for. It is possible, however, to make such an accounting by establishing the energy flows through the conventional system in the absence of the new processes, and then considering these processes as perturbations to the conventional system. The result of the calculations is an indication of the changes in energy resource consumption that would take place if a given fraction of the conventional energy supply were replaced by fuels derived from the new processes.

In the case of synthetic liquid fuels, the conventional supply system is the production and import of crude petroleum and subsequent refining into products and distribution of these products. The production of synfuels will induce changes in energy consumption in all these areas. The most likely result is that synfuels will replace imported petroleum, since this course of action has been expressed as a national goal.

In the cases in which some of the synfuels can be used more efficiently in a particular end-use application, this effect can be explicitly accounted for in the calculation of incremental energy resource consumption.

B. Energy Flows in the U.S. Petroleum System--1973

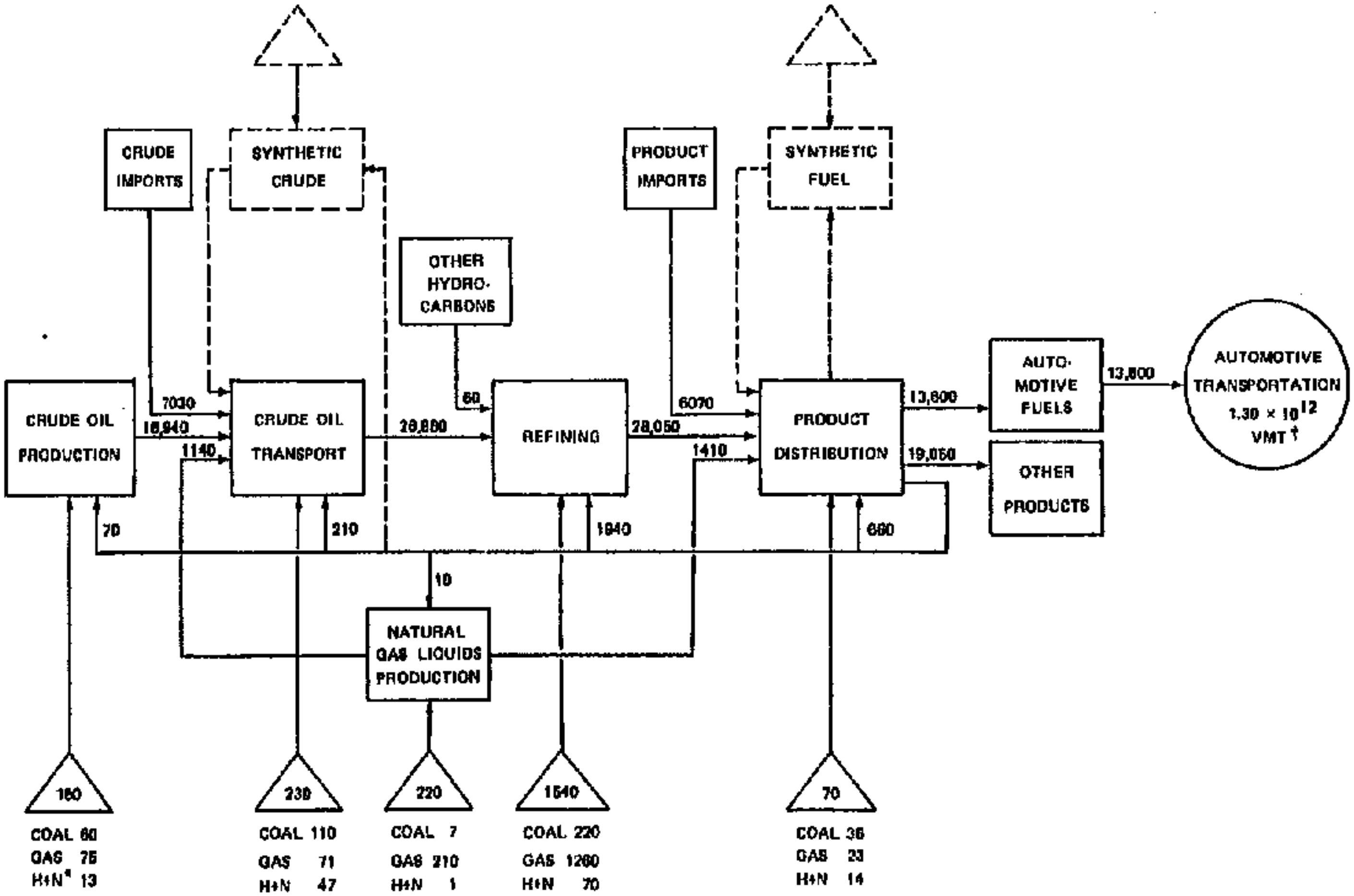
To provide a reference case with which to compare the production of synfuels, we have derived energy flows through the U.S. petroleum supply system in 1973. These energy flows, both direct and indirect, account for all the energy required to deliver refined petroleum products to the U.S. economy. The major sources of data are the Mineral Industry Surveys of the Bureau of Mines,[1] DOD transportation and energy statistics,[2] and a recent net energy study by Development Sciences, Inc.[3]

The flows of energy associated with this system are displayed in Figure A-1 in units of trillion Btu per year. In this figure, rectangles represent activities within the system, such as petroleum refining, and triangles represent the input of energy resources other than petroleum—coal, natural gas, and the fossil fuel equivalent of hydro and nuclear power. Horizontal arrows represent energy flows through the system, and vertical arrows represent direct and indirect inputs of energy required to operate and maintain the system. The feedback arrow issuing from the "Product Distribution" box represents the consumption of petroleum products by the various activities within the system.

We have divided the output of products from the system into "Automotive Fuels" and "Other Products" because further analysis will concentrate on automotive fuel demand as the specific end-use of interest. In 1973, the net automotive fuel demand of cars, trucks, and buses was 12,650 trillion Btu of gasoline and 950 trillion Btu of diesel fuel. Taken together, these quantities provided 1.30 trillion vehicle-miles of transportation (VMT). These figures are exclusive of the automotive fuels consumed within the petroleum supply system itself.

The energy flows in Figure A-1 are aggregated to a high degree, and have been averaged over different types of crude oil production, different modes of petroleum transport, and the like. They are based, however, on much more detailed data, which can only be summarized here.

The dashed portions of Figure A-1 indicate how liquid synfuels would be introduced into the conventional petroleum system. Syncrudes derived from coal and oil shale would be shipped to refineries for refining into



* H + N = HYDRO AND NUCLEAR POWER

† VEHICLE MILES TRAVELED

FIGURE A-1. ENERGY FLOWS IN THE U.S. PETROLEUM SUPPLY SYSTEM IN 1973 (10^{12} Btu/Yr) various product slates. Fuels that can be used directly without refining, such as methanol derived from coal, would be introduced directly into the product distribution system. In both cases, any direct or indirect consumption of energy resources, including petroleum, would be accounted for.

Looking at only the automotive fuels component of the petroleum product slate, we can trace through the system the contributions of the various energy sources to the production of automotive fuels. To facilitate later comparisons of different synfuels with different end-use efficiencies, automotive energy consumption can be expressed as Btu/VMT. The figures for automotive energy consumption in 1973 are shown in Table A-1. Of the total of 12,020 Btu/VMT, 10,460 went directly into the fuel tanks of cars, trucks, and buses. The difference, 1560 Btu, was consumed in the production, transport, and refining of petroleum. About 52% of this indirect energy consumption was supplied by resources other than petroleum. Of the total energy consumed, 27% was supplied by imports.

C. Use of Energy Resources in Synthetic Liquid Fuel Production

To understand the changes in energy consumption that the introduction of liquid synfuels into the U.S. petroleum supply system would involve, we must first calculate the energy requirements for each synfuel technology of interest. The appropriate methods of energy accounting by which this energy consumption is computed have been described in Chapter 5 of Volume II of this series. Basically, direct duel consumption data are obtained from engineering process analysis, whereas indirect energy consumption data are derived from cost estimates for plant construction and operation by using the energy input-output tables of Herendeen and Bullard.[4]

Energy consumption calculations have been carried out on the following technologies, based on engineering data supplied in the references noted: liquefaction of Powder River coal and Illinois coal via the H-coal process;[5] TOSCO II oil shale retorting;[6] Paraho oil shale retorting;[7] Garrett modified in-situ oil shale retorting;[8] methanol from coal via Lurgi gasification of New Mexico coal;[9] methanol from coal via Koppers-Totzek gasification of Illinois coal;[10] and methanol from coal via the Lawrence Livermore Laboratory (LLL) process for in-situ gasification of Powder River coal.[11]

Table A-1

TOTAL CONSUMPTION OF ENERGY REQUIRED TO PROVIDE FUEL FOR ONE VEHICLE-MILE OF AUTOMOTIVE TRANSPORTATION IN 1973

Energy Source	Btu
Domestic Crude and NGL*	7,960
Imported Crude	2,680
Imported Petroleum Products	570
Coal	160
Natural Gas	600
Hydro and Nuclear	50
Total	12,020
Direct Fuel Consumption	10,460

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*NGL = Natural Gas Liquids

The results of the calculations for each technology are presented in Table A-2, which shows the quantity of each type of energy resource required to produce 1 Btu of liquid synfuel. The numbers include mining of the coal or oil shale, and upgrading of the raw shale oil. The coal conversion facilities are assumed to be located at the minemouth. Energy consumption for transporting the product from the plant has not been included. Note that totals in the last column are not net energy ratios but simply ratios of total energy "in" to energy "out." (We present the results in this way to avoid the confusion that often arises when net energy ratios are presented.)

There are several reasons for the variations of energy requirements among technologies producing the same product. For oil shale, much of the variation is due to the different grades of shale assumed for each technology. For methanol, the in-situ process consumes considerably less coal as fuel than above ground gasification, even though the original fuel requirement contained in the LLL[11] estimate was too low and was doubled for this calculation. In addition, the estimates of the efficiency of in-situ gasification may be somewhat optimistic.

D. Incremental Transportation Energy Requirements for Use of Synthetic Fuels

Although the numbers in Table A-2 may be of some use in themselves, they do not readily indicate how consumption of energy resources would change if synfuels were introduced into the U.S. petroleum supply system. Using the scheme shown in Figure A-1 along with the energy requirements in Table A-2 we can calculate the changes in energy consumption induced by synfuel production. The major assumptions that have been made for this calculation are:

- Automotive transportation demand (total VMT) remains constant, as does the demand for other petroleum products
- The production of syncrude displaces imported crude oil
- The production of methanol displaces gasoline derived from imported crude oil, ultimately displacing imported crude.

Table A-2

TOTAL ENERGY RESOURCE COMMITMENT REQUIRED TO PRODUCE 1 BTU OF SYNTHETIC LIQUID FUEL

	Energy Resource (Btu)				
Technology	Coal	Crude Oil and Gas	Hydro and Nuclear	Oil Shale	Total
Syncrude from coal					
H-Coal process					
Powder River Coal	1.586	0.056	0.018	NA*	1.66
Illinois Coal	1.475	0.051	0.016	NA	1.54
Syncrude from Oil Shale					
Tosco II (35 gal/ton)	0.052	0.048	0.020	1.309	1.43
Paraho (28 gal/ton)	0.008	0.014	0.001	1.440	1.46
Modified in-situ (20 gal/ton)	0.007	0.014	0.001	1.728	1.75
Methanol from coal					
Lurgi gasification					
New Mexico Coal	2.467	0.042	0.007	NA	2.52
Koppers-Totzek Gasification					
Illinois Coal	2.581	0.051	0.007	NA	2.64
LLL In-Situ Gasification					
Powder River Coal	1.970	0.035	0.003	NA	2.01

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*NA = not applicable

A parameter must also be chosen to indicate the degree increased synfuel supply replaces fuels derived from conventional sources--imports in this case. Because the end-use here is automotive transportation, the most useful parameter is the fraction of automotive transportation provided by methanol or by gasoline and diesel fuel derived from syncrude. The results of the calculation can then be expressed as the incremental consumption of each type of energy resource required to replace a fraction, F, of automotive fuel demand by synfuels. The incremental energy requirements are expressed as coefficients of the fraction F, and are expressed in Btu/VMT. The coefficients contain all positive or negative changes in energy consumption that would occur in the petroleum supply system, relative to the base year, with the introduction of synfuels. These include changes in the amount of imported crude oil, changes in crude oil transportation energy requirements, and so forth. Thus, to obtain the total energy requirements for a given value of F, the coefficients are multiplied by F and added to the base case energy requirements.

Tables A-3a and A-3b display the incremental energy requirement coefficients for each energy resource, for the eight technologies under consideration, along with the total incremental energy requirement coefficients. In addition, the total requirement for the use of domestic resources to supply automotive transportation via synfuels is tabulated.

In Table A-3b, the calculacions for methanol assume that methanol can be burned in a properly designed internal combustion engine with an efficiency 1.33 times that of gasoline. This figure reflects quantitatively a recent assessment of methanol-fueled engines by LLL.[12] (In other words, 0.75 Btu of methanol can substitute for 1 Btu of gasoline.)

By assigning a specific value to F, we can visualize the additional demands on domestic resources required by reducing dependence of automotive transportation on imported petroleum through the use of synfuels. For example, using a value of F = 0.1 (10 percent of automotive fuel demand supplied by synfuels), the total energy consumption per vehicle-mile of transportation would increase by 4 to 8 percent; the consumption of domestic

Table A-3a

INCREMENTAL ENERGY REQUIRED TO REPLACE A FRACTION, F, OF AUTOMOTIVE FUEL DEMAND WITH SYNTHETIC LIQUIDS DERIVED FROM COAL AND OIL SHALE--BASE YEAR 1973

(Units: Btu/VMT[*])

		Syncrude				
Energy Source	Base Case	Oil Shale (Tosco II)	Oil Shale (Paraho)	Oil Shale (In-Situ)	Powder River Coal (H-Coal)	Illinois Coal (H-Coal)
Domestic Crude and NGL[**]	7,960	0	0	0	0	0
Imported Crude	2,680	-10,620F[†]	-10,800F	-10,800F	-10,570F	-10,600F
Imported Petroleum Products	570	0	0	0	0	0
Coal	160	+ 610F	+ 130F	+ 120F	+17,390F	+16,150F
Oil Shale	0	+14,290F	+15,730F	+18,900F	0	0
Natural Gas	600	+ 330F	+ 130F	+ 130F	+ 380F	+ 360F
Hydro and Nuclear	50	+ 240F	+ 30F	+ 30F	+ 220F	+ 180F
Total	12,020	+ 4,850F	+ 5,210F	+ 8,350F	+ 7,410F	+ 6,090F
Total Domestic Resources	8,770	+15,470F	+16,010F	+19,140F	+17,980F	+16,690F

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[*] VMT = Vehicle Mile of Transportation

[**] NGL = Natural Gas Liquids

[†] F = Fraction of automotive demand replaced by synfuel

Table A-3b

INCREMENTAL ENERGY REQUIRED TO REPLACE A FRACTION, F, OF AUTOMOTIVE FUEL DEMAND WITH SYNTHETIC LIQUIDS DERIVED FROM COAL AND OIL SHALE--BASE YEAR 1973

(Units:Btu/VMT[*])

	Methanol		
Energy Source	New Mexico Coal (Lurgi)	Illinois Coal (Koppers-Totzek)	Powder River Coal (In-situ)
Domestic crude and NGL[**]	0	0	0
Imported crude	-10,740F[†]	-10,700F	-10,790F
Imported petroleum products	0	0	0
Coal	+19,480F	+20,140F	+15,350F
Oil shale	0	0	0
Natural gas	- 350F	- 320F	- 370F
Hydro and nuclear	+ 20F	+ 20F	- 10F
Total	+ 8,680F	+ 9,140F	+ 4,180F
Total domestic resources	+19,420F	+19,840F	+14,970F

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[*] VMT = vehicle mile of transportation

[**] NGL = natural gas liquids

[†] F = fraction of automotive demand replaced by synfuel

energy resources would increase by 17 to 23 percent.*

E. Conclusions

The calculation of incremental resource energy requirements summarized in Tables 3a and 3b indicates that recovery of the higher grades of oil shale results in the lowest consumption of domestic energy resources of all the synfuel options. The conversion of coal to syncrude is second lowest, and the conversion of coal to methanol is the highest (with the exception of in-situ recovery), even when increased end-use efficiency is taken into account. The production of methanol from coal gasified in-situ compares quite favorably with other options. However, this process is still in the conceptual stage, and much experimental work is needed before actual operating efficiencies are known. If the favorable conversion and end-use efficiencies in Table 3a can be achieved, then the methanol route may prove attractive for coal reserves that are not efficiently recoverable by mining.

The efficiency of using in-situ recovery of lower grade oil shale resources is not as attractive as that of other syncrude options. However, the advantages of recovering a large part of the oil shale resource not otherwise recoverable should be a major consideration.

One should not imagine that these calculations are sufficient to determine the most attractive alternative for providing automotive fuels. Each option will have its own set of economic costs, environmental impacts and technical problems that will contribute to its ultimate acceptability. However, the calculations do provide an assessment of the ways in which domestic energy resource production will be affected if any of the options is pursued. This assessment is realistic in the sense that it recognizes the prior existence of a large-scale petroleum supply network with which synfuel production must interface.

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*Note that the use of methanol as an automotive fuel would actually decrease the consumption of natural gas, due primarily to the decrease in refinery fuel consumption.

The method of analysis applied in this Appendix can also be applied to the calculation of economic costs and environmental impacts associated with synfuel production. Such analysis could lead to a more comprehensive assessment of the relative attractiveness of these technologies.

REFERENCES FOR APPENDIX A

1. "Crude Petroleum, Petroleum Products and Natural Gas Liquids: 1973," U.S. Bureau of Mines, Mineral Industry Surveys Annual Petroleum Statement (1975).
2. "Summary of National Transportation Statistics," U.S. Department of Transportation, Report DOT-TSC-OST-74-8, and Energy Statistics, Report DOT-TSC-OST-74-12 (1974).
3. A. J. Frabetti et al., "A Study to Develop Energy Estimates of Merit for Selected Fuel Technologies," Development Sciences, Inc. (1975).
4. R. A. Herendeen and C. W. Bullard, "Energy Cost of Goods and Services, 1963 and 1967," University of Illinois Center for Advanced Computation Document 140 (1974).
5. R. L. Goen et al., "Synthetic Petroleum for Department of Defense Use," Stanford Research Institute (1974).
6. "An Environmental Impact Analysis for a Shale Oil Complex at Parachute Creek, Colorado," Colony Development Operation (1974).
7. S. K. Kunchal, "Energy Requirements in an Oil Shale Industry: Based on Paraho's Direct Combustion Retorting Process," Quarterly of the Colorado School of Mines: Proceedings of the Eighth Oil Shale Symposium, 70(3), 21 (July 19, 1975).
8. C. Y. Cha and D. E. Garrett, "Energy Efficiency of the Garrett In-Situ Oil Shale Process," Quarterly of the Colorado School of Mines: Proceedings of the Eighth Oil Shale Symposium 70(3), 31 (July 1975).
9. F. K. Chan, "A SASOL Type Process for Gasoline, Methanol, SNG, and Low-Btu Gas from Coal," U.S. Environmental Protection Agency Report EPA-650/2-74-072 (1974).
10. J. Pangborn et al., "Alternative Fuels for Automotive Transportation," U.S. Environmental Protection Agency, EPA-460/3-74-012c (1974).
11. A. Pasternak, "Methyl Alcohol Production by In-Situ Coal Gasification," Lawrence Livermore Laboratory, UCRL-51600 (1974).
12. H. C. Vantine et al., "The Methanol Engine: A Transportation Strategy for the Post-Petroleum Era," Lawrence Livermore Laboratory, UCIR-961 (1975).