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ENERGY INPUTS AND OUTPUTS OF FUEL-ALCOHOL PRODUCTION.

SUMMARY VOLUME,

FINAL REPORT

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Prepared by

JACK FAUCETT ASSOCIATES, INC.
5454 Wisconsin Avenue, 1100
Chevy Chase, Maryland 20815

and

BATTELLE-COLUMBUS LABORATORIES
505 King Avenue
Columbus, Ohio 43201

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ABBREVIATIONS

B	billion
Btu	British thermal unit
bbl	barrel
bu	bushel
C	degrees Centigrade
cu ft	cubic foot
d	distance
DDG	distiller's dark grains
DTE	dry ton equivalent
F	degrees 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
ton	2,000 lb
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
Petrochemicals	Btu/gal	125,000
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 wheat	=	60 lb
1 psi	=	6895 pascals
1 square mile	=	640 acres

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. As part of that assessment, Jack Faucett Associates and Battelle-Columbus Laboratories, under contract to the Department of Energy's Office of Vehicle and Engine Research and Development (OVERD), have developed estimates of energy requirements for producing alcohol fuels and compared these requirements to the energy content of the alcohol produced. These comparisons represent a form of net energy balance. The comparisons were developed for three alcohol production alternatives: ethanol from grain, methanol from cellulose, and methanol from coal. These were judged by OVERD to be the most likely alternatives for alcohol fuel development in the near term. The framework of the presentations is such that other technologies and feedstocks can be substituted for those selected.

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 one-third of the energy input in coal. We nevertheless burn coal 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 petroleum refining, manufacturing tractors, manufacturing an alcohol 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 will have a significant impact on the results.

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 hydro-powered. 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, the analysis does not include solar energy inputs. As a result, the energy balances developed may be positive; i.e., they may show a net energy gain.

In assessing the outputs to 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.

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." This issue of fuel value 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 heat content (in Btu). An alternative analysis might weight energy by the market price of the fuel in question.

Within this limitation, 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 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. This information is being developed in a parallel study for OVERD being performed by Bonner and Moore Management Science under Contract No. DE-AC01-81CS50007.

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 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, ethanol is also 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 used as a liquid fuel, primarily in the gasoline/ethanol blend known as gasohol.

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, 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) and so is less likely to be attractive from a net energy standpoint.

The first section of this chapter presents estimates of the energy required for increasing production of corn and grain sorghum (the two grains most likely to be used for ethanol production). These estimates are developed in Appendix A, along with estimates of average energy requirements for present production of corn, grain sorghum, wheat, barley and rye.

Section 2.2 presents estimates of energy requirements for two alternative processes for converting corn to ethanol as well as estimates of the energy savings resulting from the various conversion by-products. Additional information about the conversion processes and the by-product energy credits 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.

2.1 Grain

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 blances; 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 energy requirements for increasing production of corn and grain sorghum are developed from the results produced by an interregional linear programming model developed at Iowa State University (Dvoskin and Heady, 1976). This model was designed to determine the response of U.S. agricultural production to various energy supply and price conditions and to changes in demand for major export crops. The estimates developed in Appendix A are shown in Exhibit 2-1. The figures shown in this exhibit represent energy consumed in transporting the grain to the ethanol plant as well as for increased fertilization, irrigation of additional land, and all other components of grain production.

EXHIBIT 2-1: ENERGY REQUIREMENTS PER BUSHEL FOR INCREASING CORN AND GRAIN SORGHUM PRODUCTION

	Petroleum Products							
	Motor Gasoline (gal/bu)	Distillate (gal/bu)	Residual Fuel (gal/bu)	LPG (gal/bu)	Natural Gas (cu ft/bu)	Coal* (lb/bu)	Total Petroleum Products (Btu/bu)	Total Energy (Btu/bu)
CORN	0.1296	0.1066	0.0012	0.0534	114.83	1.763	36,400	173,300
GRAIN SORGHUM	0.1335	0.1064	0.0012	0.0541	116.45	1.788	36,900	175,800

*Based on use of 11,250 Btu/lb coal.

Source: Derived from Dvoskin and Heady (1976) (see Appendix A).

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The Iowa State University model has recently be adapted to produce direct analyses of he effects of the use of corn or grain sorghum for ethanol production (instead of the indirect analysis developed in Appendix A). The results of these analyses, however, were not available in time to be incorporated into the present report. We plan to update the present report with these results in the near future. Preliminary information indicates that the updated estimates of energy requirements are likely to be lower than those presented in Exhibit 2-1.

The estimates of energy consumption for increasing grain production shown in Exhibit 2-1 are 173,300 Btu per additional bushel for corn and 175,800 Btu per additional bushel for grain sorghum. These estimates are nearly three times as large as estimates of average energy consumption for producing these grains in states where relatively little irrigation is required (cf. Exhibit A-22 in Appendix A). The major reason for the high estimates of energy consumption is the determination by the model that the most economic way of increasing production is by increasing fertilization. Natural gas required for producing nitrogen fertilizer accounts for about two-thirds of the increase in energy consumption. Irrigation of new cropland accounts for another fifteen percent of the total[1].

2.2 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.

2.2.1 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.

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[1]*The estimates shown in Exhibit 2-1 do not reflect adjustments in crop-planting patterns which will result from the substitution of feed by-products of ethanol production for soy meal. It appears that resulting reductions in soybean acreage would make it possible to obtain the required increase in corn or grain sorghum production with, perhaps, 20,000 to 30,000 fewer Btu per bushel than indicated in the exhibit. This saving, not reflected in the present analysis, would be in addition to the energy credit for reduced production of feed products discussed in Section 2.2.3, below (which is incorporated in the present analysis).*

There are several vendors of proprietary dry-milling ethanol technology. These include .CR, 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. The distillation system is similar to a double effect evaporator in energy consumption. 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.

2.2.2 Wet Milling

The wet milling of corn 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 corn 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; nd the gluten separation from starch and drying. The selected process is described in Section 2 of Appendix B.

2.2.3 Energy Requirements and By-Product Energy Credits

The energy requirements of both dry and wet-milling processes are summarized in Exhibit 2-2, along with estimates of energy saved as a result of the feed by-products produced. 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 3.3 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).

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 corn oil. Corn oil competes with other vegetable oils, including soy oil, while the other products displace both soy meal and corn. It is assumed that this displacement occurs in such a way that both protein supplied and total weight of the feed remain constant. The energy credit for these products is taken on the basis of the average energy to grow (and, for oil, to crush) soybeans and the marginal energy required to increase production of corn. These credits are estimated in Section 3 of Appendix B. The fuel-mix components of these credits (and, to a lesser extent, their overall size) are relatively sensitive to the feed products displaced: the energy credit for corn is predominantly natural gas, that for soy meal is predominantly for liquid fuels (see Exhibit B-7 in Appendix B).

EXHIBIT 2-2: INPUTS AND OUTPUTS FOR PRODUCING 1000 GALLONS OF ETHANOL

		Petroleum Products							
		Motor Gasoline (gal)	distillate (gal)	Residual fuel (gal)	LPG (gal)	Natural Gas (M cu ft)	Coal (1) (tons)	Liquid Fuels (M Btu)	Total Energy (M Btu)
DRY MILLING									
	Feedstock Requirements								
	388 bushels of corn								
• PROCESS ENERGY:	2.24 tons of coal 1310 kwhr electricity						+2.24(2) +0.64		+47,700 +13,600
• LIME:	0.12 tons		+1.1	+4.27		+1.9	+0.27	+800	+8,800
• BY-PRODUCT:	3.54 tons DDG	-22.2	-20.7	-0.14	-4.7	-7.1	-0.09	-6,100	-15,400
	Primary Product								
	1000 gallons of ethanol								
NET ENERGY REQUIRED FOR PROCESS, LIME AND BY-PRODUCT		-22.2	-19.6	+4.13	-4.7	-5.2	+3.06	-5,300	+54,700
WET MILLING									
	Feedstock Requirements								
	388 bushels of corn								
• PROCESS ENERGY:	2.19 tons of coal 1260 kwhr electricity						+2.19(2) +0.62		+46,600 +13,100
• LIME:	0.12 tons		+1.1	+4.27		+1.9	+0.27	+800	+8,800
• BY-PRODUCTS:	600 lb corn oil	-2.3	-4.1	-1.79	-0.2	-0.9	-0.04	-1,200	-3,000
	1080 lb gluten meal 5500 lb gluten feed	-20.7	-19.3	-0.14	-4.3	-6.4	-0.09	-5,700	-14,200
	Primary Product								
	1000 gallons of ethanol								
NET ENERGY REQUIRED FOR PROCESS, LIME AND BY-PRODUCT		-23.0	-22.3	+2.34	-4.5	-5.4	+2.95	-6,100	+51,300

(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.

2.3 Results

In the first section of this chapter, estimates were presented of the energy requirements for increasing national production of corn and grain sorghum. In the second section, estimates were presented of the energy requirements for deriving ethanol from corn using two alternative milling processes and of the energy savings resulting from the conversion by-products. Exhibit 2-3 shows a summary of the energy inputs and outputs for obtaining 1,000 gallons of ethanol from corn using wet-milling and assuming that the corn used for this purpose is obtained by increasing national production of corn.

The major energy requirements are for increasing corn production and for conversion to ethanol. All energy requirements for conversion are assumed to be supplied by coal. However, only about 11 percent of the energy required for increasing corn supplies is from coal; two-thiids is obtained from natural gas (primarily for fertilizer), and the rest is obtained from various petroleum products. Energy requirements for increasing production of grain sorghum (an alternative feedstock) were found to be only slightly higher. 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 2-3 in conventional units. This information is also presented in Exhibit 2-4, for both dry and wet milling, 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 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 2-5.

It can be seen from Exhibit 2-5 that production of ethanol from corn requires small amounts of various petroleum products as well as moderate amounts of natural gas and 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 ten percent of that of the ethanol produced. Total energy consumed, however, exceeds the energy of the ethanol produced.

EXHIBIT 2-3: ENERGY INPUTS AND OUTPUTS FOR PRODUCING 1000 GALLONS OF ETHANOL FROM CORN VIA WET MILLING

			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		-50.3	-41.4	-0.47	-20.7	-44.6	-0.34	-14,100	-59,600	-67,200
• ENERGY:	2.19 tons of coal							-2.19 (2)			-46,600
	1260 kwhr electricity							-0.62			-13,100
• LIME:	0.12 ton			-1.1	-4.27		-1.9	-0.27	-800	-2,700	-8,800
OUTPUTS											
• BY-PRODUCTS:	600 lb corn oil		+2.3	+4.1	+1.79	+0.2	+0.9	+0.04	+1,200	+2,100	+3,000
	1080 lb gluten meal 5500 lb gluten feed		+20.7	+19.3	+0.14	+4.3	+6.4	+0.09	+5,700	+12,100	+14,200
• ETHANOL:	1000 gallons	+1,000							+84,200	+84,200	+84,200
NET ENERGY PRODUCTION/CONSUMPTION		+1,000	-27.3	-19.1	-2.81	-16.2	-39.6	-3.29	+76,200	+36,100	-34,300

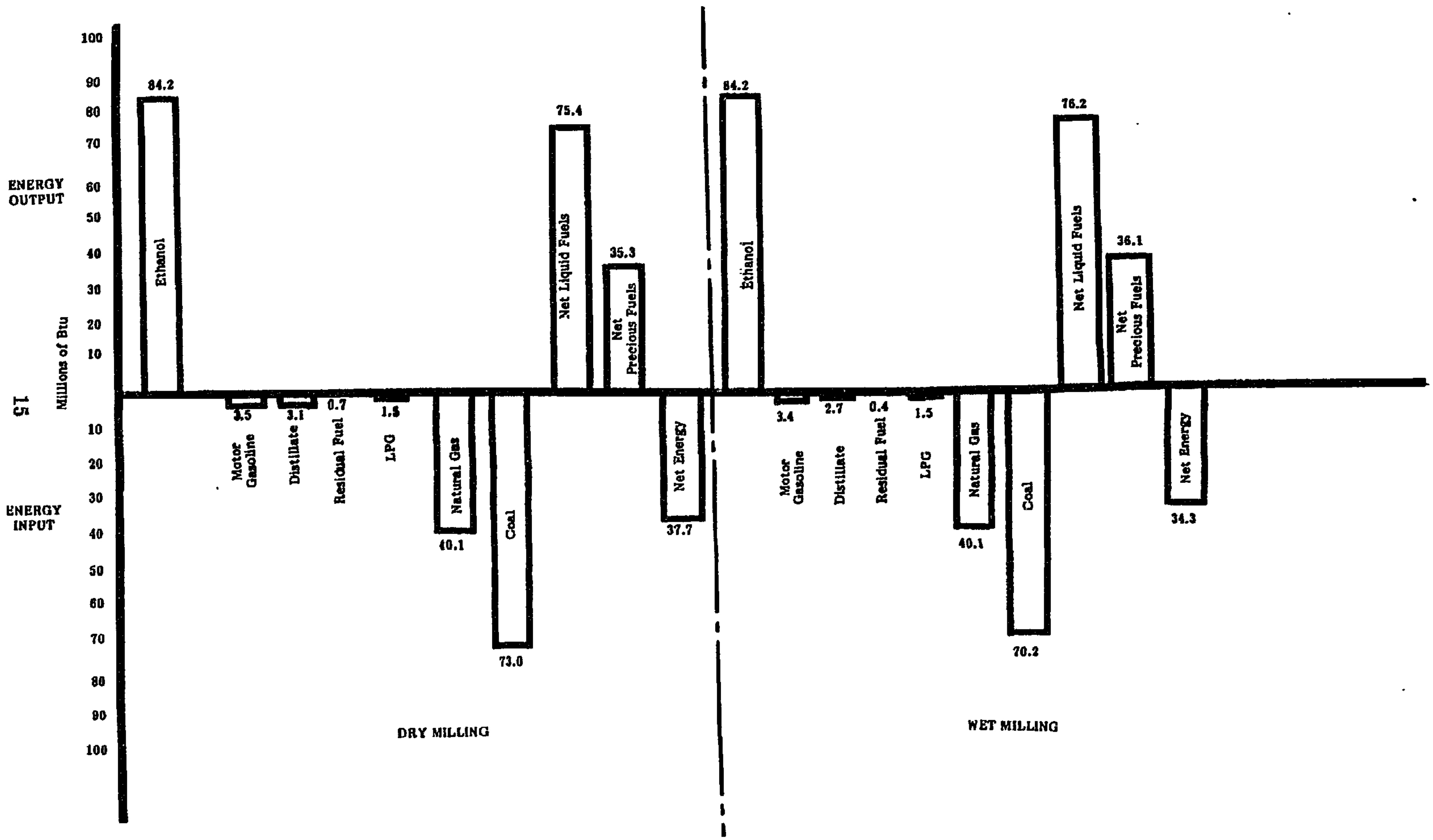
(1) Based on use of 11,250 Btu/lb coal except as noted.
(2) Based on use of 10,630 Btu/lb coal.
(3) Consists of liquid fuels and natural gas.

EXHIBIT 2-4: ALTERNATE MEANS OF EXPRESSING ENERGY CHANGES RESULTING FROM THE PRODUCTION OF 1000 GALLONS OF ETHANOL FROM CORN

	Change in Available Energy			
	Conventional Units		MM Btu	Gallons of Ethanol Equivalent (1)
Dry-Milling Process				
Ethanol	+ 1,000	gal	+ 84.2	+ 1,000
Motor Gasoline	- 28.1	gal	- 3.5	- 41
Distillate	- 21.8	gal	- 3.1	- 37
Residual Fuel	- 4.6	gal	- 0.7	- 8
LPG	- 16.0	gal	- 1.5	- 18
Natural Gas	- 39.4	M cu ft	- 40.1	- 477
Coal	- 3.40	tons	- 73.0	- 867
Net Liquid Fuels			+ 75.4	+ 896
Net Precious Fuels			+ 35.3	+ 419
Net Energy			- 37.7	- 448
Wet-Milling Process				
Ethanol	+ 1,000	gal	+ 84.2	+ 1,000
Motor Gasoline	- 27.3	gal	- 3.4	- 41
Distillate	- 19.1	gal	- 2.7	- 32
Residual Fuel	- 2.8	gal	- 0.4	- 5
LPG	- 16.2	gal	- 1.5	- 18
Natural Gas	- 39.4	M cu ft	- 40.1	- 477
Coal	- 3.29	tons	- 70.2	- 836
Net Liquid Fuels			+ 76.2	+ 904
Net Precious Fuels			+ 36.1	+ 427
Net Energy			- 34.3	- 409

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

EXHIBIT 2-5: ENERGY INPUTS AND OUTPUTS FOR PRODUCING ETHANOL FROM CORN



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Much of the energy consumed is coal which, though nonrenewable, is relatively plentiful nd less valuable than liquid fuels. An appreciable amount, however, is natural gas. Net consumption of natural gas and the various petroleum products represents about 48 million Btu per thousand gallons of ethanol -- nearly 60 percent 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 2-6. 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 about 76 MM Btu (about 900 gallons of ethanol equivalent).

The components of change of precious fuels (liquid fuels and natural gas) are shown graphically in Exhibit 2-7. The precious fuel requirements for lime and the net increase in precious fuel requirements for crop production are substantially higher than they are for liquid fuels alone. The net increase in precious fuels for each of the processes is about 36 MM Btu (about 420 gallons of ethanol equivalent). This represents a 76 MM Btu increase in liquid fuels and a 40 MM Btu decrease in natural gas.

The components of change of total energy are shown graphically in Exhibit 2-8. In order to produce 1000 gallons (84.2 MM Btu) of ethanol, about 120 MM Btu of coal, natural gas, and liquid fuels are required.

The results presented in Exhibits 2-3 through 2-8 incorporate estimates of the energy required for <u>increasing</u> national production of corn. Because agricultural production tends to become more energy intensive as total production increases, an equal decrease in corn 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 the production of corn would be slightly less than that required for increasing the production of corn. For small changes in overall production, however, the difference will be small. The results presented in Exhibits 2-3 through 2-8 are thus appropriate

EXHIBIT 2-6: NET LIQUID FUELS FOR PRODUCING ETHANOL FROM CORN

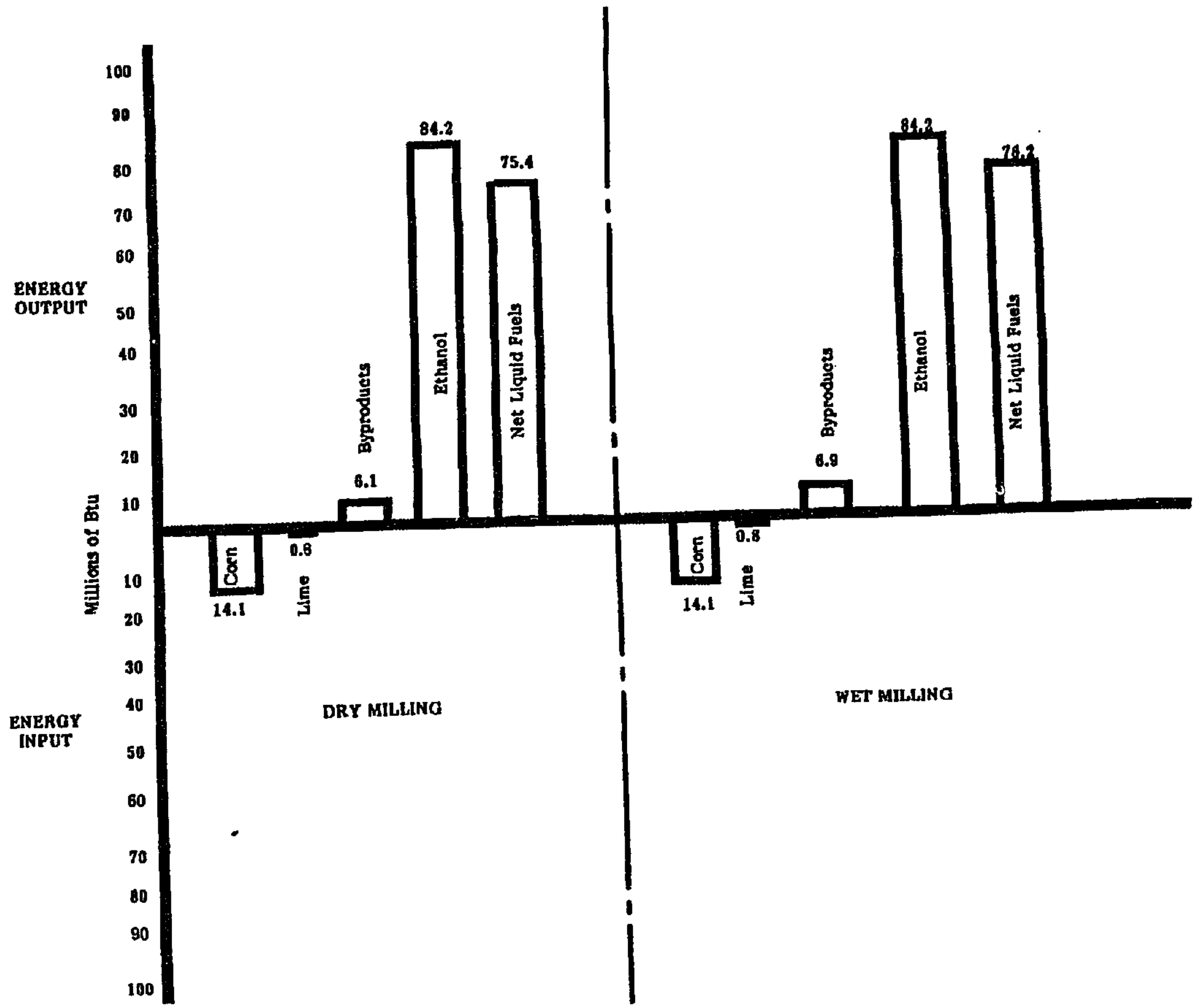


EXHIBIT 2-7: NET PRECIOUS FUELS FOR PRODUCING ETHANOL FROM GRAIN

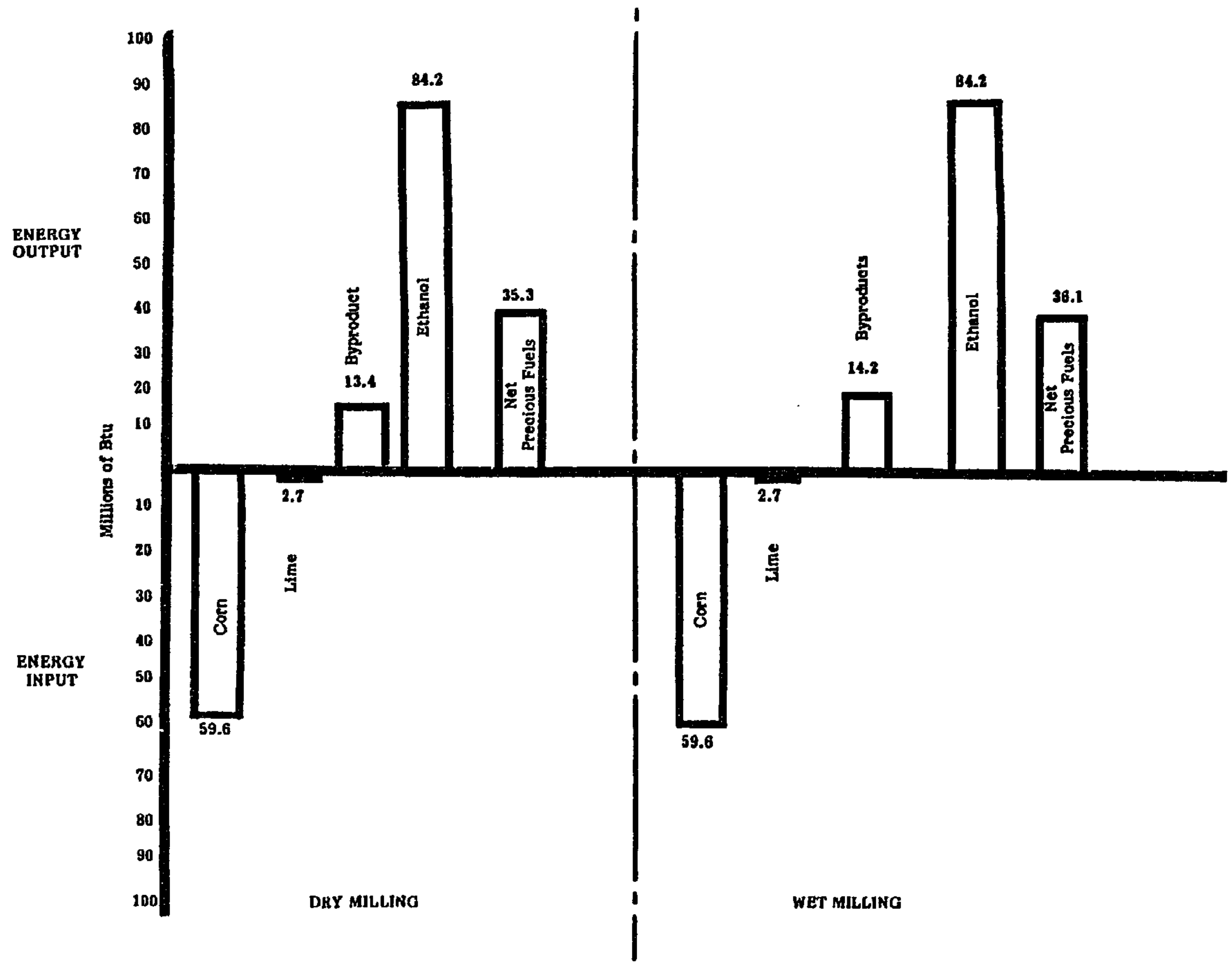
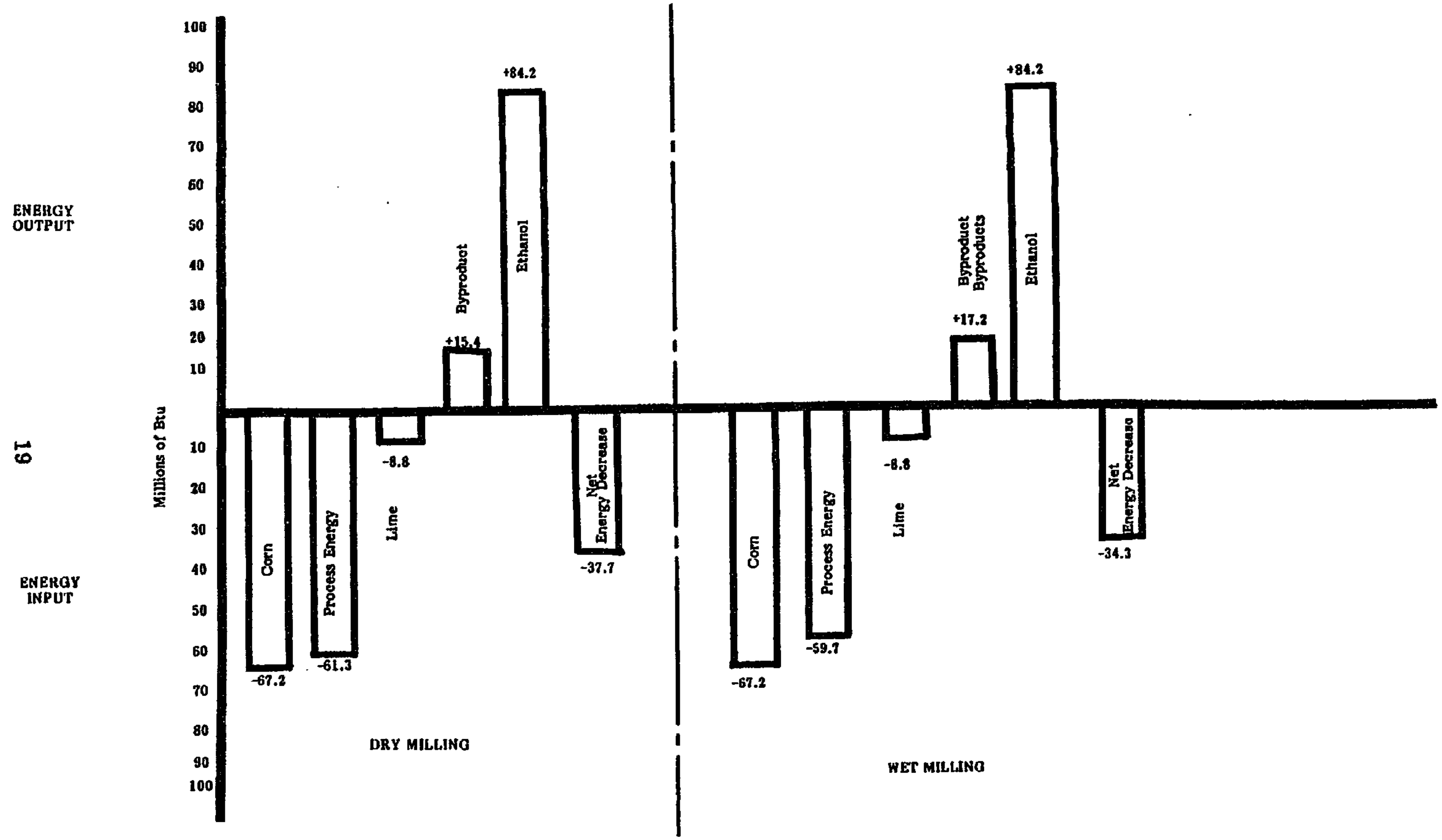


EXHIBIT 2-8: NET ENERGY FOR PRODUCING ETHANOL FROM GRAIN



estimates[1] of the change in energy consumed in order either to increase or to decrease ethanol production from corn purchased on the open market[2].

In summary, the production of ethanol from corn requires only limited use of petroleum products. Thus, about 90 percent of the energy contained in the ethanol represents an increase in the availability of liquid fuels. Despite the use of a renewable feedstock, however, total energy consumed exceeds the energy of the ethanol produced; overall energy efficiency for the entire system is about 69 percent when the dry-milling process is used and 71 percent when the wet-milling process is used. Although much of the energy consumed is obtained from or can be obtained from coal, an appreciable amount is obtained from natural gas (primarily for the fertilizer used to increase corn production).

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[1] As previously observed, some downward revision of these estimates may be appropriate as a result of work now being completed at Iowa State University.

[2] 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

Region	Operation	Petroleum Products							
		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

p

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. The biomass grown on an energy plantation would be used to generate electricity (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 or transportation energy costs associated with the collection of such non-field residues.

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 WOOD FEEDSTOCK FROM A SILVICULTURAL BIOMASS FARM

Energy Consuming Element	Petroleum Products: Motor Gasoline (gal)	Petroleum Products: Distillate (gal)	Petroleum Products: 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). These conditions exist at a time when residue removal (which can increase soil loss by a factor of two) is only rarely practiced. 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.

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. Additional details concerning all information presented in this exhibit may be found in Appendix E.

For five of the six areas studied, between 1.5 and 2.0 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.

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) Corn	Usable Residues (tons/acre) Small Grains	Average Distance (miles)	Petroleum Products: Motor Gasoline (gal)	Petroleum Products: Distillate (gal)	Petroleum Products: Residual Fuel (gal)	Petroleum Products: LPG (gal)	Natural Gas (cu ft)	Coal[1] (tons)	Btu Petroleum Products	Btu Total Energy
• CORN BELT											
Major Land Resource Area 102	1.08	1.39	20.8	0.23	4.58	0.037	0.094	778.4	0.00358	693,000	1,567,000
Major Land Resource Area 115	0.95	1.24	32.2	0.23	5.77	0.037	0.094	827.5	0.00377	865,000	1,794,000
Major Land Resource Area 107	1.02	1.32	31.5	0.23	5.79	0.039	0.094	888.8	0.00398	853,000	1,827,000
• GREAT PLAINS											
Major Land Resource Area 80	—	0.66	36.1	0.23	6.44	0.032	0.094	545.4	0.00273	945,000	1,563,000
Major Land Resource Area 73	0.89	0.35	41.8	0.23	8.56	0.035	0.094	666.0	0.00317	1,240,000	1,994,000
Major Land Resource Area 63	—	0.18	144.9	0.23	21.73	0.032	0.094	545.4	0.00273	3,150,000	3,718,000

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 feedstock, 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 burned in the boiler. Fuel gas generated in the process is used in reforming and in the boiler.

Total process-related fuel and energy requirements for obtaining methanol from wood are summarized in Exhibit 3-4. 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 3-5 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 3-4. 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 3-4: ENERGY INPUTS FOR THE CELLULOSE CONVERSION FACILITY PER 1000 GALLONS METHANOL PRODUCED

Energy Consuming Element	Assumptions	Petroleum Products: Motor Gasoline (gal)	Petroleum Products: Distillate (gal)	Petroleum Products: Residual Fuel (gal)	Natural Gas (cu ft)	Coal[(1)] (tons)	Btu Petroleum Products	Btu Precious Fuels	Btu Total Energy
	Feedstock Requirements 6.63 DTE Wood 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 3-5: ENERGY INPUTS AND OUTPUTS
FOR PRODUCING 1000 GALLONS OF METHANOL FROM SILVICULTURAL BIOMASS

		Petroleum Products							
	Methanol (gal)	Motor Gasoline (gal)	Distillate (gal)	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 3-5 in conventional units. This information is also presented in Exhibit 3-6, 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 3-7.

It can be seen from these exhibits that the production of 1000 gallons of methanol (64.35 million Btu) from silvicultural biomass 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 nonrenewable fuels is estimated to be somewhat smaller: 37.8 million Btu.

The results presented in Exhibits 3-5 and 3-6 for methanol derived from silvicultural biomass are compared in Exhibit 3-8, in summary form, to corresponding results for methanol derived from forest residues and agricultural residues. The summary data presented in Exhibit 3-8 are derived from data in Exhibits 3-1 through 3-4. Additional detail (such as that shown in Exhibit 3-5) for energy requirements for obtaining forest and agricultural residues can be found in Appendices C and E.

It can be seen from Exhibit 3-8 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 3-9 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 3-6: 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 3-7: ENERGY INPUTS AND OUTPUTS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS

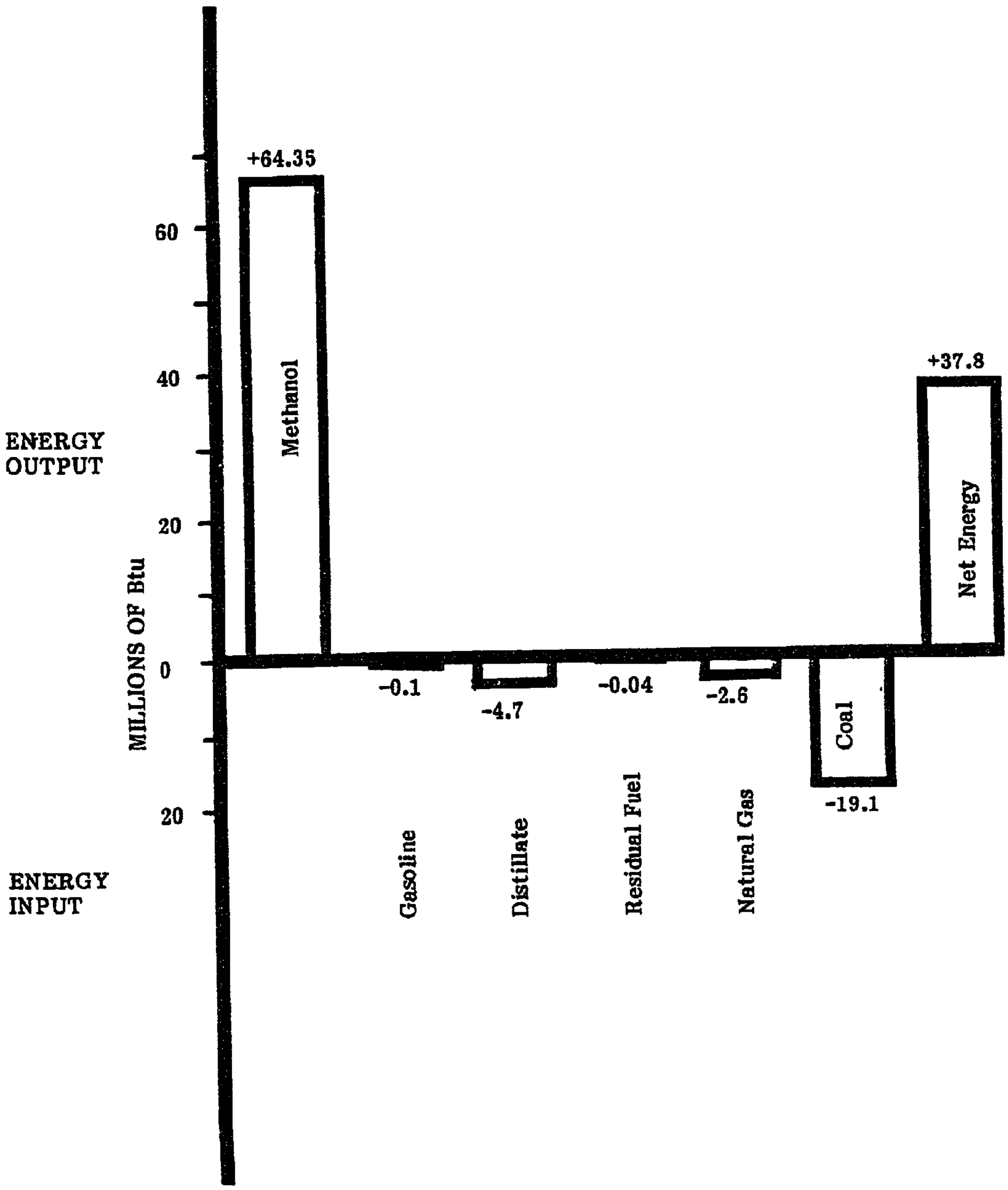
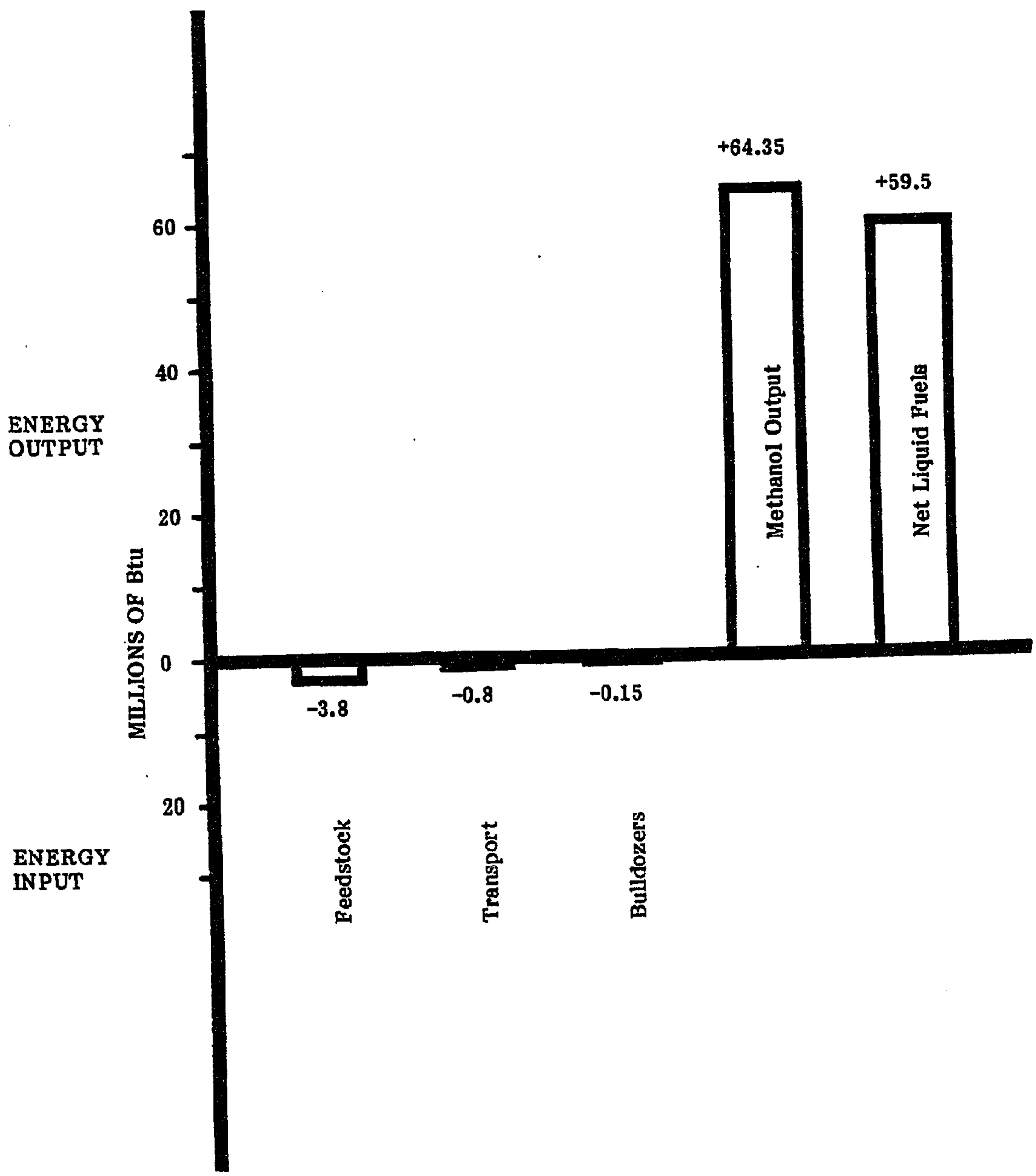


EXHIBIT 3-8: NET ENERGY INPUTS AND OUTPUTS
FROM PRODUCING 1000 GALLONS OF METHANOL FROM VARIOUS SOURCES OF CELLULOSE

		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
FOREST RESIDUES										
• EASTERN UNITED STATES										
Commercial Thin or Commercial Harvest	+1,000		-19.85				-0.82	+61,750	+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
SILVICULTURAL BIOMASS										
Populus, Southeastern United States	+1,000	-0.86	-33.31	-0.27		-2,560	-0.85	+59,540	+56,930	+37,800
AGRICULTURAL RESIDUES										
• 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 3-9: NET LIQUID FUELS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS



The components of change in available precious fuels are shown graphically in Exhibit 3-10. 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 3-11. 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. 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 side effect of increasing the rate of soil erosion.

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

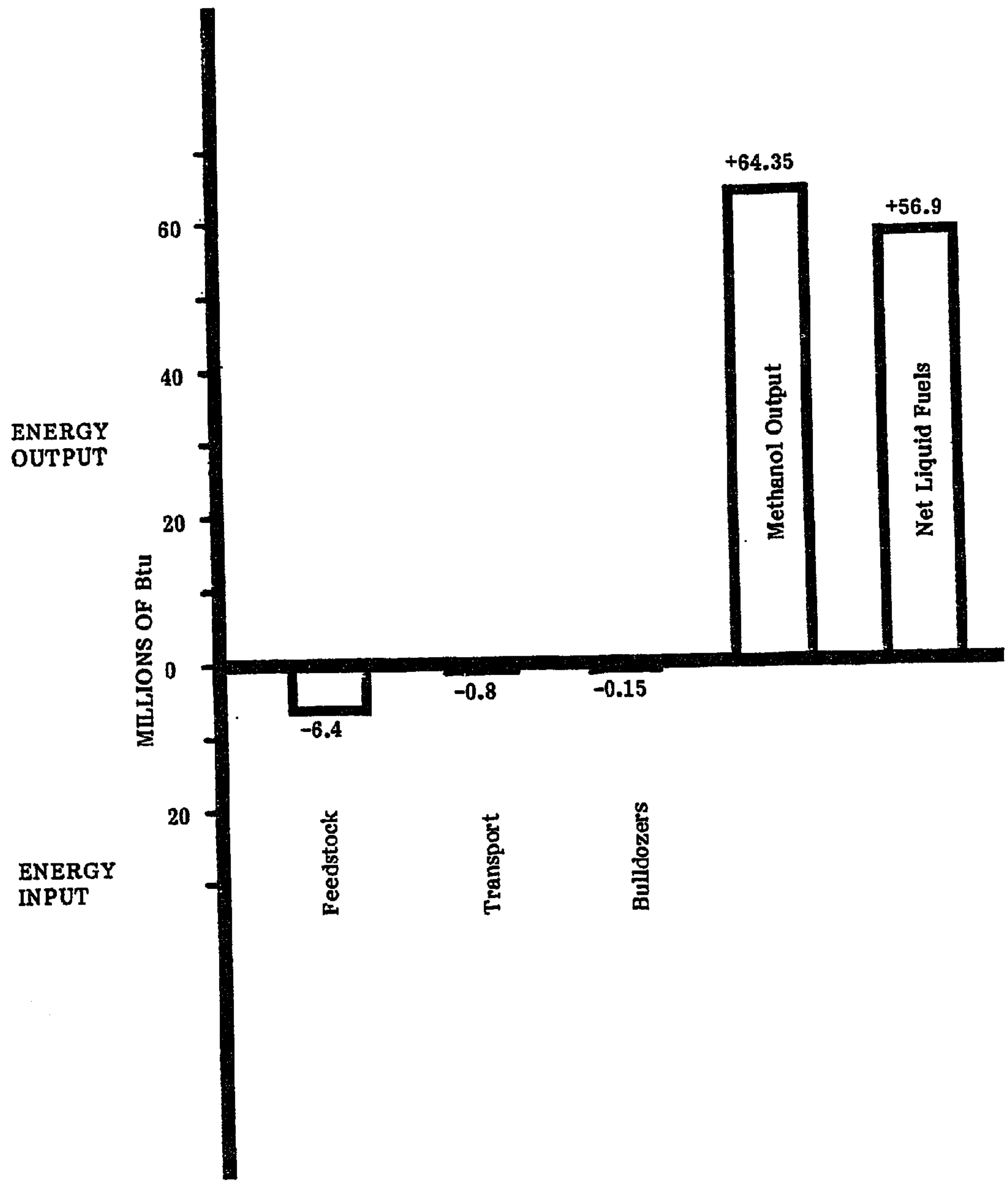
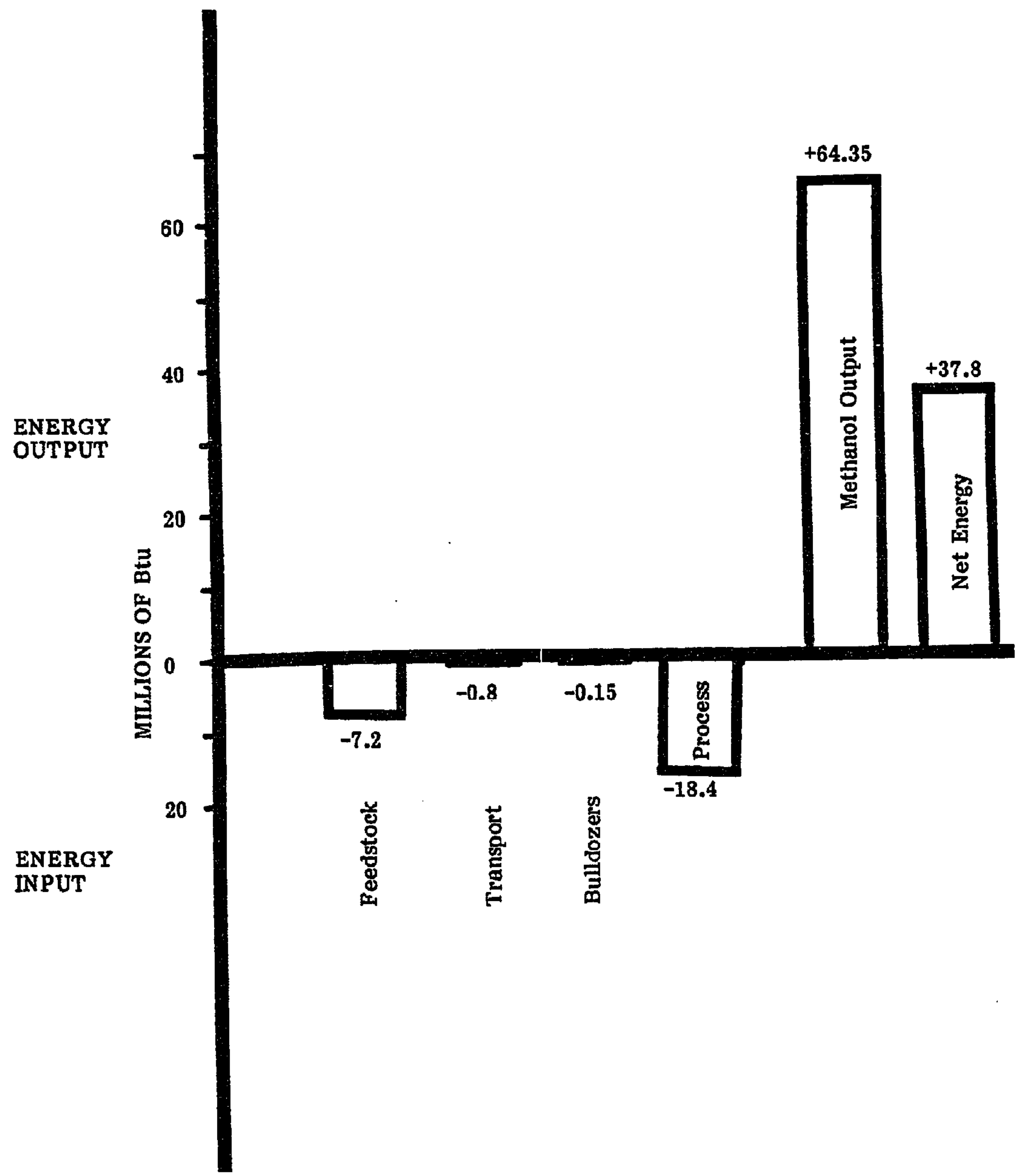


EXHIBIT 3-11: ENERGY INPUTS AND OUTPUTS FOR PRODUCING METHANOL FROM SILVICULTURAL BIOMASS



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.

p

4.1 Energy Requirements

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

a. energy required to mine the coal;

b. energy required to transport the coal to the conversion plant;

c. energy required to convert the coal to methanol; and

d. the energy content of the coal itself.

The fourth 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 d - a (where a and d 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 (a + b + c), plus the net energy value of the unmined coal (d - a). Hence, total energy required is given by:

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

Note that the energy required to mine the coal (a) 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:

$$b + c + d - e$$

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 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.

p

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. Commercial-scale Texaco coal-gasification units are now being built in the U.S. for demonstration purposes.

[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 (plus four under construction) and eight MGC (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: 5.5 tons of bituminous coal						5.5 (1)			-124,740
• STORAGE: Bulldozers move coal			0.15				20	20	20
• PROCESS: All energy from feedstock									
			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.

Overall, the net energy consumed by the methanol production process is 1.91 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 (58.8 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

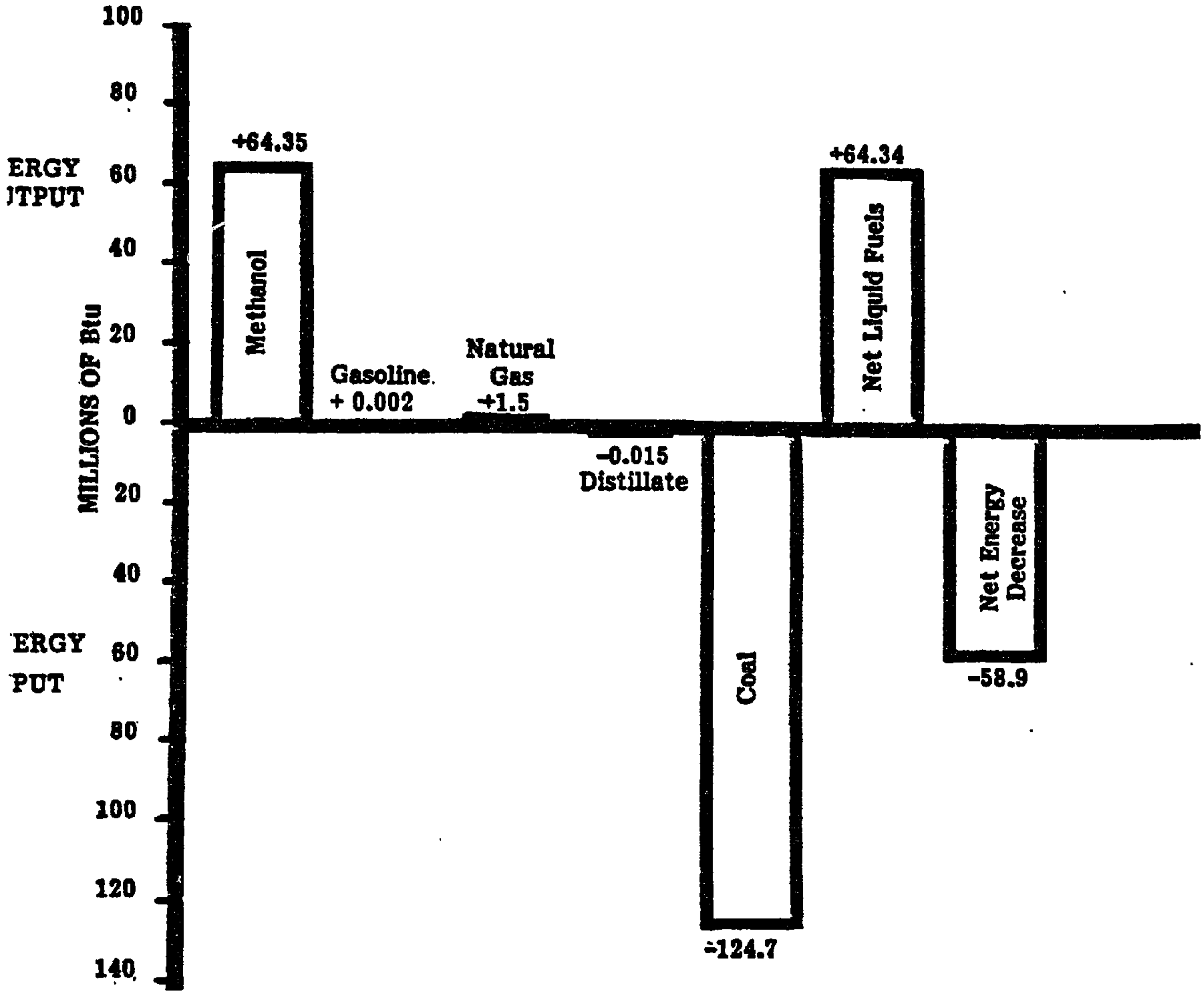
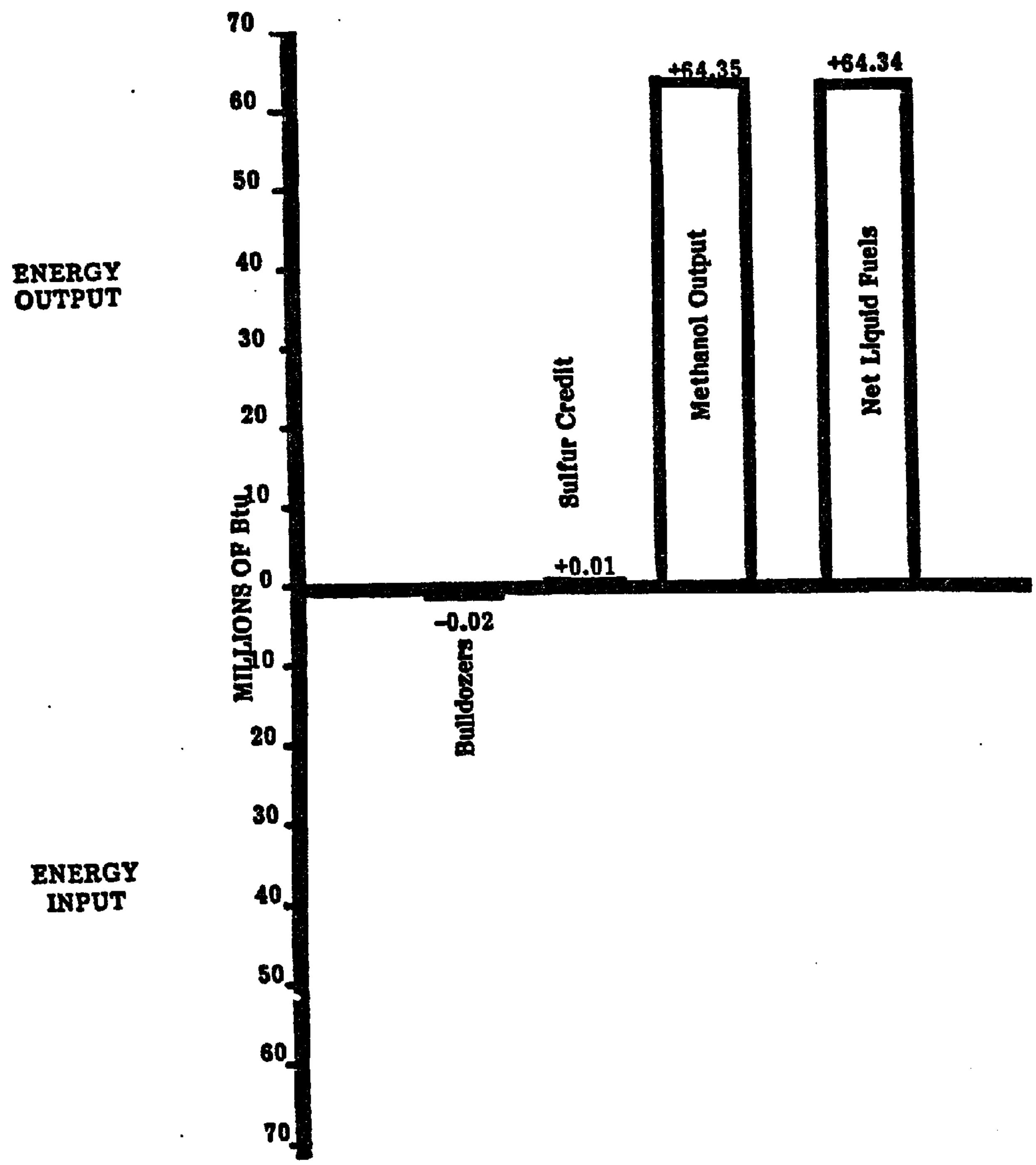


EXHIBIT 4-4: NET LIQUID FUELS FOR COAL CONVERSION



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 58.8 million Btu, which is the energy equivalent of 914 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

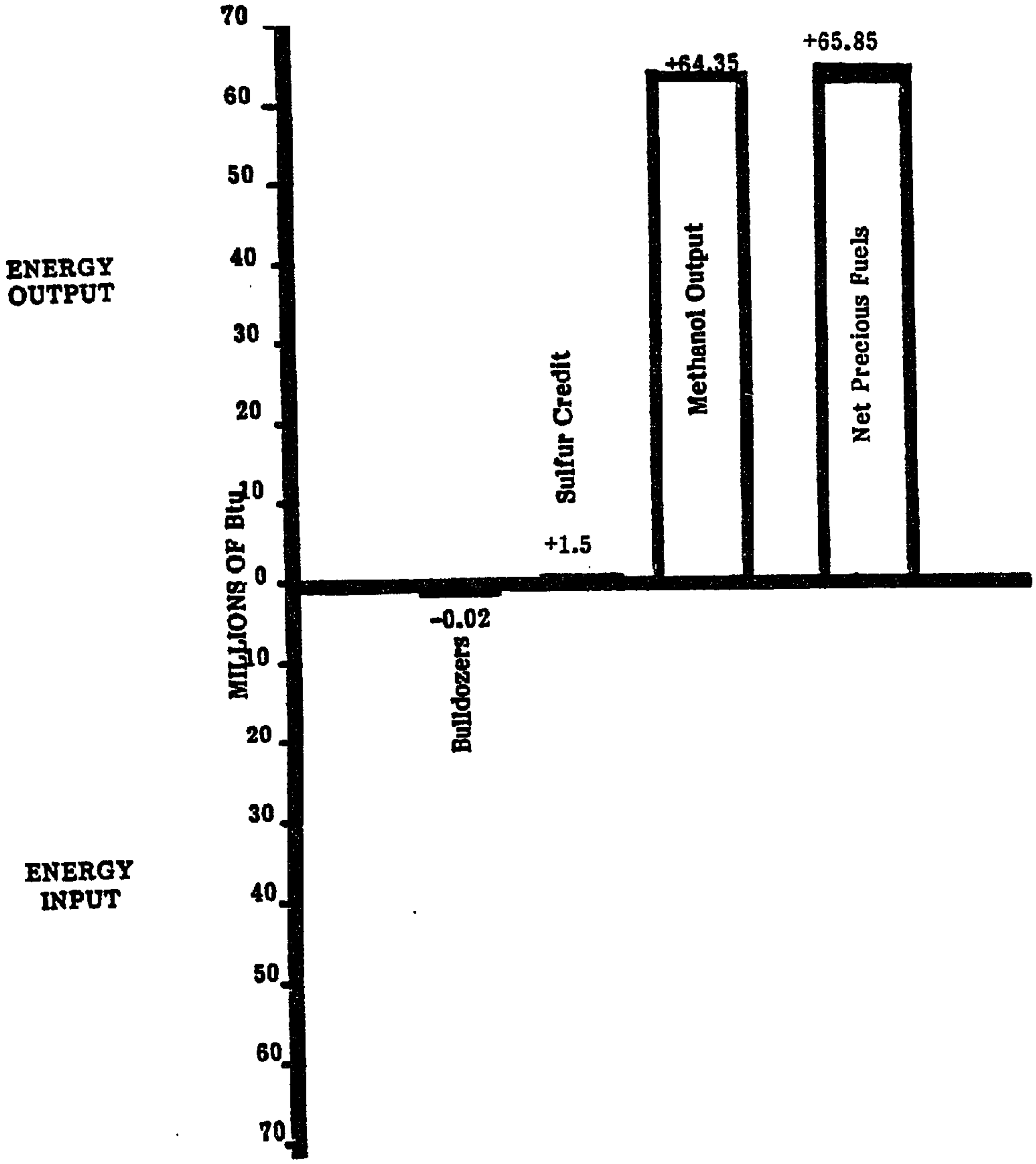
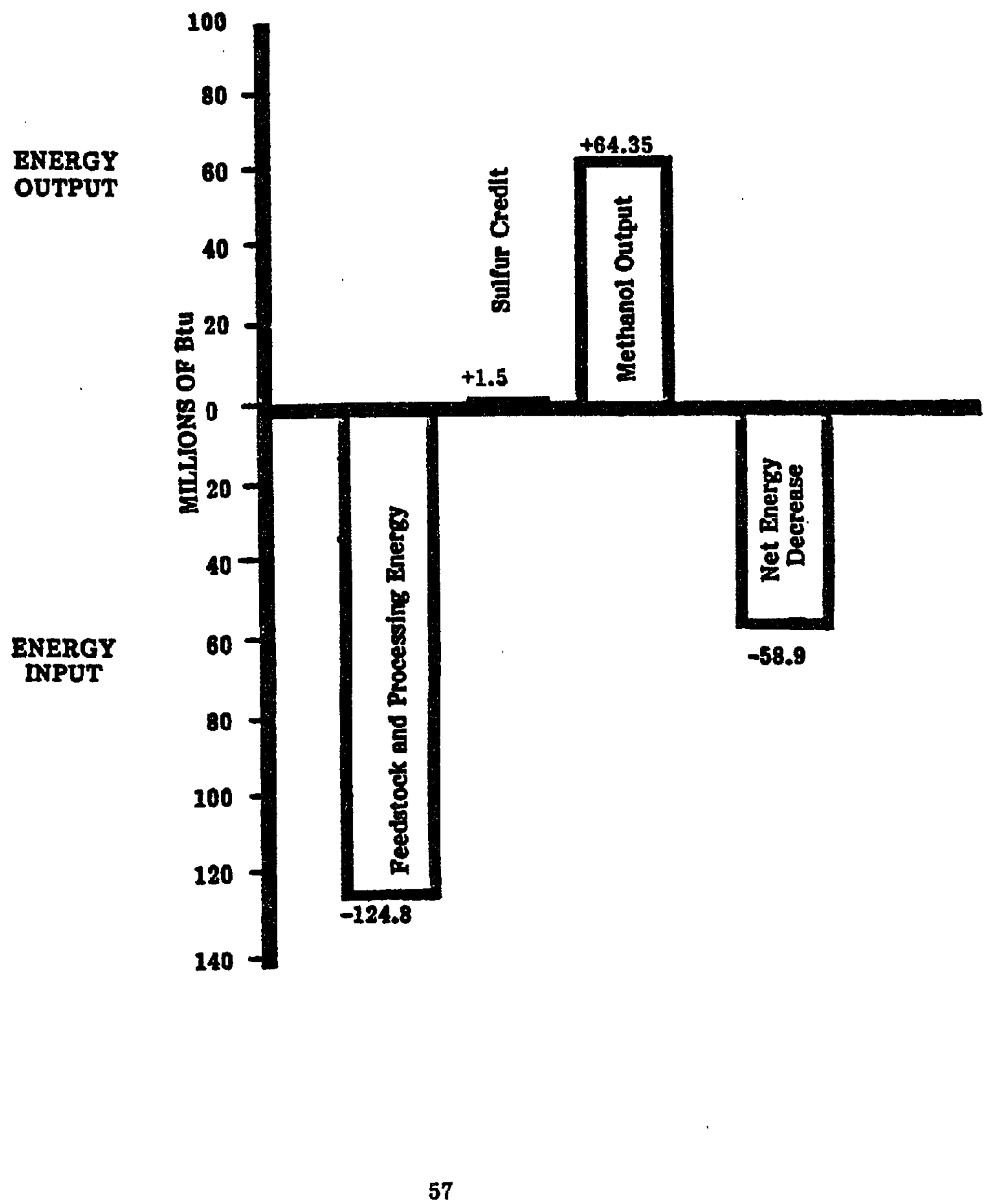


EXHIBIT 4-6: NET ENERGY CHANGES
FOR COAL CONVERSION



5. SUMMARY AND 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 grain, 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 results from differing requirements for coal and natural gas. The cellulose process (methanol from silviculture biomass) requires relatively little coal, which, for this feedstock, is primarily used to generate electricity[1]. Methanol from coal, on the other hand, requires very 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 more moderate amounts of coal (for process fuel and for electricity) but substantially 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 is 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), but the energy content of the petroleum consumed by the other processes is only seven to ten percent of that of the alcohol produced.

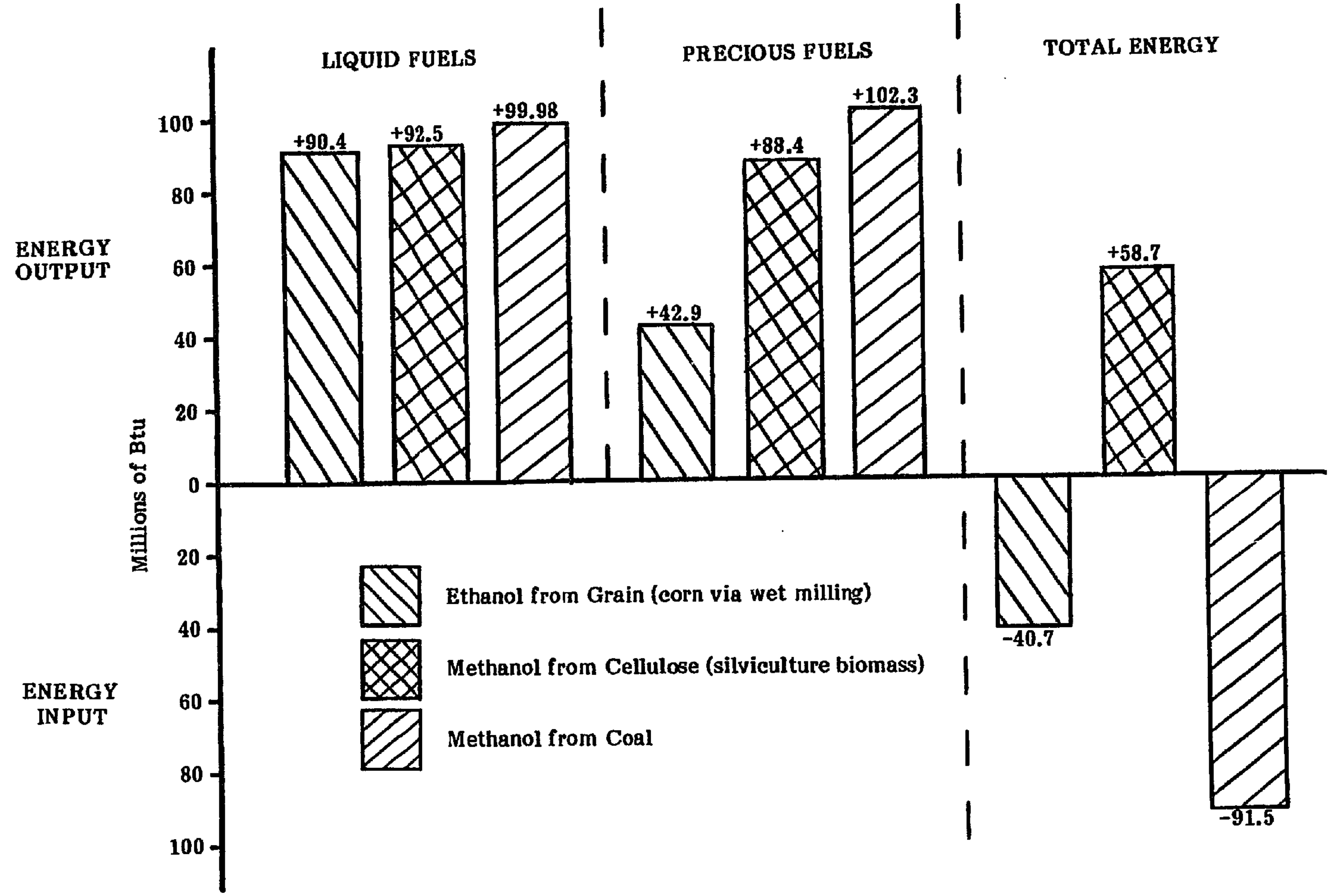
When one looks at the net production of precious fuels (which include natural gas as well as liquid fuels), greater differences arise. When methanol is derived from silvicultural biomass, the energy content of the petroleum products and natural gas

[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 (corn via wet milling)	+1,188 gal	-32.43 gal	-22.7 gal	-3.34 gal	-19.2 gal	-47.07M cu ft	-3.91 tons			
Methanol from Cellulose (silvicultural biomass)	+1,554	-1.43	-51.8	-0.42		-3.98	-1.32			
Methanol from Coal	+1,554	+0.92	-0.17			+2.27	-8.55			
	MM Btu									
Ethanol from Grain (corn via wet milling)	+100	-4.054	-3.18	-0.468	-1.82	-47.54	-83.6	+90.4	+42.9	-40.7
Methanol from Cellulose (silvicultural biomass)	+100	-0.179	-7.25	-0.059		-4.06	-29.7	+92.5	+88.4	+58.7
Methanol from Coal	+100	+0.002	-0.024			+2.32	-10.8	+99.98	+102.3	-91.5

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



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 corn, however, for every 100 Btu of ethanol produced, about 57 Btu of natural gas and petroleum products is consumed, leaving a net increase of only 43 Btu. The ethanol process is thus significantly less effective in increasing the availability of precious fuels than the other alternatives.

The differences between the three feedstock alternatives are even 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 and natural gas) exceeds that of the ethanol produced. (As discussed in Chapter 2, it is expected that work now underway at Iowa State University will reduce somewhat the estimated requirements for fossil fuels, primarily those for natural gas.)

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 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 grain residues are somewhat less favorable. The results for grain 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 lesser extent) grain will result in a reduction in total energy available. The use of corn also results in a fairly significant requirement for natural gas, resulting in net precious-fuel benefits which are appreciably smaller than the liquid-fuel benefits. Accordingly, unless little value is placed on the natural gas consumed, 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 would appear to be a less desirable way of producing alcohol fuel than the prodduction of methanol from either coal or cellulose.

BIBLIOGRAPHY

American Pulpwood Association, "Fuel Survey," Washington, D.C. (1975).

Blankenhorn, P.R., T.W. Bowersox and W.K. Murphy, "Recoverable Energy from the Forests: An Energy Balance Sheet," Journal of the Technical Association of the Pulp and Paper Industry, 61, No. 4 (1978).

Bowersox, T.W. and P.R. Blankenhorn, Energy Sensitivity and Variability Analysis of Populus Hybrid Short-Rotation Plantations in Northeastern United States, Pennsylvania State University School of Forest Resources, prepared for the U.S. Department of Energy, Washington, D.C. (1979).

Buras, N., "Water Constraints on Energy Related Activities," presented at the American Society of Civil Engineering Specialty Conference Proceedings, Conservation and Utilization of Water and Energy Resources (August 1979).

Chambers, R.S., R.A. Herendeen, J.J. Joyce and P.S. Penner, "Gasohol: Does It or Doesn't It Produce Positive Net Energy?," Science, 206, pp. 789-795 (November 16, 1979).

Chia, W.S., et al., Coal-to-Methanol Via New Processes Under Development: An Engineering and Economic Evaluation, C.F. Braun and Co., Report to the Electric Power Research Institute, EPRI AF-1227, Palo Alto, CA (1979).

Chow, T.K., et al., Screening Evaluation: Synthetic Liquid Fuels Manufacture, Ralph M. Parsons Company, Report to the Electric Power Research Institute, EPRI AF-523, Palo Alto, CA (1977).

Colorado Energy Research Institute, Net Energy Analysis: An Energy Balance Study of Fossil Fuel Resources, Golden, CO (April 1976).

Cuff, D.J., and W.J. Young, The United States Energy Atlas, The Free Press, New York, NY (1980).

Dvoskin, D. and E.O. Heady, U.S. Agricultural Production Under Limited Energy Supplies, High Energy Prices, and Expanding Agricultural Exports, Iowa State University, Center for Agricultural and Rural Development, CARD Report 69, Ames, IA (November 1976).

Georgia Forestry Commission, Forest Management Department, Fuel Consumption -- Whole Tree Chipping Operation, Macon, GA (1980).

Howlett, K. and A. Gamache, Silvicultural Biomass Farms -- Forest and Mill Residues as Potential Sources of Biomass, Prepared for U.S. Department of Energy, Washington, D.C. (1977).

Jenkins, D.M., T.A. McClure and T.S. Reddy, Net Energy Analysis of Alcohol Fuels, Battelle Memorial Institute, prepared for the American Petroleum Institute, API Publication 4312, Washington, D.C. (November 1979).

Katzen (Raphael) Associates, Grain Motor Fuel Alcohol Technical and Economic Assessment Study, U.S. Department of Energy Report HCP/J6639-01, Washington, D.C. (June 1979).

Knapton, D., An Investigation of Truck Size and Weight Limits, Technical Supplement, Vol. 3: Truck and Rail Fuel Effects of Truck Size and Weight Limits, U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA (July 1981).

Lindstrom, M.J., S.C. Gupta, C.A. Onstad, W.E. Larson, and R.F. Hoft, "Tillage and Crop Residue Effects on Soil Erosion in the Corn Belt," Journal of Soil and Water Conservation, 34, No. 2 (1979).

Lockeretz, W., Using Crop Residues to Provide Alcohol (May 1980). (To be published by NTIS).

McGeorge, A., Economic Feasibility Study, Fuel Grade Methanol from Coal, Dupont Company, Report to the U.S. Energy Research and Development Administration, Washington, D.C. (1976).

Middleton, P., R. Argue, T. Burrell and G. Hathaway, Canada's Renewable Energy Resources, Middleton Associates, Toronto, Canada (1976).

MITRE Corporation, Silvicultural Biomass Farms, Four Volumes, Technical Report #7347, prepared for the U.S. Energy Research and Development Administration, Washington, D.C. (1977).

Mudge, L.K., S.L. Weber, D.H. Mitchell, L.J. Sealock, Jr., and R.J. Robertus, Investigations on Catalyzed Steam Gasification of Biomass, Five Volumes, Battelle Memorial Institute, Pacific Northwest Laboratory, PNL-3695, Richland, WA (January 1981).

Pettersson, E., "Bio-Energy in Sweden," Bio-Energy Conference Proceedings, Bio-Energy Council, Washington, D.C. (1980).

Pimentel, D., Handbook of Energy Utilization in Agriculture, CRC Press, Boca Raton, FL (1980).

Pimentel, D., et al, "Biomass Energy from Crop and Forest Residues," Science, 212, pp. 1110-1115 (June 5, 1981).

Rogozen, M., et al., "Environmental Impacts of Coal Slurry Pipelines and Unit Trains," in A Technology Assessment of Coal Slurry Pipelines, Vol. II, Part 2, U.S. Congress, Office of Technology Assessment, Washington, D.C. (1978).

Sanderson, F.H., "Benefits and Costs of the U.S. Gasohol Program," Resources, No. 67, pp. 2-13 (July 1981).

Schnittker Associates, Ethanol: Farm and Fuel Issues, National Alcohol Fuels Commission, Washington, D.C. (1980).

Skidmore, E.L., M. Kumal and W.E. Larson, "Crop Residue Management for Wind Erosion Control in the Great Plains," Journal of Soil and Water Conservation, 34, No. 2 (1979).

Solar Energy Research Institute, A Guide to Commercial Scale Ethanol Production and Financing, SERI Publication SP-751-877 US-61 (November 1980).

Southwide Energy Committee, Petroleum Product Consumption and Efficiency in Systems for Energy Wood Harvesting, Jackson, MS (1980).

Tyson, Belzer and Associates, "1979 Energy Use Survey," The Fertilizer Institute, Washington, D.C. (1980).

U.S. Congress, Office of Technology Assessment, Energy from Biological Processes, Three Volumes, Washington, D.C.: GPO (1980).

U.S. Department of Agriculture, Forest Service, The Outlook for Timber in the United States, FRR No. 20, Washington, D.C. (1974).

U.S. Department of Agriculture, Forest Service, North Central Experiment Station, Forest Residues Energy Program, Final Report, St. Paul, MN (1978a).

U.S. Department of Agriculture, 1979 Fertilizer Situation, FS-9 (1978b).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Manufactures, "Concrete, Plaster, and Cut Stone Products," Industry Series, MC77-I-32D, Washington, D.C.: GPO (1980a).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Manufactures, "Fats and Oils," Industry Series, MC77-I-20G, Washington, D.C.: GPO (1980b).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Manufactures, "Fuels and Electric Energy Consumed," Subject Series, MC77-SR-4 (Part 1, Revised), Washington, D.C.: GPO (1980c).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Mineral Industries, "Fuels and Electric Energy Consumed," Industry Series MIC77-SR-5, Washington, D.C.: GPO (1981).

U.S. Department of Energy, The Report of the Alcohol Fuels Policy Review, #DOE-PE-0012, Washington, D.C. (1979b).

U.S. Environmental Protection Agency, Preliminary Environmental Assessment of Biomass Conversion to Synthetic Fuels, EPA-600/7-78-204, Washington, D.C. (1978).

U.S. National Alcohol Fuels Commission, Fuel Alcohol: An Energy Alternative for the 1980's, Washington, D.C., (1981).

Zerbe, J.I., "Impacts of Energy Developments on Utilization of Timber in the Northwest," Proceedings of Northwest Private Forestry Forum, Portland, OR (1978).

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ENERGY INPUTS AND OUTPUTS OF FUEL ALCOHOL PRODUCTION,

APPENDICES A AND B,

ETHANOL FROM GRAIN

Prepared for the

Office of Vehicle and Engine Research and Development
U.S. Department of Energy

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Prepared by

JACK FAUCETT ASSOCIATES, INC.
5454 Wisconsin Avenue, 1100
Chevy Chase, Maryland 20815

and

BATTELLE-COLUMBUS LABORATORIES
505 King Avenue
Columbus, Ohio 43201

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LIST OF EXHIBITS

LIST OF EXHIBITS (Continued)

ABBREVIATIONS

A	acre
B	billion
Btu	British thermal unit
bbl	barrel
C	degrees Centigrade
cu ft	cubic foot
d	distance
F	degrees Fahrenheit
gal	gallon
ha	hectare
HHV	higher heating value
hp	high pressure
hr	hour
kw	kilowatt
kwhr	kilowatthour
lb	pound
lp	low pressure
LPG	liquefied petroleum gas
M	thousand
MM	million
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
Petrochemicals	Btu/gal	125,000
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 wheat	=	60 lb
1 psi	=	6895 pascals
1 square mile	=	640 acres

APPENDIX A

AGRICULTURAL CROP RESOURCES

Carbohydrates for ethanol production, in concept, can be obtained from any crop containing starch or sugar. If a significant volume of ethanol is to be obtained for fuel, however, it must be obtained from sources which are capable of supplying large volumes of carbohydrates at relatively low cost. The agricultural resources with the greatest apparent potential are the grains.

In this appendix, estimates are developed of present energy requirements for producing five grains (corn, grain sorghum, winter wheat, barley and oats) and of energy requirements for increasing production of two of these grains (corn and grain sorghum). The estimates of energy requirements for ethanol production presented in the body of this report are based on the estimate of energy required for increasing corn production developed in Sections A.2 and A.4, below. Brief discussions are also included in this appendix of the overall potential for increasing crop land and for increasing grain production for conversion to ethanol.

A.1 Energy Presently Used in Grain Production

Various authors have estimated the quantity of energy consumed in grain production. Each has approached the question in a slightly different way, reflecting their own views and chosen assumptions. In addition to individual attitudes, the different approaches reflect the various methods of producing grain, in which planting rates, fertilization rates, tillage practices, drying methods, and need for irrigation may vary according to climate, soil, latitude, etc. These variations naturally affect the amount of energy consumed in producing the crop.

The baseline data for estimating the energy presently used in producing grain crops in the United States was taken from Energy and U.S. Agriculture: 1974 Data Base, Volumes 1 and 2 (USDA, September 1976 and April 1977). In this study, an agricultural energy accounting model was developed to accomodate energy data in a systematized framework. The model contains five major dimensions: energy, geography, commodity, time, and function. The energy sector consists of consumption, by crop, of gasoline, diesel fuel, fuel oil, LP gas, natural gas, electricity, and the energy invested in producing and transporting fertilizers and pesticides. The fifty states represent the geographic dimension, with over 70 crop and livestock commodities being detailed in the study. The functional breakdown includes all energy-using operations which occur on the farm for crop or livestock production purposes as well as a share of other energy consumed by farms (e.g., "farm auto" and "farm pickup").

A subsequent USDA study by Torgerson and Cooper (1980) (Energy and U.S. Agriculture: 1974 and 1978) revised the 1974 estimates and also updated them to 1978 levels to reflect changes in fuel usage due to changing technology, energy conservation measures, real petroleum prices, etc. The resulting estimates of national energy consumption in 1978 for all crops are presented in Exhibit A-1. It can be seen that the largest single component of energy use in crop production is for fertilizers, which account for approximately 33 percent of total Btu usage. Nationally, the second largest energy consumer is irrigation, which accounts for approximately 20 percent of total usage. However, usage for irrigation varies substantially between states -- such usage is negligible in some states (e.g., Wisconsin) while it is the dominant energy consumer in other states (e.g., Arizona and New Mexico).

For consistency with data presented throughout this report, the estimates of total energy requirements for each operation shown in Exhibit A-1 were derived from data on fuel requirements shown in the table and the Btu conversion factors used throughout this study (see page v), and so differ somewhat from those provided in the source. In particular, the energy required for electricity has been estimated as 10,400 Btu coal per kwhr of electricity consumed.

Energy identified in Exhibit A-1 as being derived from petroleum products represents about 45 percent of the total. In addition, about 7 percent of the energy invested in fertilizer and pesticides is from petroleum products. (The USDA reports do not provide an explicit breakdown of the sources of energy used for producing and transporting fertilizer and pestisides, though an approximate breakdown will be developed later in this appendix.) Overall, petroleum products provide about 49 percent of total agricultural energy requirements. Natural gas provides about another 33 percent of these energy requirements, primarily in the form of energy "invested" in fertilizer.

A comparison of national energy use for crop production in 1974 and 1978 is shown in Exhibit A-2. During this period, there was a substantial increase in the production of

EXHIBIT A-1: TOTAL ENERGY CONSUMPTION FOR AGRICULTURAL CROPS (1978)

	Petroleum Products								
	Motor Gasoline (M gal)	Distillate (M gal)	Residual Fuel (M gal)	LP Gas (M gal)	Natural Gas (MM cu ft)	Electricity (M kwhr)	Invested Energy (1) (B Btu)	Total Energy of Identified Petroleum Products (2) (B Btu)	Total Energy (3) (B Btu)
Preplant	45,949	1,212,328		17,214				177,105	177,105
Plant	31,178	315,600		2,076				48,278	48,278
Cultivate	20,310	338,682		5,406				50,468	50,468
Harvest	523,994	582,510		88,593				155,467	155,467
Farm Pickup	1,018,323	1,057		22,234				129,551	129,551
Fertilizer Appl.	24,251	70,084		2,567				13,087	13,087
Pesticide Appl.	25,271	92,764		9,535				17,052	17,052
Farm Truck	535,485	5,747						67,740	67,740
Farm Auto	486,159							60,770	60,770
Grain Handling (Vehs.)	15,253							1,907	1,907
Grain Handling (Mach.)						34			354
Crop Drying			62,102	629,396	700	565		69,108	75,698
Irrigation	73,622	136,894		242,512	134,222	19,453		51,407	390,624
Frost Protection	38,866	27,634	218,548	1,458		200		41,648	43,728
Fertilizer							652,532		652,532
Pesticides							68,130		66,130
Electricity						1,696			17,633
Miscellaneous	72,633	37,162						14,282	14,282
TOTAL ALL CROPS	2,911,293	2,829,464	280,651	1,020,990	134,923	21,948	720,662	897,870	1,984,411

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Source: Derived from Torgerson and Cooper (1980).

EXHIBIT A-2: COMPARISON OF ENERGY USED IN U.S. CROP PRODUCTION, 1974 AND 1978

	Total Energy Used				Energy Use Per Acre Planted (1)			
Energy Type	Units	1974	1978	% Increase 1974-78	Units	1974	1978	% Increase 1974-78
Gasoline	MM gal	3,042	2,911	-4.3	gal/A	9.23	8.69	-5.9
Diesel Fuel	MM gal	2,284	2,820	23.5	gal/A	6.93	8.42	21.5
Fuel Oil	MM gal	283	281	-0.7	gal/A	0.86	0.84	-2.3
LP Gas	MM gal	989	1,021	3.2	gal/A	3.00	3.05	1.7
Natural Gas	MM cu ft	132,809	134,922	1.6	cu ft/A	403.1	402.8	-0.1
Electricity	MM kwhr	21,737	21,948	1.0	kwhr/A	66.0	65.5	-0.8
Invested Energy	T Btu	671	721	7.5	M Btu/A	2,036.	2,152.	5.7
Total (2)	T Btu	1,869	1,978	6.2	M Btu/A	5,654.	5,906.	4.4

(1) Planted area of principal crops = 329.5 million acres in 1974; 335.0 million acres in 1978.

(2) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Source: Derived from Torgerson and Cooper, 1980.

most major crops, though not in acreage planted. Energy consumption increased 6.2 percent overall, and energy consumption per acre increased 4.4 percent. Most of the increase occurred in the use of diesel fuel and invested energy. The increase in diesel fuel consumption is partly due to a switch from gasoline to diesel fuel, but overall the increase in consumption of petroleum products accounts for more than half the increase in energy consumption. The increase in invested energy primarily results from increased fertilizer usage.

The 1978 estimates and the revised 1974 data base did not provide the detailed energy consumption for each crop which was included in the original 1974 estimates. Therefore, to estimate usage for specific grain crops grown in each state, it was necessary to disaggregate the 1978 data, which was reported only for all crops in the state. This disaggregation was accomplished in the following manner:

1. The first step was to identify and select the states that were representative of (a) low energy, (b) medium energy, and (c) high energy consumption per bushel of grain produced for the five selected grains: corn, grain sorghum, winter wheat, barley, and oats. Three states were selected for each crop based upon the data presented in the 1974 detailed study. The selection criteria consisted of a combination of the number of acres planted to the specified crop, the energy consumed per acre, and the crop yield per acre.

2. Following the selection of the states, the next step was to determine the amount of energy consumed by type (gasoline, diesel fuel, LP gas, etc.) and by commodity for each state during 1974. The information was obtained from Volume 1 of Energy and U.S. Agriculture: 1974 Data Base.

3. The same data source was then used to determine the ratio between total energy consumed by type for all crops grown in the state, and the amount of energy consumed by type that could be attributed to the specific crops under investigation in that state. For example, the data revealed that in Ohio approximately 40 percent of the total gasoline consumed for crop production in 1974 was utilized for corn; 38 percent of the diesel fuel; 76 percent of the LP gas; etc.

4. Volume 2 of the 1974 data base was then used to obtain an overview, on an aggregated national basis, of the amounts and type of energy used, by operation, for each of the crops being investigated in 1974. The operations were preplant, plant, cultivate, harvest, irrigate, etc.

5. The information from the preceding steps was then analyzed, tabulated, and the results used to provide a reasonable indication of the energy consumed, by type and operation, for each of the selected states and crops during 1974.

6. In order to update and project the 1974 data to 1978, the aforementioned USDA study providing 1978 data (Torgerson and Cooper, 1980) and USDA's annual summary of crop production for 1978 were reviewed. Using the information from these sources, the total amount of energy consumed in 1978 was estimated by type and crop for each of the selected states. The estimates were based upon the ratios developed in Step 3 above, augmented by best judgment decisions which included such factors as trends in energy conservation, shifts in fuel utilization, more efficient equipment, and changes in the number of acres planted to a crop.

7. Finally, the totals developed during the previous step were prorated by operation (preplant, plant, cultivate, etc.). These estimates were based upon data from the 1974 tables. Using all of the previously developed information as a basis, tables were created containing estimated 1978 consumption of energy for each of the selected crops and states.

The estimates of total agricultural energy used per acre by crop for selected states are summarized in Exhibit A-3 and presented in more detail in Exhibits A-4 through A-18. The crops, in sequence, are: corn, grain sorghum, winter wheat, barley, and oats. The first state indicated for each crop is a state having low energy utilization per bushel, followed by medium and high energy utilization states.

In Exhibit A-3, the estimates of total agricultural energy used are compared to the energy content of the ethanol produced. To offset the possible effects of unusually high crop yields for 1978, the latter estimates are based on three-year average yields for 1977-1979. It can be seen that, for each crop, substantial differences exist in

EXHIBIT A-3: AGRICULTURAL ENERGY REQUIREMENTS AND ETHANOL YIELDS FOR SELECTED GRAINS AND SELECTED STATES

Grain and State	Total Agric. Energy Used per Acre (1) (M Btu/A)	1977-79 Avg. Grain Yield per Acre (2) (bu/A)	Total Agric. Energy Used per Bushel (Btu/bu)	Density of Grain (lbs/bu)	Ethanol Yield per Bushel (3) (gal/bu)	Ethanol Yield per Acre (gal/A)	Energy Content of Ethanol Yield per Acre (M Btu/A)
Corn				56	2.62		
Wisconsin	6,211	102	60,900			267	22,500
Nebraska	10,848	109	99,500			286	24,100
Kansas	17,088	105	162,700			275	23,200
Grain Sorghum				56	2.70		
Missouri	5,230	78	67,100			211	17,800
Texas	9,419	50	188,400			135	11,400
Arizona	38,688	76	509,100			205	17,300
Winter Wheat				60	2.74		
Nebraska	2,396	34	70,500			93	7,800
Kansas	2,659	32	83,100			88	7,400
Texas	4,430	25	177,200			69	5,800
Barley				48	2.05		
Ohio	1,726	50	34,500			103	8,700
Idaho	6,028	55	109,600			115	9,500
New Mexico	17,939	55	326,200			113	9,500
Oats				32	1.05		
Iowa	1,130	61	18,500			64	5,400
South Dakota	1,368	50	27,400			53	4,500
Texas	2,387	38	62,800			40	3,400

Sources:

(1) Derived from USDA (1976, 1977) and Torgerson and Cooper (1980) (see text).
(2) USDA, 1978c, 1979b and 1980b.
(3) USDA, 1980a.

EXHIBIT A-4: ENERGY CONSUMPTION OF CORN IN WISCONSIN (1978)
(a low-energy state)

Operations	Motor Gasoline (Petroleum Products)	Distillate (Petroleum Products)	Residual Fuel (Petroleum Products)	LP Gas (Petroleum Products)	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	130 M gal	8,695 M gal		1 M gal				1,234 B Btu	1,234 B Btu
Plant	816	2,550		2				459	459
Cultivate	56	2,319		1				332	332
Harvest	11,732	4,734		43				2,133	2,133
Farm Pickup	6,157	6						770	770
Fertilizer Appl.	484	305		2				103	103
Pesticide Appl.	68	1,150						170	170
Farm Truck	5,917	2						740	749
Farm Auto	4,047							506	506
Grain Handling	89							11	11
Crop Drying				10,510		5 MM kwhr		998	1,050
Irrigation	86	388				24		65	315
Fertilizer							9,505 B Btu		9,505
Pesticides							678		678
Electricity						18			187
Miscellaneous	89	55		10,562		—	—	19	19
	29,673 M gal	20,203 M gal		10,562 M gal		47 MM kwhr	10,183 B Btu	7,540 B Btu	18,212 B Btu
CONSUMPTION PER ACRE	10.1 gal	6.9 gal		3.6 gal		16 kwhr	3,473 M Btu	2,571 M Btu	6,211 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.

(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).

(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-5: ENERGY CONSUMPTION OF CORN IN NEBRASKA (1976)
(a medium-energy state)

Operations	Petroleum Products								
	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	269 M gal	13,704 M gal		183 M gal				1,970 B Btu	1,970 B Btu
Plant	34	3,108		12				441	441
Cultivate	47	5,664		24				801	801
Harvest	8,404	22,279		5,225				4,666	4,666
Farm Pickup	23,347							2,918	2,918
Fertilizer Appl.	121	1,006		73				163	163
Pesticide Appl.	67	1,111		24				166	166
Farm Truck	16,606							2,076	2,076
Farm Auto	14,297							1,787	1,787
Grain Handling	626							78	78
Crop Drying				30,145	2 MM cu ft	21 MM kwhr		2,864	3,084
Irrigation	2,519	22,649		86,100	2,538	682		11,664	21,346
Fertilizer							31,118 B Btu		31,118
Pesticides							1,542		1,542
Electricity						61			634
Miscellaneous	1,003	335						172	172
	67,342 M gal	69,847 M gal		121,800 M gal	2,540 MM cu ft	765 MM kwhr	32,660 B Btu	29,766 B Btu	72,962 B Btu
CONSUMPTION PER ACRE	10.0 gal	10.3 gal		18.0 gal	376 cu ft	113 kwhr	4,830 M Btu	4,426 M Btu	10,848 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-6: ENERGY CONSUMPTION OF CORN IN KANSAS (1978)
(a high-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	13 M gal	7,617 M gal		65 M gal				1,075 B Btu	1,075 B Btu
Plant		2,112						296	296
Cultivate		1,267						177	177
Harvest	2,050	3,450		3,147				1,038	1,038
Farm Pickup	5,421							678	678
Fertilizer Appl.	9	338		22				51	51
Pesticide Appl.	10	212		15				32	32
Farm Truck	2,326							291	291
Farm Auto	2,845							356	356
Grain Handling	75							9	9
Crop Drying				7,636		8 MM kwhr		725	809
Irrigation	230	1,125		8,925	9,540 MM cu ft	42		1,034	11,202
Fertilizer							8,923 B Btu		8,923
Pesticides							372		372
Electricity						31			322
Miscellaneous									
	12,984 M gal	16,121 M gal		19,810 M gal	9,540 MM cu ft	81 MM kwhr	9,295 B Btu	5,762 B Btu	25,631 B Btu
CONSUMPTION PER ACRE	8.6 gal	10.7 gal		13.2 gal	6,360 cu ft	54 kwhr	6,196 M Btu	3,841 M Btu	17,088 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-7: ENERGY CONSUMPTION OF GRAIN SORGHUM IN MISSOURI (1978)
(a low-energy state)

Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
	Petroleum Products								
Preplant	184 M gal	2,500 M gal		45 M gal				377 B Btu	377 B Btu
Plant	85	870		20				134	134
Cultivate	90	990		28				153	153
Harvest	1,940	1,135		290				429	429
Farm Pickup	3,080							385	385
Fertilizer Appl.	145	20		29				24	24
Pesticide Appl.	96	70		30				25	25
Farm Truck	1,430							179	179
Farm Auto	1,200							150	150
Grain Handling	48							6	6
Crop Drying				1,890	5 MM cu ft	2 MM kwhr		180	205
Irrigation	70	90		180				38	38
Fertilizer							2,516 B Btu		2,516
Pesticides							140		140
Electricity						10			104
Miscellaneous									
	8,368 M gal	5,675 M gal		2,512 M gal	5 MM cu ft	12 MM kwhr	2,656 B Btu	2,080 B Btu	4,865 B Btu
CONSUMPTION PER ACRE	9.0 gal	6.1 gal		2.7 gal	5.4 cu ft	12.9 kwhr	2,859 M Btu	2,236 M Btu	5,230 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-8: ENERGY CONSUMPTION OF GRAIN SORGHUM IN TEXAS (1978)
(a medium-energy state)

Operations	Petroleum Products: Motor Gasoline	Petroleum Products: Distillate	Petroleum Products: Residual Fuel	Petroleum Products: LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	986 M gal	35,230 M gal		980 M gal				5,149 B Btu	5,149 B Btu
Plant	23	10,177		54				1,433	1,433
Cultivate	47	8,232		81				1,166	1,166
Harvest	6,198	5,970		3,640				1,956	1,956
Farm Pickup	14,810							1,851	1,851
Fertilizer Appl.	42	238		51				43	43
Pesticide Appl.	1,174	215		566				231	231
Farm Truck	7,922	32						995	995
Farm Auto	8,265							1,033	1,033
Grain Handling	22							3	3
Crop Drying				565	29 MM cu ft	2 MM kwhr		54	104
Irrigation	2,019	2,467		10,800	18,791	420		1,824	25,159
Fertilizer							12,078 B Btu		12,078
Pesticides							2,082		2,082
Electricity						39			406
Miscellaneous									
	41,490 M gal	62,561 M gal		16,737 M gal	18,820 MM cu ft	461 MM kwhr	14,160 B Btu	15,538 B Btu	53,689 B Btu
CONSUMPTION PER ACRE	7.2 gal	10.9 gal		2.9 gal	3,301 cu ft	81 kwhr	2,484 M Btu	2,726 M Btu	9,419 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-9: ENERGY CONSUMPTION OF GRAIN SORGHUM IN ARIZONA (1978)
(a high-energy state)

Operations	Petroleum Products: Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant		395 M gal						55 B Btu	55 B Btu
Plant		60						8	8
Cultivate		136						19	19
Harvest	22 M gal	93		13 M gal				17	17
Farm Pickup	153							19	19
Fertilizer Appl.		44						6	6
Pesticide Appl.		6						1	1
Farm Truck	54							7	7
Farm Auto	50							6	6
Grain Handling				4				*	*
Crop Drying									
Irrigation					1,017 MM cu ft	140 MM kwhr			2,493
Fertilizer							395 B Btu		395
Pesticides							36		36
Electricity						3			31
Miscellaneous		11						2	2
	279 M gal	734 M gal		17 M gal	1,017 MM cu ft	143 MM kwhr	431 B Btu	140 B Btu	3,095 B Btu
CONSUMPTION PER ACRE	3.4 gal	9.1 gal		0.2 gal	12,712 cu ft	1,787 kwhr	5,387 M Btu	1,750 M Btu	38,688 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-10: ENERGY CONSUMPTION OF WINTER WHEAT IN NEBRASKA (1978)
(a low-energy state)

Operations	Petroleum Products: Motor Gasoline	Petroleum Products: Distillate	Petroleum Products: Residual Fuel	Petroleum Products: LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	93 M gal	3,370 M gal		2 M gal				484 B Btu	484 B Btu
Plant	24	2,000						283	283
Cultivate									
Harvest	2,936	5,160		63				1,095	1,095
Farm Pickup	7,150							894	894
Fertilizer Appl.	47	240						39	39
Pesticide Appl.	22	258						39	39
Farm Truck	4,802							600	600
Farm Auto	3,980							498	498
Grain Handling	211							26	26
Crop Drying				368				35	35
Irrigation	870	5,575		1,042	10 MM cu ft	15 MM kwhr		988	1,154
Fertilizer							1,691 B Btu		1,691
Pesticides							89		89
Electricity						2			21
Miscellaneous									
	20,135 M gal	16,603 M gal		1,475 M gal	10 MM cu ft	17 MM kwhr	1,780 B Btu	4,981 B Btu	6,948 B Btu
CONSUMPTION PER ACRE	6.9 gal	5.7 gal		0.5 gal	3.4 cu ft	5.8 kwhr	614 M Btu	1,718 M Btu	2,396 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-11: ENERGY CONSUMPTION OF WINTER WHEAT IN KANSAS (1978)
(a medium-energy state)

Operations	Petroleum Products: Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	80 M gal	33,970 M gal		17 M gal				4,767 B Btu	4,767 B Btu
Plant		9,679						1,355	1,355
Cultivate									
Harvest	8,760	12,800		1,392				3,019	3,019
Farm Pickup	26,500							3,313	3,313
Fertilizer Appl.	40	1,124						162	162
Pesticide Appl.	45	685						102	102
Farm Truck	15,170							1,896	1,896
Farm Auto	13,224							1,653	1,653
Grain Handling	324							41	41
Crop Drying				2,004		6 MM kwhr		190	253
Irrigation	983	3,560		2,484	1,222 MM cu ft	33		357	2,447
Fertilizer							10,407 B Btu		10,407
Pesticides							375		375
Electricity						25			260
Miscellaneous									
	65,126 M gal	61,818 M gal		5,897 M gal	1,222 MM cu ft	64 MM kwhr	10,782 B Btu	17,355 B Btu	30,050 B Btu
CONSUMPTION PER ACRE	5.7 gal	5.4 gal		0.5 gal	108 cu ft	5.6 kwhr	954 M Btu	1,536 M Btu	2,659 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-12: ENERGY CONSUMPTION OF WINTER WHEAT IN TEXAS (1978)
(a high-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	626 M gal	23,618 M gal		539 M gal				3,436 B Btu	3,436 B Btu
Plant	15	5,950		12				836	836
Cultivate									
Harvest	4,350	2,909		3,204				1,255	1,255
Farm Pickup	10,703			1,028				1,436	1,436
Fertilizer Appl.	24	102		12				18	18
Pesticide Appl.	550	95		578				137	137
Farm Truck	5,665	17						711	711
Farm Auto	5,247							656	656
Grain Handling	14							2	2
Crop Drying				210	8 MM cu ft	1 MM kwhr		20	39
Irrigation	1,283	1,198		4,397	8,375	197		746	11,337
Fertilizer							4,251 B Btu		4,251
Pesticides							727		727
Electricity						19			198
Miscellaneous	1,338	341						215	215
	29,815 M gal	34,230 M gal		9,980 M gal	8,383 MM cu ft	217 MM kwhr	4,978 B Btu	9,468 B Btu	25,254 B Btu
CONSUMPTION PER ACRE	5.2 gal	6.0 gal		1.7 gal	1,470 cu ft	38 kwhr	873 M Btu	1,661 M Btu	4,430 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-13: ENERGY CONSUMPTION OF BARLEY IN OHIO (1978)
(a low-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of identified Petroleum Products (2)	Total Energy (3)
Preplant	1 M gal	9 M gal						1 B Btu	1 B Btu
Plant	1	6						1	1
Cultivate									
Harvest	9	8						2	2
Farm Pickup	20							3	3
Fertilizer Appl.									
Pesticide Appl.									
Farm Truck	9							1	1
Farm Auto	10							1	1
Grain Handling									
Crop Drying				14 M gal				1	1
Irrigation									
Fertilizer							8 B Btu		8
Pesticides							1		1
Electricity									
Miscellaneous									
	50 M gal	23 M gal		14 M gal			9 B Btu	10 B Btu	19 B Btu
CONSUMPTION PER ACRE	4.5 gal	2.1 gal		1.2 gal				908 M Btu	1,726 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-14: ENERGY CONSUMPTION OF BARLEY IN IDAHO (1978)
(a medium-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	38 M gal	1,295 M gal		12 M gal				187 B Btu	187 B Btu
Plant	12	510		2				73	73
Cultivate				2				*	*
Harvest	667	1,258		100				269	269
Farm Pickup	826							103	103
Fertilizer Appl.	16	207		2				31	31
Pesticide Appl.		213						30	30
Farm Truck	444	140						75	75
Farm Auto	429							54	54
Grain Handling	15							2	2
Crop Drying									
Irrigation	513	77		471	53 MM cu ft	327 MM kwhr		120	3,575
Fertilizer							1,185 B Btu		1,185
Pesticides							91		91
Electricity						5			52
Miscellaneous									
	2,960 M gal	3,700 M gal		589 M gal	53 MM cu ft	332 MM kwhr	1,276 B Btu	944 B Btu	5,727 B Btu
CONSUMPTION PER ACRE	3.1 gal	3.9 gal		0.6 gal	56 cu ft	349 kwhr	1,343 M Btu	994 M Btu	6,028 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-15: ENERGY CONSUMPTION OF BARLEY IN NEW MEXICO (1978)
(a high-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	1 M gal	112 M gal						16 B Btu	16 B Btu
Plant		19						3	3
Cultivate									
Harvest	15	49		6 M gal				9	9
Farm Pickup	50							6	6
Fertilizer Appl.		3						*	*
Pesticide Appl.		2						*	*
Farm Truck	19							2	2
Farm Auto	46							6	6
Grain Handling									
Crop Drying									
Irrigation	134	217		370	325 MM cu ft	9 MM kwhr		82	507
Fertilizer							38 B Btu		38
Pesticides							5		5
Electricity									
Miscellaneous									
	265 M gal	402 M gal		376 M gal	325 MM cu ft	9 MM kwhr	43 B Btu	124 B Btu	592 B Btu
CONSUMPTION PER ACRE	8.0 gal	12.2 gal		11.3 gal	9,848 cu ft	273 kwhr	1,303 M Btu	3,757 M Btu	17,939 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-16: ENERGY CONSUMPTION OF OATS IN IOWA (1978)
(a low-energy state)

Operations	Motor Gasoline (Petroleum Products)	Distillate (Petroleum Products)	Residual Fuel (Petroleum Products)	LP Gas (Petroleum Products)	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	93 M gal	1,304 M gal		29 M gal				197 B Btu	197 B Btu
Plant	98	345		118				72	72
Cultivate									
Harvest	1,490	644		587				332	332
Farm Pickup	3,015							377	377
Fertilizer Appl.	88			12				12	12
Pesticide Appl.	57			23				9	9
Farm Truck	1,433							179	179
Farm Auto	802							100	100
Grain Handling	51							6	6
Crop Drying				348		1 MM kwhr		33	43
Irrigation	7	7		58		1		7	18
Fertilizer							439 B Btu		439
Pesticides							5		5
Electricity						7			73
Miscellaneous	29							4	4
	7,165 M gal	2,300 M gal		1,175 M gal		9 MM kwhr	444 B Btu	1,328 B Btu	1,866 B Btu
CONSUMPTION PER ACRE	4.3 gal	1.4 gal		0.7 gal		5.5 kwhr	269 M Btu	804 M Btu	1,130 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-17: ENERGY CONSUMPTION OF OATS IN SOUTH DAKOTA (1978)
(a medium-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	60 M gal	2,338 M gal		5 M gal				325 B Btu	325 B Btu
Plant	102	849						132	132
Cultivate									
Harvest	1,343	2,890		73				579	579
Farm Pickup	4,878			1				610	610
Fertilizer Appl.	36	67						14	14
Pesticide Appl.	34	53		53				12	12
Farm Truck	2,099							262	262
Farm Auto	1,819							227	227
Grain Handling	239							30	30
Crop Drying				201				19	19
Irrigation	238	171		143		5 MM kwhr		67	119
Fertilizer							999 B Btu		999
Pesticides							11		11
Electricity						10			104
Miscellaneous	505							63	63
	11,353 M gal	6,368 M gal		423 M gal		15 MM kwhr	1,010 B Btu	2,350 B Btu	3,516 B Btu
CONSUMPTION PER ACRE	4.2 gal	2.5 gal		0.2 gal		5.8 kwhr	393 M Btu	914 M Btu	1,368 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-18: ENERGY CONSUMPTION OF OATS IN TEXAS (1978)
(a high-energy state)

Operations	Motor Gasoline (Petroleum Products)	Distillate (Petroleum Products)	Residual Fuel (Petroleum Products)	LP Gas (Petroleum Products)	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	138 M gal	5,899 M gal		55 M gal				848 B Btu	848 B Btu
Plant	4	1,874		2				263	263
Cultivate									
Harvest	899	1,227		247				308	308
Farm Pickup	2,419							302	302
Fertilizer Appl.	6	30		1				5	5
Pesticide Appl.	165	26		30				27	27
Farm Truck	1,285							161	161
Farm Auto	1,995							249	249
Grain Handling	3							*	*
Crop Drying									
Irrigation	241	589		167		7 MM kwhr		128	201
Fertilizer							1,845 B Btu		1,845
Pesticides							37		37
Electricity						1			10
Miscellaneous		300						42	42
	7,155 M gal	9,945 M gal		502 M gal		8 MM kwhr	1,882 B Btu	2,333 B Btu	4,298 B Btu
CONSUMPTION PER ACRE	3.9 gal	5.5 gal		0.3 gal		4.4 kwhr	1,045 M Btu	1,296 M Btu	2,387 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

agricultural energy requirements, primarily as a result of irrigation requirements. In Arizona (grain sorghum) and New Mexico (barley) the energy required to grow the grains exceeds the energy content of the ethanol produced (without considering either the additional energy required for processing and distillation or the energy value of by-products). The energy of the ethanol, however, is in liquid form, while most of the energy consumed for production in these two states is in the form of natural gas or electricity.

The detailed breakdown shown in Exhibits A-4 through A-18 shows energy consumption by type of fuel and by type of operation. For energy invested in fertilizers, the levels required for production assumed in the USDA studies are:

Nitrogen	31,100 Btu per pound
Phosphate (P_2O_5)	5,560 Btu per pound
Potash (K_2O)	4,280 Btu per pound

Ethanol yield per acre is highest for corn and second highest for grain sorghum. The yields for the other three crops are appreciably lower because of lower grain yields per acre (particularly in the case of wheat) and (except for wheat) low weights per bushel. For commercial ethanol production, corn would appear to be the most attractive grain in areas which are suitable for corn production, and grain sorghum would appear to be most attractive in most other grain-growing areas.

A.2 Energy Requirements for Increased Grain Production

Estimates of the energy requirements of increased grain production can be derived from an interregional linear programming model developed at Iowa State University (ISU). This model is designed to determine the response of U.S. agricultural production to various energy supply and price conditions and to changes in demand for major export crops.

The model has recently been adapted to determine the effects of the use of corn or grain sorghum for ethanol production. The results of this adaptation were not available in time to be incorporated into the present report. Instead, the estimates of increased energy production developed here are based on data from an earlier application of the ISU model by Dvoskin and Heady (1976). We plan to update the present report with more current ISU results in the near future. Preliminary information indicates that the updated estimates of energy requirements are likely to be lower than those developed here.

The results of two of the runs of the Dvoskin and Heady version of the ISU model are summarized in Exhibit A-19. The first of the runs, labeled "normal production" in the exhibit, represents the projected long-run adjustment of agricultural production if real energy prices double relative to their 1974 level and exports remain "normal". The second run, labeled "expanded production", represents the corresponding results if grain exports increase substantially. The level of exports for these two scenarios were obtained by Dvoskin and Heady from OBERS Series E' projections for 1985 (U.S. Water Resources Council, 1975). The OBERS projections show a total of 2.9 billion bushels of corn grain, grain sorghum, wheat, barley, oats and soybeans exported under normal conditions and 4.5 billion bushels under high export conditions.

As can be seen from Exhibit A-19, increasing exports was estimated to stimulate an increase in production of these six crops by 23 percent, from 12.2 billion bushels to 15.0 billion bushels. The increase is accomplished primarily as a result of increasing land use, increasing fertilization, and decreasing use of corn silage. Land used for the crops analyzed increases by six percent. Of 20.7 million acres of new cropland, 37 percent requires irrigation. Irrigated cropland increases by 43 percent, and energy required for irrigation by 50 percent.

An even greater increase in energy consumption is due to increased fertilization required to achieve higher crop yields per acre. Nitrogen used in fertilizers increases by 62 percent, and both nitrogen used in commercially produced fertilizers and energy consumption for obtaining such nitrogen more than triple. (Noncommercial sources of fertilizer are manure and legume crops such as alfalfa and soybeans.)

A relatively large (31 percent) increase also occurs in energy consumed for transportation. This increase is due, in part, to the substantial increase in exports assumed in the high production scenario. Using increased production locally for ethanol conversion would be likely to produce a smaller increase in energy used for transport.

Overall, energy consumption increases by about 35 percent, with increased use of nitrogen fertilizers accounting for about two-thirds of the increase.

EXHIBIT A-19: EFFECT OF CROP PRODUCTION LEVEL ON ENERGY USE

	Normal Production Level		High Production Level		Percent Increase
'roduction					
Corn grain	5,800	MM bu	6,599	MM bu	13.8%
Grain sorghum	1,044	"	1,375	"	31.7
Wheat	1,709	"	2,307	"	35.0
Barley	1,046	"	1,124	"	7.5
Oats	953	"	1,014	"	6.4
Soybeans	1,613	"	2,566	"	59.1
Subtotal	12,165	MM bu	14,985	MM bu	23.2%
Hay	343	MM tons	374	MM tons	9.0%
Silage	126	"	74	"	-41.3
Sugar beets	34	"	34	"	--
Cotton	11	MM bales	11	MM bales	--
,and Used					
Unirrigated	329,026	M A	341,988	M A	3.9%
Irrigated	17,905	"	25,615	"	43.1
Total	346,931	M A	367,603	M A	6.0%
litrogen					
Total used	6,520	M tons	10,554	M tons	61.9%
From commercial sources	1,829	"	5,573	"	204.7
:nergy Sources					
Diesel fuel	5,407	MM gal	5,964	MM gal	10.3%
LPG	625	"	740	"	18.4
Natural gas	152,966	MM cu ft	400,458	MM cu ft	161.8
Electricity	8,915	MM kwhr	13,025	MM kwhr	46.1
Total (1)	1,065.2	T Btu	1,449.3	T Btu	36.1%
:nergy Uses (2)					
Fuel for machinery	680.7	T Btu	732.0	T Btu	7.5%
Pesticides	29.8	"	31.3	"	5.0
Nitrogen fertilizers (3)	124.5	"	379.2	"	204.6
Nonnitrogen fertilizers	28.0	"	31.8	"	13.6
Crop drying	51.3	"	56.8	"	10.7
Irrigation	118.4	"	178.0	"	50.3
Transportation	67.9	"	89.0	"	31.1
Total (2)	1,100.6	T Btu	1,482.1	T Btu	34.7%

1) Based on Btu conversion factors stated at front of this volume.
2) As derived by Dvoskin and Heady model incorporating conversion factors of 140,000 Btu/gal of diesel fuel, 94,500 Btu/gal of LPG, 1,067.5 Btu/cu ft of natural gas, and 10,560 Btu of fuel used per kwhr of electricity consumed.
3) Commercial nitrogen fertilizers only.

;ource: Dvoskin and Heady, 1976.

Additional data on land and energy use for corn and grain sorghum are shown in Exhibit A-20. (Corresponding data for barley and oats were not derivable from the source.) For both corn and grain sorghum, expanded production is accomplished by increasing both acreage and yields. Largely because of the increased fertilization required for the higher yields, for both crops, energy use on both a per acre and a per bushel basis is higher in the expanded production scenario than in the normal production scenario. In the case of corn, national average energy consumed in the normal production scenario is 65,500 Btu per bushel produced - only slightly higher than the USDA estimate of 60,900 Btu/bu for Wisconsin, a state with low energy requirements per bushel (see Exhibit A-18). However, average energy consumed rises to 79,100 Btu/bu in the expanded production scenario.

Of more significance for the present study is the energy required to expand production, which is shown in the last column of Exhibit A-20. To increase corn production by 799 million bushels, 142 trillion Btu are required - 178,000 Btu per bushel of increased production.

This estimate is appreciably larger than the estimate of 114,000 Btu per bushel of production used in a study published by the U.S. Congress Office of Technology Assessment (OTA) (1979). The latter figure, however, presumes that the entire increase in corn production will be obtained from use of marginal land. The role of increasing fertilization of existing land is not considered in the OTA analysis.

If significant amounts of grain are grown for ethanol production, the energy for the increased production may be presumed to be similar to those derived from a comparison of the two scenarios presented in Exhibits A-19 and A-20. Some differences, however, will exist. In particular:

1. the increases in production that will occur will be concentrated in the grains that are most likely to be used for ethanol: corn and grain sorghum; rather than distributed among several grains and soybeans as had been assumed in the simulation from which these results were derived[1]; and

[1] Indeed, since high protein feeds, such as DDG and gluten meal, are by-products of the ethanol conversion process, some reduction in demand for soybeans may result.

EXHIBIT A-20: EFFECT OF PRODUCTION LEVEL ON ENERGY USE FOR CORN AND GRAIN SORGHUM

	Area Harvested (M A)	Total Production (MM bu)	Yield (bu/A)	Energy Used (T Btu)	Energy Use per Acre (M Btu/A)	Energy Use per Bushel (Btu/bu)	Energy Use per Incremental Bushel (Btu/bu)
Corn Grain							
Normal production	64,017	5,800	90.6	380.0	5,936	65,500	
Expanded production	65,539	6,599	100.7	522.2	7,968	79,100	
Increment	1,522	799		142.2			178,000
Grain Sorghum							
Normal production	20,388	1,044	51.2	85.9	4,214	82,300	
Expanded production	22,844	1,375	60.2	145.3	6,360	105,700	
Increment	2,456	331		59.4			179,500

Source: Derived from Dvoskin and Heady, 1976.

2. since the increased production will be used locally (for ethanol) rather than exported (as assumed in the simulation), fuel requirements for transportation will be somewhat lower than indicated in the exhibits[1].

An appropriate correction for the second effect can be readily accomplished by assuming that transport fuel requirements per ton of production in the high-production scenario will be approximately the same as in the normal-production scenario. This correction will be incorporated in the tables presented in the concluding section of this appendix.

The effect of the different distribution of the production increases among the various crops, however, is more complex and would require a new simulation run in order to be incorporated fully into the results.[2] It may be observed, however, that regardless of which crops will be produced in greater quantity, the increased production will be accomplished through a combination of increased acreage planted, disproportionate increases in the use of irrigated land, and increased fertilization of all land used. Since corn and grain sorghum require relatively less land and more fertilizer than soybeans or the other grains, if only production of corn and grain sorghum are to be increased, less land and more fertilizer will be required than shown in Exhibit A-19[3]. Since fertilizer is the most significant energy-using element in the analysis, concentrating the increase in production on corn and grain sorghum is unlikely to result in total energy requirements per bushel of increased production which are any lower than those shown in Exhibit A-20.

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[1]The Dvoskin and Heady analyses include all transport of grain, including transport to export terminals. By contrast, the USDA studies on which the results of the previous subsection are based include only transport in farm trucks to local elevators.

[2]Such simulations are presently being performed at Iowa State University of the Dvoskin and Heady model. The results of these simulations, however, will not be available in time to be incorporated into the present study.

[3]This trade-off between land and fertilizer becomes even more pronounced when one considers the effect of the feed by-products which, in part, will result in reduced demand for soybeans (see Section B.3 of Appendix B). Reduced production of soybeans will permit changes in the normal corn/soybean/alfalfa rotational pattern. These changes, in turn, will permit increased corn production without any further increase in land used, but (because of reduced planting of a crop which is host to nitrogen-fixing bacteria) with a substantial increase in commercial-fertilizer requirements. The energy credit for the feed by-products is estimated in Section B.3.

For the purposes of the present study, it will be assumed that, (except for the transportation correction discussed previously) total energy requirements for increased corn and grain sorghum production are those given in Exhibit A-20[1]. The distribution of total energy requirements over energy sources will be derived (in Section A.4, below) primarily from data in Exhibit A-19; accordingly it is likely that natural gas requirements will be underestimated while other energy requirements will be overestimated.

A.3 The Potential for Obtaining Ethanol From Increased Grain Production

Production of grain and soybeans under the two scenarios shown in Exhibits A-19 and A-20, above, differ by about 2.8 billion bushels. If 2.8 billion bushels of corn and grain sorghum were to be converted to ethanol, about 7.5 billion gallons of ethanol would be produced. This estimate does not represent the potential production of ethanol from grain under the "expanded production" scenario. Since conversion of grain to ethanol produces feed by-products, ethanol production will result in some reduction in the demand for grain and soybeans for feed. Data presented in Appendix B (Section B.3) indicate that the feed by-products resulting from conversion of a bushel of corn to ethanol are capable of replacing about 0.31 bushels of corn and soybeans. Taking this by-product into account, it can be determined that an overall production increase of 2.8 billion bushels could provide enough corn to yield about 10.5 billion gallons of ethanol. The energy content of this volume of ethanol, 890 trillion Btu, represents about 4.5 percent of the 20.3 quadrillion Btu of liquid transportation fuels consumed annually.

The 2.8 million bushel increase in grain and soybean production used in the "expanded production" scenario does not represent the limit of the nation's ability to increase grain production. In this scenario, cropland used increases by 20.7 million acres over usage under "normal production." However, if the entire increase is production consisted of corn (or corn and grain sorghum), as observed previously, appreciably less new cropland would be required. A greater increase in production can be achieved either by increase new cropland above this reduced level and/or by increasing fertilization.

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[1]As previously observed, it is expected that lower estimates of these energy requirements will be obtained from new analyses presently being performed by ISU.

The increase in cropland need not be limited by the 20.7 million-acre increase shown in Exhibit A-19. The U.S. Department of Agriculture Soil Conservation Service (SCS) conducted a land inventory survey in 1977. On the basis of this survey, SCS estimated the potential for converting pasture and rangeland, forests, and other land into cropland given commodity price relationships and development and production costs that prevailed in 1976. These estimates are presented in Exhibit A-21. Potential cropland was classified four ways, depending on the ease of conversion and environmental restrictions:

- Land rated as having "zero potential" has virtually no cropping potential and consists primarily of land with very poor soil characteristics for crop production.

- Land classified as "low potential" indicates that conversion is unlikely in the foreseeable future because of existing development problems.

- "Medium potential" land includes areas that could be converted in the long-run with adequate care to minimize any environmental degradation. This category includes land that is poorly drained, subject to wind or water erosion, or that could produce only lower-yielding crops.

- Land with "high potential" for conversion is described as having low or no conversion costs and situated in a locality where similar land had undergone conversion in prior years. These lands would be expected to convert to cropland over the next 10-15 years if economic conditions were to continue about as they were in 1976.

It can be seen from Exhibit A-21 that 36.2 million acres have been identified as having high potential for conversion to cropland, and another 90.8 million acres as having medium potential. Such an increase in cropland could permit grain production to increase by several times the 2.8 million bushel figure used above. The total potential for deriving ethanol from grain may thus be several times the 10.5 billion gallon estimate presented above.

It should be observed, however, that the Dvoskin and Heady analysis indicates that even the moderate increase in production levels studied under the "expanded production"

EXHIBIT A-21: POTENTIAL FOR CROPLAND OF 1977 PASTURE, FOREST, AND OTHER LAND, BY STATE

State	High Potential	Medium Potential	Conversion Unlikely	Zero Potential	Total
	1000 Acres				
Alabama	1,064	3,083	7,428	12,923	24,498
Arizona	155	216	3,625	34,327	38,323
Arkansas	637	2,634	8,243	7,868	20,402
California	800	2,009	5,029	30,591	38,429
Colorado	365	2,369	7,570	19,856	30,160
Connecticut	23	89	306	1,420	1,838
Delaware	28	87	185	194	495
Florida	1,117	2,334	11,022	8,754	23,427
Georgia	2,120	3,670	8,484	11,502	25,776
Hawaii	39	62	543	2,674	3,318
Idaho	525	916	1,727	9,318	12,486
Illinois	582	1,385	2,414	3,228	7,609
Indiana	804	1,008	2,068	2,909	6,789
Iowa	700	1,488	2,144	2,771	7,103
Kansas	1,893	3,673	5,593	9,622	20,781
Kentucky	1,302	1,801	2,936	11,011	17,050
Louisiana	1,129	1,864	6,272	10,683	19,948
Maine	29	286	9,093	8,621	18,029
Maryland	145	382	1,116	1,466	3,109
Massachusetts	33	144	764	2,353	3,294
Michigan	561	1,409	5,750	11,790	19,510
Minnesota	1,108	2,845	8,516	9,219	21,688
Mississippi	1,306	2,491	4,934	10,319	19,050
Missouri	2,226	4,395	7,154	10,881	24,656
Montana	1,339	4,360	11,264	32,306	49,269
Nebraska	1,083	2,871	7,260	14,916	26,130
Nevada	50	238	1,669	7,212	9,169
New Hampshire	27	217	1,998	2,080	4,320
New Jersey	116	310	701	1,482	2,609
New Mexico	474	822	8,638	37,985	47,919
New York	358	1,352	4,569	14,258	20,537
North Carolina	1,398	3,661	5,932	9,001	19,992
North Dakota	984	1,898	4,581	6,568	14,031
Ohio	528	1,394	3,490	4,360	9,772
Oklahoma	1,683	4,119	7,564	15,483	28,849
Oregon	325	862	3,042	18,549	22,778
Pennsylvania	270	1,160	4,328	12,536	18,294
Rhode Island	5	18	54	294	371
South Carolina	629	1,635	6,128	4,307	12,699
South Dakota	1,090	4,403	7,602	13,328	26,423
Tennessee	1,428	2,351	3,626	10,428	17,833
Texas	3,534	10,727	46,960	65,280	126,501
Utah	73	447	1,166	12,347	14,033
Vermont	45	168	931	3,470	4,614
Virginia	546	1,605	5,732	9,489	17,732
Washington	506	1,049	3,247	15,669	20,471
West Virginia	64	388	1,302	10,493	12,247
Wisconsin	618	2,041	7,582	8,583	18,824
Wyoming	253	1,688	5,064	22,038	29,043
Caribbean	78	150	77	1,140	1,445
Total	36,215	90,774	268,422	587,902	983,313

Source: USDA, 1979a.

scenario would result in a doubling of production costs. Thus it appears that potential production levels of ethanol from grain will be relatively modest unless significant advances are made in increasing grain yields inexpensively or appreciable declines occur in exports or domestic consumption of grain (beyond those resulting from the substitution of ethanol by-products for grain).

A.4 Energy Requirements for Grain Production - Summary

In the preceding sections, estimates of energy presently used in grain production and of energy required to increase grain production were presented. These estimates were obtained from separate sources and were presented in somewhat different formats. In this section, modified versions of some of these estimates are presented in a third format which provides greater information about the fuels used and which is consistent with that used elsewhere in this report. These estimates are presented only for the two grains most likely to be used for ethanol production: corn and grain sorghum.

In Exhibit A-22, estimates are presented of current energy usage for producing and transporting corn and grain sorghum in states with low energy use per bushel of grain. These estimates have been derived by modifying those previously presented (in Exhibits A-3 and A-6) in four ways:

1. As is the case throughout this study, it has been assumed that all electricity will be derived from coal.

2. Estimates of the actual fuels used for producing and transporting fertilizer have been developed from information presented in Exhibit A-23. (The estimates shown for soybeans are used in Appendix B.)

3. Estimates of the fuels used for producing and transporting pesticides have been developed from information in the Handbook of Energy Utilization in Agriculture (Pimentel, 1980).

4. Additional gasoline use for transporting grain to the ethanol conversion plant has been incorporated into the estimates. The original sources (USDA, 1976 and 1977; Torgerson and Cooper, 1980) included fuel consumed by farm trucks in transporting grain to the elevator. However,

EXHIBIT A-22: PRESENT ENERGY REQUIREMENTS FOR PRODUCING CORN AND GRAIN SORGHUM FOR ETHANOL IN STATES WITH LOW ENERGY USE PER BUSHEL OF GRAIN

	Petroleum Products							
	Gasoline (gal/bu)	Distillate (gal/bu)	Residual Fuel (gal/bu)	LPG (gal/bu)	Natural Gas (cu ft/bu)	Coal* (lb/bu)	Total Petroleum Products (Btu/bu)	Total Energy (Btu/bu)
Corn								
Direct Agricultural Energy Use (1)	0.0990	0.0676		0.0353		0.145	25,200	26,800
Fertilizer (2)	**	0.0150	0.0010		23.20	0.522	2,200	31,800
Pesticides (3)		0.0068			0.84	0.040	1,000	2,300
Additional Transport (4)	0.0097						1,200	1,200
TOTAL — CORN	0.1087	0.0894	0.0010	0.0353	24.04	0.707	29,600	62,100
Grain Sorghum								
Direct Agricultural Energy Use (5)	0.1154	0.0782		0.0346	0.07	0.153	28,700	30,500
Fertilizer (2)	**	0.0157	0.0011		25.48	0.562	2,400	34,700
Pesticides (3)		0.0059			0.72	0.034	800	1,900
Additional Transport (4)	0.0097						1,200	1,200
TOTAL — GRAIN SORGHUM	0.1251	0.0997	0.0011	0.0346	26.27	0.749	33,100	68,300

*Based on use of 11,250 Btu/lb coal.

**Less than 0.00005 gal/bu.

Sources:

(1) Derived from Exhibits A-3 and A-4.
(2) Total energy distributed among fuel sources on basis of data in Exhibit A-23.
(3) Total energy distributed among fuel sources on basis of data in Pimentel, 1980; all oil feedstocks used treated as distillate.
(4) See text.
(5) Derived from Exhibit A-3 and A-7.

EXHIBIT A-23: ENERGY CONSUMPTION FOR PRODUCING AND TRANSPORTING FERTILIZER

	Petroleum Products						
	Gasoline (gal/lb)	Distillate (gal/lb)	Residual Fuel (gal/lb)	Natural Gas (cu ft/lb)	Coal* (lb/lb)	Total Petroleum Products (Btu/lb)	Total Energy (Btu/lb)
Nitrogen (1)		0.00418	0.00041	19.67	0.247	647	23,490
Phosphate (1)	0.000006	0.00774	0.00091	1.23	0.228	1,221	5,040
Potash (1)		0.00643	0.000004	0.57	0.124	901	2,880
Used for Corn in Wisconsin (2)							
43% Nitrogen		0.00180	0.000176	8.46	0.106	278	10,102
23% Phosphate	0.000001	0.00178	0.000209	0.28	0.053	281	1,156
34% Potash		0.00219	0.000001	0.19	0.042	307	976
	0.000001	0.00577	0.000386	8.93	0.201	866	12,234
Used for Grain Sorghum in Missouri (2)							
45% Nitrogen		0.00188	0.000185	8.85	0.112	291	10,571
25% Phosphate	0.000002	0.00193	0.000228	0.31	0.057	305	1,260
30% Potash		0.00193	0.000001	0.17	0.037	270	864
	0.000002	0.00574	0.000414	9.33	0.206	866	12,695
Used for Soybeans (2)							
11% Nitrogen		0.00046	0.000045	2.16	0.027	71	2,575
40% Phosphate	0.000002	0.00310	0.000364	0.49	0.091	488	2,017
49% Potash		0.00315	0.000002	0.28	0.061	442	1,412
	0.000002	0.00671	0.000411	2.93	0.179	1,001	6,004

*Based on use of 11,250 Btu/lb coal.

Sources:

(1) Derived from Pimentel, 1980, and Tyson, Belzer and Associates, 1980.
(2) Derived from above data and from fertilizer distribution from USDA, 1978b.

typical hauls to a commercial plant, which might be capable of producing 30 million gallons of ethanol per year, would generally be longer than those from the farm to the elevator. It is assumed in Exhibit A-22 that the average haul to an ethanol plant is ten miles longer than to an elevator. It is also assumed that grain is hauled in farm trucks averaging 5.4 miles per gallon of gasoline empty and 4.3 miles per gallon with a twelve-ton load (derived from Knapton, 1981).

The resulting estimates of energy consumption, shown in Exhibit A-22, represent average consumption, by fuel type, for producing and transporting corn and grain sorghum in states where production of these grains is relatively energy efficient. In the case of corn, the estimates were derived for Wisconsin, but they are reasonably appropriate for Indiana, Illinois, Iowa, Michigan, Minnesota, and Ohio[1]. As can be determined from Exhibit A-3, due primarily to irrigation requirements, energy consumption per bushel of corn is about 60 percent higher than this in Nebraska and 165 percent higher in Kansas. In the case of grain sorghum, the estimates were derived for Missouri, but they are reasonably representative of many areas where irrigation is not required.

It has been observed that the estimates shown in Exhibit A-22 represent current energy requirements for growing corn and grain sorghum in areas where energy requirements for growing these grains are low. If significant amounts of ethanol are to be produced from grain without reducing either exports or present meat and grain consumption, then total grain production must be increased. As observed in Section A.3, energy requirements for increased grain production are substantially higher than they are for present production.

Estimates of energy and fuel requirements for increasing corn and grain sorghum production are presented in Exhibit A-24. These estimates have been derived from the estimates of energy requirements for increased production from Dvoskin and Heady (1976) presented previously in Exhibit A-20. The derivation involved the distribution of the energy requirements among fuel sources (using data in Exhibit A-19) and one further

[1]Data from Pimentel (1980) indicates that, among these states, corn production is most energy efficient in Illinois, where overall energy requirements are 20 percent below those in Wisconsin; and least energy efficient in Minnesota, where overall energy requirements are about 17 percent higher than in Wisconsin.

EXHIBIT A-24: ENERGY REQUIREMENTS PER BUSHEL FOR INCREASING CORN AND GRAIN SORGHUM PRODUCTION

	Petroleum Products							
	Motor Gasoline (gal/bu)	Distillate (gal/bu)	Residual Fuel (gal/bu)	LPG (gal/bu)	Natural Gas (cu ft/bu)	Coal* (lb/bu)	Total Petroleum Products (Btu/bu)	Total Energy (Btu/bu)
CORN	0.1296	0.1066	0.0012	0.0534	114.83	1.753	36,400	173,300
GRAIN SORGHUM	0.1335	0.1064	0.0012	0.0541	116.45	1.788	36,900	175,800

*Based on use of 11,250 Btu/lb coal.

Source: Derived from Exhibits A-19 and A-20 (see text).

adjustment in estimated requirements for transportation fuel. The derivation involved the following steps.

1. For each of the four energy sources shown in Exhibit A-19 (diesel fuel, LPG, natural gas and electricity), the increase in consumption between the two scenarios was obtained.

2. The increase in diesel fuel consumption was then reduced from 557 million gallons to 482 million gallons. The reduced value corresponds to the increase in diesel fuel consumption which would have been shown if transport fuel requirements per ton of production (exclusive of silage) had been held constant. (The data in Exhibit A-19 correspond to a 13 percent increase in such fuel consumption per ton. As has previously been observed, this increase is largely due to the assumption that in the original analysis the increased production would be transported to ports for export. This modification is designed to produce estimates of transport fuel requirements which are more appropriate for grain used for ethanol production.)

3. For each of the four energy sources, the increase in consumption obtained above was divided by the total estimated increase in energy consumption (388.1 trillion Btu, from Exhibit A-19) and multiplied by the estimated energy required per bushel of increased production for each of the two crops (from Exhibit A-20). (Because of the adjustment made in Step 2, the resulting estimates of total energy required per bushel are reduced from those shown in Exhibit A-20; for corn, the reduction is from 177,000 Btu/bu to 173,300 Btu/bu.)

4. For consistency with other study results, the resulting estimate of electricity requirements was restated in terms of coal required for generating electricity.

5. Since Dvoskin and Heady did not provide separate estimates of gasoline and residual fuel requirements, the resulting estimates of diesel fuel requirements were assumed to represent gasoline and residual fuel requirements as well as distillate requirements. These estimates were

therefore distributed among gasoline, distillate and residual fuel on the basis of relative energy content of the volumes of these fuels presently used for grain production (obtained from Exhibit A-22).

The resulting estimates of energy and fuel requirements per bushel for increasing corn and grain sorghum production are shown in Exhibit A-24[1]. Overall energy requirements are about two and one-half times as large as those shown in Exhibit A-22 for present production. Most of the difference is in natural gas requirements, which are more than four times as high as those in the earlier exhibit. As has been previously observed, this difference is primarily due to higher fertilization to increase grain yields. The estimates of coal requirements for increased production are more than twice as large as those for present production, and the estimates of LPG are more than fifty percent higher. These differences are primarily the result of the increased use of irrigated land when production is increased.

Natural gas accounts for about 68 percent of the energy required to increase grain production[2]. Petroleum products account for about 21 percent, and coal (primarily for generating electricity) for about 11 percent.

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[1]As previously observed, it is expected that lower estimates of these energy requirements will be obtained from new analyses presently being performed by ISU.

[2]Genetic engineers have recently begun to investigate the possibility of developing nitrogen-fixing bacteria that would be associated with corn plants. If such bacteria are developed, a significant reduction in the natural gas requirements for growing corn will result.

APPENDIX B

ETHANOL FROM GRAIN

Processes for the conversion of grain to ethanol are generally divided into those that use dry milling and those that use wet milling. In this appendix, both dry milling and wet milling technologies are considered. There are many variations possible upon these two major approaches, and the sensitivity to some of these variations is explored. Nevertheless, consideration of every ethanol technology currently being offered is beyond the scope of the study.

In general, the wet milling processes consume slightly less energy per gallon ethanol than dry milling processes. The wet milling processes also require higher investment and produce more co-products along with the ethanol.

B.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. In wet milling the grain is separated into the starch, gluten, and germ during the milling operation.

B.1.1 Process Selection

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. The distillation system is similar to a double effect evaporator in energy consumption. Overall, the design selected consists of proven technologies and is considered to be very energy efficient.

B.1.2. Process Decription

Exhibit B-1 is a simplified block flow diagram of the process steps in the manufacture of ethanol from corn based on a typical, currently available dry milling technology. Corn is received in bulk by rail or truck and is stored in a grain elevator or storage bins. Grain is removed from storage and transferred to a surge hopper, which feeds the process plant as required.

Grain from the surge hopper is first cleaned to remove sand, tramp metal, and light dusty (cob & chaff) materials. It is then ground to the required size in a hammer mill. The ground corn is then conveyed to a precooker where it is mixed with water and recycled stillage at about 150 F. The corn slurry is then cooked for about 1.5 minutes at 350 F in a continuous cooker.

The cooked mash is then cooled to about 145 F in a series of flash coolers which operate at progressively lower temperatures. After cooling, an enzyme (amylase) is added to convert starch to sugar. This enzymatic hydrolysis is known as saccharification.

In the design considered for this analysis, amylase is produced in the ethanol facility. This is economic only for large scale plants. Most smaller-scale ethanol plants would purchase commercial enzymes. Manufacturers of commercial enzymes contacted during this study were unable to provide data on the energy consumed in enzyme

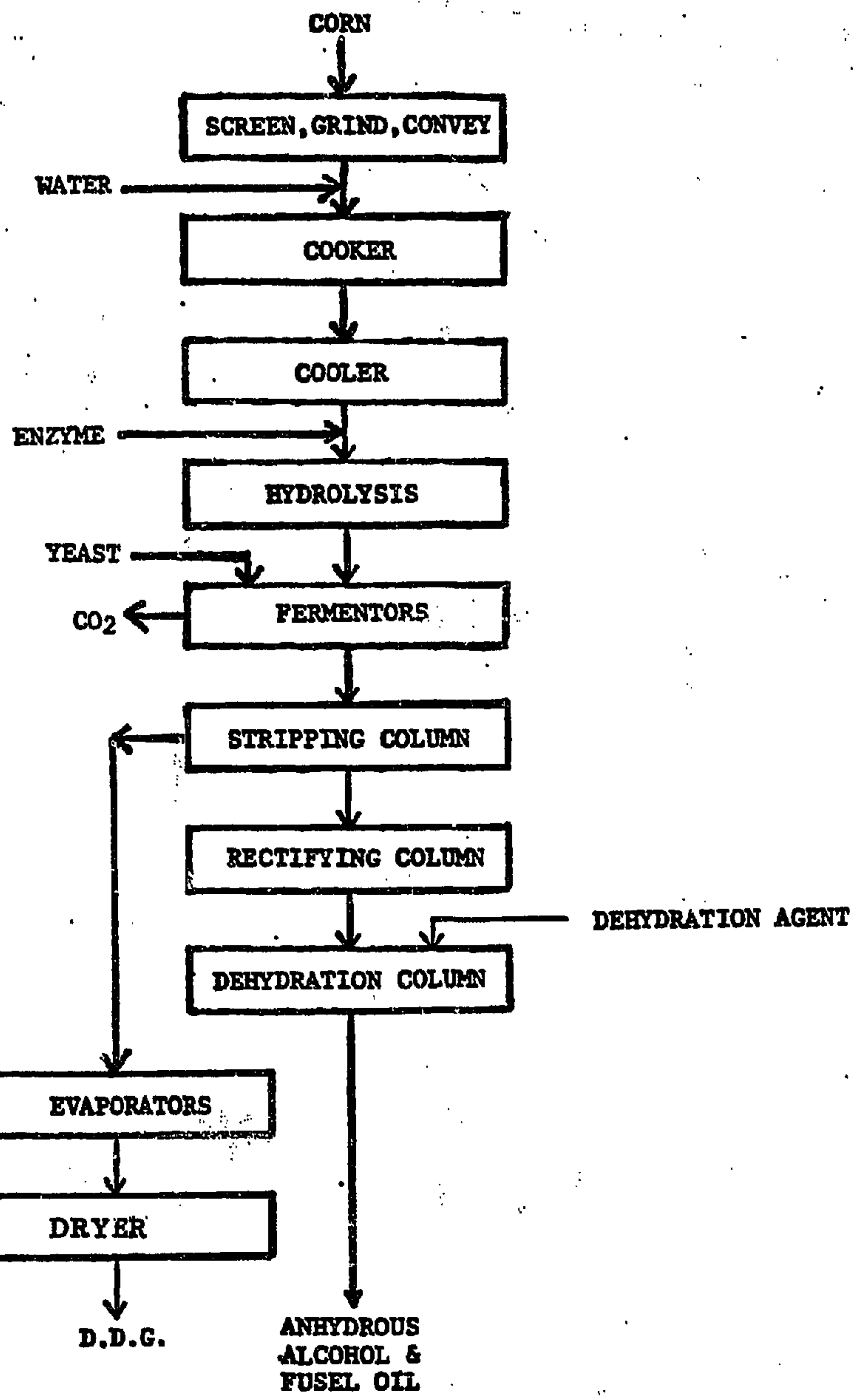

EXHIBIT B.1: ETHANOL FROM CORN: BLOCK FLOW DIAGRAM FOR DRY MILLING PROCESS

manufacture except to indicate that energy cost was small compared to other costs. By including enzyme manufacture in the ethanol plant, we have attempted to account for energy invested in enzymes. As can be seen in the data presented in the next section, the energy invested in enzyme manufacture is indeed small, though the energy required to produce commercial enzymes may be slightly different.

Following the saccharification, the mash is cooled to about 80 F. Chemical nutrients and yeast are added and the mixture is allowed to ferment in batch fermenters. Continuous fermentation has been proposed and has been demonstrated on pilot scale and in some commercial operations. Changing from batch to continuous operation might improve the economics but would have little effect on the energy requirements. During the fermentation, the mixture is kept between 77 and 90 F. Carbon dioxide released by the fermentation is exhausted to the atmosphere through a condenser, which removes entrained liquid and returns it to the fermenter.

Upon completion of the fermentation, the alcohol is purified and recovered in a series of distillation columns. The bottom stream from the first column, which is known as the stripping column, contains water and suspended and dissolved organic materials. The solids are removed by centrifugation. The liquid is then concentrated by evaporation, recombined with solids, dried, and sold as distillers dark grains (DDG). The evaporation and drying of DDG is one of the major energy consumers. Nevertheless, recovery of this byproduct is essential to the overall economics of ethanol manufacture from grain. DDG contains most of the protein originally present in the grain. It is sold as animal feed.

The evaporation system selected for this analysis is a vapor recompression evaporator with the compressor driven by a steam turbine. Exhaust low pressure steam from the turbine is used to provide process heat. This cogeneration of shaft power and process heat improves the energy efficiency of the overall process but requires additional capital investment. Other typical designs use multiple-effect evaporators, which also reduce steam consumption. The choice of evaporation system in a plant depends on a detailed economic comparison. Such a comparison is beyond the scope of this study.

The concentrated stillage from the evaporator is dried in a steam tube dryer using steam from the boiler. This makes it possible to use coal as the only fuel. Gas-fired dryers, which directly contact hot combustion gases with the wet distillers grains, are used in many designs. One published design (Katzen, 1978) uses combustion gas from a coal-fired boiler for drying. Since the DDG will be used as animal feed, we are concerned that the components of fly ash from coal combustion may contaminate the DDG. To our knowledge, no DDG dried directly with coal combustion gases is sold in the United States.

The overhead from the stripping column contains a mixture of water, ethanol, and impurities. These include both low boiling impurities (ester-aldehyde) and high boiling impurities (fusel oil). This mixture is sent to the rectifying column. In many designs, the stripping and rectifying columns are combined into a single column. In the design used for this study, it was assumed that the ester-aldehyde would be recovered and recycled to boilers for use as fuel within the plant. The quantity of ester-aldehyde produced depends upon the way in which the fermentation is operated. It is generally small.

In the rectifying column, ethanol is concentrated to about 95 percent by volume and sent to a dehydration column where it is further concentrated to anhydrous (99.5 percent) ethanol by azeotropic distillation. In azeotropic distillation, a dehydrating agent (such as benzene, ethyl ether, or other hydrocarbon) is added to remove the water. Fusel oil, which is removed from an intermediate plate of the rectification column and separated by decantation, is combined with the product alcohol. This fusel oil contributes slightly to the energy content of the liquid fuel. There are small dehydrant losses during the azeotropic distillation. This small dehydrant loss was not included in the net energy balance because it is believed that most of the loss goes with the liquid fuel product.

The distillation columns are cascaded so that the overhead condenser from the rectifying column is the reboiler for the dehydration column. This concept, which is similar to double effect evaporation, has been used in the petroleum refining and petrochemical industries for years. It is fairly new to ethanol production, however. Among others, Katzen and Vulcan-Cincinnati use this concept in their proprietary ethanol purification designs. This concept offers significant energy savings over the conventional ethanol purification. Both Katzen and Vulcan-Cincinnati distillation systems require about 21.5 pounds steam per gallon anhydrous ethanol.

Process steam at 600 psig, 600 F is generated in a pulverized coal-fired boiler equipped with cyclones and a double alkali flue-gas desulfurization system. The cleaned flue gas is reheated by 50 F with steam before discharge to the stack. The overall boiler efficiency was taken as 86 percent, which is typical of pulverized coal boilers with rated capacities above 200,000 pounds per hour (McKee, 1979). This would be suitable only for large ethanol plants. The impact of plant size is discussed under the section on sensitivity analysis.

B.1.3 Process Chemistry

The chemistry of grain fermentation is complex, but the basic concepts and overall reactions are simple. The major reactions reduce starch to sugar, which is then fermented to ethanol.

Starch is first gelatinized by cooking. The starch is then hydrolyzed to sugars by enzymes.

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow n\, C_6H_{12}O_6$$

The hydrolysis or saccharification usually occurs in two steps. First the molecular weight of starch is reduced by random cleavage catalyzed by amylase, followed by conversion of the resulting malto-dextrins to glucose by the enzyme amyloglucosidase.

The sugar is then converted to ethanol and carbon dioxide by yeast in the fermentation step. The overall reation is

$$C_6H_{12}O_6 \rightarrow 2\, C_2H_5OH + 2\, CO_2$$

There are many intermediate reactions. There are also some side reactions in which various impurities, especially higher alcohols, are formed. The impurities are made from amino acids, sugars and other carbohydrates.

B.1.4 Energy and Materials Consumption

The material and energy consumption for the dry-milling ethanol process are:

Corn	0.388	bushels/gal ethanol
Coal	0.0022	ton/gal or 0.566 Btu/Btu
Electricity	1.31	kwhr/gal or 0.162 Btu/Btu
Makeup Azeotroping Agent	0.00018	gal/gal
Lime	0.00012	ton/gal

The coal used 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 3.3 percent on a moisture free basis. Estimated energy consumption for producing lime is shown in Exhibit B-2.

In addition, about 0.02 (formerly 0.05) gallons gasoline are consumed per gallon ethanol as a denaturant (27 CFR 212.13, FR 8417, Jan 81). 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, the makeup azeotroping agent (benzene or other hydrocarbon) may be 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 as can be seen from the data above.

The energy in the various steps of the dry milling process is summarized in Exhibit B-3. Most of the energy is consumed as process steam generated by burning coal. The most energy intensive steps are the distillation of ethanol and the concentration and drying of DDG (distillers dark grains).

The output from the process is fuel grade ethanol and DDG. The DDG by-product amounts to 7.08 lb per gallon ethanol (Katzen, 1979). Small amounts of higher alcohols (fuel oils) produced in the fermentation are blended with the ethanol and included in the ethanol volume.

Sludge from water treatment and a small amount of light ends from the distillation are burned as boiler fuel, thereby reducing the coal consumption slightly.

EXHIBIT B-2: ENERGY REQUIRED FOR PRODUCTION OF LIME

Assumptions	Petroleum Products: Motor Gasoline (gal/ton)	Petroleum Products: Distillate (gal/ton)	Petroleum Products: Residual Fuel (gal/ton)	Natural Gas (M cu ft/ton)	Coal and Other (tons coal/ton)	Total Petroleum Products (M Btu/ton)	Total Energy (M Btu/ton)
Total production in 1977: 1419 M tons (1)							
Total energy consumption in 1977 (2):							
—Electricity: 830.5 MM Kwhr					0.271		6,100
—Direct fuels: Distillate: 308.6 M bbl; Residual: 1202.7 M bbl; Natural Gas: 22.5 B cf; Coal: 2033.4 M tons		9.13	35.6	15.8	1.972 (4)	6,600	67,100 (3)
TOTAL ENERGY CONSUMED		9.13	35.6	15.8	2.243	6,600	73,200 (5)

Sources:

(1) Estimated from DOC, 1980a.

(2) DOC, 1980c.

(3) Estimated directly from source data. Includes coke, other purchased fuels, and undistributed fuels.

(4) Equals number of 22.5 MM Btu/ton coal necessary to produce all energy not accounted for by petroleum and natural gas consumption. Actual consumption of coal is 1.433 ton per ton of lime produced.

(5) Does not include energy for mining limestone (about 300,000 Btu per ton of lime produced) or for transporting limestone (about 1 to 2 million Btu per ton of lime, depending on transport mode and distance).

EXHIBIT B-3: ETHANOL FROM CORN: ENERGY BALANCE FOR DRY MILLING PROCESS

Process Section	Electricity[c] Btu per Btu Ethanol	Coal Btu per Btu Ethanol	By Product[b] Consumed Btu per Btu Ethanol	By Product[b] Produced Btu per Btu Ethanol	Hp Steam[a] Consumed Btu per Btu Ethanol	Hp Steam[a] Produced Btu per Btu Ethanol	Mp Steam[a] Consumed Btu per Btu Ethanol	Mp Steam[a] Produced Btu per Btu Ethanol	Lp Steam[a] Consumed Btu per Btu Ethanol	Lp Steam[a] Produced Btu per Btu Ethanol
Corn Receiving Storage & Milling	-0.010									
Mash Cooking & Saccharification	-0.004						0.136			0.039
Enzyme Production	-0.033						0.003			
Fermentation	-0.006									
Distillation	-0.003						0.262		0.039	
DDG Recovery	-0.044				0.479		0.158	0.444		
Storage & Denaturing	-0.001									
Steam Generation	-0.003	-0.566	0.009			0.479		0.139		
FGD Reheat							0.009			
Utilities & Misc.	-0.058			0.009			0.015			
TOTAL	-0.162	-0.566	0		0		0		0	

(a) Hp steam is at 600 psig, 600 F; Mp steam at 150 psig, saturated; Lp steam at 15 psig. Energy of steam taken as enthalpy above water at OC (32F).
(b) By-product represents sludge from water treatment plus a small amount of ester aldehyde from distillation.
(c) Electricity at fuel needed to generate (10,400 Btu/Kwh).

The moist sludge from flue gas desulfurization is about 0.85 lb per gallon ethanol. It has been assumed that this sludge would be landfilled adjacent to the plant with negligible energy penalty for loading, transporting, and dumping.

B.2 Wet Milling

The following is an analysis of the energy balance for production of ethanol from a corn wet milling process. The selected process scheme includes production of byproduct corn oil, gluten feed, and gluten meal.

It should be noted that each wet miller incorporates proprietary variations in the process. The information given here is considered typical of current commercial practice. 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.

B.2.1 Process Description

The wet milling of corn is more complex than dry milling. 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. A simplified overall process flow diagram is shown in Exhibit B-4. The following is a brief description of each major process step.

Shelled corn is received in bulk by either truck or rail. It is then stored and cleaned to remove all large and small pieces of cob, chaff, sand, and other undersirable foreign material. This section would use electric power to operate conveyors, screens, and aspirators.

The cleaned corn is then steeped for about 30-50 hours at a temperature of about 125 F. Wash water from the starch separation is sent countercurrently to the steeping operation via fiber separation and degermination. The SO_2 concentration of about 0.1-0.2 percent is maintained in the wash water before it enters the steeping operation.

After steeping, the corn is degerminated in an attrition (cracking) mill. The mill gap is adjusted to maximize recovery of germ and minimize breakage. Any oil liberated in the

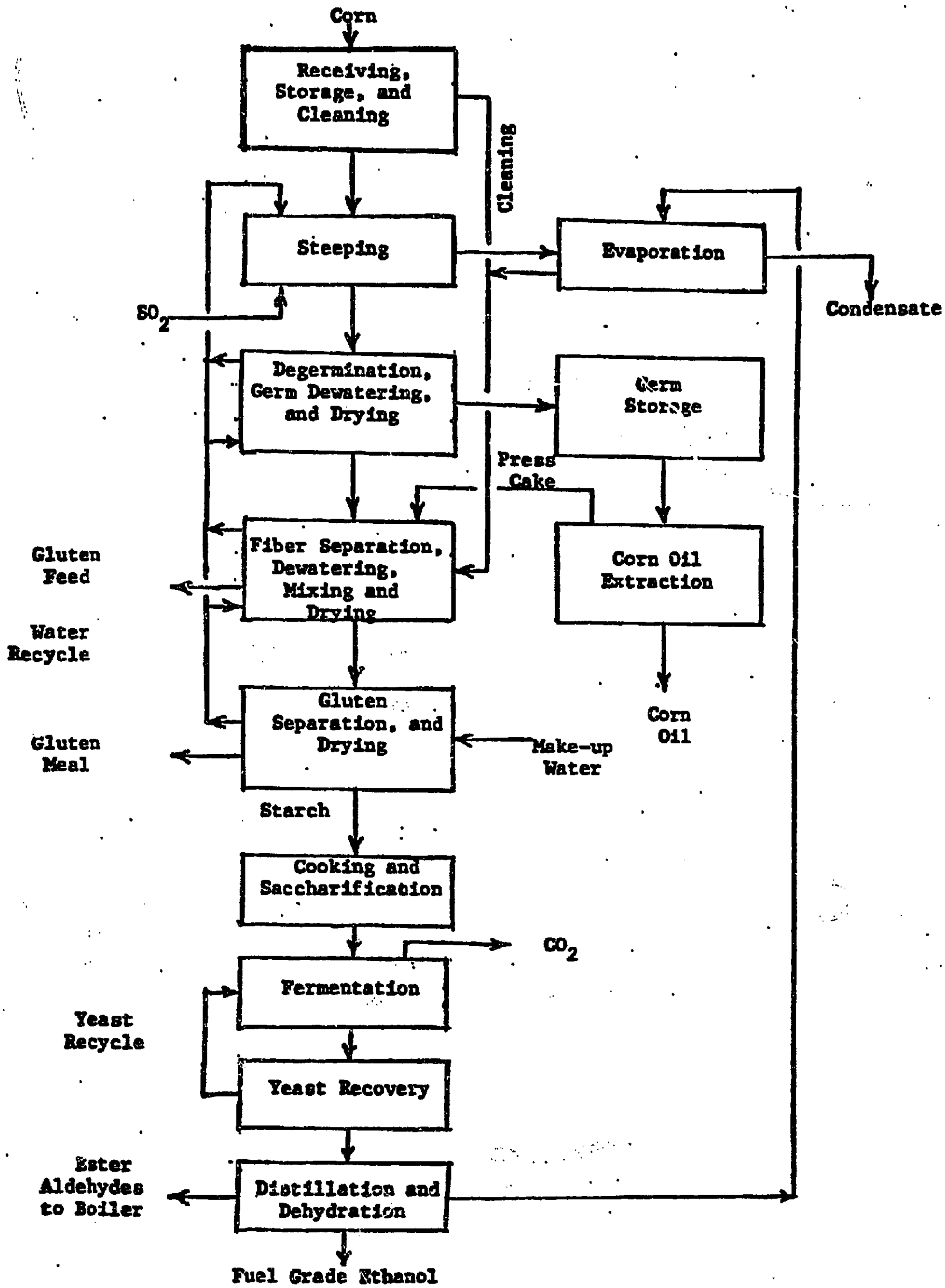

EXHIBIT B-4: ETHANOL FROM CORN: BLOCK FLOW DIAGRAM FOR WET MILLING PROCESS step is lost through absorption on the gluten. The germ is first separated from starch, gluten, and fiber in a hydrocyclone and then washed, dewatered by pressing, and dried. The electrical power used for the dewatering machinery and the steam requirements of the dryer are the major energy consumers of the section.

Corn oil may be extracted from the germ by either mechanical or solvent processes. For this study, the extraction of oil by a mechanical process is assumed. The energy consumed in a mechanical process is mostly electric power, with very little steam use. The press cake from the corn oil extraction process is blended into the corn gluten feed. A significant portion of corn oil in the germ is lost through the press cake. The corn oil recovery can be increased by adding a solvent extraction step. Solvent extraction increases capital requirements and energy consumption. The additional energy requirements are mostly steam plus solvent losses. Recovery of additional corn oil by solvent extraction is usually economic only for very large corn oil plants.

The fiber is separated from the starch and gluten by screening. The fiber is then washed and dewatered by means of screens and presses, respectively. Recycled water is used to wash the fiber, thereby minimizing water consumption and overall evaporaton requirements. The wet fiber is mixed with corn cleanings, the bottoms from the exhaust steep-liquor/stillage evaporator, and press cake, and then dried to form the gluten feed product. The dewatering and drying operations are the major energy consumers.

Starch and gluten are separated in a centrifuge. The separated gluten is dewatered by filtration and dried to form the product known as gluten meal. The centrifugation and drying operations are the major consumers of energy in the section.

After deglutenization, the starch is washed and subjected to cooking and saccharification. These operations are similar to those for the dry milling alcohol process. Flash steam from cooking is used to heat the boiler feed water.

The saccharified solution is sent to the fermentation section. The fermentation is conducted in batch mode and is followed by centrifugation to recover yeast. Most of the yeast is recycled while any excess produced in the fermenter is combined with the gluten meal. The clear fermentation beer is sent on to distillation, which is similar to the dry milling case.

Exhausted steep liquor and clarified stillage from the stripper column are concentrated in an evaporator. The concentrated slurry (about 45 percent solids) from the evaporator is then mixed with press cake, wet fiber and corn cleanings to form the gluten feed. The evaporator was assumed to be a vapor recompression type with the compressor driven by a steam turbine.

Steam used in the process is mostly at 150 psig. Steam is generated at 600 psig, 600 F in a pulverized coal boiler with a boiler efficiency of 86 percent. The boiler is equipped with a double alkali flue gas desulfurization system.

The high pressure steam is then reduced to process steam pressure through a turbine which drives an electric generator. Part of the plant's electric power is provided by this cogeneration.

A major difference between the wet and dry milling alcohol process is that in wet milling nearly all of the nonfermentable components of grain are removed prior to the cooking and saccharification. This means that the yeast can be easily recoved by centrifuging the fermentation beer and can be recycled. Another major difference is the reuse of water. A portion of the stillage is centrifuged, and the clarified water is recycled to the cooking step. Water from the deglutenizing and starch washing steps is recycled to washing operations associated with fiber and germ separations, and to steeping. The counter-current water flow and water reuse minimizes the evaporation load and is the major reason that ethanol by wet milling requires less steam energy than dry milling.

B.2.2 Energy and Materials Consumption

The material and energy consumption for the wet milling ethanol process are:

Corn	0.388 bu/gal ethanol
Coal	0.00219 ton/gal or 0.553 Btu/Btu
Electricity	1.26 kwhr/gal or 0.156 Btu/Btu
Makeup Azeotroping Agent	0.00018 gal/gal
Lime	0.00012 ton/gal
Sulfur Dioxide	0.0445 lbs/gal

As in the dry milling case, the coal used 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 coal contained 3.34 percent sulfur, as received. As in the dry milling process, the makeup azeotroping agent and the 0.02 gallon gasoline denaturant per gallon ethanol may be excluded from the overall energy balance.

The energy consumed in various steps of the wet milling process is indicated in Exhibit B-5. Most of the process energy is provided by burning coal to raise steam. In addition to the electricity generated within the process, a significant quantity of electricity must be purchased.

The output from the wet milling process are fuel grade ethanol (99.5%), corn oil, and various animal feed products. The byproducts are:

Corn Oil	0.60 lb/gal ethanol
Gluten Meal	1.08 lb/gal
Gluten Feed	5.5 lb/gal

As in the dry milling case, there is also about 0.85 lb/gal moist solids from the flue gas desulfurization which would be disposed of at an adjacent landfill.

B.3 By-product Energy Credits

Both the dry and wet milling alcohol processes produce animal feed by-products and the wet milling process produces corn oil. Corn oil competes with other vegetable oils, including soy oil, while the other products displace both soy meal and corn. It is assumed that this displacement occurs in such a way that both protein supplied and total weight of the feed remain constant. The typical crude protein content of the various feed products (Feedstuffs, 1981) are:

Corn	9%
Soybeans	38%
Soy Meal	44%
Distillers Dark Grains (DDG)	27%
Gluten Feed	21%
Gluten Meal	60%

EXHIBIT B-5: ETHANOL FROM CORN: ENERGY BALANCE FOR WET MILLING PROCESS

Process Section	Electricity[a] Consumption Btu per Btu Ethanol	Electricity[a] Generation Btu per Btu Ethanol	Coal Consumed Btu per Btu Ethanol	Hp Steam[b] Consumed Btu per Btu Ethanol	Hp Steam[b] Produced Btu per Btu Ethanol	Lp Steam[b] Consumed Btu per Btu Ethanol	Lp Steam[b] Produced Btu per Btu Ethanol
Receiving, Storage and Cleanings	0.005						
Steeping	0.007					0.009	
Degermination, Germ Dewatering and Drying	0.018					0.028	
Fiber Separation, Dewatering, Mixing and Drying	0.046					0.091	
Enzyme Manufacture	0.033					0.003	
Gluten Separation and Drying	0.017					0.025	
Starch Washing, Cooking and Saccharification	0.008					0.053	
Fermentation	0.006						
Distillation and Dehydration	0.003					0.304	
Steep Liquor and Stillage Evaporation	0.006			0.179		0.008	0.166
Corn Oil Extraction	0.008						
Electricity Generation		0.075		0.408			0.378
Steam Generation and Utilities	0.065		0.553		0.587		
Flue Gas Reheat						0.010	
Miscellaneous	0.009					0.013	
Total	0.156		0.553	0		0	

(a) Electricity taken as fuel to generate, i.e., 10,400 Btu/kwh.
(b) Hp steam is at 600 psig, 800 F; Lp steam is at 150 psig, saturated. Energy steam taken as enthalpy above water at 0 C (32 F).

The corn oil credit is the energy to produce an equivalent amount of soy oil. The soy oil and soy meal are produced by crushing soybeans and extracting the oil. Since the crushing is performed primarily to obtain oil, all the energy of crushing has been allocated to the oil. Energy to grow soybeans, on the other hand, has been allocated to soy oil and soy meal on the basis of weight. The average energy to produce soy oil and soy meal is shown in Exhibit B-6.

The energy used for milling, 3,723 Btu/lb oil, is equivalent to 1,167 Btu/lb of soybeans used. This is comparable to the 1,032 Btu/lb value published by the American Soybean Association (Erickson and Dixon, n.d.) and is somewhat higher than the 751 Btu/lb of soybeans mill studied by Battelle (Devine, 1977). The latter study is based on a mill with higher than average electricity use and use of purchased steam. When adjusted to a fuel consumption basis, the 751 Btu/lb converts to 1,120 Btu fuel per pound soybeans, nearly the same as the 1,167 Btu/lb value derived from the Census data in Exhibit B-6.

The energy credits for soy oil and soy meal reflect an energy credit for soybean production based on national average energy consumption per bushel in 1978. The energy saved due to decreased production might differ from average energy consumption; however, estimates of marginal energy consumption were not available. The difference between average and marginal energy consumption for soybean production is unlikely to be as great as it is for corn (see Appendix A) because, unlike corn, increases in soybean production are not obtained by increasing use of energy-intensive nitrogen fertilizer.

The energy credits estimated for the various by-products are shown in Exhibit B-7. It may be observed that credits for reduced corn production are predominantly for natural gas (because of the use of nitrogen fertilizer to achieve marginal changes in corn production), while credits for soy meal are predominantly for petroleum products. If the various feed products were to displace soy meal and corn in proportions other than those assumed in this analysis, some shift would result in the amounts of petroleum products and natural gas saved.

B.4 Discussion and Sensitivity Analysis

For the processes selected for this study the energy consumed in the process is nearly the same for both processes:

	Motor Gasoline (gal)	Distillate (gal)	Residual Fuel (gal)	LPG (gal)	Natural Gas (cu ft)	Coal (1) (lb)	Total Petroleum Products (Btu)	Total Energy (Btu)
	Petroleum Products							
Soybeans (Energy per bushel)								
Grow and Harvest								
Direct Agricultural Energy (2)	0.235	0.208		0.023	1.25	0.20	60,680	64,210
Fertilizer (2, 3)	*	0.011	0.001		4.75	0.29	1,550	1,740
Pesticides (2, 4)		0.014			1.69	0.81	1,910	4,540
	0.235	0.233	0.001	0.023	7.69	1.30	64,140	78,490
Soy Oil (Energy per pound of oil)								
Grow and harvest soybeans (5)	0.00391	0.00388	0.00002	0.00038	0.01	0.022	1,070	1,308
Milling:								
Net shipments in 1977 (6): 14,846 MM lbs								
Total energy consumption in 1977 (7):								
—Electricity: 1422.8 MM kwhr						0.089		999
—Direct fuels:		0.00301	0.00296		1.50	0.029 (10)	865	2,724 (9)
Distillate: 1062.7 M bbl								
Residual: 1045.4 M bbl								
Natural gas: 22.3 B cu ft								
Coal na (8)								
	0.00391	0.00689	0.00298	0.00038	1.51	0.118	1,935	5,031
Soy Meal (Energy per pound)								
Grow and harvest soybeans	0.00391	0.00388	0.00002	0.00038	0.013	0.022	1,070	1,306

*Less than 0.0005 gal/bu.

(1) Assumes use of 11,250 Btu/lb coal.
(2) Derived from USDA (1976, 1977) and Torgerson and Cooper (1980).
(3) Total energy distributed among fuel sources on basis of data in Exhibit 2-23.
(4) Total energy distributed among fuel sources on basis of data in Pimentel, 1980; all oil feedstocks used treated as distillate.
(5) Energy to grow and harvest soybeans allocated to soy oil and soy meal on basis of weight.
(6) DOC, 1980b.
(7) DOC, 1980c.
(8) Data for coal use withheld by Census.
(9) Estimated directly from source data.
(10) Estimated by assuming that all energy from sources not separately identified was obtained from coal.

EXHIBIT B-7: ENERGY CREDITS FOR ETHANOL BY-PRODUCTS
(Per Gallon of Ethanol Produced)

By-Product	Assumptions	Petroleum Products: Motor Gasoline (gal)	Petroleum Products: Distillate (gal)	Petroleum Products: Residual Fuel (gal)	Petroleum Products: LPG (gal)	Natural Gas (cu ft)	Coal (lb)	Total Petroleum Products (Btu)	Total Energy (Btu)
DRY-MILLING PROCESS									
DDG	7.08 lb produced Replaces:								
	3.44 lb corn	0.0080	0.0065	0.00007	0.0033	7.05	0.108	2,200	10,600
	3.64 lb soy meal	0.0142	0.0141	0.00007	0.0014	0.05	0.080	3,900	4,800
TOTAL CREDITS - DRY MILLING		0.0222	0.0206	0.00014	0.0047	7.10	0.188	6,100	15,400
WET-MILLING PROCESS									
Corn Oil	0.60 lb produced Replaces 0.60 lb soy oil	0.0023	0.0041	0.00179	0.0002	0.91	0.071	1,200	3,000
Gluten Meal Gluten Feed	1.08 lb produced 5.5 lb produced Replaces:								
	3.12 lb corn	0.0072	0.0059	0.00007	0.0030	6.40	0.098	2,000	9,700
	3.46 lb soy meal	0.0135	0.0134	0.00007	0.0013	0.04	0.076	3,702	4,500
TOTAL CREDITS - WET MILLING		0.0230	0.0234	0.00193	0.0045	7.35	0.245	6,900	17,200

Source: Derived from Exhibits A-24, B-6 and protein content of feed (see text).

	Dry milling	Wet milling
Coal	0.57	0.55
Electricity Fuel	0.16	0.16
	0.73 Btu/Btu of ethanol	0.71 Btu/Btu of ethanol

These figures do not include the energy embodied in feedstock or in byproducts. These values are lower than the published value for one commercial process of 72,500 Btu/gallon or 0.86 Btu/Btu (Bohler Brothers of America, 1981) and higher than the published value of 0.65 Btu/Btu for a much quoted conceptual design (Katzen, 1979). Both of these are dry milling processes. The latter design incorporates energy conservation features which we do not consider commercial state of the art. That design differs from the one used in this study primarily in the method of drying DDG and of desulfurizing flue gas.

The largest consumers of process energy are the distillation and dehydration of the ethanol to reduce water to 0.5 percent maximum and the recovery and drying of the animal feed byproducts: DDG for dry milling, gluten feed and gluten meal for wet milling.

The energy required for distillation is sensitive to the selection of the distillation process and to the use of heat recovery whenever feasible. The designs selected for this study use one of the most energy-efficient distillation systems currently available. This energy efficiency is achieved by cascading the distillation column so that the condenser of one still becomes the reboiler for another. By this technique the steam energy for distillation is reduced to about 0.30 Btu/Btu ethanol compared to 0.37 - 0.46 Btu/Btu for conventional azeotropic distillation (Black, 1980). Extractive distillation with gasoline is also an energy efficient commercially available separation technique which consumes about 0.35 Btu/Btu, but extractive distillation with ethylene glycol consumes about 0.69 Btu/Btu (Black, 1980). Other separation methods which are not yet commercially available are discussed elsewhere in this report.

Since process heat is consumed as steam but derived from coal (or other fuel), the boiler efficiency can have a significant impact on the overall energy balance. For this study, a pulverized coal fired boiler with an overall efficiency* of 86 percent was selected. The pulverized coal boilers are economic only in larger sizes (about 200,000

*Overall boiler efficiency is defined as energy transferred to the steam divided by the higher heating value of the fuel.

pounds steam per hour or more) and are suitable for alcohol plants with capacities in excess of 35 to 40 million gallons per year. Smaller plants would use either coal-fired stoker boilers or oil or gas-fired boilers. The typical boiler efficiencies (McKee, 1979) are:

Stoker coal less than 50,000 lb/hr	80%
Stoker coal 100,000 lb/hr steam	84%
Pulverized coal 200,000+ lb/hr	86%
Oil 10,000 - 400,000 lb/hr	85%
Gas 10,000 - 50,000 lb/hr	81%
Gas 100,000+ lb/hr	82%

These efficiencies were based on boiler manufacturer estimates for commercial units. It may be possible to improve the efficiency of some units through careful design and operating control, although this may not be economic at the smaller sizes. One of the reasons for the lower efficiency of stoker boilers is the large amount of excess air required for operation.

Because of the boiler limitations, a small alcohol plant with a coal-fired stoker boiler and an identical design would be expected to consume 1.075 times as much coal per gallon of ethanol as a large alcohol plant.

Plant scale also has an impact on the amount of energy saving equipment which can economically be incorporated into the design. For example, the economic attractiveness of cogeneration decreases as plant size decreases. The analysis of the breakeven size for cogeneration is beyond the scope of this study. In general, as alcohol plant size decreases, unit energy consumption will increase.

For the recovery of the byproducts such as gluten meal, gluten feed and germ, steam-tube dryers were considered for the energy analysis. However, in some locations the use of direct or indirect fired natural gas dryers might be more economical than the steam-tube dryers, but the impact on the overall energy balance for the ethanol production would be very insignificant. The direct-fired natural gas dryers appear to be a little more efficient than the steam-tube dryers by about 3-4 percentage points.

The energy embodied in the manufacture of lime for the flue gas desulfurization system is significant. The base case assumes coal with 3.34 percent sulfur, and a double alkali desulfurization system removing 90 percent of the sulfur dioxide and utilizing 5 percent stoichiometric excess of lime. This system consumes 0.00012 ton lime per gallon ethanol, which has an embodied energy of 73.2 million Btu per ton. This is equivalent to 8800 Btu per gallon ethanol.

Using the double alkali desulfurization system, which was chosen for reliability and ease of operation, this embodied energy is directly proportional to the sulfur content of the coal and inversely proportional to the coal heating value. The sulfur content of coal varies over a wide range and is more likely to affect overall energy.

The energy embodied in lime is also sensitive to the fuel and the local environmental regulations. If natural gas were used there would be no need for flue gas desulfurization. Similarly, if the plant were located in an area with less restrictive regulations, a lower fraction of the sulfur would be removed, with a corresponding lower lime consumption.

Finally, the energy embodied in lime use is also dependent on the flue-gas desulfurization system selected. If a lime scrubbing system were selected, the stoichiometric excess would be about 25 percent, and the embodied energy in lime would be about 19 percent higher. On the other hand, if limestone were used instead of lime, there would be none of the energy embodied in lime. However, there are few desulfurization units using limestone operating at less than electric utility scale.

Finally, if one used an ammonia scrubbing system as proposed by Katzen (1979) and used the resulting ammonium sulfate solution as fertilizer, there would be no energy penalty. There could be significant economic penalty, however, since a concentrated nitrogen fertilizer, ammonia, would be converted to a dilute nitrogen fertilizer, ammonium sulfate, by the process. A market for the ammonium sulfate would have to be established.

B.5 Potential for Reduced Energy Consumption

Much research attention has been given to ethanol purification, since the distillation of ethanol to meet the 99.5 percent fuel grade specification is a major process energy consumer. The processes under consideration are improved distillation, solvent extraction, and absorption technologies.

The use of vapor recompression in distillation is a commercially available technology that can reduce distillation energy consumption. To be economic, however, one needs a supply of relatively inexpensive shaft power. This is best accomplished by cogeneration. The use of vapor recompression distillation would probably not be economic in a design which already incorporated cogeneration.

Efficient and economic solvent extraction depends upon the choice of the solvent. While the literature abounds with extraction research studies, none has reached commercial status. At present, A.D. Little is developing an ethanol extraction process which uses liquid carbon dioxide as the solvent. Ethanol is recovered by flash distillation of the solvent, followed by recompression and recycle of the carbon dioxide. It has been claimed that this process can recover fuel grade ethanol from fermentation beer with the expenditure of only 8,000 - 10,000 Btu/gal, about one-third that for conventional processes (Eakin, 1981). The economic and continued operability of the process remain to be demonstrated.

Absorption is suitable for removing the last several percent of water for ethanol that has been distilled from fermentation beer. There are two absorption systems that appear promising: molecular sieves and corn meal. Both would replace the azeotropic distillation. Molecular sieves are commercially available and may be used by some farm-scale ethanol plants; however no commercial ethanol plant is known to use this technology. The sieves can be used to absorb water preferentially from a water-ethanol mixture. The sieves are usually regenerated with hot gas (about 400 F). The estimated energy required is 4,700 - 6,300 Btu per gallon, or about half the 9,400 Btu of conventional azeotropic distillation (Eakin, 1981).

Cracked corn or corn meal can also be used as an absorbant to remove water from ethanol (Ladisch, 1979). The technology is still being developed, but it appears that the energy consumption to regenerate corn meal when drying from the azeotrope to fuel grade is 600 Btu per gallon (Ladisch, 1980). Furthermore, the regeneration temperature is low (120 C), which enhances the opportunity to use low grade heat. It is possible that the overall process energy can be reduced by stopping the distillation with 10-15 percent water remaining and then drying by absorption on corn meal.

Another major energy consumer is the evaporation of stillage to recover DDG in the dry milling process and the evaporation of steep liquor and stillage in the wet milling process. There is a potential to reduce energy consumption by reduction of the quantity of water to be evaporated by higher water recycle. The recycling, however, can have adverse impact on fermentation operations. This is an area for research.

BIBLIOGRAPHY FOR APPENDICES A AND B

Black, C., "Distillation Modeling of Ethanol Recovery and Dehydration Processes for Ethanol and Gasohol," Chem. Eng. Progress, 76,78 (September 1980).

Bohler Brothers of America, Inc., Vogelbusch Division, "Power Alcohol Technology," Houston, TX (1981).

Chambers, R.S., R.A. Herendeen, J.J. Joyce and P.S. Penner, "Gasohol: Does It or Doesn't It Produce Positive Net Energy?," Science, 206, pp. 789-795 (November 16, 1979).

Code of Federal Regulations, Title 27, Part 212, Paragraph 212.13, GPO: Washington, D.C. (FR 8471, January 27, 1981).

Divine, T.E., D.P. Alzheimer, and W.F. Smith, "Estimates of Process Energy Use in Four Key Food Products Industries," paper presented to Am. Soc. Ag. Eng., Pendleton, OR (September 1977).

Dovring, Folke, Robert Herendeen, Randall Plant and Mary Ann Ross, Fuel Alcohol from Grain, University of Illinois Energy Research Group Document No. 313, Urbana, IL (December 1980).

Dvoskin, Dan and Earl O. Heady, U.S. Agricultural Production Under Limited Energy Supplies, High Energy Prices, and Expanding Agricultural Exports (November 1976).

Eakin, E.E., J.M. Donovan, G.R. Cysewski, S.E. Petty and J.V. Maxham, Preliminary Evaluation of Alternative Ethanol Water Separation Processes, Battelle Pacific Northwest Laboratories (May 1981).

Environmental Protection Agency, IERL, Sulfur Oxide Control Technology: Flue Gas Desulfurization Dual Alkali Process, EPA 625/8-80-004 (October 1980).

Erickson, D.R. and P. Dixon, "Soy Oil as Diesel Fuel," American Soybean Association.

Feedstuffs, Vol. 53, No. 25 (July 23, 1981).

Jenkins, D.M., T.A. McClure and T.S. Reddy, Net Energy Analysis of Alcohol Fuels, API Publication 4312 (November 1979).

Halsey, J., D. Hazard, K. Kawaoka, K. Stephens and G. D'Alessio, Near-Term Goals for Alcohol Fuels from Biomass: An Overview of Resource Requirements, Land Use, Environmental and Socioeconomic Impacts, Argonne National Laboratory, ANL/EES-TM-149, Argonne, IL (December 1980).

Katzen (Raphael) Associates, Grain Motor Fuel Alcohol Technical and Economic Assessment Study, U.S. Department of Energy Report HCP/J6639-01 (June 1979).

Knapton, D., An Investigation of Truck Size and Weight Limits, Technical Supplement, Vol. 3: Truck and Rail Fuel Effects of Truck Size and Weight Limits, U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA (July 1981).

Ladisch, M.R., "Energy Efficient Production of Anhydrous Ethanol," Interim Progress Report to U.S. Department of Agriculture (March 1980).

Ladisch, M.R. and K. Dyck, "Dehydration of Ethanol: New Approach Gives Positive Energy Balance," Science 205, 898 (1979).

McKee (Arthur G.) & Co., Cost Comparison Study of Industrial Size Boilers, Report to U.S. Department of Energy (January 1979).

Meekhof, R., M. Gill and W. Tyner, Gasohol: Prospects and Implications, U.S. Department of Agriculture, AER No. 458, Washington, DC (June 1980).

Michigan State University, Cooperative Extension Service, Energy Facts, Energy Management for Field Crop Production, Extension Bulletin E-1407, File 18.85 (June 1980).

Pimentel, David, Handbook of Energy Utilization in Agriculture, CRC Press, Boca Raton, FL (1980).

Pimentel, D., et al, "Biomass Energy from Crop and Forest Residues," Science, 212, pp. 1110-1115 (June 5, 1981).

Sanderson, Fred H., "Benefits and Costs of the U.S. Gasohol Program," Resources, No. 67, pp. 2-13 (July 1981).

Schnittker Associates, Ethanol: Farm and Fuel Issues, National Alcohol Fuels Commission, Washington, D.C. (1980).

Solar Energy Research Institute, A Guide to Commercial Scale Ethanol Production and Financing, SERI Publication SP-751-877 US-61 (November 1980).

Torgerson, David and Harold Cooper, Energy and U.S. Agriculture: 1974 and 1978, U.S. Department of Agriculture, Economics, Statistics and Cooperative Service, Statistical Bulletin No. 632 (April 1980).

Tyson, Belzer and Associates, "1979 Energy Use Survey," The Fertilizer Institute, Washington, D.C. (1980).

U.S. Congress, Joint Economic Committee, Alcohol Fuels Policy, Washington, D.C.: GPO (June 25, 1980).

U.S. Congress, Office of Technology Assessment, Energy from Biological Processes, Three Volumes, Washington, D.C.: GPO (1980).

U.S. Department of Agriculture, Energy and U.S. Agriculture: 1974 Data Base, Volume I (September 1976).

U.S. Department of Agriculture, Energy and U.S. Agriculture: 1974 Data Base, Volume II: Commodity Series of Energy Tables (April 1977).

U.S. Department of Agriculture, Crop Reporting Board, Commercial Fertilizer Consumption for Year Ended June 30, 1978 (1978a).

U.S. Department of Agriculture, 1979 Fertilizer Situation, FS-9 (1978b).

U.S. Department of Agriculture, Crop Production, 1977, 1978 and 1979 Annual Summaries (1978c, 1979b and 1980b).

U.S. Department of Agriculture, Basic Statistics, 1977 National Resources Inventory, Inventory and Monitoring, Soil Conservation Service, Washington, D.C. (November 1979a).

U.S. Department of Agriculture, Small-Scale Fuel Alcohol Production (March 1980a).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Manufactures, "Concrete, Plaster, and Cut Stone Products," Industry Series, MC77-I-32D, Washington, D.C.: GPO (1980a).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Manufactures, "Fats and Oils," Industry Series, MC77-I-20G, Washington, D.C.: GPO (1980b).

U.S. Department of Commerce, Bureau of the Census, 1977 Census of Manufactures, "Fuels and Electric Energy Consumed," Subject Series, MC77-SR-4 (Part 1, Revised), Washington, D.C.: GPO (1980c).

U.S. Department of Energy, Technical Information Center, Fuel From Farms -- A Guide to Small-Scale Ethanol Production (February 1980).

U.S. National Alcohol Fuels Commission, Fuel Alcohol - An Energy Alternative for the 1980's, Washington, D.C., 1981.

U.S. Water Resources Council, 1972 OBERS Projections of Regional Economic Activity in the U.S.: Series E' Supplement Agricultural Projections, Vols. 1, 2, and 4, GPO (1976).