Chapter 1

INTRODUCTION

A. The Concept of Energy Analysis

As the nation strives to reduce its dependence on foreign petroleum sources, technologies for converting coal and oil shale to liquid and gaseous fuels become increasingly important. Our study in Volume II of this series, "Synthetic Liquid Fuels Development: Assessment of Critical Factors,"[1] was addressed to policy makers investigating alternative pathways to synthetic fuel (synfuel) development. The study detailed the anticipated impacts of the new, large-scale industry required for such development.

These new synfuel systems must be examined for multiple factors: economic and technical feasibility, environmental impact, socioeconomic effect, and capital availability. But it is an additional factor—these systems' effective use of energy resources—that primarily concerns us here. The analytical tool that we have found useful for determining the energy resources required to produce and deliver a given quantity of synfuel is energy analysis, sometimes called net energy analysis or energy accounting.

Energy analysis applied to the production of fuels determines the yield of useful energy of any energy-conversion process after extraction, processing, transportation, and distribution of the final product have taken place. The "energy cost" derived by this analysis represents the total energy that must be consumed to deliver a unit of energy product such as gasoline. Thus, energy analysis accounts for all energy flows in a single resource-to-fuel system. It also allows the comparison of different energy systems that provide the same end-use to determine their relative energy resource intensities.

B. Comparisons with Economic Analysis

Many economists assert that explicit consideration of energy inputs into energy supply systems does not appreciably enhance traditional economic analysis. This would indeed be the case if energy prices reflected the true costs, including environmental and social costs, of producing and delivering energy. Such energy pricing, coupled with a free market, could then provide optimal allocation of energy resources.

In practice, such conditions do not hold. The government regulates domestic energy markets, and the OPEC cartel arbitrarily maintains the petroleum prices that influence those markets. Thus, real-world energy prices are determined by other factors than those that would yield optimal allocation of resources.

Economic analysis must recognize the role of energy consumption because the price of raw energy, working through a feedback mechanism, is a primary force in driving inflation. As raw energy prices increase, the cost of delivered energy in the form of fuels and electricity increases. As a result, the costs of goods and services, which are all energy-dependent to some extent, increase, in turn raising the cost of refining petroleum, mining coal, exploring for new energy deposits, and similar activities. This cost rise increases delivered energy prices, and the cycle continues.

Thus, the cost of fuels is doubly sensitive to the price of raw energy, both through use of the resources themselves and through the further use of energy in processing. For example, it may be calculated that at 1975 prices, about 20% of the cost of converting western subbituminous coal to synthetic crude oil (syncrude)—assuming the technology were available—would be due to the cost of raw energy—coal, crude oil and gas, and hydro and nuclear power. Of this 20%, feed coal for the liquefaction process comprises two-thirds of the cost; the other one-third is due to the direct and indirect consumption of energy required to run the process. In other words, coal liquefaction requires 530,000 Btu of raw energy to produce one dollar worth of product (1975 costs). This may be compared with the 40,000 Btu consumed per dollar of output for U.S. industry as a whole and the 370,000 Btu per dollar of output (gasoline) fc⁻ petroleum refining.

What must be concluded, therefore, is that energy analysis is a useful descriptive tool to complement economic analysis. The physical analysis of energy flows brings to light energy policy implications that may be buried in economic analysis. For example, energy analysis indicates that a national strategy to replace all imported crude oil with syncrude derived from coal would require (assuming imports at today's levels) the additional yearly production of 540 million tons of coal, 0.25 trillion ft^3 of natural gas, and 13 billion kWh of electricity from hydro and nuclear power. The economic impacts of such a policy would also be enormous, of course, but perhaps no more so than the other impacts of producing these additional domestic resources.

Energy analysis indicates where increases in raw energy prices will have the greatest impact in the economy and indicates steps that industry can take to keep costs down as energy price increases. Of course, we do not argue that analysis of energy flows is <u>the</u> single, sufficient factor. Depending on the situation, analysis of other material flows could provide equally useful insights. However, recent abrupt increases in world energy prices and domestic supply constraints have made energy the focus of such analysis.

C. The Utility of Energy Analysis

Can energy analysis be used prescriptively in energy policy making? Or is it merely a useful descriptive tool to supplement economic analysis? In some cases the answer to the first question is clearly "yes." The simplest example would be an energy conservation program designed to save energy through the installation of insulation and double-glazed windows. Energy analysis could determine whether energy consumed in manufacturing insulation materials was greater or less than the potential energy savings to be derived over a designated time. When energy conservation is the goal, such a policy would be useless—regardless of economic costs or benefits—if there were no net savings of energy.

In many areas, however, energy analysis is open to question, and its utility in policy decisions has yet to be determined. Given these considerations, we have concluded that it seems best applied to energy conservation. Energy analysis applied to various resources, conversion technologies, distribution systems, and end-uses can clearly indicate options that conserve the nation's resources. These options will be strongly influenced by government policies toward research and development and energy prices (tax incentives or penalties, loan guarantees, depletion allowances, and so on). If the government decides that the development of certain options is in the national interest, then it may attempt to influence the market to enhance that development. Thus, because conservation of domestic energy resources has become a national goal, energy analysis can be important in guiding policy formulation.

However, conservation policy is not made in isolation, and energy price will ultimately determine the acceptability of any energy supply option. Thus, questions arise whether energy and economic analyses will support one another or will they reach divergent conclusions about the attractiveness of various options. It is desirable, for example, to attain the most energy-conservative options at low cost. This makes the decision-maker's task easier: Difficult tradeoffs are avoided. If the opposite is true, with costly implementation required for energy-conservative supply options, the question of tradeoffs must be addressed. Ultimately, a compromise will assign appropriate weights to the desirability of achieving conservation goals and the necessity of supplying energy at acceptable prices.

REFERENCES FOR CHAPTER 1

1. E. M. Dickson, et al, "Synthetic Liquid Fuels Development: Assessment of Critical Factors," U.S. Energy Research and Development Administration, ERDA 76-129/2 (1976).

Chapter 2

OBJECTIVES OF THE STUDY

A. Examination of Coal-Based Systems

To examine the relationship between energy consumption and monetary costs associated with different energy systems, we will analyze a number of coal-based systems potentially useful for supplying automotive propulsion. We include the coal-electricity-electric vehicle system, even though it represents a markedly different automotive technology. The other systems considered are compatible with conventional (albeit modified) automobiles that use internal combustion engines. We have structured our analysis for parallel calculations of energy consumption and money costs of delivered automotive energy.

All the systems analyzed represent technologies proposed as alternatives for supplying automotive energy within the 1985-2000 time frame. These systems (shown in Figure 2-1) include:

- Coal-fired electric power; electric vehicles.
- Coal liquefaction; refining to gasoline and distillates.
- Coal gasification/Fischer-Tropsch gasoline synthesis.
- Coal gasification/methanol synthesis.
- Coal gasification/methane synthesis.
- Coal gasification/conversion to hydrogen.
- In-situ coal gasification/methanol synthesis.
- In-situ coal gasification/methane synthesis.

The energy systems we consider also include transportation of coal and transportation and distribution of its conversion products.

B. Limitations of Idealized Systems

These systems are idealized and have been constructed to examine energy/economic tradeoffs. In practice, the production and distribution

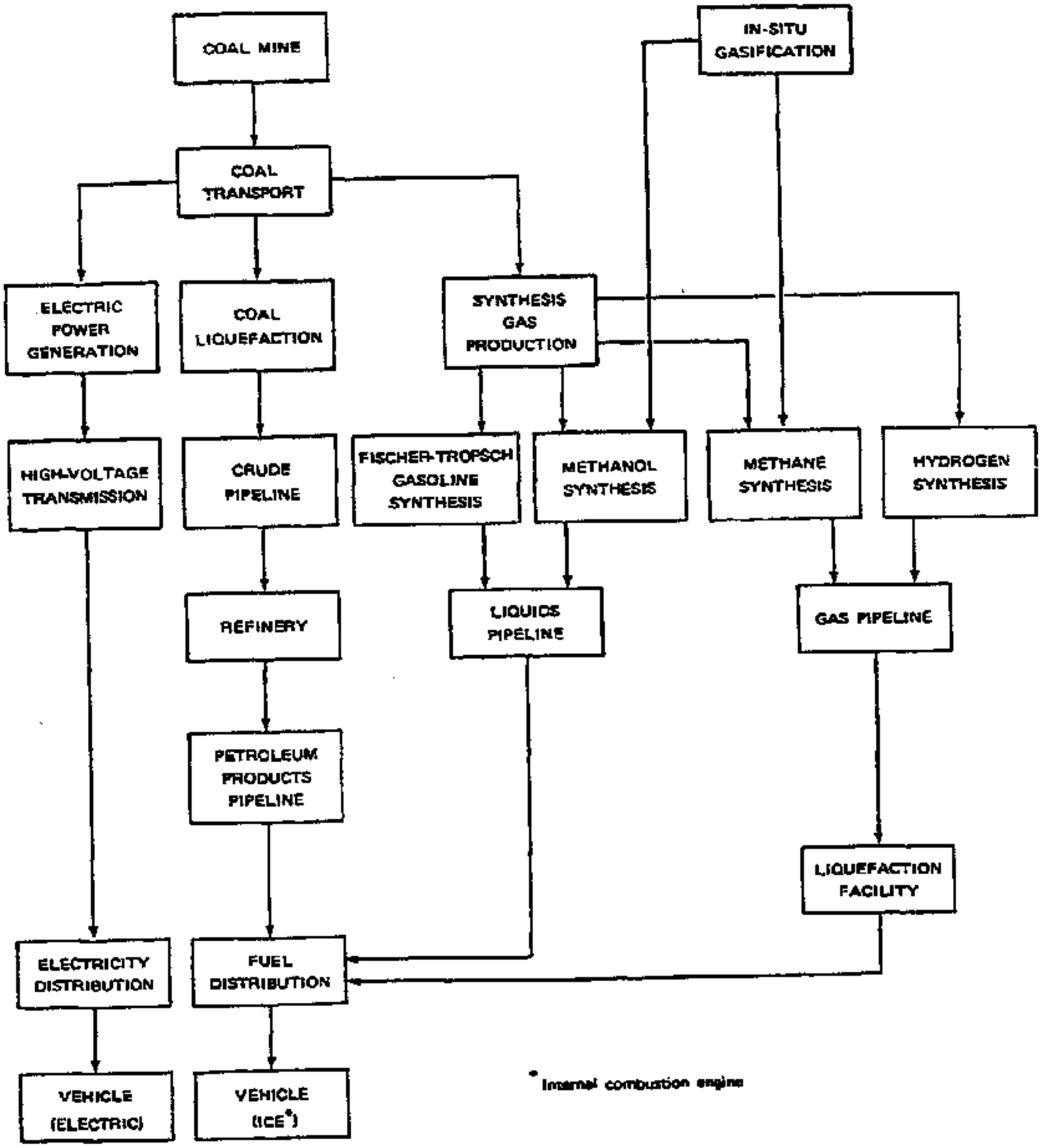

FIGURE 2-1. COAL-BASED AUTOMOTIVE ENERGY SUPPLY SYSTEMS

of synfuels would be considerably more complex than the subsequent analysis indicates. For example, syncrude produced from coal will probably be pipelined to refineries to be blended with natural crudes for refining into numerous products. Thus, the consumer will not pay the full price appropriate to a pure syncrude case; rather, he will pay an average price that accounts for the blending of the more expensive syncrude with the less expensive natural crude.

For electricity, the situation is the same. The utility will not distinguish among different electricity sources when billing its customers. The consumer will be billed at a rate that represents overall cost of producing electricity, rather than just the costs to build and operate a new coal-fired power plant. In contrast, however, a consumer would more than likely pay the full costs of delivering new fuels such as hydrogen or methanol if he chose to purchase them.

Thus, the analysis in the following sections considers only the marginal, or incremental, energy or money costs of adding new units of production to the automotive fuel supply system. To ascertain the weighted impact of such new units on average costs throughout the system, one would need to know the fraction of total automotive fuel supply made up by synfuels. Appendix A illustrates how the weighted energy impacts may be determined for syncrudes from coal and oil shale, and methanol from coal.

Note that the energy and money costs of producing vehicles that will use the synfuels (or electricity) are not considered. For this analysis, we assume that these costs are the same for all types of vehicles. This assumption represents a zeroth-order approximation. It is likely that the costs of a hydrogen-powered vehicle will differ from those of a gasoline-powered vehicle, which will differ from those of an electric vehicle, and so on. However, for many new vehicles, the engine/fuel storage combinations are still speculative and their costs are unknown. In addition, external factors such as pollution control regulations will play an important role. A hydrogen-powered vehicle, for example, would not require the use of a catalytic converter. This would help to offset the expense of a cryogenic fuel storage system. To illustrate the effect of vehicle costs, Appendix B summarizes the findings of an analysis of (1) vehicles powered by gasoline derived from synfuels and (2) electric vehicles.

The energy and money costs of producing the vehicles are considered explicitly.

We emphasize that the analyses that follow are not intended to be sufficient for choosing one system over another. Furthermore, the cost figures used in the economic analysis, which are derived from estimates published in publically available literature, are illustrative rather than definitive. The calculated costs of delivered fuels are indicative only of general cost trends and are not as accurate as more detailed engineering/economic analysis.

Chapter 3

ECONOMIC ANALYSIS

A. Objectives and Background

The analysis here is primarily concerned with developing information that can provide an economic perspective for the information generated by the energy analysis that follows in Chapter 4. This will enable the comparison of dollar costs with energy costs that are associated with the various technologies needed to produce automotive fuel.

A secondary purpose is determining total cost sensitivity to changing values assigned to factors dependent on the location of various energy facilities, as well as to significant cost-determining variables.

The analysis may also shed some light on policy-making aspects related to the development of alternative automotive fuels. In particular, the analysis will examine the relative merits of substitutes for the conventional petroleum system supplying automotive fuel; and the implications of uncertainties in cost-determining variables.

The considerations that follow underlie this study's economic analysis. Consistency between the economic and the energy analyses is essential. Therefore, identical energy supply systems with the same components--location of coal mines, conversions plants, and the markets for fuels and electricity--are analyzed for the two cases. Consistency among data (e.g., capital costs of gasification, liquefaction, and coal-fired power plants) is also important. We have attempted to ensure that costs are based on reasonable and consistent assumptions about financing, coal characteristics, and like factors. In the case of financing coal conversion facilities, for example (with the exception of electricity generation). we have assumed 100% equity financing and a 15% rate of return on capital based on the discounted cash flow (DCF) method in all cases.

Figure 3-1 shows the major components of the system that supplies gasoline produced from coal-based syncrude. Here, the cost of gasoline depends upon the costs of extracting, transporting, and converting coal; transporting and refining syncrude; and transporting, distributing, and marketing the gasoline. Each component cost depends on the values assigned to a number of cost-determining variables. For example, the coal extraction cost depends on such variables as the mining method used, coal-bed seam and thickness, and coal mine location. Consequently, we have to determine changes in gasoline cost that result from changes in the values of the cost-determining variables.*

B. Major Assumptions and Their Implications

The assumptions that have shaped our study and their implications are discussed below.

1. Costs Derived from the Coal Depletion Model

To make this study consistent with the synfuel impact assessments in Volumes II and III of this series, we use the results generated by the Coal Depletion Model in Volume III to estimate the following costs: coal extraction, coal transportation, and coal conversion.

However, actual costs could differ. To offset this difference, we include a sensitivity analysis to help determine the impact of cost changes on the total cost of synfuel supply.

2. Advanced Technology and Its Costs

Out cost estimates correspond to 1975 estimates of the most advanced technology and its costs. We have not allowed for additional

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*Our analysis reflects current knowledge about the technologies needed to produce automotive fuel. Given the pace of synfuel research, our cost estimates may rapidly become obsolete. However, we are more interested in allowing the decision maker to weigh the relative merits of the various options than in generating precise numbers.

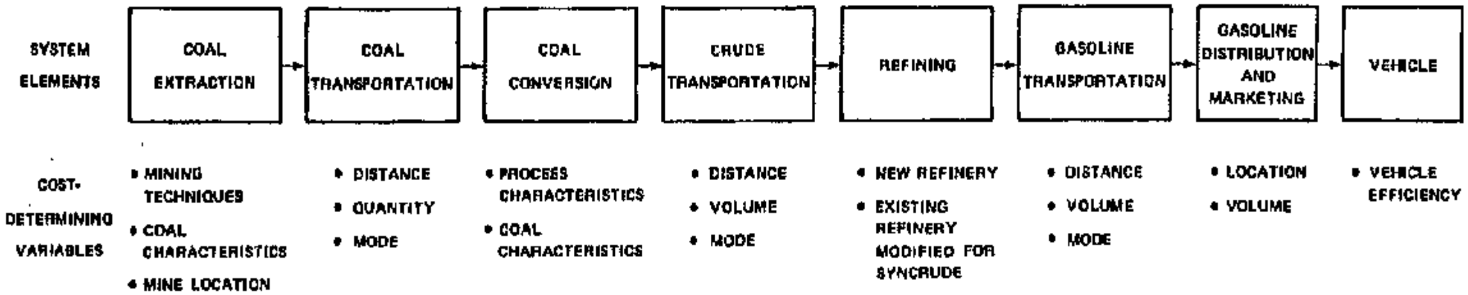

FIGURE 3-1. COMPONENTS OF THE SYNCRUDE/GASOLINE SYSTEM

economies-of-scale considerations, the "learning curve" phenomenon, or subsequent cost escalation.

However, the costs used here are likely to be lower than current estimates and the state of the art of technology is unlikely to be static. Both of these implications can be explored through sensitivity analysis.

3. Variations in Locations

The locations of coal mines, coal conversion plants, refineries, coal-fired power plants, and the markets for fuel and electricity can produce significant variations in the total cost of delivering fuel products to an automobile. Thus, we assume aggregate regionalization schemes and locate refineries in the seven regions that constitute the five Petroleum Allocation Districts (PADs), with PADs 4 and 5 each divided into two subregions.*

However, further division of these regions could improve the cost estimates. Nonetheless, we use the Federal Energy Administration (FEA) regionalization schemes for simplicity. To minimize data collection, we generally use publicly available data.

4. Use of Historical Costs

The cost estimates for transporting crude oil and petroleum products, distributing and marketing gasoline, and transmitting and distributing electricity are based on historical data to 1974. We have inflated these costs to 1975 dollars using appropriate indices.

However, actual costs could differ from these assumed costs. Again, we employ sensitivity analysis to determine the impact on total cost of delivering gasoline or electricity to the automobile if the costs should differ from those in the analysis.

5. Vehicle Efficiencies

We assume that vehicles operating on different fuels will have different efficiencies. For example, vehicles using conventional internal

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*This scheme was first used by FEA in the Project Independence Report.[1]

combustion engines are assumed to be less efficient than electric automobiles.

Therefore, costs expressed in cents/mi exhibit different trends than those expressed in units such as $\$/10^6$ Btu. Assumed efficiencies may not carry over to the real world. Thus, we have analyzed variations in the cost of transportation resulting from different efficiencies.

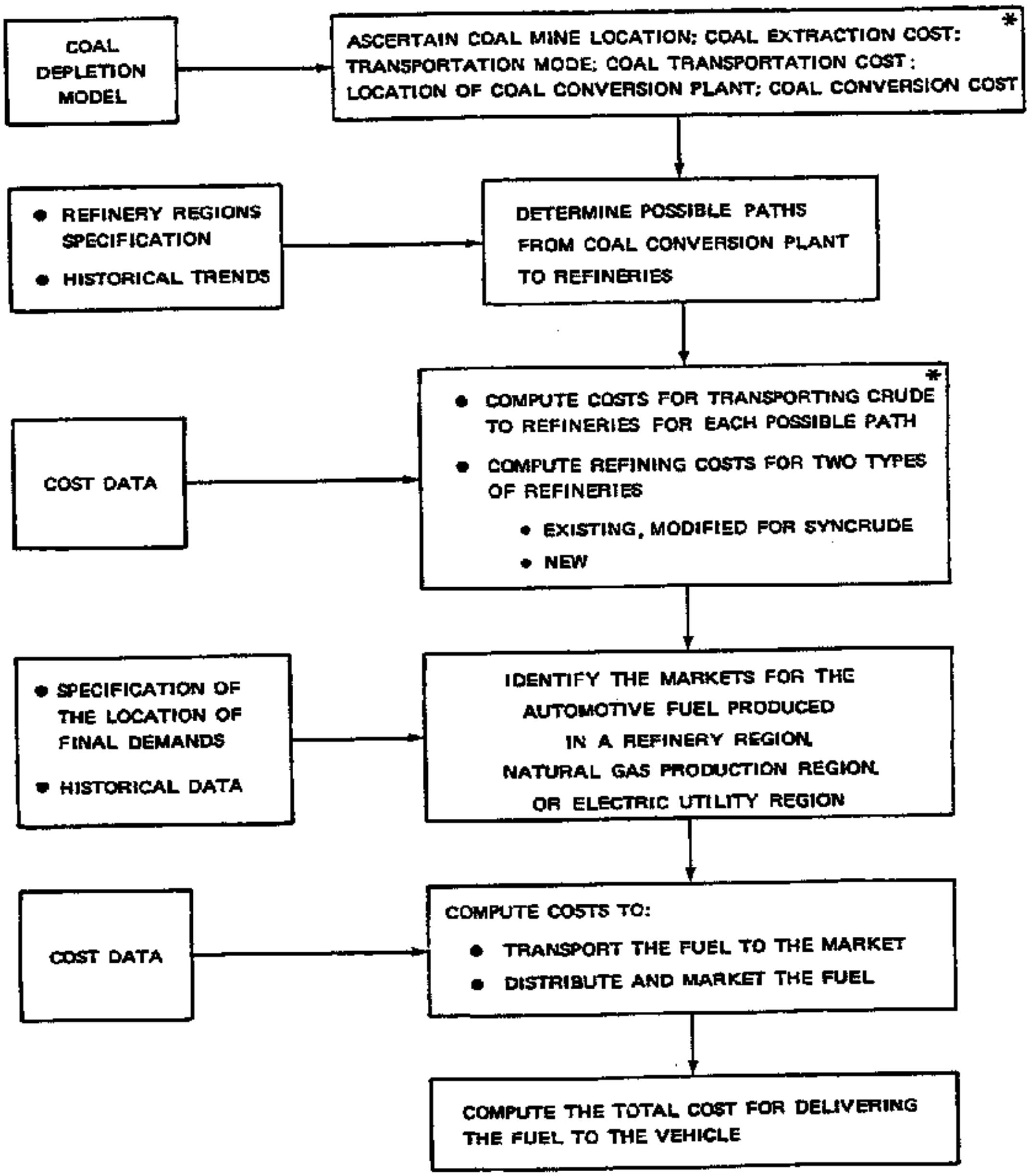
C. Approach

We develop means to ascertain the total cost of delivering automotive fuel in terms of the component costs for alternative pathways for using coal in automotive transportation (see Figure 2-1). The final cost of delivered energy is calculated by a "value added" approach. The cost of each component is referred to the quantity of energy delivered so that the total cost may be evaluated by a simple summation.

Figure 3-2 is a flow chart that depicts the components of total cost for the alternatives in this study. Because a comprehensive analysis of locational impacts on cost would be inordinately time consuming, we determine the range over which the costs could vary. For example, the cost for a given transportation mode of transporting crude from a syncrude production facility to a refinery depends on the location of the two facilities. The cost can be precisely determined in a number of ways; they range from detailed engineering/economic analysis to optimization model use. Our approach is to first locate the syncrude production facility in 1 of the 14 crude supply regions, and then determine the cost by considering all possible paths to refineries in various PADs. This procedure yields a range of values for transporting crude; the range is determined by the number of possible supply-demand pairs considered. The maximum, minimum, and average values are then identified from this range of values.

1. Component Cost Computation

The following components of the total cost were obtained from the Coal Depletion Model: coal extraction costs, coal transportation



* These computations are made only if the coal conversion plant produces syncrude

FIGURE 3-2. FLOW CHART FOR AUTOMOTIVE ENERGY COST CALCULATIONS costs, and coal conversion costs for syncrude, methane, and electricity. The locations of the coal conversion plants were also supplied by this model and were based on the Dispersed Scenario for 1990. Coal conversion costs not contained in the Coal Depletion Model--hydrogen, methanol, and Fischer-Tropsch gasoline--were obtained from the literature and are employed in the same way as the model outputs. Sources for these cost estimates are referenced in Appendix D. Using these component costs, the method of calculating the overall cost is discussed below.

The cost of transporting syncrude to a refinery is determined by first translating the location of coal conversion plants into one of the FEA's crude oil supply regions. Using historical information, the possible pathways to the refinery regions from this supply region are determined. The refinery regions correspond to the FEA's refinery regions.[1] The transportation costs from the supply region to the refinery region were obtained from published sources, particularly FEA and the Department of Transportation (DOT).[2] These figures represent distances and volumes involved, and correlate well with other sources such as American Petroleum Institute (API) data.[3]

The costs of refining the syncrude are obtained for two cases: an existing refinery, modified to handle crude; and a new refinery. The cost data were obtained from previous SRI work[4] and work done by Exxon[5], and updated to 1975 costs.

The cost of transporting fuel from the refinery to the market (or the fuel from coal conversion plant, to the market, when refining is not involved) can be calculated if the locations of the supply source and the demand center are known. For the demand side, the Bureau of Census regions are used. For the supply side, the modified PADs are used for locating refineries, as well as conversion plants that produce synthetic gasoline or methanol. For methane and hydrogen, natural gas-producing regions used in the FEA Project Independence Report are used.[1] For electricity, FEA electric utility regions are used. With the location of supply and demand centers known, the transportation costs are determined from published data, principally from FEA[1], DOT[2], Federal Power Commission (FPC)[6] and API.[3]

For each demand center, the distribution and marketing costs are obtained from FEA statistics for gasoline[7], from FPC publications concerning electricity[6], and from Exxon for remaining fuels[5]. These data seem representative when compared with other sources such as Energy Prices 1960-73 by Foster Associates[8]. For fuels such as methanol and hydrogen, the data allow for handling such fuels[5]. For methane and hydrogen, the cost of liquefaction is also included[5].

2. Computer Program

Our approach uses a computer program to determine the component costs for each alternative system shown in Figure 2-1. The program computes the delivered energy costs for each pathway. It also prints the minimum, maximum, and average delivered energy costs for coal conversion originating in each crude production, gas production, refinery, or electric utility region where the Coal Depletion Model has located a facility.

Program inputs are the type of fuel and the location of the coal conversion plant. The data on possible pathways from supply to demand centers, as well as the costs of conversion, transportation, and distribution, are stored in the program. Program outputs are the cost of each component (e.g., refining) and the total cost of delivering energy to the automobile.

D. Computational Results

The results obtained from the computational approach are described in the following three subsections. To simplify comparisons, only the maximum and minimum costs for all possible pathways are shown for each option. The costs derived by our computations correspond only to the fuel portion of the total cost of an automobile. The data accuracy, especially the production costs of synfuels, is mixed. Therefore, the interfuel comparison is not exact and should be considered only in relative terms. Because the estimates of production costs of synfuels undergo rapid revisions as costs escalate, a relative comparison is more significant. (This assumes, of course, that the cost revisions for all synthetic fuels occur in the same direction.)

1. Comparison of the Options

The comparison of the six options above is shown in Figure 3-3 in units of $\$/10^6$ Btu (delivered to the vehicle) as well as in units of cents/mi. The translation of $\$/10^6$ Btu into cents/mi requires assumptions about efficiency of vehicles with internal combustion engines that operate with different fuels and vehicles powered by electricity. The following automotive efficiencies are assumed[9]:

Gasoline - 4200 Btu/mi*
Methanol - 3430 Btu/mi
Methane - 3860 Btu/mi
Hydrogen - 3190 Btu/mi
Electricity - 1540 Btu/mi†

In Figure 3-3, the various options are compared with a gasoline derived from natural crude and costing 50 cents/gal, excluding taxes. The comparison shows that, in terms of $\$/10^6$ Btu, syncrude/gasoline is the least costly option, whereas electricity is the most costly option.

Between syncrude and electricity, the option range is as follows (in order of increasing costs): syncrude, methanol, methane, Fischer-Tropsch gasoline, and hydrogen. In relative terms, the hydrogen option costs twice as much as syncrude/gasoline, which in turn is about 1.5 times as expensive as the natural crude/gasoline option. However, the differences between options vary considerably. For example, the difference between hydrogen and electricity is about 5%, between methanol and Fischer-Tropsch gasoline about 14%, and between hydrogen and methane options about 23%. Considering the uncertainties in the estimates of various component costs, and in production costs in particular, these differences should be interpreted cautiously. The syncrude/gasoline option, however, does appear to be superior, on a $\$/10^6$ Btu basis, to any other option.

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*For this analysis, the base case gasoline-powered automobile is a subcompact with fuel economy of 30 mpg.

†0.45 kWh/mi, corresponding to an electric car powered by an advanced battery (e.g., lithium-sulfur)[10].

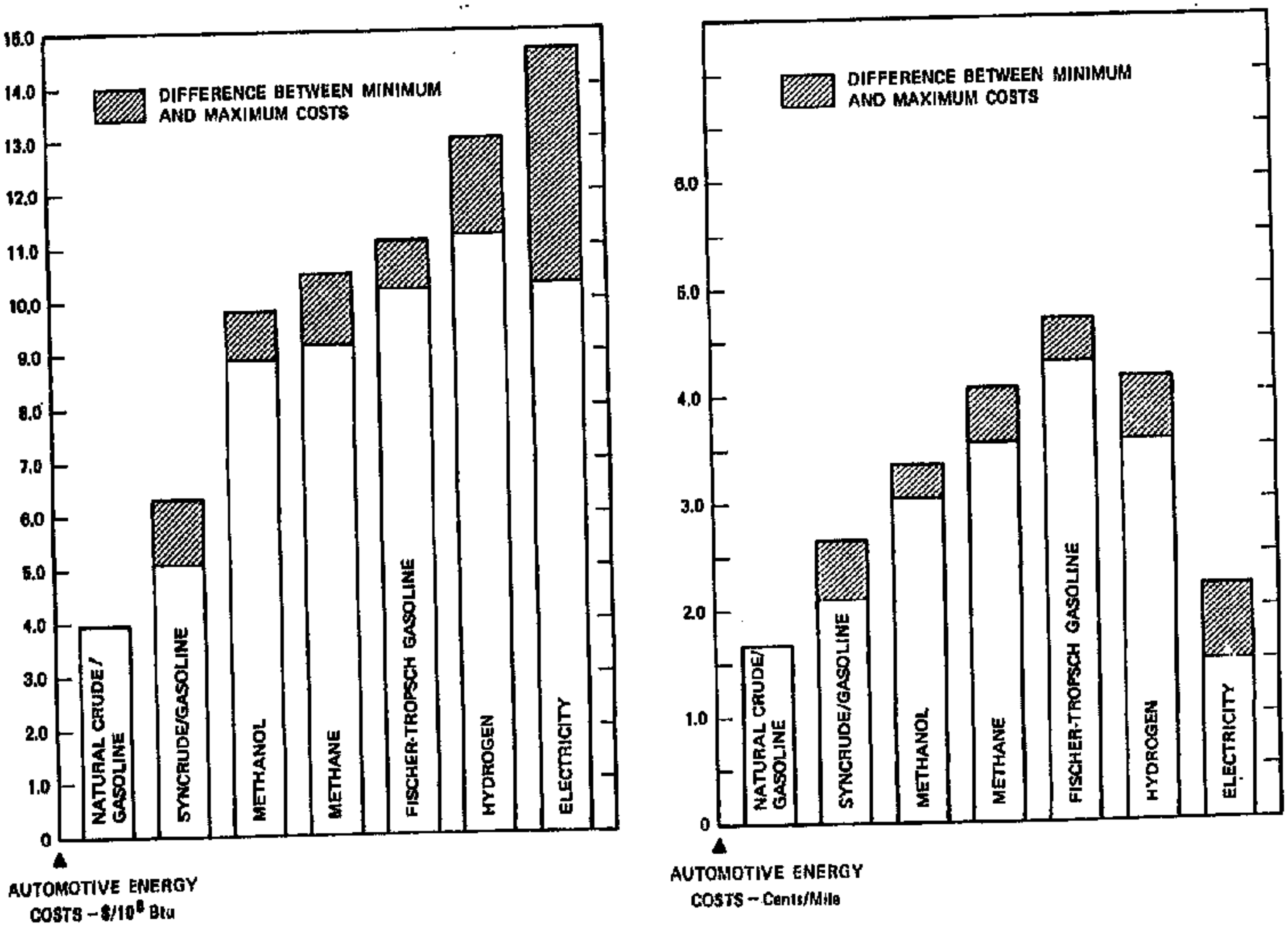

FIGURE 3-3. COMPARISON OF AUTOMOTIVE ENERGY COSTS

2. Impact of Changing Vehicle Efficiencies

If the vehicle efficiencies (in Btu/mi) are considered, the comparisons are different. The electricity option becomes the least-cost option, primarily because of the assumed high efficiency of the electric vehicle (see Figure 3-3). Differences among other synfuels are not so pronounced, with the exception of syncrude/gasoline. All the synfuel options are still more costly than the natural crude gasoline option.

Of course, the validity of the assumed vehicle efficiencies can be questioned. Figure 3-4 shows the sensitivity of the cost to the changes in the values assumed for vehicle efficiency, using average costs to compute the straight line slopes and vertical bars to represent the minimum/maximum variations.

Three groupings with considerable differences can be observed. These are, in order of increasing costs: electricity and syncrude/gasoline; methanol, methane, and hydrogen; and Fischer-Tropsch gasoline. The differences between these groups are significant.

If other options are to match the cents/mi cost of electric vehicles, the relevant engine efficiencies must increase by the following factors: syncrude/gasoline--1.27; methanol--1.68; methane--1.99; Fischer-Tropsch gasoline--2.33; and hydrogen--1.99.

These figures must be cautiously interpreted, however, because other costs of the electric option (i.e., costs of producing an electric vehicle and of overcoming institutional inertia) may outweight its fuel cost advantages. Nevertheless, Figure 3-4 does show that the electric vehicl- option greatly improves its standing in respect to the synfuel options if the proper vehicle efficiencies are taken into account. Also, if the efficiencies of vehicles running on fuels other than gasoline are significantly lower than those in Figure 3-4, the gap between syncrude/gasoline and these options widens even further.

3. Costs of In-situ Gasification Options

In-situ costs were calculated for two cases: methane and methanol. The costs were computed by the same procedure as that used for

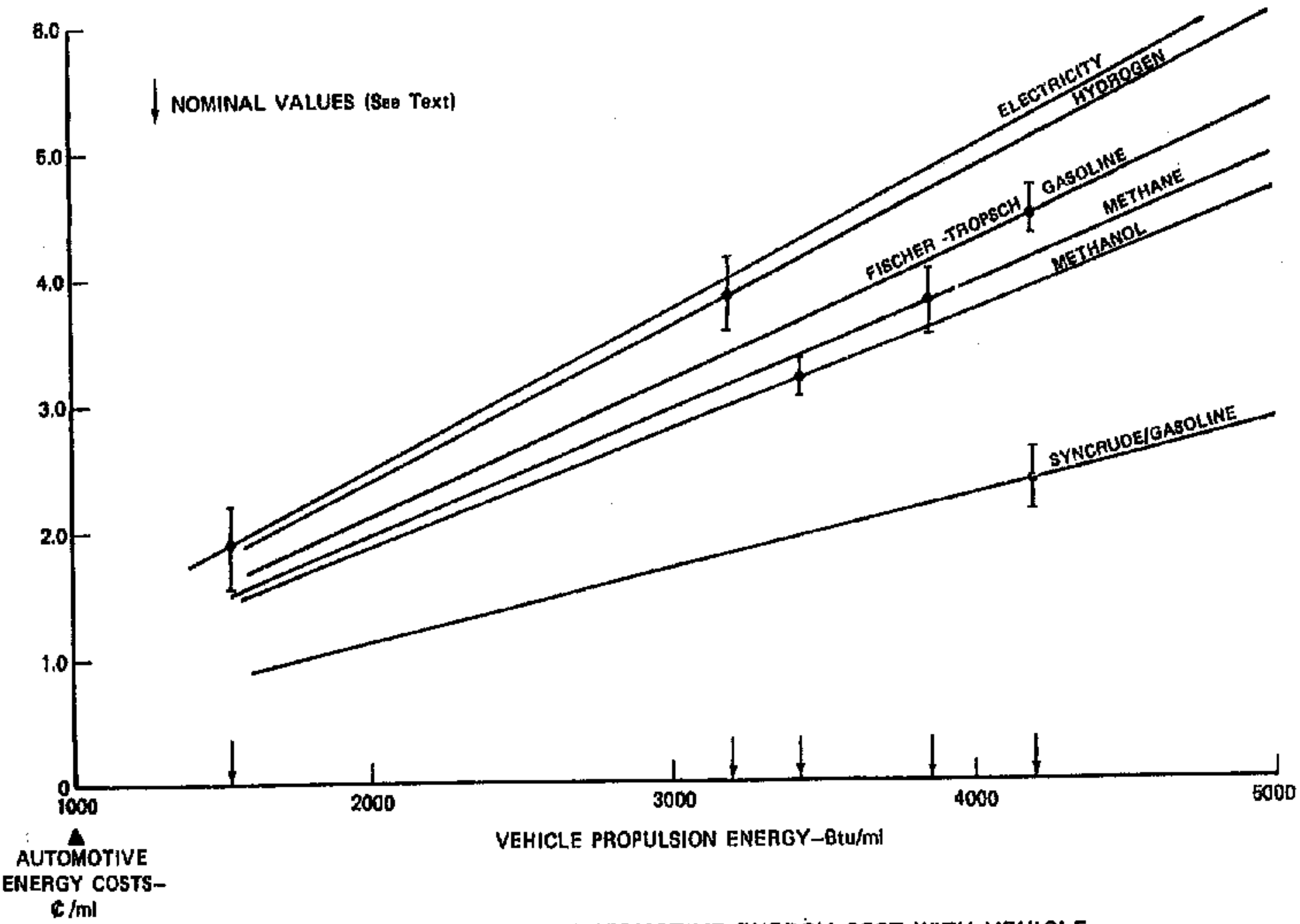

FIGURE 3-4. VARIATION OF AUTOMOTIVE ENERGY COST WITH VEHICLE PROPULSION ENERGY REQUIREMENTS

the conventional mining cases. The costs for in-situ gasification were obtained from the Coal Depletion Model, and the costs of methanation and methanol systhesis were obtained from publications cited in Appendix D. The costs for fuel transportation and distribution are identical to the case where the fuels are derived using conventional mining technologies.

The minimum and maximum costs for the two cases is shown in Figure 3-5. Comparison with the conventional mining case indicates significantly lower costs for the in-situ option. If the vehicle efficiencies are considered, both options are comparable to the syncrude/gasoline option.

The sensitivity analysis indicates that the total cost for the case of methane is quite sensitive to the changes in cost estimates for liquefaction and product distribution and moderately sensitive to other parameters. For the case of methanol, the total cost is quite sensitive to coal conversion and product distribution costs and least sensitive to changes in methanol transportation costs. The variations in total costs due to regional differences are smaller than those for the conventional mining case, mostly because only one region--Wyoming--was considered for in-situ conversion, and the only variation in delivered fuel cost is due to the variation in transportation distances for methanol and methane.

E. Sensitivity to the Regional Differences

The differences between the minimum and maximum values for automotive energy costs displayed in Figure 3-3 are contributed by regional variations resulting from: (a) coal conversion plant location, (b) refinery location for syncrude, and (c) market location. The differences resulting from the location of coal conversion plants are directly reflected in the coal extraction cost, coal transportation cost, cost of transporting synthetic crude to a refinery, and the cost of transporting methane, methanol, hydrogen, and electricity to market. The refinery location causes differing costs of transporting gasoline to the market. Market locations affect the cost of distributing and marketing the final product.

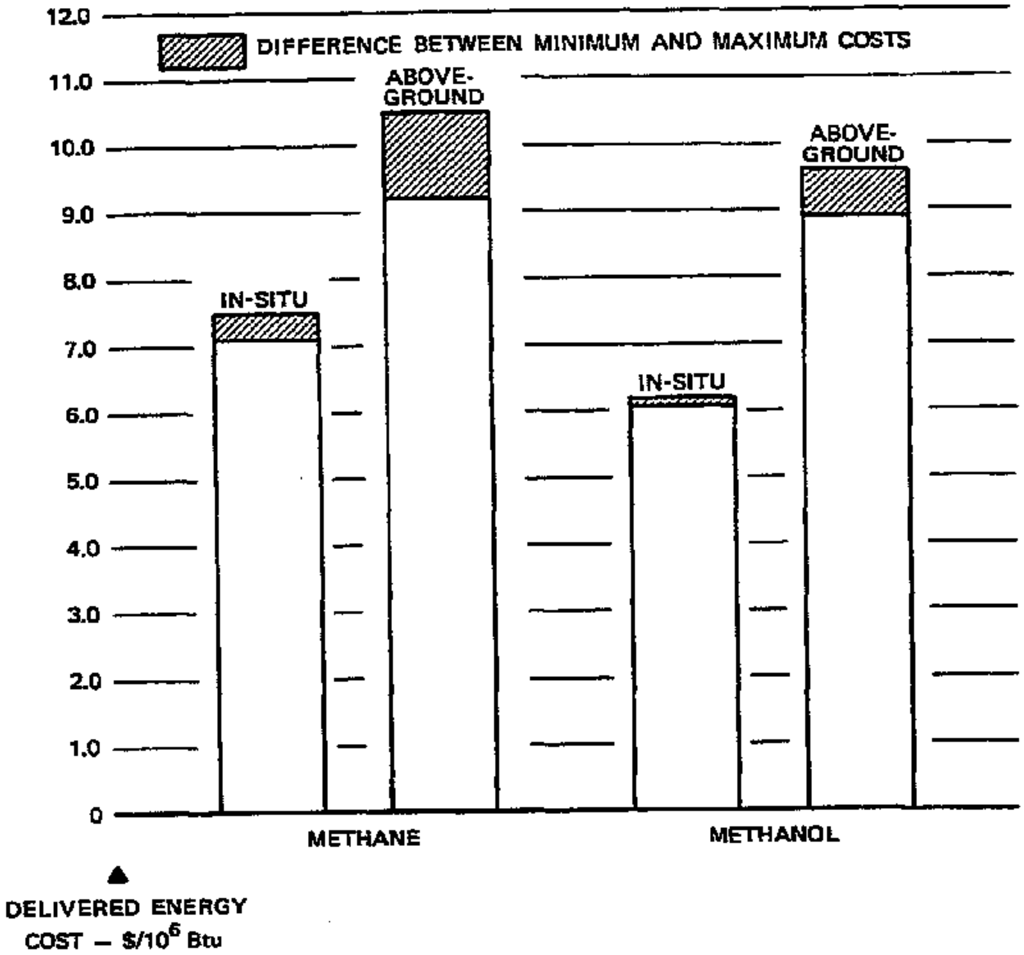

FIGURE 3-5. COMPARISON OF DELIVERED METHANE AND METHANOL COSTS USING IN-SITU AND ABOVE-GROUND COAL GASIFICATION