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# Energy and Precious Fuels Requirements of Fuel Alcohol Production

**Volume I**

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Herbert Weinblatt and Michael F. Lawrence
Jack Faucett Associates

and

David Jenkins
Battelle Columbus Laboratories

**December 1982**

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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for
**U.S. DEPARTMENT OF ENERGY**
**Conservation and Renewable Energy**
**Office of Vehicle and Engine R&D**

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# Energy and Precious Fuels Requirements of Fuel Alcohol Production.

## Volume I

DOE/NASA/0292--1-Vol.1

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Herbert Weinblatt and Michael F. Lawrence
Jack Faucett Associates
Chevy Chase, Maryland 20815

and

David Jenkins
Battelle Columbus Laboratories
Columbus, Ohio 43201

December 1982

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16. Abstract


In this study, energy requirements for producing alcohol fuels are estimated and are compared to the energy content of the alcohol produced. The comparisons are developed for three alcohol production alternatives: ethanol from grain, methanol from cellulose, and methanol from coal. In the analysis, alcohol fuel and all nonrenewable fuels are valued on the basis of their higher heating value (in Btu), while byproducts and grain and cellulose feedstocks are valued on the basis of the effect their production would have on the consumption of nonrenewable fuels. The effects of changes in agricultural production were analyzed on the basis of their effects on overall agricultural energy consumption (not on average energy consumption associated with present production). All three alcohol production alternatives were found to be effective means of increasing supplies of liquid fuels. The cellulose-to-methanol alternative, however, produces more energy than it consumes. (The favorable energy balance for this feedstock results largely from the use of cellulose as a boiler fuel as well as a feedstock.) The grain-to-ethanol alternative yields a slightly negative energy balance, while the coal-to-methanol alternative (which uses a nonrenewable fuel as both feedstock and boiler fuel) results in a substantially negative energy balance. The report is presented in four volumes. Volume I (NASA CR-168090) contains the main body of the report, and the other three volumes contain appendices:

II - Appendices A and B: Ethanol from Grain (NASA CR-168091)
III - Appendices C to F: Methanol from Cellulose (NASA CR-168092)
IV - Appendices G and H: Methanol from Coal (NASA CR-168093)


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## FOREWORD

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This report is the product of a team of persons from Jack Faucett Associates (JFA), Battelle-Columbus Laboratories (BCL), and the Center for Agricultural and Rural Development (CARD) of Iowa State University (ISU). Dr. Herbert Weinblatt and Michael F. Lawrence of JFA had overall responsibility for performing the study. Dr. Weinblatt had primary responsibility for final editing and for preparing Volume I and Appendices A and G of the report. Rena K. Margulis of JFA was responsible for Appendix E. Geoffrey Back of JFA was responsible for Appendix D and contributed to Appendix G.

David M. Jenkins had overall responsibility for BCL's contributions to the report. T.S. Reddy of BCL drafted Appendices B, F and H. Karen St. John of BCL drafted Appendix C, and Dr. Thomas McClure of BCL contributed to Appendix A.

Dr. Anthony J. Turhollow, Jr., of CARD performed all runs of the ISU Model reported in Appendices A and E and contributed to the drafting of Appendix A.

Thomas J. Timbario of the Transportation/Fuel Systems Department of Mueller Associates, Inc., Baltimore, Md., along with members of his staff, provided consultation and critiqued all draft reports.

The manuscript was typed by Pamela C. Brockington with assistance from other members of the JFA secretarial staff.

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## VOLUME I

## ABBREVIATIONS

| | |
|---|---|
| B | billion |
| Btu | British thermal unit |
| bbl | barrel |
| bu | bushel |
| C | Centigrade |
| cu ft | cubic foot |
| cwt | hundred weight (100 lb) |
| d | distance |
| DDG | distillers' dark grains |
| DTE | dry ton equivalent |
| F | Fahrenheit |
| gal | gallon |
| ha | hectare |
| HHV | higher heating value |
| hp | high pressure |
| hr | hour |
| K | Potassium |
| kw | kilowatt |
| kwhr | kilowatthour |
| lb | pound |
| lp | low pressure |
| LPG | liquefied petroleum gas |
| M | thousand |
| MLRA | major land resource area |
| MM | million |
| N | Nitrogen |
| P | Phosphorus |
| psia | pounds per square inch absolute |
| psig | pounds per square inch gauge |
| T | trillion |
| wt | weight |
| yr | year |

## BTU CONVERSION FACTORS

| Fuel | Units | HHV |
|---|---|---|
| Coal | Btu/ton | 22,500,000[a] |
| Distillate | Btu/gal | 140,000 |
| Electricity Consumption | Btu/kwhr | 3,413 |
| Ethanol | Btu/gal | 84,200 |
| LPG | Btu/gal | 95,000 |
| Lubricating Oil | Btu/gal | 145,000 |
| Methanol | Btu/gal | 64,350 |
| Motor Gasoline | Btu/gal | 125,000 |
| Natural Gas | Btu/cu ft | 1,020 |
| Residual Fuel Oil | Btu/gal | 150,000 |

## ELECTRICITY CONVERSION FACTOR

| Fuel | Btu's consumed/Btu electricity produced |
|---|---|
| Coal | 3.05 |

[a] *When no specific coal characteristics were known, the energy content of a "standard ton" of coal (22,500,000 Btu) was used. Other values were used when more appropriate and are indicated in footnotes.*

## SI CONVERSION FACTORS

| | | |
|---|---|---|
| 1 acre | = | 4046.8564 square meters |
| 1 bbl | = | 158.98284 liters |
| 1 Btu | = | 1054.35 joules |
| 1 cu ft | = | 0.028316847 cubic meters |
| 1 gal | = | 3.7854118 liters |
| 1 lb | = | 453.592 grams |
| 1 mile | = | 1609.344 meters |
| 1 psi | = | 0.0680460 atmospheres |
| 1 ton | = | 907184.74 grams |
| 273.15 + 5/9(F-32) | = | degrees Kelvin |
| 273.15 + C | = | degrees Kelvin |

## OTHER CONVERSION FACTORS

| | | |
|---|---|---|
| 1 acre | = | 0.40468564 ha |
| 1 bbl | = | 42 gal |
| 1 Btu | = | 252 calories |
| 1 bu barley | = | 48 lb |
| 1 bu corn | = | 56 lb |
| 1 bu grain sorghum | = | 56 lb |
| 1 bu oats | = | 32 lb |
| 1 bu soybeans | = | 60 lb |
| 1 bu wheat | = | 60 lb |
| 1 psi | = | 6895 pascals |
| 1 square mile | = | 640 acres |
| 1 ton | = | 2000 lb |

## EXECUTIVE SUMMARY

In this study, energy requirements for producing alcohol fuels are estimated and are compared to the energy content of the alcohol produced. The comparisons are developed for three alcohol production alternatives: ethanol from grain, methanol from cellulose, and methanol from coal. These were judged to be the most likely alternatives for alcohol fuel development in the near term.

The analysis of energy inputs and outputs of fuel alcohol production presented in this report is a form of net-energy analysis. In developing this analysis, several conventions have been adopted:

- All nonrenewable fuels are valued on the basis of their gross (or higher) heat content (in Btu), as is the alcohol fuel which is produced.
- All electricity is assumed to be derived from coal and is valued on the basis of the gross heat content of the coal from which it is generated.
- Solar energy is treated as being free.
- Grain and cellulose feedstocks are valued on the basis of the effect which increasing feedstock production would have on the consumption of nonrenewable fuels.
- Energy credits are provided for all by-products on the basis of the effect which their production from conventional processes would have on the consumption of nonrenewable fuels.
- Energy used to produce materials and equipment required to produce alcohol is counted only for certain materials (fertilizer, pesticides and lime) for which such energy is considered significant.

Exhibit S-1 presents a tabular summary and comparison of the energy inputs and outputs for producing 100 million Btu of alcohol from representative versions of the three alternatives studied: ethanol from corn and grain sorghum, methanol from cellulose, and methanol from coal. One hundred million Btu corresponds to 800 gallons of gasoline and, as the table indicates, to 1188 gallons of ethanol or 1554 gallons of methanol. The

EXHIBIT S-1: ENERGY INPUTS AND OUTPUTS FOR PRODUCING 100 MILLION BTU OF ALCOHOL FUEL FROM VARIOUS SOURCES

|  | Alcohol | Petroleum Products: Motor Gasoline | Petroleum Products: Distillate | Petroleum Products: Residual Fuel | Petroleum Products: LPG | Natural Gas | Coal | Liquid Fuels | Precious Fuels | Total Energy |
|---|---|---|---|---|---|---|---|---|---|---|
| **Conventional Units** | | | | | | | | | | |
| Ethanol from Grain (wet milling) | +1,188 gal | -4.2 gal | -33.6 gal | -3.1 gal | -27.9 gal | -18.8 gal | -3.83 tons | | | |
| Methanol from Cellulose (silvicultural biomass) | +1,554 | -1.43 | -51.8 | -0.42 | | -3.98 | -1.32 | | | |
| Methanol from Coal | +1,554 | +0.02 | -0.17 | | | +2.27 | -8.55 | | | |
| **MM Btu** | | | | | | | | | | |
| Ethanol from Grain (wet milling) | +100 | -0.520 | -4.70 | -0.46 | -2.65 | -19.1 | -81.8 | +91.6 | +72.5 | -9.3 |
| Methanol from Cellulose (silvicultural biomass) | +100 | -0.179 | -7.25 | -0.063 | | -4.06 | -29.7 | +92.5 | +88.4 | +58.7 |
| Methanol from Coal | +100 | +0.002 | -0.024 | | | +2.32 | -193.8 | +99.98 | +102.3 | -91.5 |

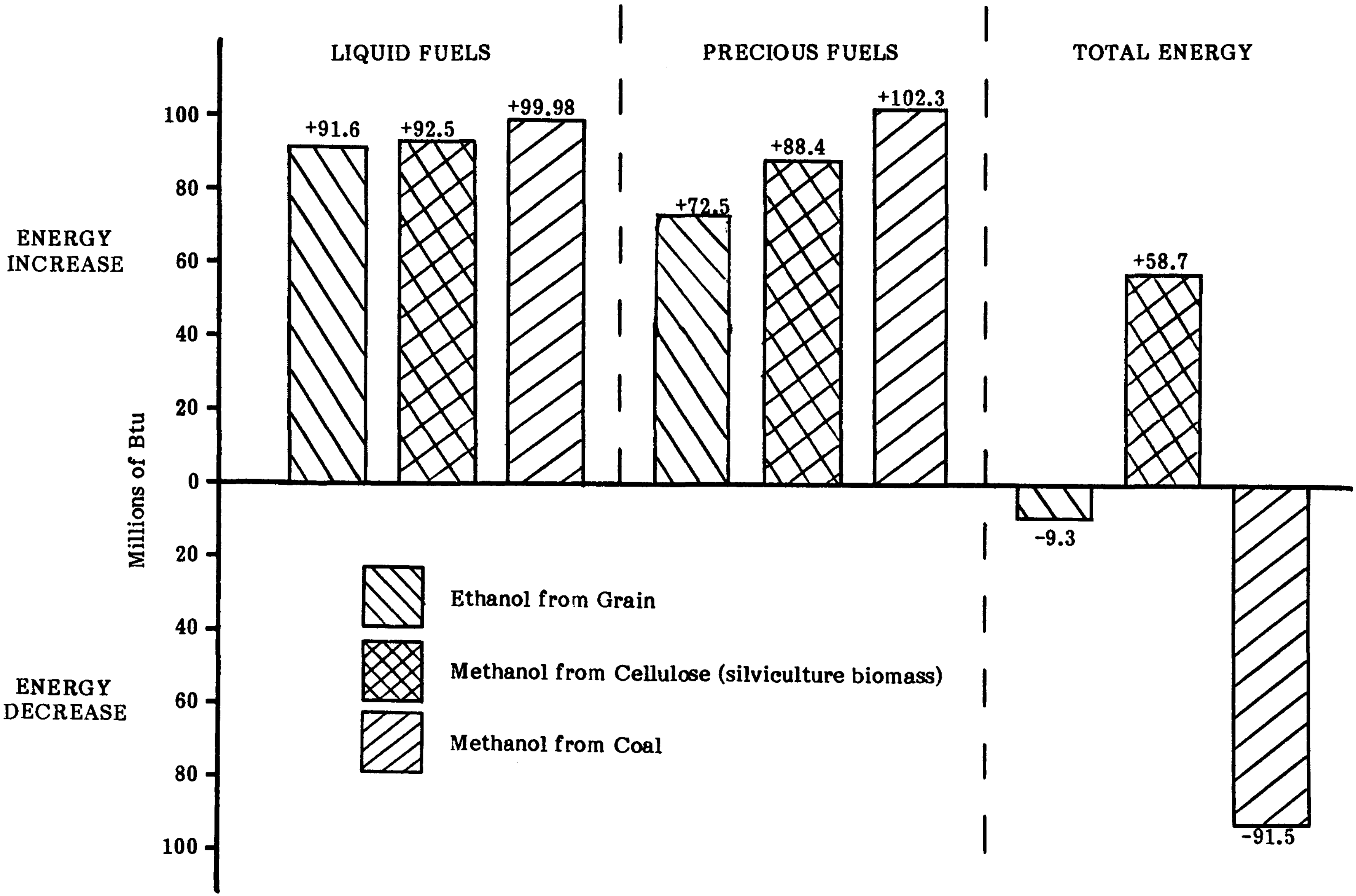
energy inputs and outputs are expressed in conventional units in the top half of the table and in thousands of Btu in the lower half.

An examination of the figures in the lower half of the table reveals that the most significant energy differences in the three processes results from differing requirements for coal. The cellulose process is the only one which does not use coal as a boiler fuel (using cellulose instead); most of the coal which is required by this process is used to generate electricity. Methanol from coal, on the other hand, requires substantial amounts of coal, which is used as process fuel and as a feedstock as well as for electricity generation. (This process also results in small increases in the availability of natural gas and motor gasoline resulting from an energy credit for the sulfur by-product.)

Ethanol from grain requires moderate amounts of coal (for process fuel and for electricity) and somewhat more natural gas than the other two processes; most of the natural gas is for nitrogen fertilizer used to increase grain yields. The estimates of energy requirements for ethanol production incorporate the results of an analysis of the overall effects on the agricultural system of using grain to produce ethanol. These results were obtained from an interregional linear-programming model of agricultural production developed at Iowa State University. The substitution value of the feed by-products of ethanol production (e.g., gluten meal) was based on both the protein and calorie content of the by-products, and the estimates of the overall change in agricultural energy consumption reflect the resulting effects of increasing grain production and reducing soybean production. It was observed that the change in energy consumed per unit of increased production resulting from a change in agricultural production levels is generally higher than the average energy consumed per unit of present production.

The overall use and generation of energy by the three processes is summarized in the last three columns of Exhibit S-1 and displayed graphically in Exhibit S-2. All three processes produce substantially more liquid fuels than they consume. The net increase in liquid fuels is greatest for methanol from coal (which requires virtually no liquid fuels), while the energy content of the petroleum consumed by the other processes is only about eight percent of that of the alcohol produced. The liquid-fuels results consider only the energy value (in Btu) of the petroleum products consumed and that of the alcohol produced. They do not provide a complete evaluation of the net liquid-fuel

EXHIBIT S-2: NET ENERGY, BY TYPE, FOR PRODUCING 100 MILLION BTU OF ALCOHOL FUEL FROM VARIOUS SOURCES



benefits of alcohol production. (To accomplish the latter objective, additional information is required relating to the amount of conventional motor-vehicle fuel that can be saved by using ethanol or methanol, either as an octane enhancer, a fuel extender, or neat (i.e., as a straight fuel), as well as the refinery losses involved in producing both the petroleum products used in alcohol production and those that are saved when alcohol is used as a motor-vehicle fuel.)

When one looks at the net production of precious fuels (which are defined to consist of liquid fuels and natural gas), somewhat greater differences arise. When methanol is derived from silvicultural biomass, the energy content of the petroleum products and natural gas consumed equals only about twelve percent of that of the methanol produced; and when methanol is derived from coal, because of the energy credit for the sulfur by-product, the net change in the available energy from precious fuels actually exceeds that of the methanol produced. In the case of ethanol from grain, however, for every 100 Btu of ethanol produced, about 27 Btu of natural gas and petroleum products is consumed, leaving a net increase of only 73 Btu. The ethanol process is thus somewhat less effective in increasing the availability of precious fuels than the other alternatives.

The differences between the three feedstock alternatives are more striking when one considers changes in the availability of all forms of energy. On this basis, cellulose feedstocks are the only ones capable of yielding net increases in available energy -- for silvicultural biomass: about 59 Btu per 100 Btu of methanol produced. The use of coal, a nonrenewable feedstock, of course results in the consumption of substantially more energy than is produced -- though the energy consumed is solid and that produced is liquid. Similarly, when grain is purchased on the open market for use as a feedstock, the energy of the fossil fuels consumed (predominantly coal) exceeds that of the ethanol produced.

On the basis of these results, methanol from cellulose would appear to be the most attractive of the alternatives from a net-energy standpoint. The cellulose results highlighted in Exhibits S-1 and S-2 are for silvicultural biomass, though the results for other cellulose feedstocks are fairly similar. Those for forest residues are slightly more favorable, while those for crop residues are somewhat less favorable. The results for crop residues are in part dependent upon the amount of residues collected per acre, a figure that will vary with crops, crop yields, tillage methods, erosion-control requirements, and the willingness of individual farmers to sell their residues to a methanol facility.

The other two feedstocks studied, grain and coal, can be used effectively to increase supplies of liquid fuel, though use of coal and (to a much lesser extent) grain will result in a reduction in total energy available. The use of grain also results in somewhat greater use of natural gas than the other feedstocks, resulting in net precious-fuel benefits which are appreciably smaller than the liquid-fuel benefits. Accordingly, from the standpoint of net liquid and gaseous fuel benefits (and ignoring other considerations, such as cost, fuel characteristics, or the effects on exports and food prices), the production of ethanol from grain is a somewhat less desirable way of producing alcohol fuel than the production of methanol from either coal or cellulose.

# 1. INTRODUCTION

Since 1974, the rise of the price of oil has contributed to a high rate of inflation and economic instability. Continuing concern exists that any significant disruption of petroleum imports presents a threat to our national and economic security. This threat adds a certain social cost to the already high price of crude oil. The Federal Government has responded to this nationally-incurred social cost by seeking to reduce our oil imports, through conservation and the use of alternative energy sources.

Economic theory suggests that the most effective method of reducing oil imports would be to tax them, thus adding oil's social cost, in terms of the United States' dependence on foreign oil, to oil's market value. This would induce the substitution of other fuels for oil and reduce overall fuel use. However, given the long lag time required for the energy market to adjust to oil price increases through the development of new fuel sources, such a tax would add unproductively to inflation and be income regressive. Nevertheless, the clear danger of dependence on foreign oil impels Congress to induce the effect of a tax on imported oil in the domestic energy market. This has been done through the Energy Security Act and other programs by subsidizing alternatives to imported oil. This subsidization is designed to create a differential between the price of imported oil and the price of domestic alternatives similar to the differential that would exist in the presence of a tax. In providing such subsidies, the government must assess which technologies are the most energy and cost effective in reducing dependence on foreign oil.

In this study, energy requirements for producing alcohol fuels are estimated and are compared to the energy content of the alcohol produced. The comparisons are developed for three alcohol production alternatives: ethanol from grain, methanol from cellulose, and methanol from coal. These were judged to be the most likely alternatives for alcohol fuel development in the near term.

Any process will always be judged inefficient on a net-energy-balance basis. Energy is lost in the conversion of sunlight to plant matter, coal to synthetic crude, and methanol to gasoline. Available energy output is always less than the energy input, and therefore the net energy balance of the conversion of any form of energy into any other form of energy is always negative. When coal is burned to generate electricity, the energy of the output in electricity is about one-third of the energy input in coal. Coal is nevertheless burned to create electricity because electricity has unique characteristics that make its energy more than three times as valuable as that of coal.

Similarly, because liquid fuels have unique value as a power source for transportation, converting coal to a liquid fuel and then burning that liquid is considered. Burning the coal directly would provide more available energy, but energy in the form of a liquid fuel is simply more valuable than energy in the form of coal.

The analysis of energy inputs and outputs of fuel alcohol production presented in this report is a form of net-energy analysis. As such, it is limited by several problems inherent in the technique.

One such problem is selecting the boundary of the system to be analyzed. Since any of a large number of energy flows could be included within the analysis, the result is dependent on the selection of those boundaries. Changing the boundary can change the result. The definition of the system boundary followed in this report is to include all direct use of fuels in the production of alcohol feedstocks and conversion to alcohol and to exclude most of the secondary energy inputs. Energy inputs to refining petroleum, manufacturing tractors, manufacturing an alcohol production facility, etc., are considered as secondary inputs outside of the boundary. However, some secondary inputs (e.g., fertilizer manufacture) are included within the boundary, since these inputs have a significant impact on the results.

Another analytic problem relates to the issue of the value placed on the energy contained in various fuels, sometimes referred to as the "form-value problem." The valuation of fuels influences judgments of net energy efficiency vs. inefficiency. An inefficient process or fuel may nonetheless be preferred when questions of convenience, cleanliness, and ease of transport are also considered. This analysis has valued different fuels on the basis of gross (or higher) heating content (in Btu). An alternative analysis might weight energy by the market price of the fuel in question.

Electricity use is analyzed on the basis of the (nonrenewable) fuel used in its production, rather than on that of the energy content of the electricity itself. Demand for electricity resulting from alcohol production is assumed to be reflected primarily in the form of increased demand for base-load generation of electricity. The utility industry anticipates that expansion of such capacity will be coal-, nuclear- and hydropowered. However, because additions to planned base-load capacity are primarily produced by coal, the analysis is simplified by assuming that all electricity comes from coal. The factor of 3.05 Btu of coal to produce 1.0 Btu of electricity is used throughout the analysis.

Because the focus of the study is on the effect of alcohol production on the availability of nonrenewable fuels, it is assumed that feedstocks obtained from renewable sources (i.e., grain or cellulose) will be obtained by expanding production of the feedstock. Thus the energy consumed when such feedstocks are used is the energy consumed in their production, not the energy content of the feedstock. Furthermore, since there are essentially no alternate uses for the solar energy consumed, the solar energy is treated as being free and only the nonrenewable fuels are counted. As a result, the energy balances developed for alcohol derived from renewable sources may be positive; i.e., they may show a net energy gain. For alcohol from a nonrenewable fuel, coal, the net energy content of the fuel is counted as an input, and the resulting energy balance must be negative.

In assessing the outputs of alcohol production, the energy of the output fuel is counted. Also, energy credits are provided for by-products which result in a reduced need for nonrenewable fuels in other sectors. One such by-product is sulfur resulting from coal-to-methanol conversion; substitution of such sulfur for sulfur mined by the Frasch process results in some saving of natural gas. Similarly, the energy credits provided for the feed by-products of ethanol production are taken as equaling the nonrenewable energy required for producing the feed (corn, soy meal, etc.) for which these by-products substitute. It should be noted that both feedstocks and by-product are valued consistently in terms of their effect on the availability of nonrenewable fuels (and not on the basis of their intrinsic energy content).

Within these limitations, this analysis is designed to determine the additional consumption of various categories of nonrenewable sources of energy that will accompany additional production of ethanol or methanol. For each potential source of alcohol fuel, three different energy balances are developed. A "total-energy balance" relates total nonrenewable energy consumed (in Btu) to the energy value of the alcohol produced. A "liquid-fuels balance" relates the energy value of petroleum products consumed to that of the alcohol produced. And a "precious-fuels balance" relates the energy value of petroleum products and natural gas consumed to that of the alcohol produced. The framework of the presentations is such that individual components of each analysis can be modified to reflect alternative assumptions, technologies or feedstocks to those used in this study.

The liquid-fuels balances developed in this study compare only the energy value (in Btu) of the petroleum products consumed to that of the alcohol produced. They do not provide a complete evaluation of the net liquid-fuel benefits of alcohol production. To accomplish the latter objective, additional information is required relating to the amount of conventional motor-vehicle fuel that can be saved by using ethanol or methanol, either as an octane enhancer, a fuel extender, or neat (i.e., as a straight fuel), as well as the refinery losses involved in producing both the petroleum products used in alcohol production and those that are saved when alcohol is used as a motor-vehicle fuel.

The following three chapters summarize the results obtained for the three alcohol-production alternatives studied: ethanol from grain, methanol from cellulose, and methanol from coal. The concluding chapter of this summary volume compares the results obtained for the three alternatives and presents the overall conclusions drawn from the study. Additional detail relating to the analysis is presented in three volumes of appendices, corresponding to the three alternative sources of alcohol fuel studied. A general bibliography is presented at the end of this summary volume, and more extensive, and partially annotated, bibliographies for the three production alternatives are presented in the corresponding volumes of appendices.

## 2. ETHANOL FROM GRAIN

Ethanol is most commonly obtained from starches and sugars by saccharification of starches to sugar and fermentation of the sugar. Processes for obtaining ethanol from cellulose are presently being developed but have not yet attained economic feasibility. For industrial uses, virtually all ethanol is obtained from ethylene gas which, in turn, is derived from natural gas or petroleum. Starches and sugars thus represent the only feedstock for ethanol production which is both economically feasible at the present time and potentially capable of yielding net increases in our supplies of precious fuels. Indeed, ethanol obtained from such sources is now being blended with gasoline for use as a liquid fuel.

Several processes for obtaining fuel-grade ethanol from various carbohydrate feedstocks exist. In concept, any source of sugar or starch could be used, though economic considerations limit interest to feedstocks which can be obtained relatively inexpensively. Most ethanol presently being produced for fuel is derived from grain, especially from corn; though some is derived from other carbohydrates, particularly from those materials, such as cheese whey, whose alternative uses are limited.

If a significant volume of ethanol fuel is to be obtained from carbohydrates, it will be necessary to use a feedstock which can be supplied in large quantities at relatively low cost. The most likely sources are various grains. Sugar beets or fodderbeets are alternative feedstocks which could be attractive from a net energy standpoint but which do not appear to be economically competitive at the present time. Sugar cane is a more energy-intensive crop (Pimentel, 1980)[1] and so is less likely to be attractive from a net energy standpoint.

The first section of this chapter presents estimates of the changes which occur in agricultural energy consumption when production is increased to provide grain for ethanol production. Corn and grain sorghum are used as the ethanol feedstock, while production of soybeans and other feed crops is reduced as a result of the availability of feed by-products resulting from the ethanol process. These estimates are developed in Appendix A, along with estimates of average energy requirements for present production of corn, grain sorghum, wheat, barley and oats. The estimates of changes in

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[1] *Parenthetical references to authors and dates identify bibliographic references. Full citations are contained in the bibliography at the end of this volume.*

agricultural energy consumption are followed by a discussion, in Section 2.2, of factors which may affect the size of these changes.

Section 2.3 presents estimates of energy requirements for two alternative processes for converting grain to ethanol as well as estimates of the processing energy saved as a result of the by-product vegetable oil resulting from one of these processes. Additional information about the conversion processes is presented in Appendix B.

The final section of this chapter presents a summary of the energy inputs and outputs estimated for deriving ethanol from corn and grain sorghum.

## 2.1 Agricultural Energy Consumption

The use of grain as a feedstock for producing ethanol represents a new source of demand for grain. In the absence of grain surpluses, this new source of demand will result in some increase in the price of grain and resulting increases in grain production and decreases in its use for other purposes (for exports or for domestic consumption by animals or humans). For the purposes of this study, we shall ignore the effect of ethanol production on exports and domestic consumption and assume that grain feedstocks are obtained entirely by expanding grain production.

The increase in the demand for grain results in an increased price, making it profitable for farmers to cultivate their land more intensively and/or bring additional land into production. The former response involves increased fertilization, while a larger than average share of new cropland is likely to require irrigation. Since fertilization and irrigation are both energy intensive, energy requirements for increasing grain production are substantially higher than average energy requirements for present production.

Among the grains which are widely grown in the United States, corn and grain sorghum are the two which provide the most favorable energy balances; i.e., the ratio of their sugar and starch content to the energy required for production and harvesting is the highest.

In Appendix A, estimates of the effect of ethanol production on agricultural energy consumption are obtained from an interregional linear programming model of agricultural production developed at Iowa State University (ISU) (Dvoskin and Heady, 1976; Turhollow, 1982; and Turhollow, Christensen and Heady, forthcoming). In the model, the United States is divided into 28 market regions which are further divided into 105 producing areas. The model determines agricultural production levels and resource usage by production area in order to satisfy, at minimum cost, a set of demands which are exogenously specified by market region. Alcohol production is an exogenously specified activity which results in the consumption of corn and/or grain sorghum and the production of by-products which may substitute for soybean exports or for soybeans, corn or grain sorghum consumed by domestic livestock. For each market region, the Model determines whether wet or dry-milling will be used for alcohol production on the basis of the cost of the two technologies and the endogenously estimated value of the by-products of the two processes.

The estimates of the effect of ethanol production on agricultural energy consumption were obtained by comparing the results of two solutions produced by the model. The two runs differed only in that it was assumed that no grain would be used for ethanol in the "base-case" run, while, in the second run, six billion gallons of ethanol would be produced from corn and grain sorghum. An ethanol yield of 2.58 gallons per bushel of corn or grain sorghum was assumed as required by the conversion technology described in Section 2.2. In both runs, exogenous specifications of agricultural yields, energy prices, and most exports, were set to their 1981 values. A five-year average (for 1977-1981) was used for all domestic consumption and for exports of cotton.

The model indicates that all ethanol production will use wet milling and that slightly over 80 percent of the grain used will be corn, with the rest being grain sorghum. Feed by-products of the ethanol process (gluten feed and gluten meal) result in an appreciable reduction in the demand for soybeans and smaller reductions in the demand for corn and grain sorghum for feed use.

Estimates of the increase in agricultural energy consumption per bushel of grain used for ethanol production are shown in Exhibit 2-1. These estimates represent the overall effect on energy consumption of all resulting changes in the agricultural system, including changes in crops grown and in crop-transport requirements, and increases in fertilization and irrigation. The use of the feed by-products of the ethanol process to reduce demand for feed crops, and hence to moderate the resulting pressure on the agricultural system, plays a significant role in holding down the overall increase in

EXHIBIT 2-1: INCREMENTAL ENERGY CONSUMPTION ESTIMATES PER BUSHEL OF CORN AND GRAIN SORGHUM USED FOR ETHANOL PRODUCTION

| | Petroleum Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Energy Consuming Element | Motor Gasoline (gal) | Distillate (1) (gal) | LPG (gal) | Natural Gas (cu ft) | Coal (2) (lb) | Btu Petroleum Products | Btu Precious Fuels (3) | Btu Total Energy |
| • MACHINERY | | 0.0741 | | | | 10,400 | 10,400 | 10,400 |
| • IRRIGATION | | 0.0086 | 0.0081 | 4.8 | 0.45 | 2,000 | 6,900 | 11,900 |
| • CROP DRYING | | | 0.0524 | | | 5,000 | 5,000 | 5,000 |
| • NITROGEN FERTILIZER | | | | 28.1 | 0.07 | | 28,700 | 29,400 |
| • NONNITROGEN FERTILIZER | | | | 0.4 | 0.02 | | 400 | 600 |
| • PESTICIDES | | 0.0129 | | 4.5 | 0.36 | 1,800 | 6,400 | 10,400 |
| • TRANSPORTATION | 0.0089 | -0.0211 | | | | -1,800 | -1,800 | -1,800 |
| TOTAL | 0.0089 | 0.0745 | 0.0605 | 37.8 | 0.90 | 17,400 | 56,000 | 65,900 |

(1) Includes some gasoline and residual fuel included in ISU Model estimate of "diesel fuel".
(2) Based on use of 11,250 Btu/lb coal.
(3) Consists of liquid fuels and natural gas.

Source: ISU Model and supplementary estimates of effects on transportation fuel requirements (see Appendix A).

energy consumption — were these by-products not used for this purpose, energy consumption per bushel of grain used for ethanol production would be about 25 percent higher.

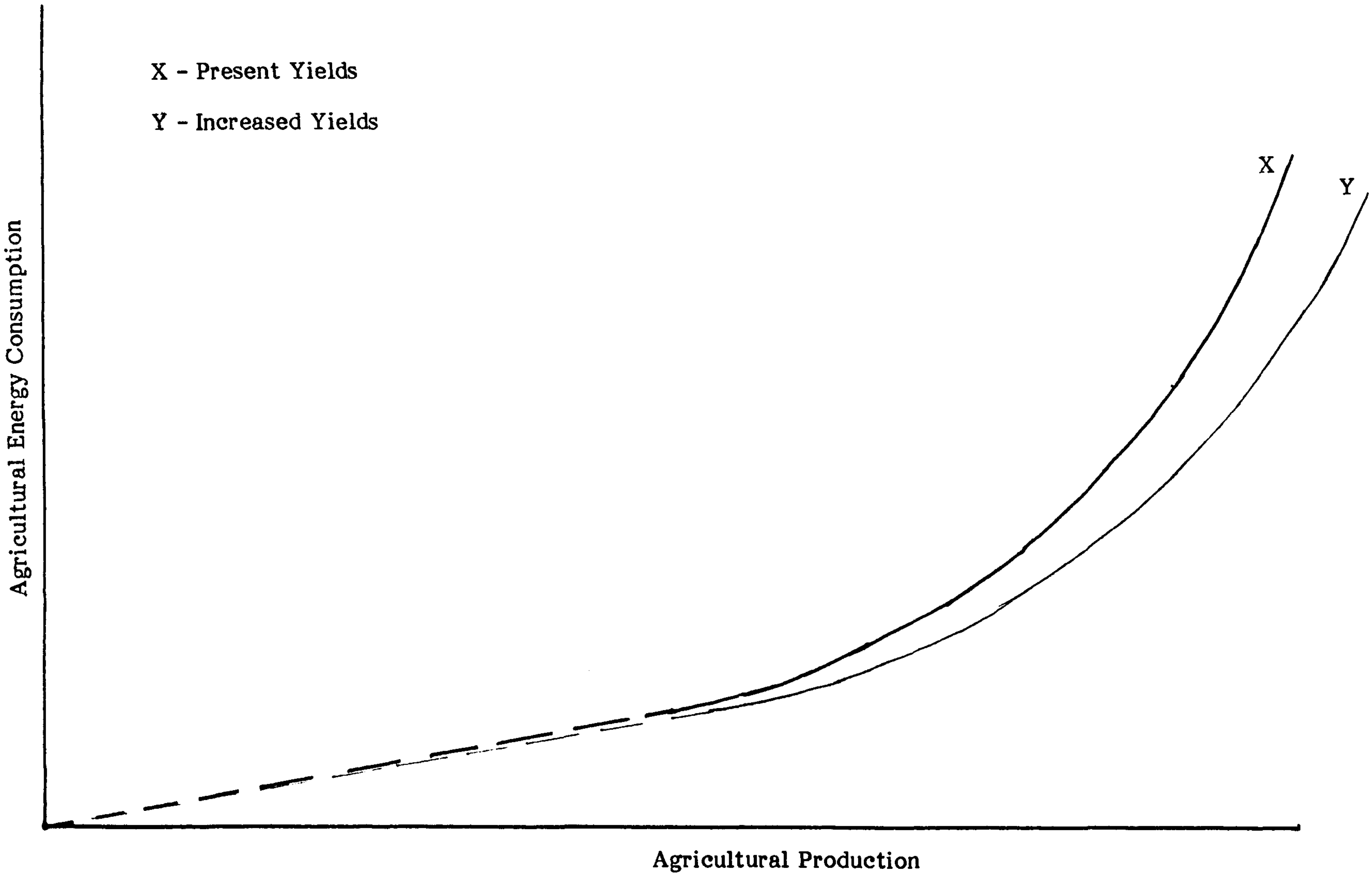
The overall increase in energy consumption is estimated to be 65,900 Btu per bushel of grain used for ethanol production. Nearly 60 percent of this energy is from natural gas and over 25 percent is from petroleum products. Increased consumption of nitrogen fertilizer accounts for over 40 percent of the total increase in energy consumption, with most of the remainder used for irrigation, operation of machinery, and production of pesticides.

## 2.2 Influences on Agricultural Energy Consumption

A limited sensitivity analysis performed using the ISU Model indicates that the level of ethanol production has no significant effect on incremental energy consumption per bushel of grain used for ethanol production (at least for annual production levels of up to twelve billion gallons). The model does indicate, however, that agricultural technology and base-case production levels can have a fairly significant effect. For example, the assumption that increased exports would result in increasing base-case corn, wheat and soybean production by 19, 13 and 35 percent, respectively, was found to result in a 40 percent increase in the incremental agricultural energy required to permit six billion gallons of ethanol to be obtained from grain. Additional discussion of these sensitivity analyses may be found in Section A.2.2 of Appendix A.

For additional insight into the results of these sensitivity analyses, consider Exhibit 2-2. The exhibit depicts the relationship between agricultural production and energy consumption. A generalized measure of total agricultural production is represented on the horizontal axis, and total energy consumed in achieving this production is represented on the vertical axis. Curve X is a generalized representation of the relationship between the two under a given set of conditions. For low levels of production this curve has been drawn as a dotted line; the shape of the curve in this region does not affect the present discussion (though it is likely that it is concave downward, at least for the lowest levels of production). For high levels of production, the curve becomes increasingly steep as total production is increased and the

EXHIBIT 2-2: THE RELATIONSHIP BETWEEN AGRICULTURAL PRODUCTION AND ENERGY CONSUMPTION



availability of prime agricultural land diminishes.[1] In this region, as production is increased, the increase in production is increasingly the result of more intensive fertilization and increased irrigation — two particularly energy-intensive activities.

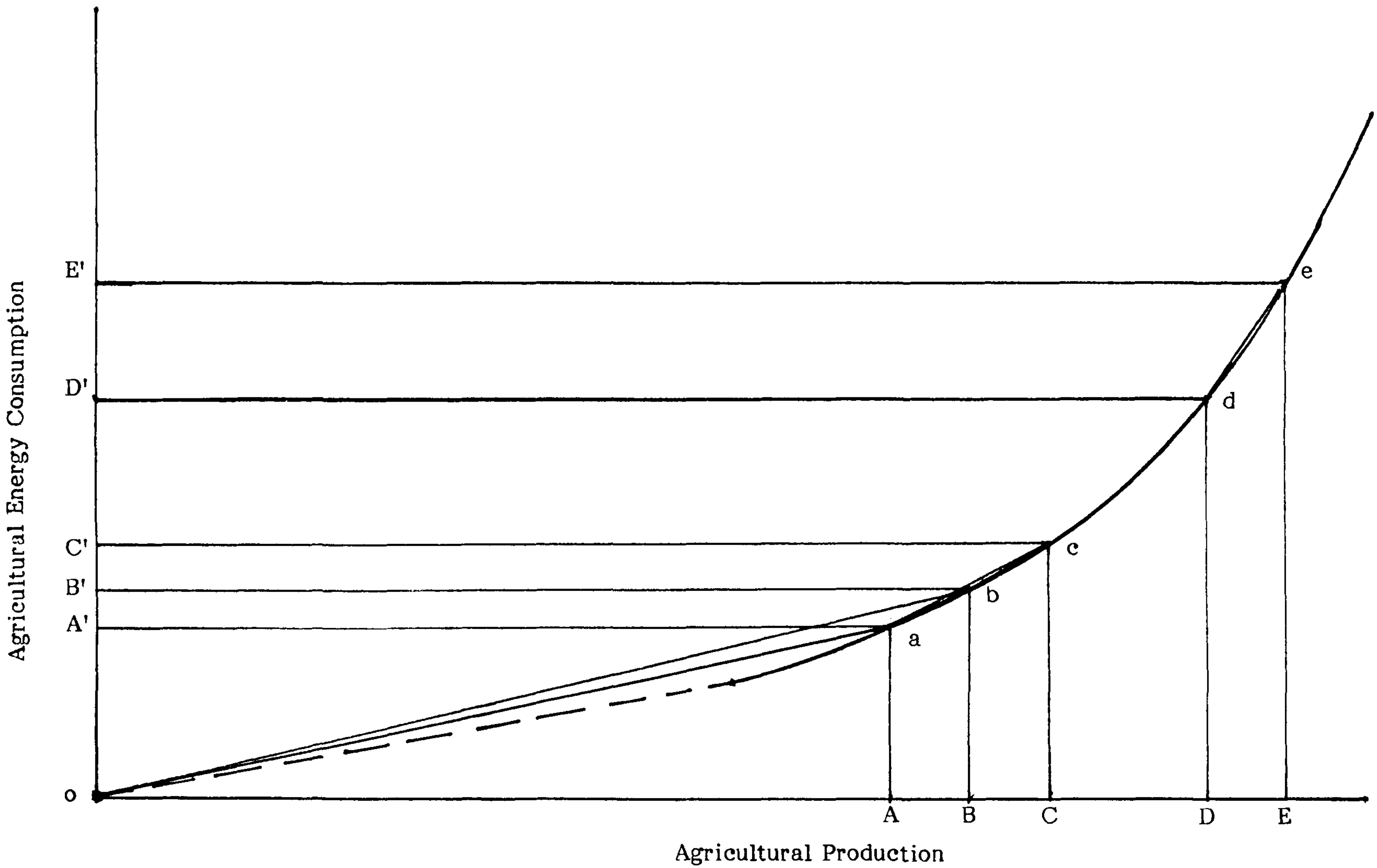
Changes in technology will result in some change in the curve. A change which permits increased yields with no significant effect on energy consumption will result in a horizontal expansion of the curve, as shown by the light line (Curve Y) in Exhibit 2-2. For any given level of agricultural production, this curve indicates that less energy will be consumed than under the original technological conditions. Technological changes which are either energy conserving or energy intensive will result in a vertical as well as a horizontal shift in the curve. The shape of the curve can also be influenced by other factors such as land availability (as a result of erosion or urbanization). Although changes in these factors will affect the precise form of the curve, its general shape will remain similar to that of the curves shown in the exhibit — becoming increasingly steep as total production is increased over moderate and high levels of production.

Curve X of Exhibit 2-2 is shown again in Exhibit 2-3. In the latter exhibit, the relationship between levels of agricultural production and energy consumption is made explicit by labeling several points on the curve (a, b, c, d and e) and the corresponding points on the horizontal axis (A, B, C, D and E) and on the vertical axis (A', B', C', D' and E'). If present agricultural production is at level A, then present agricultural energy consumption is at level A', and average energy consumption per unit of output is given by the slope of the line oa.

An increase in production to level B would result in an increase in energy consumption to level B'. The average energy consumption per unit of increased output would be given by the slope of the line ab, which may be seen to be somewhat greater than that of oa. A larger increase in production, to level C, would result in a larger increase in energy consumption, to level C'. Because of the relatively slow rate of increase in the slope of the curve, however, the slope of the line ac, which represents the average

[1] *The solid portion of Curve X has been drawn as being concave upward in its entirety. This is somewhat of a simplification. This portion of the curve would be entirely concave upward if the agricultural system achieved any given level of production with minimum expenditure of energy. The system, however, tends to minimize costs rather than energy use. Since, for this system, economic efficiency and energy efficiency are fairly well correlated, the curve appears to be generally concave upward. There are, however, points along the curve where the next increment of production (from a least-cost standpoint) will not be the least energy-consuming increment; localized departures from the apparent upward concavity of the curve will thus result.*

EXHIBIT 2-3: INCREMENTAL AGRICULTURAL ENERGY CONSUMPTION



energy consumption per unit of increased output, is only very slightly greater than that of line ab. Average energy consumption per unit of increased output thus may be seen not to be particularly sensitive to the size of the increase in production. This result is consistent with the observation made at the beginning of this subsection that the ISU Model indicates that the level of ethanol production has no significant effect on incremental energy consumption per bushel of grain used for ethanol production.[1]

Average energy consumption per unit of increased output, however, is more sensitive to the various influences on the shape of the curve (technology, the price of energy, land availability, etc.) and to the base-case level of production. If present agricultural production is at level D, instead of at A, then a moderate level of ethanol production will require that agricultural production be increased to level E; the resulting increase in agricultural energy consumption, given by D'E', may be seen to be appreciably greater than that given by A'B', which is the increase required to produce the same amount of ethanol starting from level A. As stated in the beginning of this subsection, the ISU Model indicates that when base-case agricultural production is increased (to permit increased exports) the agricultural energy required to permit a given level of ethanol production rises at a rate which is appreciably greater than the increase in base-case production.

In Exhibit 2-3, the average energy consumption per unit of output associated with production at level A is given by the slope of the line oa, and that associated with production at level B is given by the slope of line ob. The slope of the latter line is somewhat greater than that of the former line — thus increasing agricultural production results in some increase in average energy consumption per unit of output. Increasing production also has a similar effect on the cost per unit of production; i.e., increasing agricultural production results in increasing the cost of production and increasing the equilibrium prices of agricultural products. The ISU Model indicates that, if increased agricultural prices do not cause demand for domestic agricultural products to decline, using grain to produce six billion gallons of ethanol will result in about a four percent

[1] *Actually, the results reported in Section A.2.2 of Appendix A indicate a small increase in incremental energy consumption per unit in one case out of three and small decreases in the other two cases. The decreases apparently result from localized departures from the upward concavity of the energy consumption curve. These departures are discussed in the preceding footnote. (The sensitivity tests performed involved increasing ethanol production by either three billion or six billion gallons. These changes in ethanol production result in relatively small changes in overall agricultural production, especially when one considers that soybean production (which is reduced when ethanol production is increased) requires three times as much land as corn production.)*

increase in the price of wheat. The model also indicates that doubling ethanol production will more than double the effect on agricultural prices. The data presented in Appendix A suggest that our ability to produce ethanol from grain is likely to be limited by our willingness to pay such increased prices for agricultural products, or to reduce exports or domestic consumption of these products, rather than on any absolute limits on the availability of resources (cropland, irrigation water, and fertilizer).

## 2.3 Ethanol Production

Processes for the conversion of grain to ethanol are generally divided into those that use dry milling and those that use wet milling.

### 2.3.1 Dry Milling

Dry milling technology is relatively straightforward. As the name implies, the milling or size-reduction of the grain is done in the absence of water. The entire kernel of grain is reduced in size, usually to pass through a 20 mesh screen without any attempt to separate the various components of the grain.

There are several vendors of proprietary dry-milling ethanol technology. These include ACR, Buckau-Wolf, Katzen Associates, Vulcan-Cincinnati, and Vogelbusch. In addition, a number of engineering firms will design dry-milling alcohol plants using various combinations of proprietary and nonproprietary technology. While there are a number of differences between the technologies offered by various vendors, the energy consumption is most affected by the choice of the distillation system, by the use of cogeneration, by the choice of the evaporation system, and by the quantity of water which must be evaporated (which may be influenced by the use of recycle in the process).

The design chosen for analysis in this study is very similar to the design used in the U.S. Department of Energy (DOE) report, Grain Motor Fuel Alcohol Technical and Economic Study (Katzen, 1979). This design was selected because it is in the public domain and because it is one of the more energy-efficient designs available. Those portions of the published design which were not considered to be commercially proven state-of-the-art were replaced with proven technologies. The technologies changed were the drying system for the distillers' dark grains (DDG) and the flue-gas desulfurization system used in conjunction with the coal-fired boiler.

The design selected for analysis includes vapor recompression evaporators, use of high pressure steam in extraction turbines to provide shaft power to the evaporator compressors, and a cascaded azeotropic distillation system for ethanol purification. Overall, the design selected consists of proven technologies and is considered to be very energy efficient. It is described in greater detail in Section 1 of Appendix B.

### 2.3.2 Wet Milling

The wet milling of grain is more complex than dry milling, each wet miller incorporates proprietary variations in the process. From an energy-use viewpoint, the water balance is a key item. If more water can be recycled and reused within the process, less must be evaporated and less energy is consumed.

The selected process scheme includes production of by-product oil, gluten feed, and gluten meal. The wet-milling section includes several major steps: steeping; degermination, germ dewatering, and drying; fiber separation, dewatering, and drying; and the gluten separation from starch and drying. The selected process is described in Section 2 of Appendix B.

### 2.3.3 Energy Requirements and By-Product Energy Credits

The energy requirements for both dry and wet-milling of corn are summarized in Exhibit 2-4. The energy required for processing grain sorghum was not separately analyzed but is believed to be similar.

The coal used for both processes was assumed to be an Illinois No. 6 with 12 percent moisture and a higher heating value as received (wet) of 10,630 Btu/lb (12,080 Btu/lb dry basis). The sulfur content was 3.8 percent on a moisture-free basis. Lime is used for flue-gas desulfurization. Energy consumption for producing lime was derived from Census of Manufactures (1980a and 1980c) data (see Appendix B).

EXHIBIT 2-4: NON-AGRICULTURAL ENERGY INPUTS FOR PRODUCING 1000 GALLONS OF ETHANOL FROM CORN

| | | Petroleum Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Motor Gasoline (gal) | Distillate (gal) | Residual fuel (gal) | Natural Gas (M cu ft) | Coal (1) (tons) | Liquid Fuels (M Btu) | Precious Fuels (M Btu) | Total Energy (M Btu) |
| **DRY MILLING** | | | | | | | | | |
| • PROCESS ENERGY: | 2.24 tons of coal | | | | | +2.24(2) | | | +47,700 |
| | 1310 kwhr electricity | | | | | +0.64 | | | +13,600 |
| • LIME: | 0.12 tons | | +1.10 | +4.27 | +1.90 | +0.27 | +800 | +2,700 | +8,800 |
| NON-AGRICULTURAL ENERGY REQUIRED FOR PROCESS AND LIME | | | +1.10 | +4.27 | +1.90 | +3.15 | +800 | +2,700 | +70,100 |
| **WET MILLING** | | | | | | | | | |
| • PROCESS ENERGY: | 2.19 tons of coal | | | | | +2.19(2) | | | +46,600 |
| | 1260 kwhr electricity | | | | | +0.62 | | | +13,100 |
| • LIME: | 0.12 tons | | +1.10 | +4.27 | +1.90 | +0.27 | +800 | +2,700 | +8,800 |
| NON-AGRICULTURAL ENERGY REQUIRED FOR PROCESS AND LIME | | | +1.10 | +4.27 | +1.90 | +3.08 | +800 | +2,700 | +68,500 |

(1) Based on use of 22.5 MM Btu/ton coal except as noted.
(2) Based on use of 21.26 MM Btu/ton coal.

In addition, about 0.02 (formerly 0.05) gallons gasoline are consumed per gallon ethanol as a denaturant. This gasoline is not included in the overall energy balance because it is neither added nor removed from the fuel available for transportation. It is merely diverted temporarily from the gasoline pool to make the fuel grade ethanol unfit to drink.

Similarly, a makeup azeotroping agent (benzene or other hydrocarbon) has been ignored in the energy balance because the losses will end up in the fuel. Furthermore, the total energy content of the azeotroping agent is small.

Both processes produce animal feed by-products and the wet-milling process produces oil from corn or grain sorghum. These oils compete with other vegetable oils, including soy oil, while the other products displace soy meal, corn, and other feed products. The effect on agricultural energy consumption of the overall reduction in demand for feed products is reflected in the estimates of the effect on agricultural energy consumption presented primarily in Exhibit 2-1. The production of vegetable oil by the wet-milling process, however, produces an additional energy saving resulting from the reduced demand for the production of vegetable oil from other sources. An energy credit is therefore taken for the vegetable oil equal to the average energy required to extract soy oil from soybeans by crushing. The size of this credit is estimated from Census of Manufactures data (U.S. Department of Commerce 1980a and 1980b) in Section A.3 of Appendix A and shown in Exhibit 2-5.

The energy requirements of the two processes are similar, though the wet-milling process requires slightly less process energy and yields by-products which have a slightly greater energy value (in terms of the energy required to obtain the products which are replaced).

The energy requirements are sensitive to plant size, the specific design characteristics of the plant, the sulfur content of the coal, and the choice of coal as a boiler fuel; if the boiler fuel were either agricultural residues or methane derived from still bottoms or manure, the overall consumption of nonrenewable fuels would be reduced but the consumption of petroleum products and/or natural gas would be increased. Additional discussion of these issues is contained in Sections B.3 and B.4 of Appendix B.

## EXHIBIT 2-5: ENERGY CONSUMPTION FOR PRODUCING SOY OIL
(per pound of oil produced)

| | Petroleum Products | | | | | | |
|---|---|---|---|---|---|---|---|
| | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | Natural Gas (cu ft) | Coal (1) (lb) | Total Petroleum Products (Btu) | Total Energy (Btu) |
| Net shipments in 1977 (2): 14,846 MM lbs | | | | | | | |
| Total energy consumption in 1977 (3): | | | | | | | |
| — Electricity: 1422.8 MM kwhr | | | | | 0.089 | | 999 |
| — Direct fuels: | | 0.00301 | 0.00296 | 1.50 | 0.029 (6) | 865 | 2,724 (5) |
| Distillate: 1062.7 M bbl | | | | | | | |
| Residual: 1045.4 M bbl | | | | | | | |
| Natural gas: 22.3 B cu ft | | | | | | | |
| Coal na (4) | | | | | | | |
| | | 0.00301 | 0.00296 | 1.50 | 0.118 | 865 | 3,723 |

*Less than 0.0005 gal/bu.

(1) Assumes use of 11,250 Btu/lb coal.
(2) DOC, 1980b.
(3) DOC, 1980c.
(4) Data for coal use withheld by Census.
(5) Estimated directly from source data.
(6) Estimated by assuming that all energy from sources not separately identified was obtained from coal.

## 2.4 Results

In the first section of this chapter, estimates were presented of the effect of ethanol production on agricultural energy consumption. These estimates reflected the overall effects of increased production of corn and grain sorghum (for use as ethanol feedstocks) and decreased production of soybeans and some other feed crops (resulting from the substitution of feed by-products of the ethanol process). In the third section, estimates were presented of the energy requirements for deriving ethanol from corn using two alternative milling processes and of non-agricultural energy savings resulting from the availability of by-product oil resulting from one of these processes. Although energy requirements for converting grain sorghum to ethanol were not analyzed separately, they are believed to be similar to those for converting corn to ethanol.

Exhibit 2-6 shows a summary of the energy inputs and outputs for obtaining 1,000 gallons of ethanol from wet milling of grain. The figures in the exhibit presume that, nationally, corn and grain sorghum will be used in the same ratio as indicated by the results of the analysis of the model presented in Section 2.1, that the wet-milling process will be used (as indicated by that analysis), and that energy requirements for processing grain sorghum are the same as for processing corn.

The major energy requirements are for conversion of grain to ethanol and for increasing agricultural production. All energy requirements for conversion are assumed to be supplied by coal. However, only about 15 percent of the energy required for increasing agricultural production is from coal; sixty percent is obtained from natural gas (primarily for fertilizer), and the rest is obtained from various petroleum products. Additional energy is required for producing lime for flue-gas desulfurization.

The primary product is 1000 gallons of ethanol. In addition, about 3.5 tons of by-products are produced, most of which would replace soy meal and corn in animal feed.

The net change in each form of available energy is shown on the bottom line of Exhibit 2-6 in conventional units. This information is also presented in Exhibit 2-7, where the changes are presented in conventional units, in Btu, and in "gallons of ethanol equivalent." This last measure expresses a given quantity of fuel in terms of the number of gallons of ethanol required to provide the same energy. (In interpreting this

EXHIBIT 2-6: ENERGY INPUTS AND OUTPUTS FOR PRODUCING 1000 GALLONS OF ETHANOL FROM GRAIN

| | | | Petroleum Products | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ethanol (gal) | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | LPG (gal) | Natural Gas (M cu ft) | Coal (1) (tons) | Liquid Fuels (M Btu) | Precious Fuels (3) (M Btu) | Total Energy (M Btu) |
| INPUTS | | | | | | | | | | | |
| • FEEDSTOCK: | 388 bushels of corn and grain sorghum (4) | | -3.5 | -28.9 | | -23.5 | -14.7 | -0.17 | -6,700 | -21,700 | -25,500 |
| • ENERGY: | 2.19 tons of coal | | | | | | | -2.19 (2) | | | -46,600 |
| | 1260 kwhr electricity | | | | | | | -0.62 | | | -13,100 |
| • LIME: | 0.12 ton | | | -1.1 | -4.3 | | -1.9 | -0.27 | -800 | -2,700 | -8,800 |
| OUTPUTS | | | | | | | | | | | |
| • BY-PRODUCTS: | 560 lb vegetable oil (4,5) 1080 lb gluten meal (4) 5500 lb gluten feed (4) | | | +1.7 | +1.7 | | +0.8 | +0.03 | +500 | +1,100 | +1,800 |
| • ETHANOL: | 1000 gallons | +1,000 | | | | | | | +84,200 | +84,200 | +84,200 |
| NET ENERGY PRODUCTION/CONSUMPTION | | +1,000 | -3.5 | -28.3 | -2.6 | -23.5 | -15.8 | -3.22 | +77,200 | +60,900 | -8,000 |

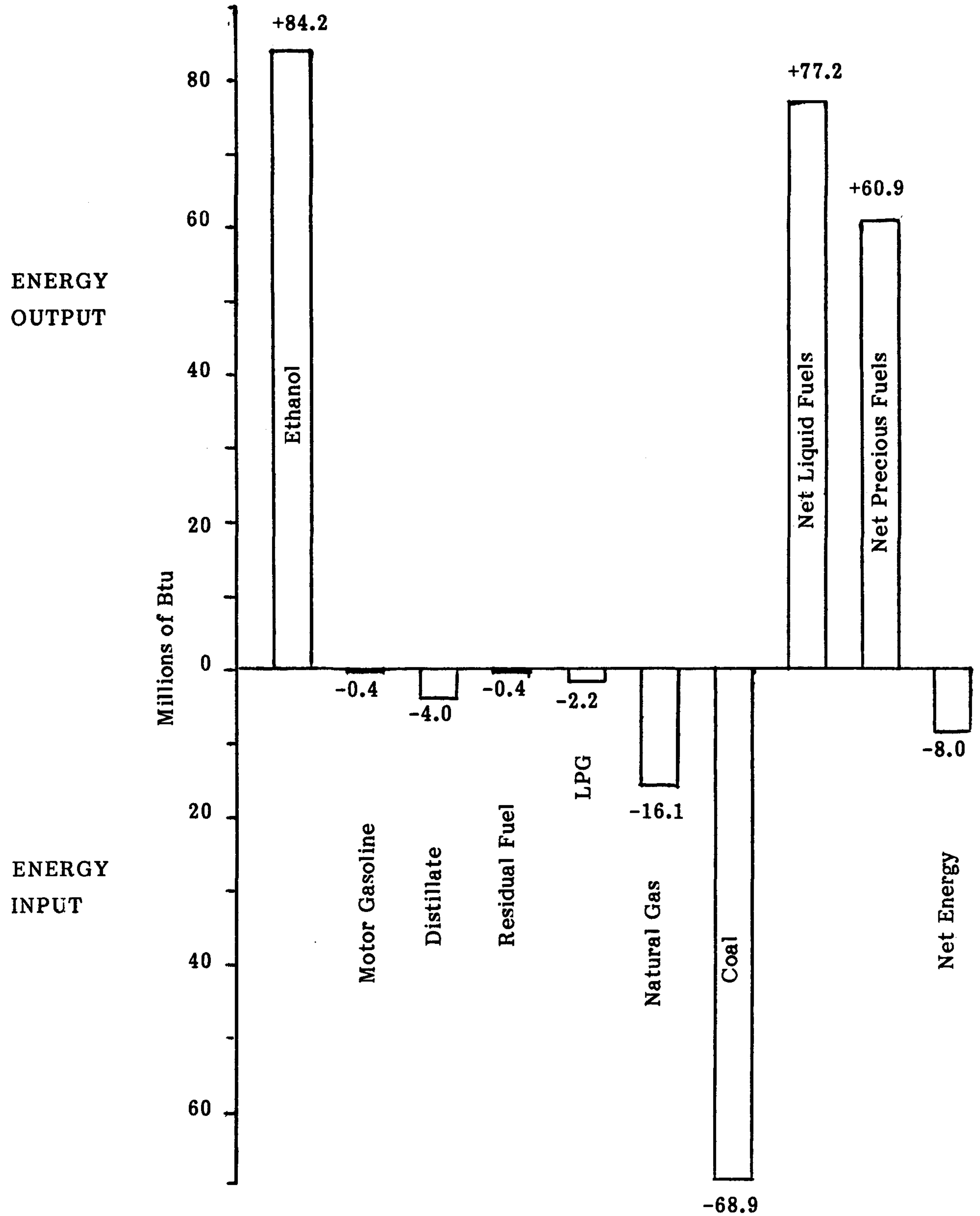
(1) Based on use of 11,250 Btu/lb coal except as noted.
(2) Based on use of 10,630 Btu/lb coal.
(3) Consists of liquid fuels and natural gas.
(4) Agricultural energy credits resulting from the availability of feed by-products are reflected in the estimate of energy requirements for feedstock production.
(5) Vegetable-oil production represents national average by-product oil from corn and grain sorghum for the mix of feedstocks selected by the ISU Model (see Section 2.1). Energy credits shown are for crushing only, and are derived from data in Exhibit 2-6.

EXHIBIT 2-7: ALTERNATE MEANS OF EXPRESSING ENERGY CHANGES RESULTING FROM THE PRODUCTION OF 1000 GALLONS OF ETHANOL FROM GRAIN

| | Change in Available Energy | | | |
|---|---|---|---|---|
| | Conventional Units | | MM Btu | Gallons of Ethanol Equivalent (1) |
| Ethanol | + 1,000 | gal | + 84.2 | + 1,000 |
| Motor Gasoline | - 3.5 | gal | - 0.4 | - 5 |
| Distillate | - 28.3 | gal | - 4.0 | - 47 |
| Residual Fuel | - 2.6 | gal | - 0.4 | - 5 |
| LPG | - 23.5 | gal | - 2.2 | - 27 |
| Natural Gas | - 15.8 | M cu ft | - 16.1 | - 191 |
| Coal | - 3.22 | tons | - 68.9 | - 818 |
| Net Liquid Fuels | | | + 77.2 | + 916 |
| Net Precious Fuels | | | + 60.9 | + 725 |
| Net Energy | | | - 8.0 | - 93 |

(1) One "gallon of ethanol equivalent" is defined to equal 84,200 Btu.

EXHIBIT 2-8: ENERGY INPUTS AND OUTPUTS FOR PRODUCING ETHANOL FROM GRAIN



measure, it should be borne in mind that a gallon of ethanol contains only about two-thirds as much energy as a gallon of gasoline.) The same information is presented a third time, graphically, in Exhibit 2-8.

It can be seen from Exhibit 2-8 that production of ethanol from corn requires small amounts of various petroleum products as well as a slightly larger amount of natural gas and an even larger amount of coal (including coal used for the generation of electricity). A substantial net increase in liquid fuels results: the energy value of net consumption of petroleum products represents only about eight percent of that of the ethanol produced. Total energy consumed, however, exceeds the energy of the ethanol produced.

Most of the energy consumed is coal which, though nonrenewable, is relatively plentiful and less valuable than liquid fuels. A moderate amount, however, is natural gas. Net consumption of natural gas and the various petroleum products represents 23.3 million Btu per thousand gallons of ethanol -- slightly more than one-quarter of the energy value of the ethanol. The combined requirements for liquid fuels and natural gas are presented under the heading "precious fuels" in the exhibits.

The components of change in available liquid fuels are shown graphically in Exhibit 2-9. One thousand gallons of ethanol (84.2 MM Btu) is produced by each of the processes. However, because of liquid fuel requirements for lime and the net increase in liquid fuel requirements for crop production (even after energy credits are taken for corn oil and feed by-products), the net increase in liquid fuels is only 77.2 MM Btu (916 gallons of ethanol equivalent).

The components of change of precious fuels (liquid fuels and natural gas) are shown graphically in Exhibit 2-10. The precious fuel requirements for lime and for increased crop production are substantially higher than they are for liquid fuels alone. The net increase in precious fuels is about 60.9 MM Btu (725 gallons of ethanol equivalent). This represents a 77.2 MM Btu increase in liquid fuels and a 16.3 MM Btu decrease in natural gas.

The components of change of total energy are shown graphically in Exhibit 2-11. In order to produce 1000 gallons (84.2 MM Btu) of ethanol, about 92.2 MM Btu of coal, natural gas, and liquid fuels are required.

EXHIBIT 2-9: NET LIQUID FUELS FOR PRODUCING ETHANOL FROM GRAIN

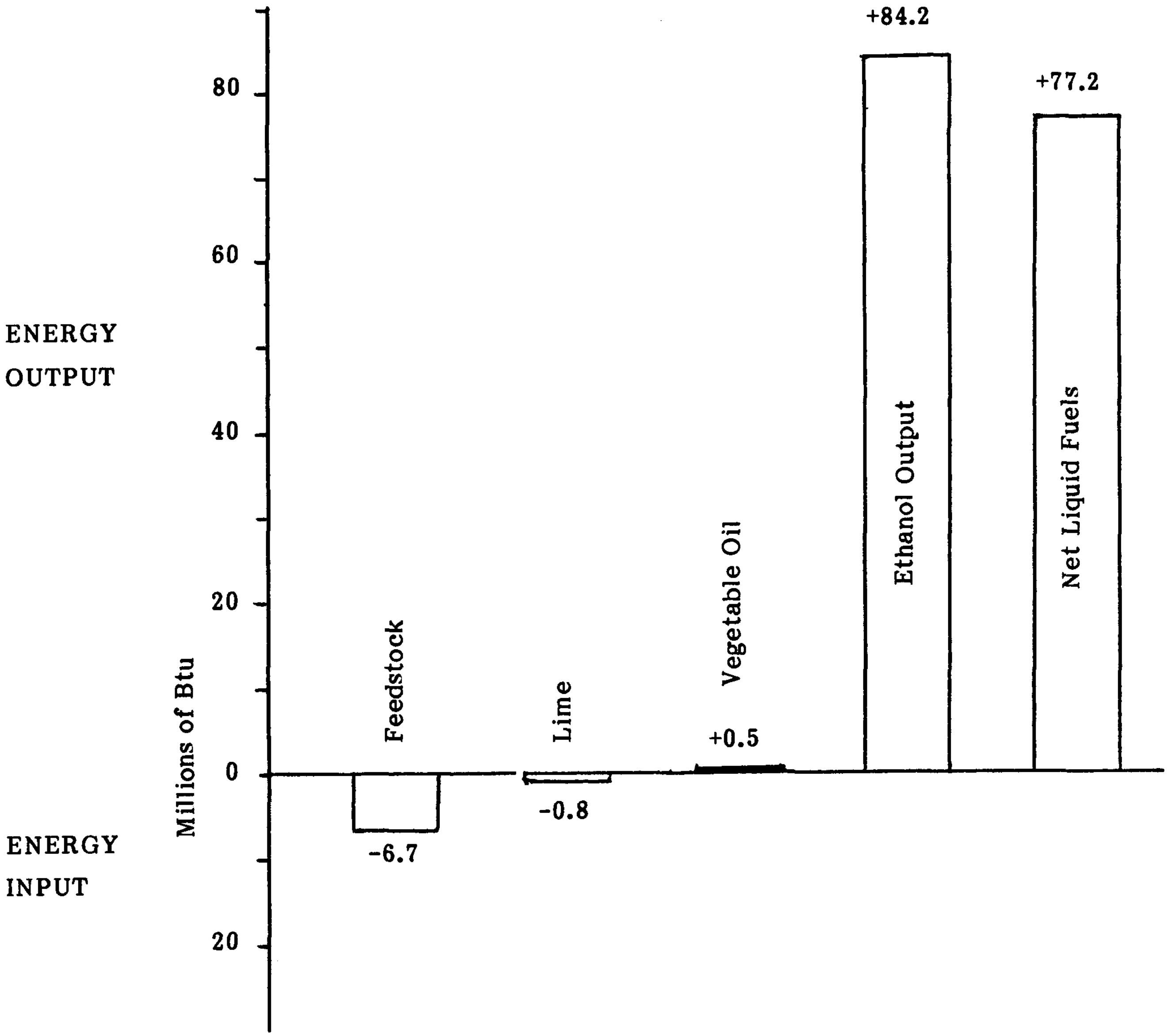


EXHIBIT 2-10: NET PRECIOUS FUELS FOR PRODUCING ETHANOL FROM GRAIN

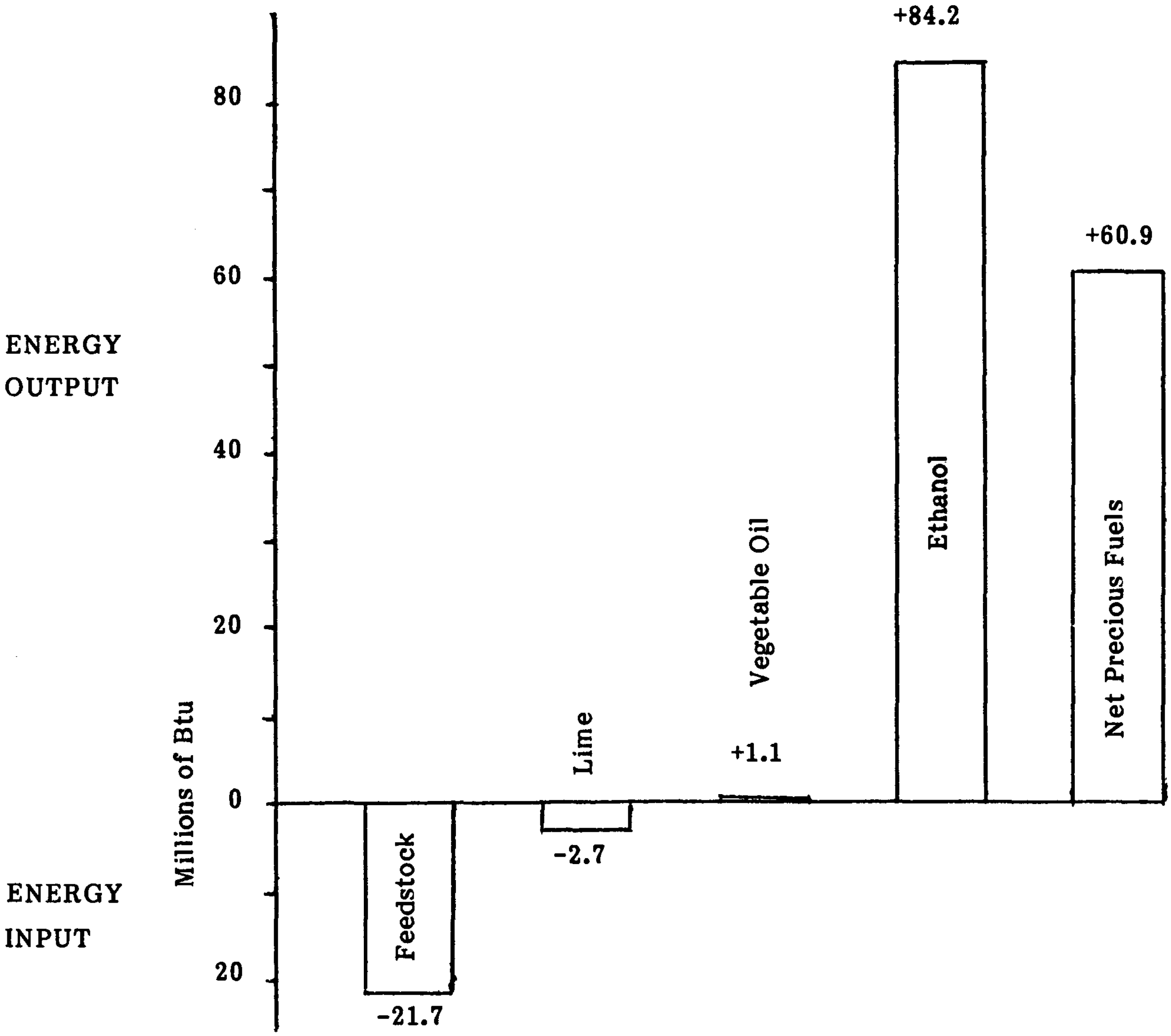
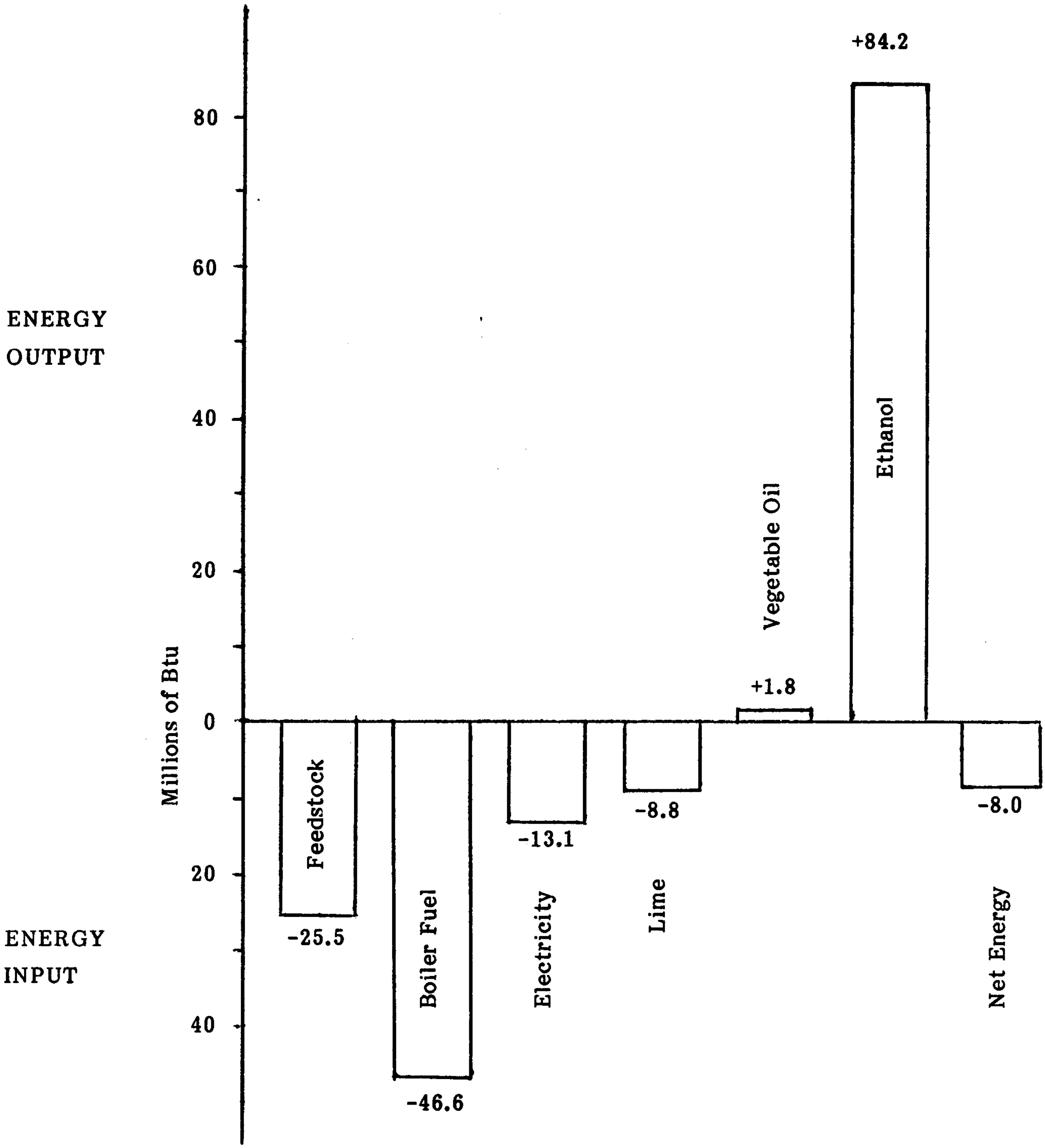


EXHIBIT 2-11: NET ENERGY FOR PRODUCING ETHANOL FROM GRAIN



The results presented in Exhibits 2-6 through 2-11 incorporate estimates of process energy consumption and of the energy required for producing lime and for increasing agricultural production. Because agricultural production tends to become more energy intensive as total production increases, an equal decrease in production from current levels will likely result in reducing energy consumption by a slightly smaller amount. Thus the energy that would be saved by reducing production would be slightly less than that required for increasing production. For small changes in overall production, however, the difference is likely to be quite small. The results presented in Exhibits 2-6 through 2-11 are thus appropriate estimates of the change in energy consumed in order either to increase or to decrease ethanol production from grain purchased on the open market[1].

In summary, the production of ethanol from corn and grain sorghum requires only limited use of petroleum products and natural gas. About 82 percent of the energy contained in the ethanol represents an increase in the availability of liquid fuels. Consumption of natural gas is somewhat higher than consumption of petroleum products; the energy content of the natural gas consumed is about 19 percent of that of the ethanol produced. However, because of other energy requirements (presumed to be provided by coal and by electricity generated from coal), total energy consumed exceeds the energy of the ethanol produced. Overall energy efficiency is about 91.5 percent when the wet-milling process is used and is likely to be slightly lower when dry milling is used.

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[1] *These results, however, may not provide appropriate estimates of energy consumption when surplus grain is used. To the extent that such grain may be purchased and disposed of in a way which does not affect grain production, energy requirements for obtaining the feedstock may be appropriately estimated as consisting solely of the energy consumed in transport to the ethanol plant.*

# 3. METHANOL FROM CELLULOSE

Cellulose, a polymer of glucose, is the main component of plants. Plants do not create the energy necessary to build cellulose molecules; they trap that energy in the form of light and store it in chemical bonds. These bonds link the atoms of carbon, hydrogen and oxygen that form cellulose molecules. When cellulose is burned, the chemical bonds are broken, and energy is released.

Although only limited fuel use is now made of wood in this country, it is a significant source of energy in many third-world countries. As a fuel, wood is most commonly burned for its heat value. Since any conversion from one form of energy to another results in a loss of available energy, such direct combustion provides more energy than could be obtained from any substance, such as methanol, derived from the wood. Thus the most energy-efficiency method for man[1] to obtain energy from cellulose is to burn the cellulose directly. To provide a convenient motor-vehicle fuel, however, it is necessary to convert the wood to a liquid fuel such as methanol.

The first three sections of this chapter discuss three alternative sources of cellulose and present estimates of incremental energy required for obtaining cellulose from these sources and transporting it to a methanol conversion plant. The three sources are forest residues, biomass farms, and agricultural residues. Additional information about each of these potential sources may be found in Appendices C, D, and E, respectively.

In Section 3.4, the selected cellulose-to-methanol process is described and its energy requirements are presented. The minimum economic size of the methanol plant was estimated to be 300,000 gallons per day. Such a plant will require annually about 725,000 dry-ton equivalents (DTE) of wood or 635,000 DTE of agricultural residues. These feedstock requirements were used in Appendices C, D, and E in determining the size of area from which the alternative feedstocks would be collected. Additional information about the cellulose-to-methanol process is contained in Appendix F.

The final section of this chapter presents a summary and discussion of the energy inputs and outputs estimated for deriving methanol from cellulose.

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[1] *Ruminants such as cattle have the ability to digest cellulose. In the digestive process the energy of a molecule's chemical bonds is utilized at body temperature. The breakdown of cellulose as a food source is therefore far more efficient than the rather clumsy method of burning cellulose for heat.*

## 3.1 Forest Residues

The high Btu content and clean-burning properties of wood make it an attractive energy source. Forest residues, because of their inherent unsuitability for other uses, are a particularly appropriate source of energy, assuming that the engineering and economic constraints are not prohibitive.

The forest products industry is currently the largest user of forest residues for fuel. Within the industry, the pulp and paper sector utilizes 92 percent of total wood energy consumed and has conducted much of the research on using wood residues for energy (Zerbe, 1978).

But despite the value of wood as a fuel, a large volume of wood fiber (1.6 billion cubic feet in 1970) is left in U.S. forests as residue from harvest operations (U.S. Forest Service, 1974). Pre-commercial cuttings, understory removal, and annual mortality are included in this estimate. These residues could be collected during normal harvesting operations using conventional harvesting equipment. They would be well-suited for conversion to methanol.

Estimates of the energy consumed in the collection of forest residues and transport to a methanol plant are developed in Appendix C and summarized in Exhibit 3-1. Separate estimates are shown for the West (consisting, roughly, of commercially forested areas from western South Dakota westward) and for the East. Separate consideration was given to three harvesting systems: commercial (or clear-cut) harvest; commercial thin (i.e., harvesting of selected trees); and stand-improvement thin. As shown in the exhibit, identical estimates were developed for the first two harvesting systems. For stand-improvement thinning, separate estimates were developed for a manual felling and delimbing system and for a mechanized system. Only the manual system was considered for the Western United States because of complications that arise when using mechanized systems on steep slopes.

The estimates of energy consumed in collecting residues of commercial harvesting and commercial thinning consist of energy consumed in loading trucks with the residues, transport to the methanol plant, unloading and chipping. The part of the forest operation attributable to obtaining sawlogs is not counted.

EXHIBIT 3-1: ENERGY CONSUMPTION ESTIMATES PER DELIVERED DRY TON EQUIVALENT OF FOREST RESIDUES

| | | Petroleum Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Region | Operation | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | Natural Gas (cu ft) | Coal (tons) | Btu Petroleum Products | Btu Precious Fuels | Btu Total Energy |
| • EASTERN UNITED STATES | — Commercial Thin or Commercial Harvest | | 2.83 | | | | 396,000 | 396,000 | 396,000 |
| | — Stand Improvement Thin: Manual System | 0.57 | 3.85 | | | | 610,000 | 610,000 | 610,000 |
| | — Stand Improvement Thin: Mechanized System | | 4.87 | | | | 682,000 | 682,000 | 682,000 |
| • WESTERN UNITED STATES | — Commercial Thin or Commercial Harvest | | 3.51 | | | | 492,000 | 492,000 | 492,000 |
| | — Stand Improvement Thin: Manual System | 0.57 | 4.42 | | | | 690,000 | 690,000 | 690,000 |

The estimates of energy consumed in collecting residues of stand-improvement thinning presume that such thinning would not occur if the wood and residues obtained were not to be converted to methanol. Accordingly, all energy consumed in such thinning operations is included in the estimate of energy required for obtaining residues for methanol conversion. The resulting improvement in in-woods growing conditions is treated as a beneficial side effect. The consumption estimates for stand-improvement thinning thus include all energy for felling, movement to the roadside, delimbing, and crew transport, as well as energy consumed in loading, truck transport, unloading, and chipping. For this reason, the estimates of energy consumed in obtaining residues for stand-improvement thinning are higher than those for obtaining residues from commercial harvesting and commercial thinning[1].

The most energy-consuming of the operations involved in residue collection is truck transport. For each system, energy consumed in truck transport was estimated to be about 210,000 Btu per dry-ton-equivalent (DTE) of forest residue collected, representing about 30-50 percent of the consumption estimates shown in Exhibit 3-1. Energy consumed in transport will vary with (among other things) distance, terrain, and moisture content of the wood. The estimate incorporated into Exhibit 3-1 is based on an average haul of 50 miles and an average load of 19 green tons with a 50 percent moisture content (i.e., 9.5 DTE).

Energy required for collecting forest residues is small relative to the energy content of the residues. The energy value of the methanol produced from one DTE of wood is typically on the order to ten million Btu (though this value varies with moisture content). Energy requirements for collection shown in Exhibit 3-1 thus represent only four to seven percent of the potential methanol yield. The overall energy balance for producing methanol from forest residues will thus be relatively insensitive to moderate changes in energy requirements for residue collection which might result from use of more energy-efficient equipment or from changes in transport distances or variation in moisture content.

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[1] *To the extent that stand-improvement thinning would be motivated by a combination of improved growing conditions and the economic value of the residues obtained, the full value of the resulting energy consumption should not be attributed entirely to the collection of forest residues. The estimate of energy required for stand-improvement thinning shown in Exhibit 3-1 thus may tend to overstate energy requirements for obtaining cellulose from such operations.*

## 3.2 Silvicultural Biomass Farms

Energy farms and energy farming represent technologies for expanding the biomass resource "pie" to accommodate the production of alternative energy supplies. Energy production is the primary purpose of these farms: biomass is grown and harvested specifically for its energy content. Biomass crops include trees, corn, sugar cane, sorghum, and ocean kelp. These can either be burned directly as fuel or be converted into various synthetic fuels. In many respects, the energy farm concept is similar to the application of intensive agricultural practices to crops grown for food. Under intensive management systems, farm sites are extensively prepared and energy crops are planted, fertilized, irrigated, and harvested using methods and equipment that have close analogs in conventional agricultural operations.

As yet, silvicultural energy or biomass farms have not been demonstrated in the U.S. However, other countries, particularly Canada and Sweden, have extensively evaluated and are actively pursuing the application of short-rotation forest harvesting to meet national energy needs. In Sweden, where oil imports account for 70 percent of the total energy supply, a large-scale program is under development to establish silvicultural energy farms on as much as five percent of Sweden's total land area (Pettersson, 1980). Canada, with its large biomass production capability per capita (i.e., large productive land mass/small population), has a significant potential for energy plantations (Middleton et al., 1976).

Estimates of energy consumption are developed in Appendix D for a conceptualized silvicultural biomass farm located in the Southeastern United States. The farm is assumed to be planted with the species Populus (e.g., Eastern cottonwoods or black cottonwoods), a fast-growing hardwood tree. As a hardwood, these trees have the ability to coppice (i.e., to sprout from stumps), thus eliminating the need for replanting after each harvest. Harvesting every three years has been assumed, with complete replanting after every third harvest. To produce high yields, intensive management practices, similar to those applied in field crop production, will have to be used; these include extensive site preparation, mechanized planting, fertilization and irrigation. In order to provide a continuous source of feedstock to the methanol facility, year-round harvesting has been assumed. Additional details are presented in Appendix D.

The energy consumption estimates developed in Appendix D are summarized in Exhibit 3-2. Total energy required per DTE of feedstock delivered to the methanol facility is estimated to be about 1.2 million Btu -- two to three times the estimates for forest residues (see the preceding section), but still small in comparison to the energy content of the wood. The major energy consuming elements are fertilization and irrigation which, together, account for eighty percent of the energy consumed. In this analysis, the irrigation system has been assumed to run on diesel fuel (though other options are available). About 60 percent of energy consumed is derived from petroleum products, with natural gas (for producing nitrogen fertilizer) supplying most of the remainder.

## 3.3 Agricultural Residues

Agricultural residues are an interesting potential source of cellulose for methanol conversion. They are a by-product of agricultural production; by definition residues are the parts of the plant other than the grain, seed or fiber for which the plant is grown.

Among agricultural residues, the present analysis is limited to field residues; these constitute 94 percent of the organic solids produced annually as crop residues. The other 6 percent are from centralized locations such as cotton mills and sugar refineries (EPA, 1978). There are no harvesting energy costs associated with the collection of such non-field residues, and, if the residues are used on site, neither are there any transportation energy costs.

Although crop residues are often perceived as a waste, they perform many functions. Crop residues are sometimes used as animal feed and bedding; corn cobs may be used in the manufacture of chemicals.

But even when the residues decay in the field, they have a value. Crop residues contain nitrogen, phosphorous, and potassium, as well as other less energy-intensive nutrients. When crop residues are left on the field, most of these nutrients eventually return to the soil. When crop residues are removed, additional fertilizer (which has a significant energy value) must be applied to the soil to maintain the soil nutrients at the level that would otherwise exist in the presence of decaying residues.

Crop residues also provide soil with organic matter, which increases soil fertility and reduces soil density. In energy terms, an increase in soil density increases the power required to plow the soil. Organic matter also maintains soil porosity, which permits

EXHIBIT 3-2: ENERGY CONSUMPTION ESTIMATES PER DELIVERED DRY TON OF WOOD FEEDSTOCK FROM A SILVICULTURAL BIOMASS FARM

| | Petroleum Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Energy Consuming Element | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | Natural Gas (cu ft) | Coal[1] (tons) | Btu Petroleum Products | Btu Precious Fuels | Btu Total Energy |
| • SITE PREPARATION | 0.13 | 0.57 | | | | 96,000 | 96,000 | 96,000 |
| • PLANTING | | 0.07 | | | | 9,800 | 9,800 | 9,800 |
| • FERTILIZER | | | | | | | | |
| — Manufacture | 0.0001 | 0.0005 | 0.04 | 386 | 0.004 | 6,100 | 399,800 | 509,800 |
| — Transport | | 0.04 | | | | 5,600 | 5,600 | 5,600 |
| — Application | | 0.01 | | | | 1,400 | 1,400 | 1,400 |
| • IRRIGATION | | 3.2 | | | | 450,600 | 450,600 | 450,600 |
| • HARVESTING AND CHIPPING | | 0.06 | | | | 8,400 | 8,400 | 8,400 |
| • FORWARDING | | 0.91 | | | | 127,000 | 127,000 | 127,000 |
| TOTAL ALL ENERGY INPUTS | 0.13 | 4.86 | 0.04 | 386 | 0.004 | 704,900 | 1,098,600 | 1,208,600 |

(1) Based on use of 11,250 Btu/lb bituminous coal.

high rates of water and oxygen infiltration and reduces the quantity of water that must be added to the soil for adequate plant growth. In dry, but as yet nonirrigated areas, this can significantly affect grain production. Even in irrigated areas, the ability of high-porosity soil to hold water may affect energy consumption due to the energy-intensive nature of irrigation.

But more important than the loss of fertilizer nutrients (which can be replaced with manufactured fertilizer) and organic content (which can be replaced with manure) is the increased loss of topsoil (due to wind and water erosion) that results from residue removal. At present, average soil loss per acre on cultivated land in the United States is well above the maximum soil loss level per acre at which current productivity can be maintained (Lockeretz, 1980). Residue removal (currently an uncommon practice) could increase soil loss by a factor of two. In much of the United States, the removal of residues would increase already intolerable levels of erosion and reduce long-term soil productivity. This would be an unacceptable result of residue collection.

In Appendix E, estimates are developed of energy requirements for obtaining crop residues in three areas of the Corn Belt and three areas of the Great Plains. The estimates presume that residues collected in any area will be the maximum amount collectible without increasing soil loss beyond tolerable levels. Estimates of collectible residues for the Great Plains were obtained from Skidmore, Kumal and Larson (1979), while those for the Corn Belt were derived from data from Lockeretz (1980) and Lindstrom et al (1979). The estimates developed in Appendix E for the Corn Belt assume the use of tillage methods (e.g., no-till) which permit the maximum removal of residues. Since such methods may not always be used and may not always be feasible, and since some farmers may be reluctant to collect residues, actual residue collection may be lower than that estimated and energy requirements for residue transport may be underestimated, particularly for the Corn Belt. On the other hand, some farmers may be attracted by the short-term profits which can be gained from collecting more than the optimal amount of residue; to the extent that this occurs, residue collections will be increased and energy requirements for transport will be decreased, but excessive soil erosion will result.

The estimates of energy requirements developed in Appendix E reflect:

- collection;
- transport to a 300,000 gallon/day methanol plant;

- increased fertilization to replace nutrient value of residues removed;
- decreased crop yields resulting from harvest-schedule revisions; and
- bacterial and transport losses (estimated to be fifteen percent of total residue collected).

A summary of estimated energy requirements for the six Major Land Resource Areas (MLRA's) studied is presented in Exhibit 3-3. The locations of these six areas are highlighted on a map of MLRA's reproduced as Exhibit 3-4. Additional details concerning all information presented in this exhibit may be found in Appendix E.

For five of the six areas studied, between 1.4 and 1.9 million Btu of energy are required per dry ton of residues, while the estimate for the sixth area (MLRA 63, in central South Dakota) is about twice as high. The high value of energy required in this area is due to a relatively long average haul (145 miles) resulting from a low yield of usable residues (0.18 tons per acre). Nearly half the energy required in this area is for transport. In the other areas studied, and particularly in the Corn Belt, more energy is required for fertilization than for transport.

The energy requirements estimated for agricultural residues are higher than those estimated for other potential sources of cellulose (see the two preceding sections). As previously observed, the estimates may be based on somewhat optimistic estimates of the amount of residues which can be collected in any area, and so average transport distances and energy requirements may be underestimated. However, even if energy requirements were somewhat higher, they would still be small in comparison to the energy content of the residues. A more significant disadvantage of the use of agricultural residues is the potential which is created for excessive collection of residues, resulting in increased erosion and eventually an adverse impact on agricultural productivity.

## 3.4 Methanol Production

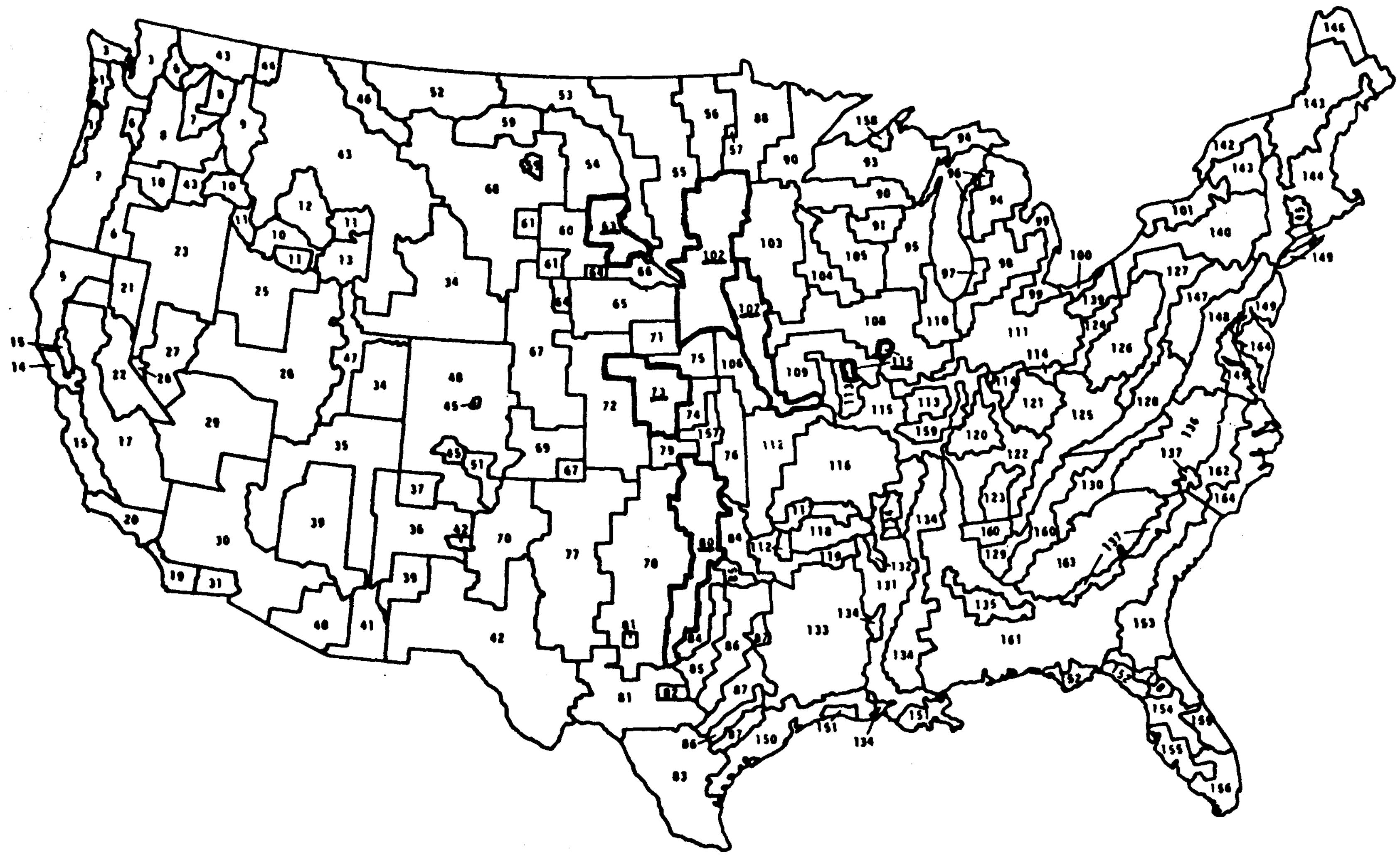
At the present time, none of the technologies available for the conversion of cellulosic feedstocks to methanol are considered commercially proven. The technology selected for analysis consists of a Battelle Pacific Northwest Laboratories catalytic wood gasifier, Benfield acid-gas removal, and ICI methanol synthesis (Mudge et al., 1981). The gasification step is the only one which has not yet been demonstrated on a commercial scale.

## EXHIBIT 3-3: ENERGY CONSUMPTION ESTIMATES PER DELIVERED DRY TON OF CROP RESIDUES

| | Usable Residues (tons/acre) | | Average Distance (miles) | Petroleum Products | | | | Natural Gas (cu ft) | Coal[1] (tons) | Btu's Petroleum Products | Btu's Total Energy |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corn | Small Grains | | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | LPG (gal) | | | | |
| • CORN BELT | | | | | | | | | | | |
| Major Land Resource Area 102 | 1.08 | 1.39 | 20.8 | 0.00018 | 4.75 | 0.035 | 0.13 | 652 | 0.00314 | 682,800 | 1,418,600 |
| Major Land Resource Area 115 | 0.95 | 1.24 | 32.2 | 0.00018 | 5.98 | 0.036 | 0.13 | 699 | 0.00331 | 854,400 | 1,642,500 |
| Major Land Resource Area 107 | 1.02 | 1.32 | 31.5 | 0.00018 | 5.99 | 0.037 | 0.13 | 758 | 0.00353 | 854,900 | 1,708,500 |
| • GREAT PLAINS | | | | | | | | | | | |
| Major Land Resource Area 80 | — | 0.66 | 36.1 | 0.00018 | 6.66 | 0.031 | 0.13 | 426 | 0.00233 | 951,300 | 1,438,400 |
| Major Land Resource Area 73 | 0.89 | 0.35 | 41.8 | 0.00018 | 8.75 | 0.033 | 0.13 | 542 | 0.00275 | 1,231,700 | 1,847,500 |
| Major Land Resource Area 63 | — | 0.18 | 144.9 | 0.00018 | 21.80 | 0.031 | 0.13 | 426 | 0.00233 | 3,070,400 | 3,557,400 |

(1) Based on 11,250 Btu/lb bituminous coal.

EXHIBIT 3-4: MAJOR LAND RESOURCE AREAS ADJUSTED TO COUNTY BOUNDARIES
(Outlines of MLRA's studied are highlighted)



Source: USDA, 1980.

The process entails drying the cellulosic feedstock to ten percent moisture and decomposing it at a high temperature to produce synthesis gas. This gas is primarily carbon monoxide and hydrogen. Steam is added to the gas; impurities are removed; and the gas is condensed under high pressure to form methanol. Distillation then removes any other impurities. The methanol plant was assumed to have an output of 300,000 gallons per day, estimated to be the minimum economic size. A more detailed description of this process is provided in Appendix F.

The primary energy input to the process is the cellulosic fe^dstock, though some electricity is also required. The feedstock is used primarily in the gasifier, but some is also used to fuel the boiler. Char from the gasifier is used for drying and is also burned in the boiler. Fuel gas generated in the process is reformed prior to mixing it with the incoming synthesis gas.

Total process-related fuel and energy requirements for obtaining methanol from wood are summarized in Exhibit 3-5. For 1000 gallons of methanol produced, about 6.63 DTE of wood with 49.5 percent moisture are required. In addition, 1767 kwhr of electricity is consumed in the plant and a small amount of diesel fuel (1.09 gallons) is consumed by bulldozers in the wood storage area. Agricultural residues are estimated .to contain only 12 to 15.5 percent moisture when used, resulting in somewhat smaller estimated requirements for feedstocks (5.8 DTE) and energy. These estimates are sensitive to the moisture content of the feedstock, to plant size, and to specific design characteristics of the plant. Additional discussion of these issues is contained in Appendix F.

## 3.5 Results

In the previous sections of this chapter, estimates have been presented of the energy requirements for converting cellulose to methanol and for deriving cellulose from several alternative sources. Exhibit 3-6 presents a summary of energy inputs and outputs for obtaining 1000 gallons of methanol when biomass from a silvicultural energy farm is used as the feedstock. This exhibit combines data presented previously in Exhibits 3-2 and 3-5. Estimated energy to produce 1000 gallons of methanol is about 26.5 million Btu, with about two-thirds of this consisting of coal to produce electricity required by the conversion plant. Only about 4.8 million Btu of petroleum products and 2.6 million Btu of natural gas are required. Petroleum and natural gas consumption is small in comparison to the energy content of the methanol produced: 64.35 million Btu.

**EXHIBIT 3-5: ENERGY INPUTS FOR THE CELLULOSE CONVERSION FACILITY PER 1000 GALLONS METHANOL PRODUCED**

| | | Petroleum Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Energy Consuming Element | Assumptions | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | Natural Gas (cu ft) | Coal[1] (tons) | Btu Petroleum Products | Btu Precious Fuels | Btu Total Energy |
| | <u>Feedstock Requirements</u> | | | | | | | | |
| | 6.63 DTE Wood<br>5.8 DTE Agricultural Residues | | | | | | | | |
| • STORAGE | - Bulldozers move and reclaim feedstock | | 1.09 | | | | 152,600 | 152,600 | 152,600 |
| • PROCESS | - Most energy from feedstock | | | | | | | | |
| | - Electricity, 1,767 kwhr[2] | | | | | 0.82 | | | 18,393,900 |
| | TOTAL PROCESS ENERGY INPUTS | | 1.09 | | | 0.82 | 152,600 | 152,600 | 18,546,500 |

(1) Based on use of 11,250 Btu/lb bituminous coal.
(2) Electricity requirement is for wood feedstock. Requirement is somewhat lower when agricultural residues are used.

EXHIBIT 3-6: ENERGY INPUTS AND OUTPUTS
FOR PRODUCING 1000 GALLONS OF METHANOL FROM SILVICULTURAL BIOMASS

| | Methanol (gal) | Petroleum Products: Motor Gasoline (gal) | Petroleum Products: Distillate (gal) | Petroleum Products: Residual Fuel (gal) | Natural Gas (cu ft) | Coal[1] (tons) | M Btu Liquid Fuels | M Btu Precious Fuels | M Btu Total Energy |
|---|---|---|---|---|---|---|---|---|---|
| INPUTS | | | | | | | | | |
| • FEEDSTOCK: 6.63 DTE Wood | | 0.86 | 26.19 | 0.27 | 2,560 | 0.03 | 3,820 | 6,430 | 7,170 |
| • TRANSPORT: 5 miles | | | 6.03 | | | | 840 | 840 | 840 |
| • STORAGE: Bulldozers move coal | | | 1.09 | | | | 150 | 150 | 150 |
| • PROCESS: Most energy from feedstock | | | | | | 0.82 | | | 18,390 |
| | | 0.86 | 33.31 | 0.27 | 2,560 | 0.85 | 4,810 | 7,420 | 26,550 |
| OUTPUTS | | | | | | | | | |
| • METHANOL: 1000 gallons | 1,000 | | | | | | 64,350 | 64,350 | 64,350 |
| NET ENERGY PRODUCTION/CONSUMPTION | +1,000 | -0.86 | -33.31 | -0.27 | -2,560 | -0.85 | +59,540 | +56,930 | +37,800 |

(1) Based on use of 11,250 Btu/lb bituminous coal.

The net change in each form of available energy is shown on the bottom line of Exhibit 3-6 in conventional units. This information is also presented in Exhibit 3-7, where the changes are expressed in conventional units, in Btu, and in "gallons of methanol equivalent." This last measure expresses a given quantity of fuel in terms of the number of gallons of methanol required to provide the same energy. (In interpreting this measure, it should be borne in mind that a gallon of methanol contains only about half as much energy as a gallon of gasoline.) The same information is presented a third time, graphically, in Exhibit 3-8.

It can be seen from these exhibits that the production of 1000 gallons of methanol (64.35 million Btu) from silvicultural biomass grown for this purpose results in a net increase in liquid fuels of 59.5 million Btu and a net increase in available precious fuels (liquid fuels plus natural gas) of 56.9 million Btu. Because of coal consumption, primarily to generate electricity used by the conversion plant, the overall increase in energy available from alcohol and nonrenewable fuels is somewhat smaller; the overall increase in energy is estimated to be 37.8 million Btu.

The results presented in Exhibits 3-6 and 3-7 for methanol derived from silvicultural biomass are compared in Exhibit 3-9, in summary form, to corresponding results for methanol derived from forest residues and agricultural residues. The summary data presented in Exhibit 3-9 are derived from data in Exhibits 3-1 through 3-5. Additional detail (such as that shown in Exhibit 3-6) for energy requirements for obtaining forest and agricultural residues can be found in Appendices C and E.

It can be seen from Exhibit 3-9 that energy requirements for obtaining methanol from forest residues are slightly lower than when silvicultural biomass is used, while those for obtaining methanol from agricultural residues are somewhat higher.

Exhibit 3-10 presents another display relating to the results obtained for deriving methanol from silvicultural biomass: the components of change in available liquid fuels. One thousand gallons (64.35 million Btu) of methanol are produced. However, moderate amounts of diesel fuel are used in growing, transporting and storing the feedstock, small amounts of gasoline are used in site preparation, and small amounts of residual fuel are used in fertilizer manufacture. As a result, the net increase in liquid fuels is only 59.5 million Btu (about 925 gallons of methanol equivalent).

## EXHIBIT 3-7: ALTERNATIVE MEANS OF EXPRESSING ENERGY CHANGES RESULTING FROM THE PRODUCTION OF 1000 GALLONS OF METHANOL FROM SILVICULTURAL BIOMASS

| | Change in Available Energy | | | | | | |
|---|---|---|---|---|---|---|---|
| | Conventional Units | | | MMBtu | | Gallons of Methanol Equivalent[1] | |
| Methanol | + | 1,000 | gal | + | 64.35 | + | 1,000 |
| Motor Gasoline | - | 0.86 | gal | - | 0.11 | - | 1.7 |
| Distillate | - | 33.31 | gal | - | 4.66 | - | 72.4 |
| Residual | - | 0.27 | gal | - | 0.04 | - | 0.6 |
| Natural Gas | - | 2,560 | cu ft | - | 2.61 | - | 40.6 |
| Coal | - | 0.85 | tons | - | 19.13 | - | 297.3 |
| Net Liquid Fuels | | | | + | 59.54 | + | 925 |
| Net Precious Fuels | | | | + | 56.93 | + | 885 |
| Net Energy | | | | + | 37.80 | + | 587 |

[1] One "gallon of methanol equivalent" is defined to equal 64,350 Btu.

EXHIBIT 3-8: ENERGY INPUTS AND OUTPUTS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS

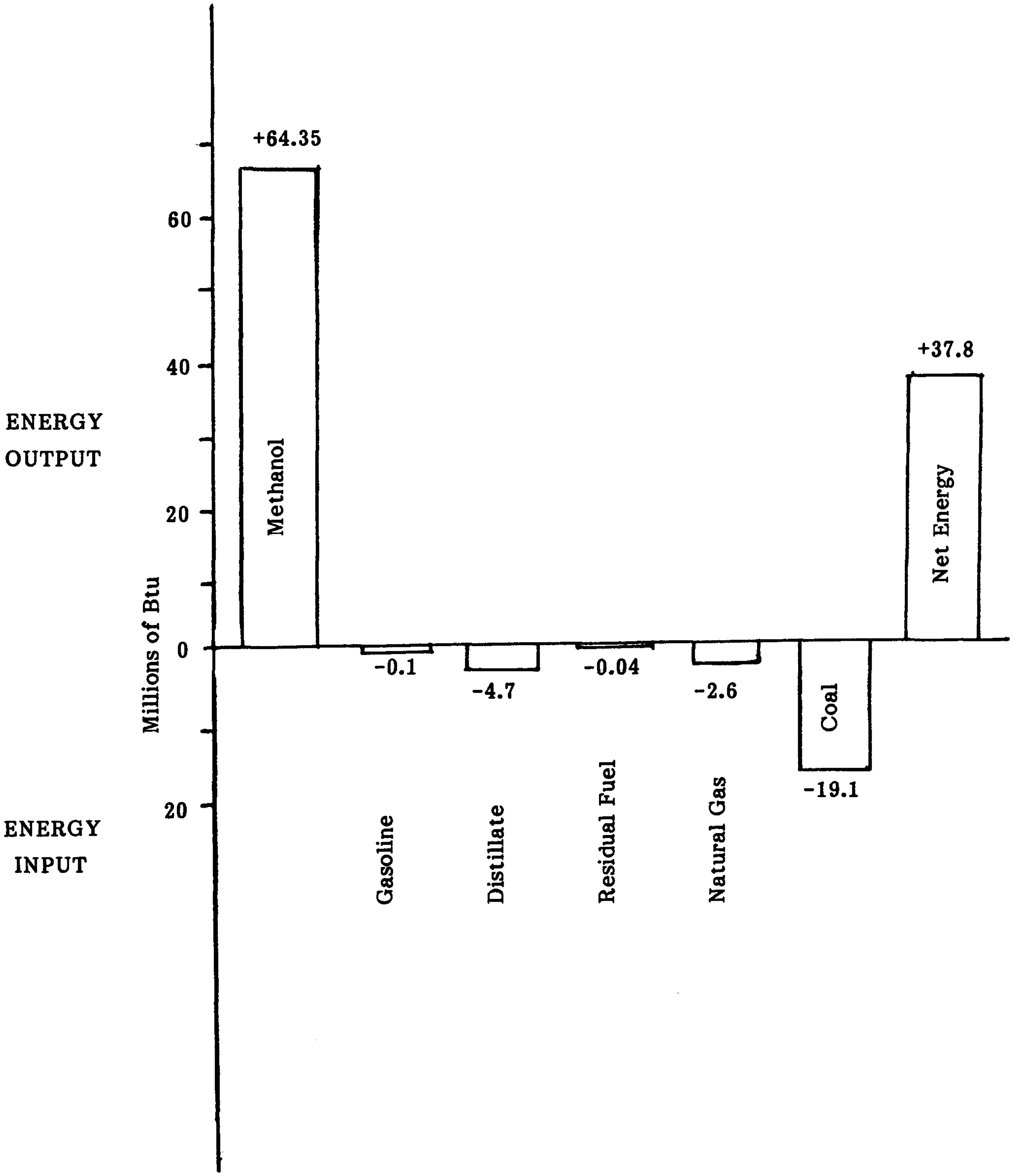
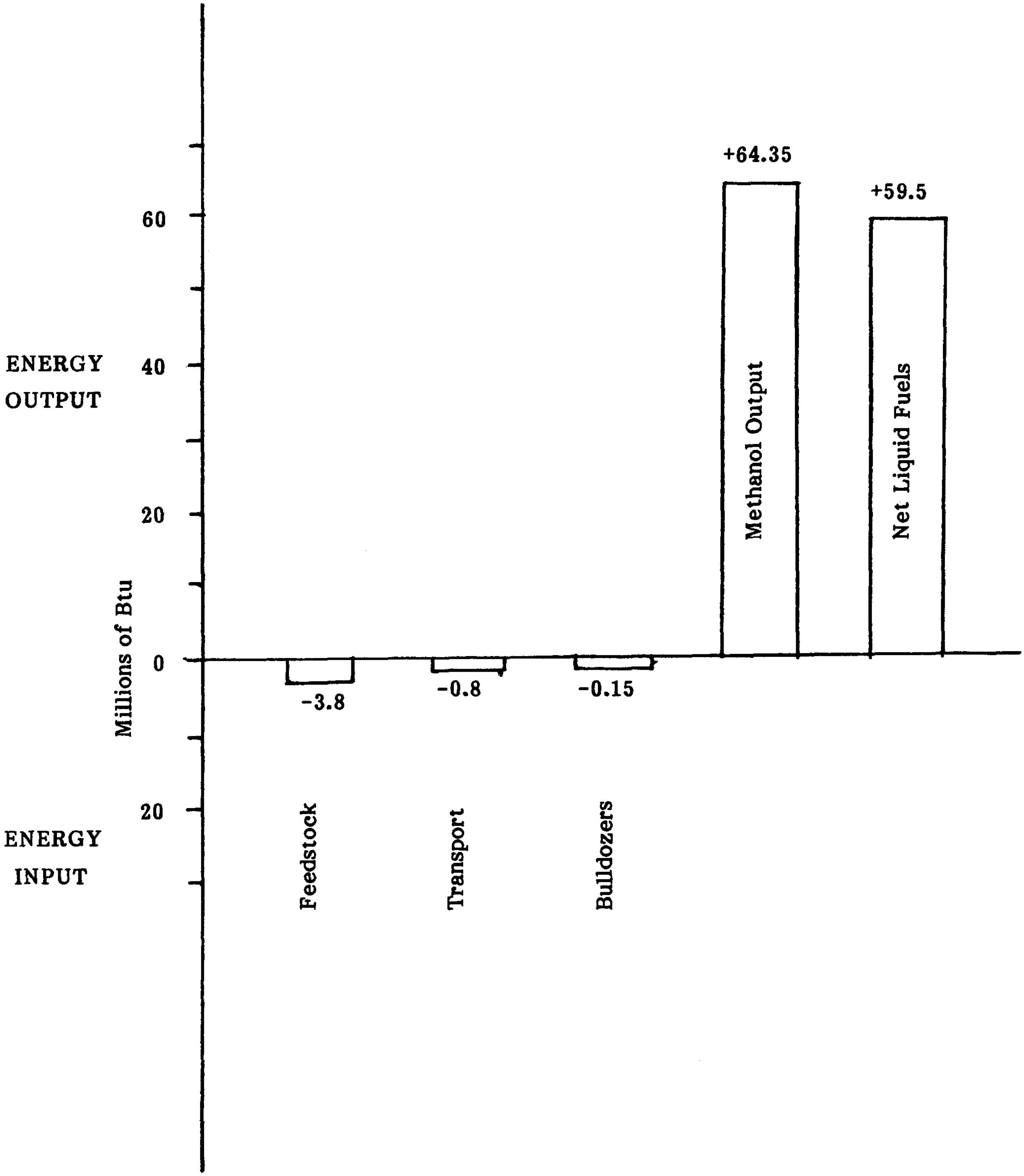


**EXHIBIT 3-9: NET ENERGY INPUTS AND OUTPUTS FROM PRODUCING 1000 GALLONS OF METHANOL FROM VARIOUS SOURCES OF CELLULOSE**

| | | Petroleum Products | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Methanol (gal) | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | LPG (gal) | Natural Gas (cu ft) | Coal[1] (tons) | Btu's Liquid Fuels | Btu's Precious Fuels | Btu's Total Energy |
| <u>FOREST RESIDUES</u> | | | | | | | | | | |
| • EASTERN UNITED STATES | | | | | | | | | | |
| Commercial Thin or Commercial Harvest | +1,000 | | -19.85 | | | | -0.82 | +61,570 | +61,570 | +43,180 |
| Stand Improvement Thin: Manual System | +1,000 | -3.78 | -26.62 | | | | -0.82 | +60,150 | +60,150 | +41,760 |
| Stand Improvement Thin: Mechanized System | +1,000 | | -33.25 | | | | -0.82 | +59,680 | +59,680 | +41,290 |
| • WESTERN UNITED STATES | | | | | | | | | | |
| Commercial Thin or Commercial Harvest | +1,000 | | -24.36 | | | | -0.82 | +60,930 | +60,930 | +42,540 |
| Stand Improvement Thin: Mechanized System | +1,000 | -3.78 | -30.39 | | | | -0.82 | +59,620 | +59,620 | +41,230 |
| <u>SILVICULTURAL BIOMASS</u> | | | | | | | | | | |
| <u>Populus</u>, Southeastern United States | +1,000 | -0.86 | -33.31 | -0.27 | | -2,560 | -0.85 | +59,540 | +56,930 | +37,800 |
| <u>AGRICULTURAL RESIDUES</u> | | | | | | | | | | |
| • CORN BELT | | | | | | | | | | |
| Major Land Resource Area 102 | +1,000 | -1.33 | -27.65 | -0.21 | -0.55 | -4,515 | -0.84 | +60,180 | +55,570 | +36,710 |
| Major Land Resource Area 115 | +1,000 | -1.33 | -34.56 | -0.21 | -0.55 | -4,800 | -0.84 | +59,180 | +54,280 | +35,400 |
| Major Land Resource Area 107 | +1,000 | -1.33 | -34.67 | -0.23 | -0.55 | -5,155 | -0.84 | +59,250 | +53,999 | +35,210 |
| • GREAT PLAINS | | | | | | | | | | |
| Major Land Resource Area 80 | +1,000 | -1.33 | -38.44 | -0.19 | -0.55 | -3,163 | -0.84 | +58,720 | +55,490 | +36,740 |
| Major Land Resource Area 73 | +1,000 | -1.33 | -50.74 | -0.20 | -0.55 | -3,863 | -0.84 | +57,000 | +53,060 | +34,240 |
| Major Land Resource Area 63 | +1,000 | -1.33 | -127.12 | -0.19 | -0.55 | -3,163 | -0.84 | +45,930 | +42,700 | +24,240 |

(1) Based on use of 11,250 Btu/lb bituminous coal.

EXHIBIT 3-10: NET LIQUID FUELS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS

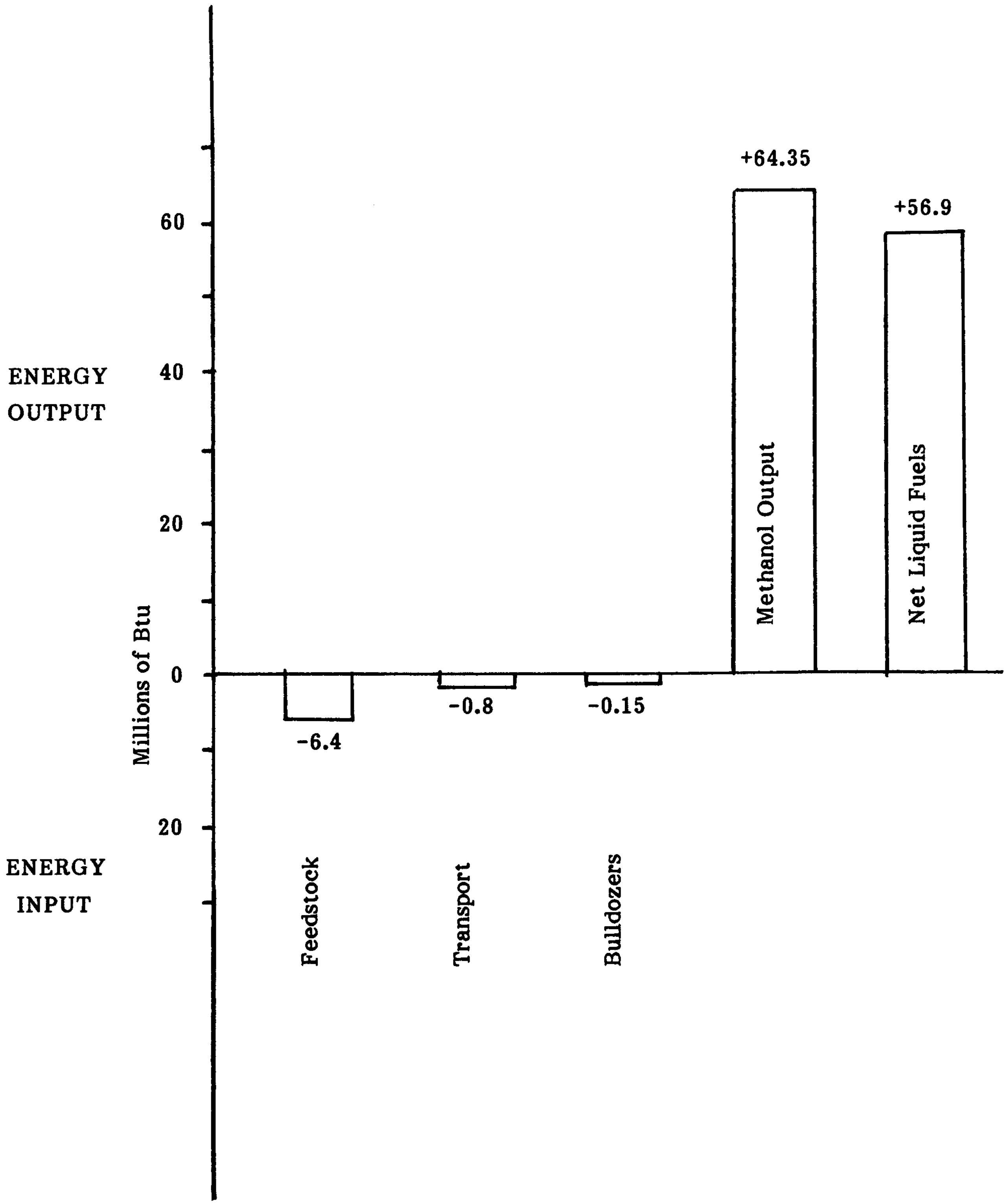


The components of change in available precious fuels are shown graphically in Exhibit 3-11. Because of the natural gas required for fertilizer production, the net increase in precious fuels is only 56.9 million Btu, somewhat lower than the net increase in liquid fuels.

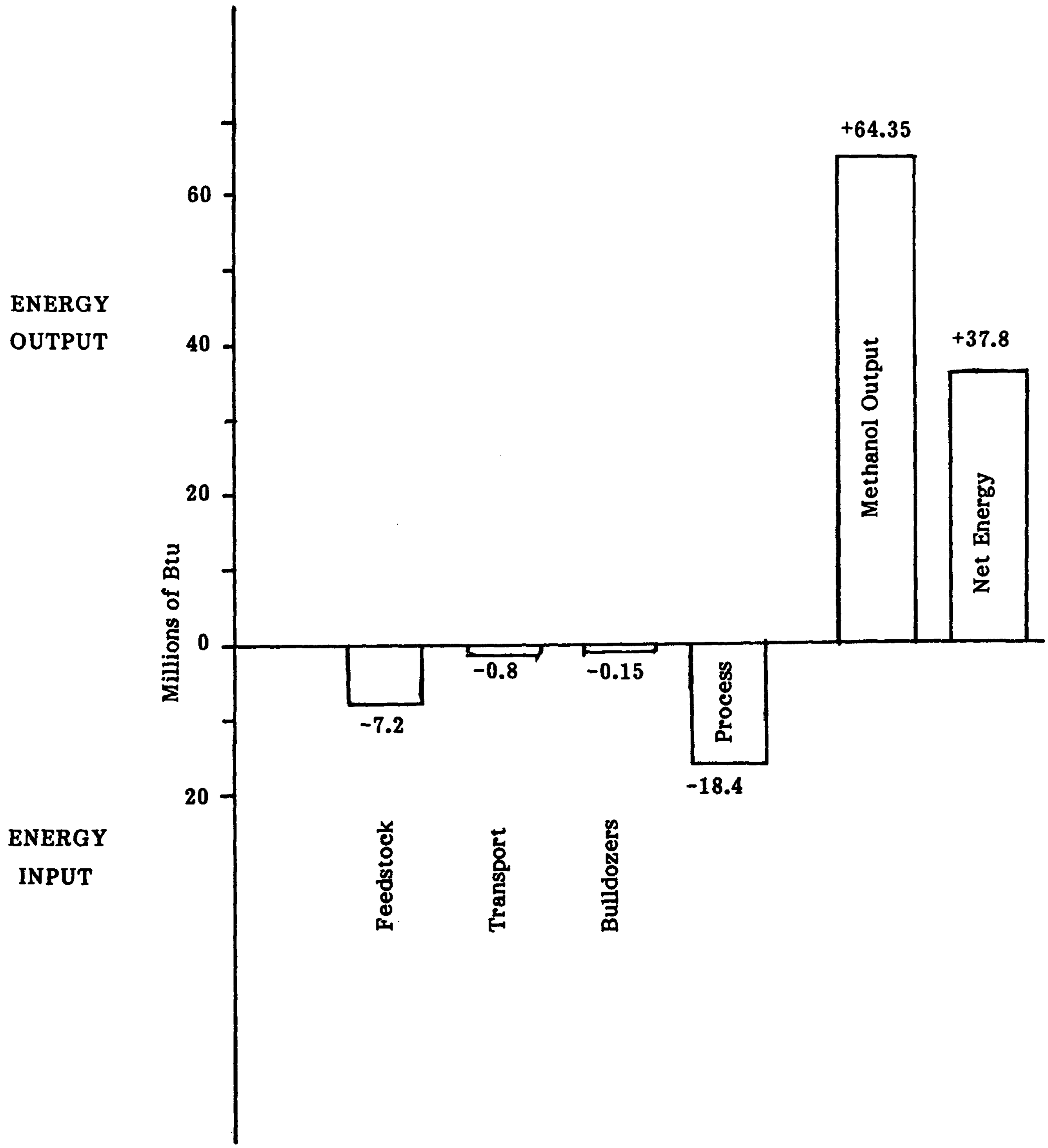
The components of change of total (nonrenewable) energy are shown graphically in Exhibit 3-12. In order to produce 1000 gallons (64.35 million Btu) of methanol, 26.5 million Btu of nonrenewable fuels are required. The net increase in total energy is 37.8 million Btu, which is the energy equivalent of 587 gallons of methanol.

It may be seen from these exhibits that deriving methanol from cellulose results in a substantial increase in the availability of liquid fuels while requiring only a small amount of natural gas and a moderate amount of coal. As shown in Exhibit 3-9, depending upon the source of the cellulose, the production of 1000 gallons of methanol is estimated to result in a net increase in liquid fuels of 46 to 62 million Btu, a net increase in precious fuels of 43 to 62 million Btu, and a net increase in all nonrenewable fuels of 24 to 43 million Btu. Use of agricultural residues as the feedstock results in the smallest estimates of increased fuel availability and also has the undesirable side effect of increasing the rate of soil erosion.

EXHIBIT 3-11: NET PRECIOUS FUELS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS



## EXHIBIT 3-12: ENERGY INPUTS AND OUTPUTS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS



# 4. METHANOL FROM COAL

Vegetal matter and the energy it contains, condensed over millions of years by the pressure of the earth's crust, produced the fossil fuels: oil, natural gas, and coal. These fossil fuels have only recently been used as energy sources. Until the seventeenth century, virtually all heat energy was derived from wood and transportation energy from animal or wind power. The discovery and subsequent utilization of coal displaced firewood as a heat source and provided a transportation energy source for railroads, ships, etc. However, the form of coal (i.e., solid chunks), required that someone feed the coal into a burner or boiler. This limitation made coal less attractive as a power source for personal transportation. Yet, such was the utility of coal that by 1920 it supplied 80 percent of U.S. energy needs (Cuff and Young, 1980).

However, since the turn of the century, coal has been steadily replaced by the more versatile, easier to transport, and cleaner burning natural gas and petroleum products. By 1960, coal supplied only slightly more than 20 percent of this nation's energy needs. However, in the present energy market, the rising price and declining availability of crude oil is now encouraging the use of petroleum alternatives. The most economical and currently available of these is coal.

In terms of getting the most energy from coal, burning it directly is the most efficient use. This may occur in industrial facilities where coal is used to replace residual or fuel oil, or in the home where anthracite stoves can be used instead of heating oil.

The direct use of coal as a power source in the transportation sector, however, is limited. The transportation sector continues to depend on petroleum-based liquid fuels and is responsible for 60 percent of all petroleum consumed. In order to increase the use of coal-based energy in the transportation sector, it will first be necessary to convert the coal to a liquid fuel, despite the energy loss that conversion must entail.

The first section of this chapter presents a general introduction to the energy analysis for deriving methanol from coal. Coal resources are discussed in Section 4.2 and coal transport in Section 4.3. In Section 4.4, the selected coal-to-methanol process is described and its energy requirements are presented. The final section of the chapter presents a summary and discussion of the energy inputs and outputs estimated for deriving methanol from coal. Additional information on coal and coal mining is presented in Appendix G and on coal-to-methanol conversion in Appendix H.

## 4.1 Energy Requirements

There are four major categories of energy required in the production of methanol from coal:

a. the energy content of the extractable coal;

b. energy required to mine the coal;

c. energy required to transport the coal to the conversion plant; and

d. energy required to convert the coal to methanol.

The first category (the energy content of the coal) is, by far, the largest.

Since coal is a nonrenewable resource, use of coal to produce methanol reduces the energy available for other purposes; the energy content of the coal is therefore one of the energy costs (and, in fact, the largest energy cost) in the production of methanol. If the coal which would be used for methanol production were, instead, left in the ground, it would represent an energy resource available for use at some future time.

The size of this energy resource, however, is somewhat less than the full energy content of the coal. Whenever the coal is mined, a certain amount of energy will be required to mine it. The net energy that will be made available by mining the coal is thus equal to a - b (where a and b are defined above). On the basis of this discussion, total energy required to produce methanol from coal may be estimated as the energy required to mine and transport the coal and to convert it to methanol ("b + c + d"), plus the net energy value of the unmined coal ("a - b"). Hence, total energy required is given by:

$$b + c + d + (a-b) = a + c + d$$

Note that the energy required to mine the coal ("b") drops out of this formula — this is energy that will be consumed whenever the coal is mined, regardless of the use to which the coal is put and (ignoring possible improvements in the energy-efficiency of coal mining) regardless of when the coal is mined. (Energy requirements for coal mining generally represent less than two percent of the energy content of the coal. Appendix

G contains estimates of both the national average of such energy requirements and the requirements for several large prototypical mines.)

The above discussion ignores one (relatively minor) factor: conversion of coal to methanol results in the production of some elemental sulfur as a by-product. To the extent that this production reduces the need to produce sulfur by other means, the energy required for such production is saved. If this energy saving (or credit) is represented by e, net energy consumption resulting from methanol production is given by:

$$a + c + d - e$$

## 4.2. Coal Resources

Coal deposits are generally distinguished by their carbon content as well as by their moisture content and heating value. The different coal types or ranks, by increasing carbon content, are: lignite, subbituminous, bituminous, and anthracite coals. Heating value or the Btu content per pound peaks at 14,000 Btu with the low volatility bituminous coals. All types of coal can be converted to liquid fuels, though economic factors make the relatively high-cost anthracite an unattractive choice.

About 90 percent of the demonstrated coal reserve base consists of bituminous or subbituminous coal. Most of the subbituminous coal is located in Montana and Wyoming. Much of the bituminous coal is located in the Appalachian Region and the eastern part of the Interior Province (i.e., Illinois, Indiana and Western Kentucky).

All types of coal are suitable for gasification (the first step in the production of methanol); however, not all sources of coal are equally likely to be used for producing methanol (or other coal-derived synthetic fuels). In particular, coal used for such purposes is most likely to come from areas containing large volumes of coal which can be mined economically and, preferably, where adequate water supplies can be obtained.

A methanol production facility must be sited in coal resource areas where sufficient quantities of coal for methanol conversion are available over and above near-term coal demands. Any one methanol plant must be large enough to achieve appropriate economies of scale. Current projections place economic plant capacity in the range of

6,000 to 25,000 tons of coal per day. This places a constraint on coal resource size. Assuming a plant life of 20 years and a 300-day per year operating schedule, between 36 million and 150 million tons of coal would be needed to supply the methanol production facility.

The most economic means of transporting large volumes of methanol is by pipeline. Since pipeline transport of methanol is both less costly and more energy efficient than transport of the coal (by rail or slurry pipeline) required to produce the methanol, location of the methanol plant in the vicinity of the coal source is generally preferred.

Gasification processes, however, require substantial amounts of water for cooling and as a source of hydrogen. The particular gasification process assumed in the present analysis requires 5.3 gallons of water for each gallon of methanol produced, or 82 gallons of water per million Btu of methanol (McGeorge, 1976). (Coal mining, by comparison, typically requires between 0.5 and 2.5 gallons per million Btu (Buras, 1979).) Other synfuel processes may require less water. In particular, direct liquefaction processes do not require the large amounts of process water required for medium and high-Btu gasification, and water consumption of all processes can be reduced (at substantial cost) by recycling of cooling water. Nonetheless, all synfuel processes are considered to be major consumers of water.

As a result, many of the Western regions which have the potential for providing coal for synfuel facilities may not contain appropriate sites for the location of these facilities, either because local water is insufficient to supply such facilities or because the water is already fully appropriated to other uses.

The analysis presented in this chapter presumes a minemouth location for the methanol plant. However, it is likely that some synfuel plants will be constructed at non-minemouth locations. In addition to lack of water, reasons for selecting non-minemouth locations may include labor costs and availability and related socio-economic factors. The lack of water in a specific area thus does not mean that coal in that area may not be appropriate for supplying synfuel plants located in areas where sufficient water is more readily available.

## 4.3 Coal Transport

The energy consumed in transporting coal to a methanol plant will depend upon the distance of the plant from the source of coal. If the plant is adjacent to the coal mine, transport requirements approximate those which are intrinsic to the mining process. Energy consumed in such transport is included in the energy required for mining, estimates of which are presented in Appendix G. (As observed in Section 4.1, energy required for mining drops out of the estimate of net energy consumed in producing methanol from coal.)

For consistency with the analyses of alcohol produced from grain and cellulose presented in the preceding two chapters, a minemouth location has been assumed for the coal-conversion plant. Minemouth plants need not actually be located adjacent to a mine; but they are generally located within a few miles of the mine. (Fifty miles is frequently defined to be the maximum distance for a location to be considered minemouth.) The additional transport energy which may be required, however, is quite small and has not been incorporated into the analysis.

As observed at the conclusion of the preceding section, however, not all coal-to-methanol plants will have minemouth locations. For plants located at a greater distance from the mine, additional energy would be consumed in transport. For several route-specific coal movements, it has been estimated (Rogozen et al., 1978) that transport by unit train requires between 350 and 540 Btu of diesel fuel per ton-mile and that (allowing for conversion losses) transport by slurry pipeline requires, per ton-mile, between 410 and 1300 Btu of fuel to generate electricity. Thus, for a 1000-mile unit-train haul of subbituminous coal from a Western mine to a Midwestern methanol plant, between 350,000 and 540,000 Btu of diesel fuel would be required, representing two to three percent of the energy content of the coal being transported. For corresponding transport by slurry pipeline, between 410,000 and 1,300,000 Btu of coal would be needed to generate electricity for slurrying, pumping and dewatering.

## 4.4 Methanol Production

A brief description of the coal-to-methanol process assumed in this study is presented below, followed by the results of the energy analysis for this process. A more detailed description of the process is provided in Appendix H.

Appendix H also contains discussions of the sensitivity of the results to the particular assumptions used in the analysis. As observed in that appendix, differences in coal characteristics and the details of process design could have a slight effect on overall energy efficiency, but this effect is unlikely to be more than a few percent.

A brief discussion of the potential of technologies now being studied or developed to improve overall energy efficiency is also provided in Appendix H. These technologies have the potential to improve the energy efficiency of methanol production somewhat, though it may be several years before such improvements can be realized.

### 4.4.1 Selection of Technology

The Texaco-gasification/ICI methanol-synthesis process was selected for evaluation in this study. This process was chosen because it is near commercial readiness and appears economically competitive. The Texaco and Koppers KBW gasifiers[1] are the most popular technologies for the methanol production projects that have applied to the Synthetic Fuels Corporation for subsidies. ICI is one of the most frequently used methanol-synthesis technologies.

Coal gasification technologies may be generally classified into three groups: fixed-bed technology, fluidized-bed technology, and entrained-bed technology. Some of the established processes are: Lurgi (fixed bed), Winkler (fluidized bed), Texaco (entrained bed), and Koppers-Totzek (entrained bed). Although these processes had a significant number of applications in the past, it appears from recent preliminary screenings that, for methanol synthesis, the Texaco process is superior to the other processes in terms of overall thermal efficiency, coal use, oxygen requirements and capital investment (McGeorge, 1976; Chow et al., 1977). The higher operating pressure of the Texaco gasifier compared to the others contributes to the higher overall thermal efficiency in methanol synthesis. Other pressurized gasifiers (for example pressurized Winkler) would be expected to give similar overall process efficiencies. Texaco coal-gasification units are now being built in the U.S. for demonstration purposes.

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[1]*The KBW gasifier is also a near-commercial gasifier. It is a newer design than the Koppers-Totzek (K-T) system. KBW has a different heat transfer system and increased capacity compared to K-T, but the gas composition and energy efficiency are similar.*

The Texaco process may be applied to a wide variety of caking and non-caking bituminous and subbituminous coals. However, the conventional Lurgi and Winkler gasifiers are limited to non-caking coals. In the United States, the latter coals are found primarily in the West.

For the liquefaction step, the ICI low-pressure synthesis was selected because it is an established process, and it is the most popular for commercial methanol synthesis. It is a good example of typical technology. Lurgi, Mitsubishi Gas Chemicals (MGC), Haldor-Topsoe and Wentworth also offer commercial methanol technology. Chem Systems is developing a methanol technology, but as it is not commercially proven it has not been considered in this analysis. However, the Chem Systems process is more energy efficient than the ICI process. The Chem Systems process has higher heat recovery from the methanol reactor and lower compression energy, because of lower operating pressure requirements for the oxygen plant.

The ICI methanol synthesis is used in many commercial installations throughout the world. In late 1979, there were 24 commercial methanol plants in operation and five in design or construction using the ICI technology. This compares to seven operating Lurgi methanol plants plants (plus four under construction) and eight MGC plants (plus three in design or construction).

Other process steps, such as the air separation and oxygen compression, shift, acid-gas removal, Claus sulfur plant, tail-gas treatment, and coal preparation, are all standard established processes and may be considered to have comparable energy requirements for the same input/output stream characteristics. Their selection depends more on the coal properties and operating pressure levels in the system as a whole.

### 4.4.2 Energy Consumption

The primary energy balance is based on the conversion of eastern bituminous coal to fuel grade methanol. The coal composition used in the analysis had a higher heating value (as received) of 11,340 Btu per pound, 6.4 percent free moisture, and 4.5 percent sulfur (McGeorge, 1976).

The only significant energy input to the process is coal. The electricity used in the process is generated in the plant. The coal is used primarily in the gasifier but some is also used to fuel the boiler. Char from the gasifier and fuel gas generated in the process are also burned in the boiler. Waste heat is recovered wherever feasible. It is estimated that 5.5 tons of 11,340 Btu/lb bituminous coal will be required per thousand gallons of methanol produced.

There is also a small amount of diesel fuel consumed by bulldozers in the coal storage area. For a plant consuming 10,000 tons of coal per day, four bulldozers operating eight hours each would consume about 280 gallons per day, or about 0.15 gallons of diesel fuel for every 1,000 gallons of methanol produced (Hoffman, 1981).

A sulfur byproduct is obtained in the process. The energy credit, which is based upon fuel consumption data for sulfur mining in the 1977 Census of Mineral Industries, is 3444 Btu per pound sulfur[1].

## 4.5 Results

The net energy and liquid fuels balance for producing 1000 gallons of methanol from coal is presented in Exhibit 4-1.

Based on the previously stated assumptions and feedstock characteristics, the energy input to the methanol manufacturing process is calculated to be 5.5 tons of 11,340 Btu/lb bituminous coal per thousand gallons of methanol produced, or 1.94 Btu of total energy input per Btu of methanol produced. All energy requirements of the Texaco gasifier and ICI methanol synthesis process are supplied by the coal. The only other identified energy-consuming element is the bulldozers which are required for coal handling and storage. For reasons presented in Section 4.1, energy consumed in coal

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[1] *The inclusion of this energy credit presumes that all of the by-product sulfur is used industrially and replaces sulfur which would otherwise be mined. This may not be true for plants in some Western locations due to the availability of by-product sulfur from Alberta and the high transportation costs to Eastern markets. Energy credits would be inappropriate for any sulfur production which does not result in a corresponding reduction in sulfur mining.*

*Although most analyses take an energy credit at the heating value of sulfur (3,990 Btu/lb), this analysis uses the fuel required for a typical Frasch sulfur mine as the credit. This is fuel not consumed in sulfur mining and thus available to the rest of the economy because of the methanol manufacture. The energy consumption in mining is close to the heating value of sulfur, and the total sulfur energy credit is small compared to the energy consumed in the process. Therefore, the method of treating the sulfur energy credit has little impact on the overall energy balance.*

## EXHIBIT 4-1: TOTAL ENERGY INPUTS AND OUTPUTS FOR PRODUCING 1000 GALLONS OF METHANOL FROM COAL

| | | Petroleum Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Methanol (gal) | Motor Gasoline (gal) | Distillate (gal) | Residual Fuel (gal) | Natural Gas (cu ft) | Coal (tons) | MBtu Liquid Fuels | MBtu Precious Fuels | MBtu Total Energy |
| INPUTS | | | | | | | | | |
| • FEEDSTOCK and PROCESS ENERGY: 5.5 tons of bituminous coal | | | | | | 5.5 (1) | | | 124,740 |
| • STORAGE: Bulldozers move coal | | | 0.15 | | | | 20 | 20 | 20 |
| | | | 0.15 | | | 5.5 | 20 | 20 | 124,760 |
| OUTPUTS | | | | | | | | | |
| • SULFUR: 440 lbs | | 0.013 | 0.04 | | 1,460 | 0.0002 | 10 | 1,500 | 1,510 |
| • METHANOL: 1,000 gallons | 1,000 | | | | | | 64,350 | 64,350 | 64,350 |
| | 1,000 | 0.013 | 0.04 | | 1,460 | 0.0002 | 64,360 | 65,850 | 65,860 |
| NET ENERGY PRODUCTION/CONSUMPTION | +1,000 | +0.013 | -0.11 | | +1,460 | -5.5 | +64,340 | +65,830 | -58,900 |

(1) Based on use of 11,340 Btu/lb bituminous coal.

mining has no net effect on the reduction in available energy resulting from methanol conversion. Since energy consumed in transporting coal out of the mine is part of the energy consumed in mining, and since a minemouth location has been assumed for the methanol plant, coal transport does not appear as an energy-consuming element. (The energy requirements for transporting coal to a non-minemouth plant are discussed in Section 4.3)

The primary product of the process is 1000 gallons of methanol. In addition, for the particular coal used in this analysis, 440 pounds of by-product sulfur is produced. The energy credit for this sulfur is taken as the energy required for Frasch mining of sulfur or 0.024 Btu of total energy per Btu of methanol.

Allowing for this sulfur credit, the net energy consumed by the methanol production process is 1.92 Btu per Btu of liquid fuel produced. Overall energy efficiency, expressed as the higher heating value (HHV) of the products (methanol and sulfur) divided by the energy content of the process inputs (coal), is calculated to be 53 percent.

The net change in each form of available energy is shown on the bottom line of Exhibit 4-1 in conventional units. This information is also presented in Exhibit 4-2, where the changes are expressed in conventional units, in Btu, and in "gallons of methanol equivalent". This last measure expresses a given quantity of fuel in terms of the number of gallons of methanol required to provide the same energy. (In interpreting this measure, it should be borne in mind that a gallon of methanol contains only about half as much energy as a gallon of gasoline.) The same information is presented a third time, graphically, in Exhibit 4-3.

It can be seen from Exhibit 4-3 that the primary effect of the process is to convert 5.5 tons of coal (124.7 million Btu) into 1000 gallons of methanol (64.35 million Btu). As a result of the sulfur credit, there are small increases in available natural gas and motor gasoline. There is also a small decrease in available distillate. The overall effect is a net decline in total energy (58.9 million Btu) but a substantial net increase in liquid fuels (64.34 million Btu).

The components of change in available liquid fuels are shown graphically in Exhibit 4-4. One thousand gallons of methanol (64.35 million Btu) is produced. However, because of very small amounts of liquid fuels consumed by the bulldozers (20,000 Btu) and saved

EXHIBIT 4-2: ALTERNATIVE MEANS OF EXPRESSING ENERGY CHANGES RESULTING FROM THE PRODUCTION OF 1000 GALLONS OF METHANOL FROM COAL

| | Change in Available Energy | | | |
|---|---|---|---|---|
| | Conventional Units | | MMBtu | Gallons of Methanol Equivalent[1] |
| Methanol | + 1,000 | gal | + 64.35 | + 1,000 |
| Motor Gasoline | + 0.013 | gal | + 0.002 | + 0.03 |
| Distillate | - 0.11 | gal | - 0.015 | - 0.2 |
| Natural Gas | + 1,460 | cu ft | + 1.49 | + 23 |
| Coal | - 5.5 | tons | - 124.74 | - 1,939 |
| Net Liquid Fuels | | | + 64.34 | + 999.8 |
| Net Precious Fuels | | | + 65.83 | + 1,023 |
| Net Energy | | | - 58.90 | - 916 |

[1] One "gallon of methanol equivalent" is defined to equal 64,350 Btu.

EXHIBIT 4-3: ENERGY INPUTS AND OUTPUTS
FOR COAL CONVERSION

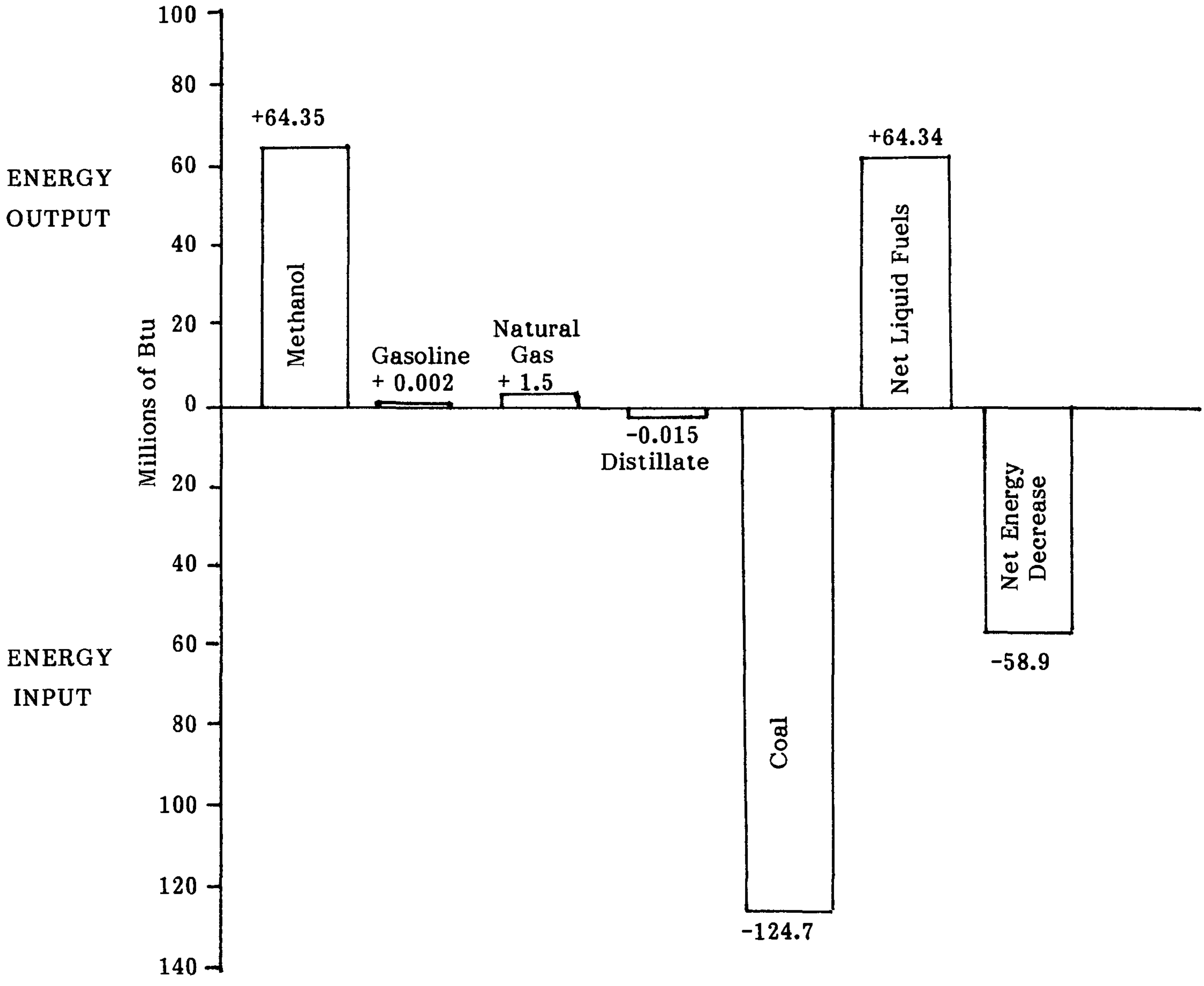
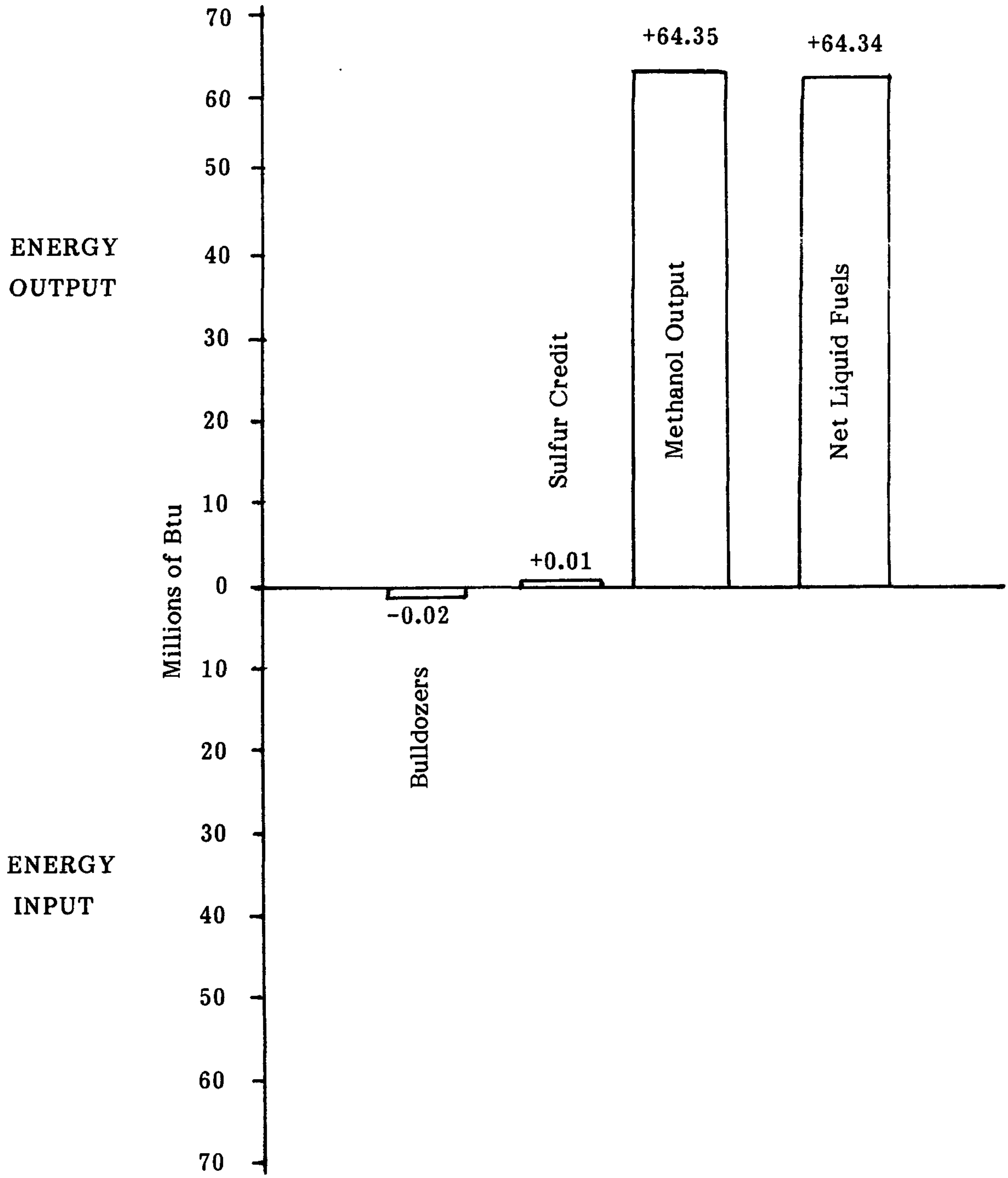


EXHIBIT 4-4: NET LIQUID FUELS
FOR COAL CONVERSION



because of the sulfur credit (7000 Btu), the net increase in liquid fuels is only 64.34 million Btu (about 999.8 gallons of methanol equivalent).

The components of change in available precious fuels are shown graphically in Exhibit 4-5. Since the sulfur credit is primarily natural gas and no natural gas is consumed, the net increase in precious fuels (65.8 million Btu) is slightly larger than the increase in liquid fuels.

The components of change of total energy are shown graphically in Exhibit 4-6. In order to produce 1000 gallons (64.35 million Btu) of methanol, 124.8 million Btu of coal and diesel fuel are required. The energy credit for the sulfur by-product is 1.6 million Btu, leaving a net decrease in total energy of 58.9 million Btu, which is the energy equivalent of 916 gallons of methanol.

It may be seen from these exhibits that converting coal to methanol is an effective means of increasing the availability of liquid fuels. The net increase in liquid fuels is virtually equal to the amount of methanol produced. Furthermore, if the by-product sulfur results in a reduction in sulfur mining, a small amount of natural gas is also saved. A moderate amount of energy is lost in the process (equal to about 91 percent of the methanol produced), though this is less than the energy lost in converting coal to electricity.

EXHIBIT 4-5: NET PRECIOUS FUELS
FOR COAL CONVERSION

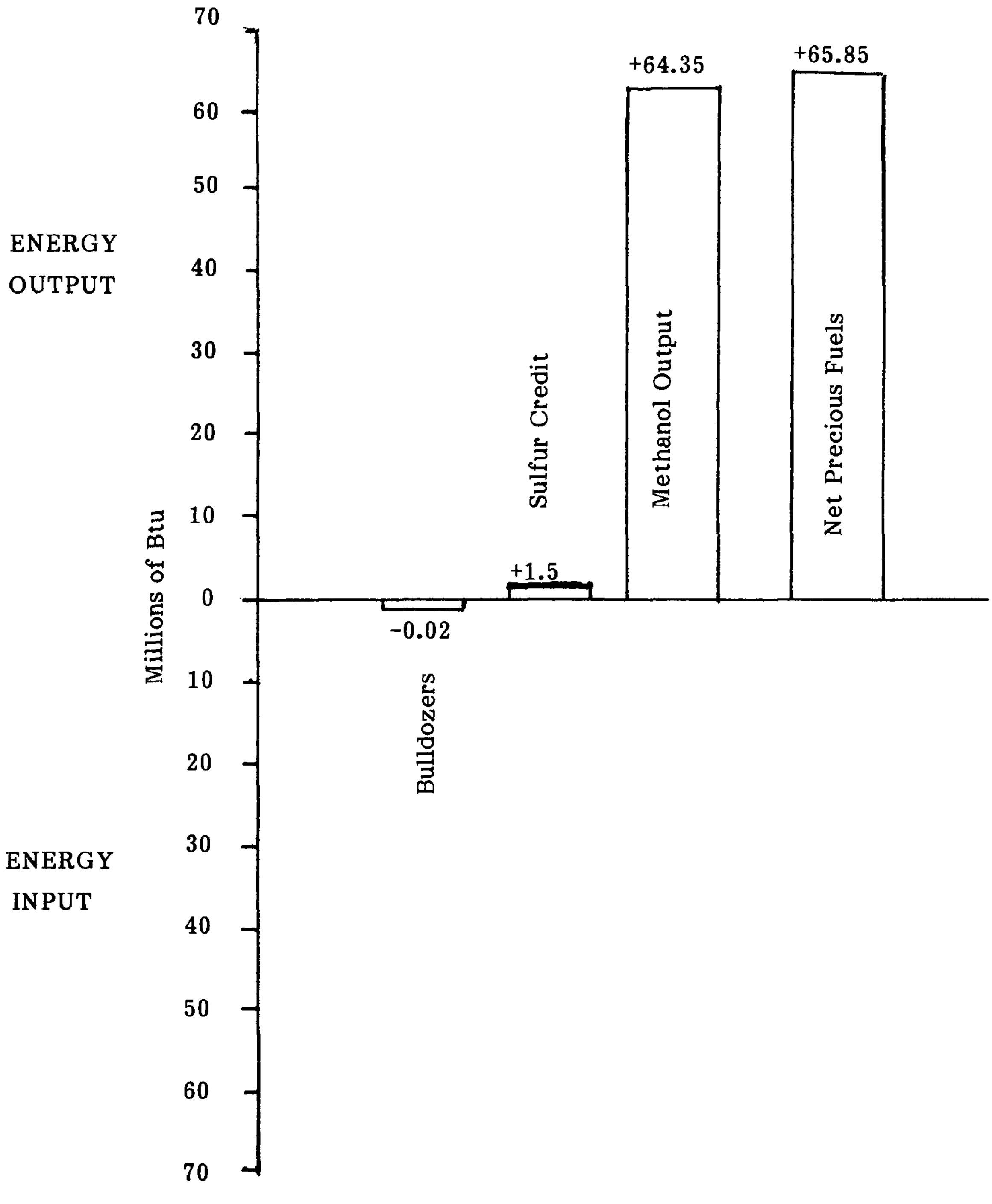
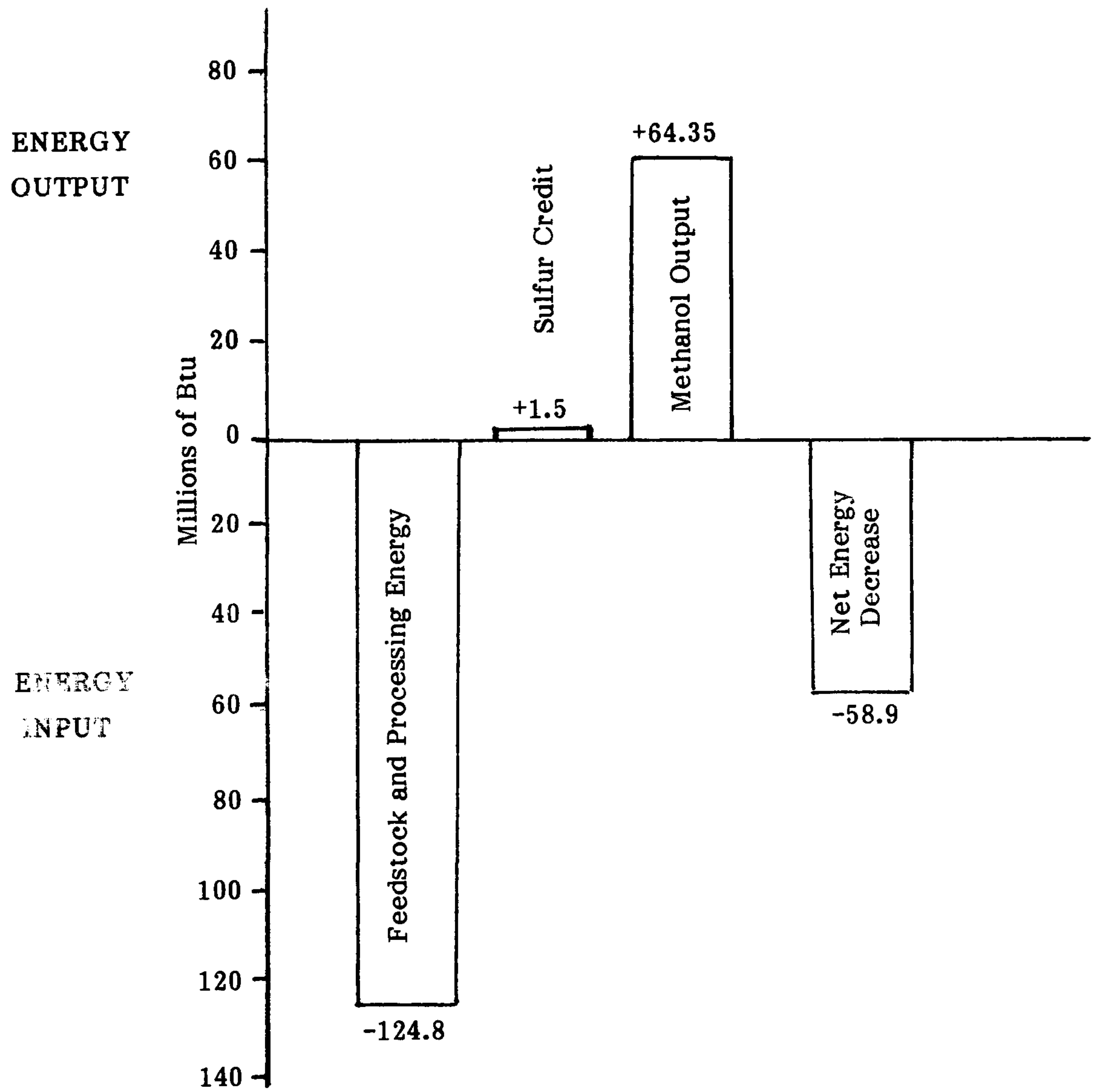


EXHIBIT 4-6: NET ENERGY CHANGES
FOR COAL CONVERSION



## 5. CONCLUSIONS

Exhibit 5-1 presents a tabular summary and comparison of the energy inputs and outputs for producing 100 million Btu of alcohol from representative versions of the three alternatives studied: ethanol from corn and grain sorghum, methanol from cellulose, and methanol from coal. One hundred million Btu corresponds to 800 gallons of gasoline and, as the table indicates, to 1188 gallons of ethanol or 1554 gallons of methanol. The energy inputs and outputs are expressed in conventional units in the top half of the table and in thousands of Btu in the lower half.

An examination of the figures in the lower half of the table reveals that the most significant energy differences in the three processes result from differing requirements for coal. The cellulose process is the only one which does not use coal as a boiler fuel (it uses cellulose instead); most of the coal which is required by this process is used to generate electricity[1]. Methanol from coal, on the other hand, requires substantial amounts of coal, which is used as process fuel and as a feedstock as well as for electricity generation. (This process also results in small increases in the availability of natural gas and motor gasoline resulting from the energy credit for the sulfur by-product.) Ethanol from grain requires moderate amounts of coal (for process fuel and for electricity) and somewhat more natural gas than the other two processes; most of the natural gas is for nitrogen fertilizer used to increase grain yields.

The overall use and generation of energy by the three processes are summarized in the last three columns of Exhibit 5-1 and displayed graphically in Exhibit 5-2. All three processes produce substantially more liquid fuels than they consume. The net increase in liquid fuels is greatest for methanol from coal (which requires virtually no liquid fuels), though the energy content of the petroleum consumed by the other processes is only about eight percent of that of the alcohol produced.

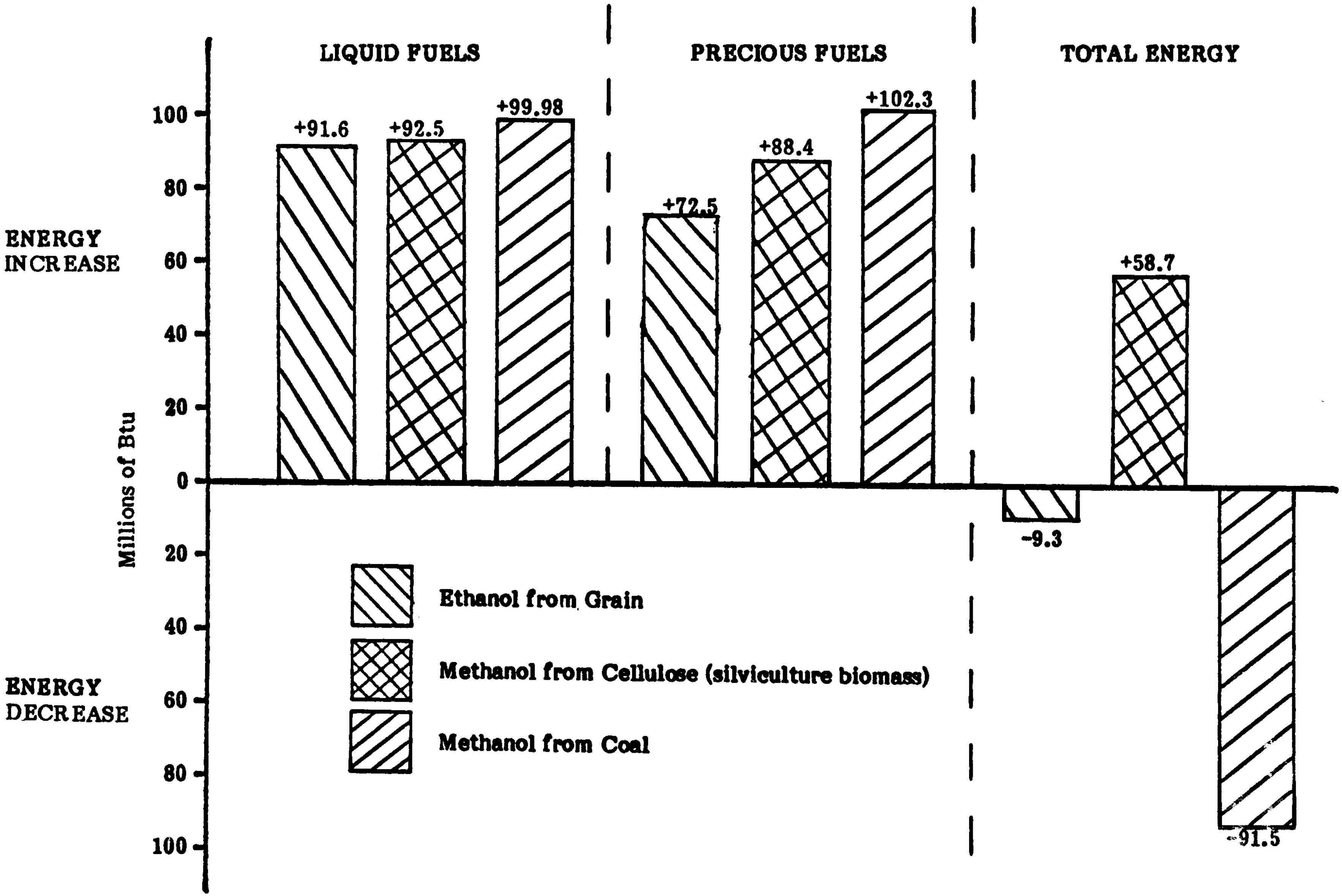
When one looks at the net production of precious fuels (which include natural gas as well as liquid fuels), somewhat greater differences arise. When methanol is derived from silvicultural biomass, the energy content of the petroleum products and natural

[1] *In all the analyses it has been assumed that electricity requirements would be met entirely through increased use of coal-fired generators.*

**EXHIBIT 5-1: ENERGY INPUTS AND OUTPUTS FOR PRODUCING 100 MILLION BTU OF ALCOHOL FUEL FROM VARIOUS SOURCES**

| | | Petroleum Products | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alcohol | Motor Gasoline | Distillate | Residual Fuel | LPG | Natural Gas | Coal | Liquid Fuels | Precious Fuels | Total Energy |
| | Conventional Units | | | | | | | | | |
| Ethanol from Grain (wet milling) | +1,188 gal | -4.2 gal | -33.6 gal | -3.1 gal | -27.9 gal | -18.8 gal | -3.83 tons | | | |
| Methanol from Cellulose (silvicultural biomass) | +1,554 | -1.43 | -51.8 | -0.42 | | -3.98 | -1.32 | | | |
| Methanol from Coal | +1,554 | +0.02 | -0.17 | | | +2.27 | -8.55 | | | |
| | MM Btu | | | | | | | | | |
| Ethanol from Grain (wet milling) | +100 | -0.520 | -4.70 | -0.46 | -2.65 | -19.1 | -81.8 | +91.6 | +72.5 | -9.3 |
| Methanol from Cellulose (silvicultural biomass) | +100 | -0.179 | -7.25 | -0.063 | | -4.06 | -29.7 | +92.5 | +88.4 | +58.7 |
| Methanol from Coal | +100 | +0.002 | -0.024 | | | +2.32 | -193.8 | +99.98 | +102.3 | -91.5 |

**EXHIBIT 5-2: NET ENERGY, BY TYPE, FOR PRODUCING 100 MILLION BTU OF ALCOHOL FUEL FROM VARIOUS SOURCES**



gas consumed equals only about twelve percent of that of the methanol produced; and when methanol is derived from coal, because of the energy credit for the sulfur by-product, the net change in the available energy from precious fuels actually exceeds that of the methanol produced. In the case of ethanol from grain, however, for every 100 Btu of ethanol produced, about 27 Btu of natural gas and petroleum products is consumed, leaving a net increase of only 73 Btu. The ethanol process is thus somewhat less effective in increasing the availability of precious fuels than the other alternatives.

The differences between the three feedstock alternatives are more striking when one considers changes in the availability of all forms of energy. On this basis, cellulose feedstocks are the only ones capable of yielding net increases in available energy -- for silvicultural biomass: about 59 Btu per 100 Btu of methanol produced. The use of coal, a nonrenewable feedstock, of course results in the consumption of substantially more energy than is produced -- though the energy consumed is solid and that produced is liquid. Similarly, when grain is purchased on the open market for use as a feedstock, the energy of the fossil fuels consumed (predominantly coal) exceeds that of the ethanol produced.

The specific energy estimates presented in the exhibits reflect the various assumptions made in the course of this study. In particular, they reflect: the conventions adopted regarding the treatment of nonrenewable fuels, electricity, solar energy, and other materials; the conversion processes used; and the energy requirements for feedstock production.

Estimated energy requirements for obtaining methanol from cellulose would have been appreciably higher if it had not been assumed that a renewable fuel would be used as a boiler fuel. Conversely, use of a renewable fuel as a boiler fuel for ethanol production would generally result in lower total energy requirements than those estimated, but somewhat greater use of precious fuels. The estimates of energy required for obtaining ethanol from grain were also affected by the decision to base these estimates on incremental agricultural energy consumption. Estimates based on average energy consumption for present agricultural production would have been lower. Another possible (but relatively extreme) assumption, that the setting of agricultural production levels is entirely independent of ethanol production considerations, with ethanol produced only from any resulting surplus grain, would have yielded even lower estimates of energy consumption. It should also be observed that the estimates of incremental agricultural energy consumption use are relatively sensitive to the particular base-case agricultural conditions assumed in the analysis.

It is believed that all results have been presented in a form that will facilitate the development of other estimates of energy requirements based on the use of different processes or alternative analytic assumptions.

Although such alternative assumptions would affect the specific energy estimates produced, it appears that, under nearly set of consistent and realistic assumptions, methanol from cellulose would be the most attractive of the alternatives from a net-energy standpoint. The cellulose results highlighted in Exhibits 5-1 and 5-2 are for silvicultural biomass, though the results for other cellulose feedstocks are fairly similar (see Chapter 3). Those for forest residues are slightly more favorable, while those for crop residues are somewhat less favorable. The results for crop residues are in part dependent upon the amount of residues collected per acre, a figure that will vary with crops, crop yields, tillage methods, erosion-control requirements, and the willingness of individual farmers to sell their residues to a methanol facility. (It should be observed that too great a willingness to sell residues is a greater concern than too small a willingness, since excessive residue collection, while reducing energy consumption, will also increase erosion and eventually will have an adverse impact on agricultural productivity.)

The other two feedstocks studied, grain and coal, can be used effectively to increase supplies of liquid fuel; though use of coal will result in a reduction in total energy available, and, under the assumptions used in this study, use of grain will have a similar, but much weaker, effect. The use of grain also results in somewhat greater use of natural gas than the other feedstocks, resulting in net precious-fuel benefits which are appreciably smaller than the liquid-fuel benefits. Accordingly, from the standpoint of net liquid and gaseous fuel benefits (and ignoring other considerations, such as cost, fuel characteristics, or the effects on exports and food prices), the production of ethanol from grain is a somewhat less desirable way of producing alcohol fuel than the production of methanol from either coal or cellulose.

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