NET ENERGY ANALYSIS OF SYNTHETIC LIQUID FUELS

Robert V. Steele

INTRODUCTION

In the past year or so, net energy analysis has received considerable attention. It has been a topic at various energy-related meetings and symposia (including this one), the subject of an NSF-sponsored workshop, and the focus of several major studies. While there is now general agreement on how net energy or energy accounting calculations should be performed, there is less agreement on the usefulness of such calculations and the ways they should be used by public or private decision-makers. This paper does not attempt to resolve disputes about the usefulness of the net energy concept. Instead, it looks at energy consumption by energy conversion technologies in a slightly different way than has been done before, and uses a somewhat different approach to caluclation. In addition, end-use considerations are included in calculations to account for differences in the efficiency with which various fuels can be used. The aim of the calculations is to provide a comprehensive view of the commitment of energy resources required to replace conventional fuels with synthetics derived from coal and oil shale, and to expand the usefulness of the net energy concept.

Robert V. Steele, Stanford Research Institute, Menlo Park, California 94025.

ENERGY FLOWS IN THE U.S. PETROLEUM SYSTEM—1973

To provide a reference case against which to compare the production of synthetic fuels, the energy flows corresponding to the United States petrply system in 1973 have been derived. These energy flows, direct and indirect, comprise all the energy required to deliver refined petroleum products to the U.S. economy. Major sources of data are: the Mineral Industry Surveys of the Bureau of Mines (1975), transportation and energy statistics of the Department of Transportation (1974), and a recent net energy study by Development Sciences, Inc. (Frabetti and others 1975).

The flows of energy associated with this system are displayed in figure 1 in units of trillion Btu per year. In figure 1, 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 hydroelectric and nuclear power). Horizontal arrows represent energy flows through the system, while vertical arrows represent direct and indirect inputs of energy required to operate and maintain the system. Notice that there is a feedback arrow issuing from the "Product Distribution" box. This

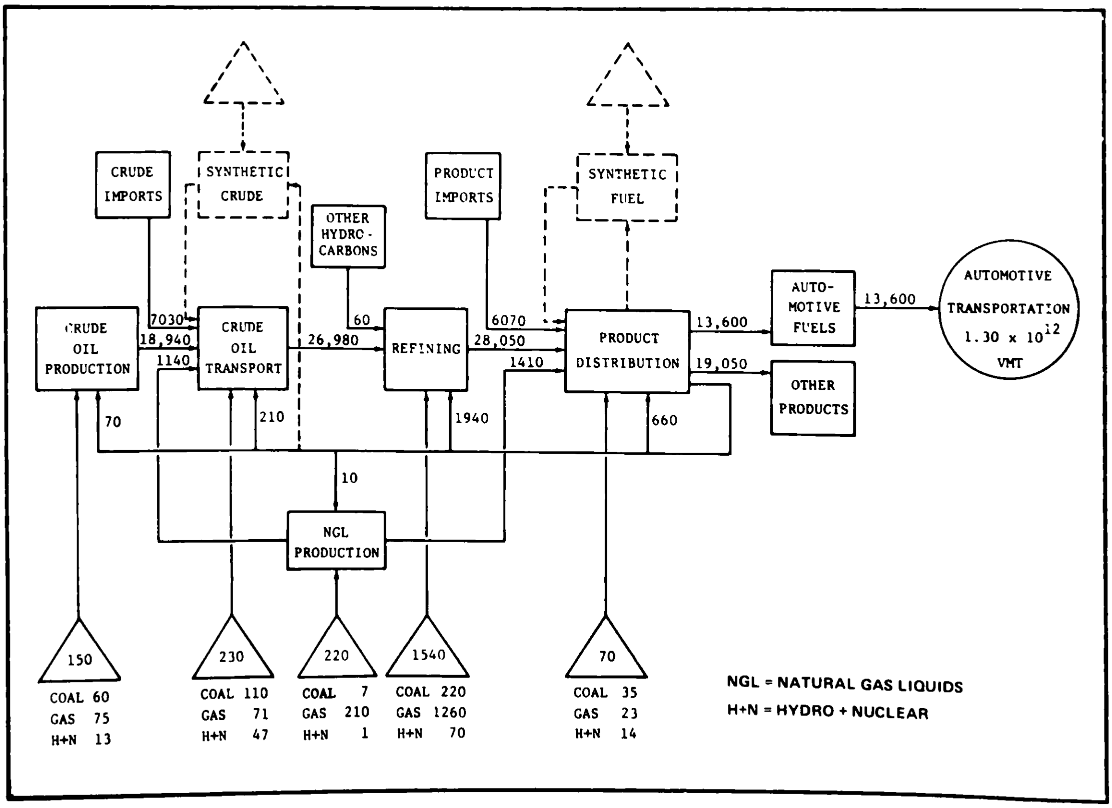

FIGURE 1.—U.S. petroleum supply system (1973 base) at 10^{12} Btu-yr.

arrow represents the consumption of petroleum products by the various activities within the system.

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

Energy flows in figure 1 are aggregated to a high degree, being averaged over different types of crude oil production, different modes of petroleum transport, etc. They are based, however, on much more detailed data which can only be summarized here.

The dashed portions of figure 1 indicate the manner in which synthetic liquid fuels would be introduced into the conventional petroleum system. Syncrudes, derived from coal and oil shale, would be shipped to refineries and be refined there into various product slates. Fuels that can be used directly without refining, such as methanol derived from coal, would be introduced into the product distribution system. In both cases, any direct or indirect consumption of energy resources, including petroleum, would be accounted for in the same manner as in the conventional petroleum system.

Looking at only the automotive fuels component of the petroleum product slate, one can trace through the system the contributions of various energy sources to the production of automotive fuels. To make later comparisons of different synthetic fuels with different end-use efficiencies easier, automotive energy consumption can be expressed as Btu per VMT. The figures for automotive energy consumption in 1973 are shown in table 1. Of the total of 12,020 Btu consumed per VMT, 10,460 went directly into the fuel tanks of cars, trucks and buses. The difference, 1,560 Btu, was consumed in the production, transport, and refining of petroleum. About 52 percent of this indirect energy consumption was supplied by resources other than petroleum. Of the total energy consumed, 27 percent was supplied by imports.

USE OF ENERGY RESOURCES IN SYNTHETIC LIQUID FUEL PRODUCTION

To understand the changes in energy consumption that the introduction of synthetic liquid fuels into the U.S. petroleum supply system would involve, one must first calculate the energy consumed by each synthetic

TABLE 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

fuel technology of interest. Appropriate methods of energy accounting for computing this energy consumption have been thoroughly described elsewhere (Frabetti and others 1975). Basically, direct fuel consumption data are obtained from engineering process analysis, while indirect energy consumption is derived from cost estimates for plant construction and operation, using the energy input-output tables of Herendeen and Bullard (1974).

As an example of this procedure, figure 2 illustrates the annual energy inputs required to produce 100,000 barrels per day (B/D) of synthetic crude oil via the H-Coal process, using strip-mined coal from the Powder River Basin of Wyoming. Materials and fuel inputs are shown as squares and ovals, respectively; energy resource consumption is shown in triangles, as in figure 1. The various energy inputs into coal mining and transport are combined for simplicity.

In addition to liquefaction of Powder River coal, energy accounting calculations have been carried out on the following technologies, based on engineering data supplied in the reference following each technology:

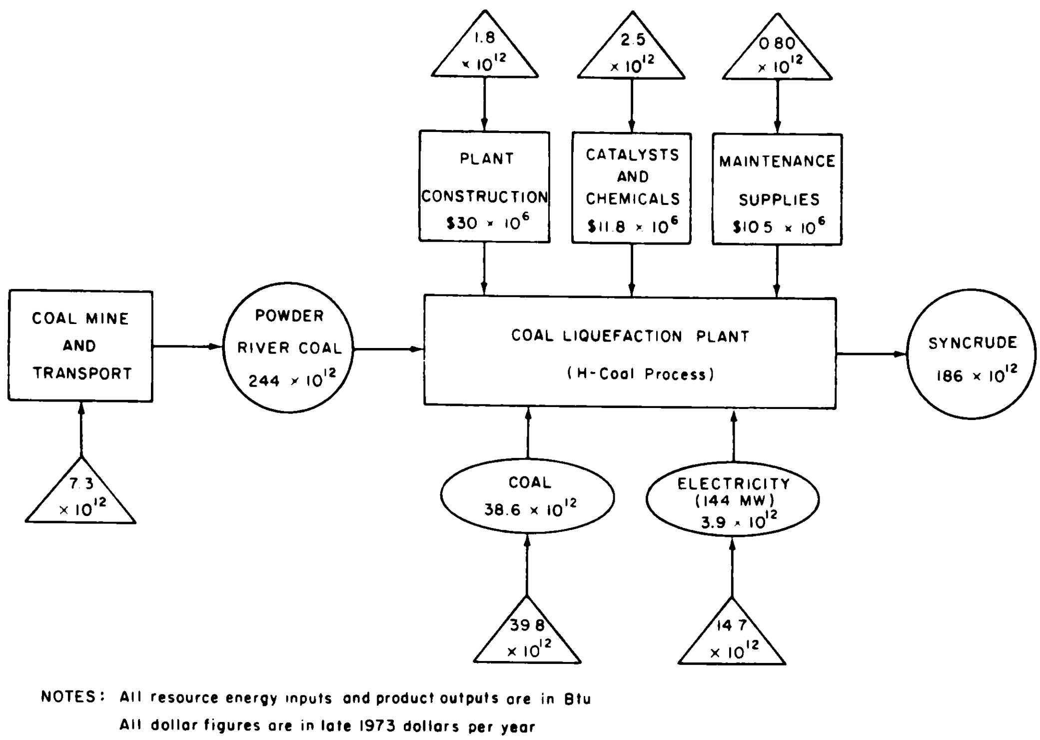

FIGURE 2.—Annual energy inputs for construction and operation of a 100,000 barrels per day H-Coal process coal liquefaction plant.

(1) liquefaction of Illinois coal via the H-Coal process (Goen, Clark, and Moore 1974);
(2) TOSCO II oil shale retorting (Colony 1974);
(3) Paraho oil shale retorting (Kunchal 1975);
(4) Garrett modified in situ oil shale retorting (Cha and Garrett 1975);
(5) menthanol from coal via Lurgi gasification of New Mexico coal (Chan 1974);
(6) methanol from coal via Koppers-Totzek gasification of Illinois coal (Pangborn and others 1974);
(7) and methanol from coal via the Lawrence Livermore Laboratory (LLL) process for in situ gasification of Powder River coal (Pasternak 1974).

The results of the calculations for each technology are presented in Table 2, which shows the quantity (in Btu) of each type of energy resource required to produce one Btu of synthetic liquid fuel. The numbers include mining of coal or oil shale, and upgrading of the raw shale oil. The coal conversion facilities are assumed to be mine-mouth. Energy consumption for transport of the product from the plant to distant destinations has not been included. It should be noted that the

TABLE 2.—*Total energy resource commitment required to produce 1 Btu of synthetic liquid fuel*

	Energy Resource (Btu)				
Technology	Coal	Crude Oil and Gas	Hydro & Nuclear	Oil Shale	Total
Syncrude from coal					
H-Coal process					
Powder River coal	1.586	.056	.018	-	1.66
Illinois coal	1.475	.051	.016	-	1.54
Syncrude from oil shale					
Tosco II (35 gal/ton)	.052	.048	.020	1.309	1.43
Paraho (28 gal/ton)	.008	.014	.001	1.440	1.46
Mod. In-situ (20 gal/ton)	.007	.014	.001	1.728	1.75
Methanol from coal					
Lurgi gasification					
New Mexico coal	2.467	.042	.007	-	2.52
Koppers-Totzek gasification					
Illinois coal	2.581	.051	.007	-	2.64
LLL In-situ gasification					
Powder River coal	1.970	.035	.003	-	2.01

totals shown in the last column are not net energy ratios but simply ratios of total energy "in" to energy "out." The results are presented in this way to avoid some of the confusion that often arises when net energy ratios are presented.

There are varoius reasons for variation in energy requirements among technologies producing the same product. For oil shale, a large part 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 for the process than aboveground gasification even though the original fuel requirement, contained in Pasternak's (1974) estimate, appears rather low and was doubled for this calculation. Also, the estimates of the efficiency of in situ gasification may be somewhat optimistic.

INCREMENTAL TRANSPORTATION ENERGY REQUIREMENTS FOR USE OF SYNTHETIC FUELS

Although the numbers in table 2 may be of some use in themselves, they do not readily provide insight into the ways in which the consumption of energy resources would change if synthetic fuels were introduced into the U.S. petroleum supply system. Using the scheme shown in figure 1, along with the energy requirements in table 2, one can calculate the changes in energy consumption induced by synthetic fuel production. To carry out the calculation, certain major assumptions are needed:

(1) Automotive transportation demand (total VMT) remains constant, as does demand for other petroleum products
(2) Production of syncrude displaces imported crude oil
(3) Production of methanol displaces gasoline derived from imported crude oil, ultimately displacing imported crude.

In addition to specifying the assumptions, a parameter must be chosen that will reflect the degree to which an increase in the supply of snythetic fuels will replace fuels derived from conventional sources; imports, in this case. Since the particular end-use under consideration is automotive transportation, the most useful parameter is the fraction of automotive transportation provided by gasoline and diesel fuel derived from syncrude, or by methanol. Then the results of the calculation can be expressed as the incremental consumption of each energy source required to replace a fraction, F, of automotive fuel demand by synthetic fuels. The incremental energy requirements are expressed as coefficients of the fraction F, and are expressed in units of Btu per VMT. The coefficients contain all changes in energy consumption, positive or negative, that would occur in the petroleum supply system, relative to the base year, with the introduction of synthetic fuels. 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 3a and 3b display the incremental energy requirement coefficients for each energy source, along with the total incremental energy requirement coefficients, for each of the eight technologies under consideration. Also tabulated is the total amount of domestic resources required to supply automotive transportation needs through synthetic fuels.

In table 3b, calculations for methanol are based on the assumption 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 Lawrence Livermore Laboratory (Vantine and others 1975). It means that 0.75 Btu of methanol can substitute for 1 Btu of gasoline.

By choosing some value of F, one can visualize the additional demands on domestic resources required by a strategy that reduces the dependence of automotive fuels on imported petroleum through the use of synthetics.

TABLE 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

TABLE 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

For example, using a nominal value of F = 0.1 (10 percent of automotive fuel demand supplied by synthetics), energy consumption per vehicle-mile of transportation would increase by 4-8 percent. Furthermore, consumption of domestic energy resources would increase by 17-23 percent.*

CONCLUSIONS

To aid in understanding the commitment of energy resources required by a strategy which replaces imported petroleum with synthetic fuels, increases in energy consumption have been calculated for eight different synthetic liquid fuel technologies, focusing on automotive transportation as the end use for these fuels.

From the calculation of incremental resource energy requirements summarized in tables 3a and 3a, it appears apparent that recovery of the higher grades of oil shale results in the lowest consumption of domestic energy resources. The conversion of coal to syncrude is intermediate, and the conversion of coal to methanol results in the highest consumption (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 favorably with other options. However, this process is still in the conceptual stage; much experimental work will have to be done before actual operating efficiencies are known. If the favorable conversion and end-use efficiencies, reflected in table 3a, can be achieved, then the in situ methanol route may prove an attractive option for use of that portion of the nation's coal reserves that are not efficiently recoverable by mining.

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

This last statement leads to a final, important point which should be raised with regard to energy efficiency or net energy calculations for new energy technologies: Such calculations provide only one of many inputs into decisions to employ such technologies. Because such calculations are carried out, and sometimes widely publicized, does not mean they are meant to be used as the sole criteria in energy policy decisions. Rather, they should be examined in a broad context along with considerations of cost, environmental impact, marketing requirements, resource availabili-

*Note: use of methanol as an automotive fuel would actually decrease the consumption of natural gas; primarily because of a decrease in refinery fuel consumption.

ty, and so forth. Properly used, such calculations can provide valuable information that can be incorporated into decisions regarding the best use of the nation's energy resources.

ACKNOWLEDGMENT

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REFERENCES

Cha, C. Y., and Garrett, D. E., 1975, Energy efficiency of the Garrett in situ oil shale process: Proc. Eighth Oil Shale Symposium, Colorado School Mines Quart., v. 70, no. 3, July, p. 31-40.

Chan, F. K., 1974, A SASOL type process for gasoline, methanol, SNG, and low-Btu gas from coal: U.S. Envirn. Prot. Agency Report no. EPA-650/2-74-072.

Colony Development Operation, 1974, An environmental impact analysis for a shale oil complex aat Parachute Creek, Colorado.

Frabetti, A. J., and others, 1975, A study to develop energy estimates of merit for selected fuel technologies: Development Sciences, Inc.

Goen, R. L., Clark, C. F., and Moore, M. A., 1974, Synthetic petroleum for d of defense use: Stanford Research Institute.

Herendeen, R. A., and Bullard, C. W., 1974, Energy cost of goods and services, 1963 and 1967, Univ. Ill. Center for Advanced Computation, Document no. 140.

Kunchal, S. K., 1975, Energy requirements in an oil shale industry: based on Paraho's direct combustion retorting process: Proc. Eight Oil Shale Symposium, Colorado School Mines Quart., v. 70, no. 3, July, p. 21-30.

Pangborn, J., and others, 1974, Alternative fuels for automotive transportation: U.S. Envirn. Prot. Agency Report no. EPA-460/3-74-012c.

Pasternak, A., 1974, Methyl alcohol production by in situ coal gasification: Lawrence Livermore Laboratory Report no. UCRL-51600.

U.S. Bureau of Mines, 1975, Crude petroleum, petroleum products and natural gas liquids: 1973, Mineral Industry Surveys Annual Petroleum Statement.

U.S. Department of Transportation, 1974, Summary of national transportation statistics: Report no. DOT-TSC-OST-74-8, and Energy Statistics, Report no. DOT-TSC-OST-74-12.

Vantine, H. C., and others, The methanol engine: a transportation strategy for the post-petroleum era: Lawrence Livermore Laboratory Report no. UCIR-961.