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Abstract

Studies conducted since the late 1970's have estimated the net energy value of corn ethanol. However, variations in data and assumptions used among the studies have resulted in a wide range of estimates. This study identifies the factors causing this wide variation and develops a more consistent estimate. We conclude that the net energy value of corn ethanol has become positive in recent years due to technological advances in ethanol conversion and increased efficiency in farm production. We show that corn ethanol is energy efficient as indicated by an energy ratio of 1.24.

Keywords: Ethanol, net energy balance, corn production, energy security

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Summary

The U.S. ethanol industry grew from practically zero production in the late 1970's to over 1 billion gallons in 1994, spurred by national energy security concerns, new Federal gasoline standards, and government incentives. Production of ethanol is energy efficient, in that it yields nearly 25 percent more energy than is used in growing the corn, harvesting it, and distilling it into ethanol.

Growth in ethanol production has provided an economic stimulus for U.S. agriculture, because most ethanol is made from corn. The increase in ethanol demand has created a new market for corn, and agricultural policymakers see expansion of the ethanol industry as a way of stabilizing farm income and reducing farm subsidies, while freeing the U.S. economy from its dependence on imported oil. Increasing ethanol production induces a higher demand for corn and raises the average corn price. Higher corn prices reduce farm commodity program payments and the participation rate in the Acreage Reduction Program.

Today's higher corn yields, lower energy use per unit of output in the fertilizer industry, and advances in fuel conversion technologies have greatly enhanced the economic and technical feasibility of producing ethanol compared with just a decade ago. Studies using older data may tend to overestimate energy use because the efficiency of growing corn and converting it to ethanol has improved significantly over the past 10 years. The net energy value (NEV) of corn ethanol was calculated as 16,193 Btu/gal when fertilizers are produced by modern processing plants, corn is converted in modern ethanol facilities, farmers achieve normal corn yields, and energy credits are allocated to coproducts.

Moreover, producing ethanol from domestic corn stocks achieves a net gain in a more desirable form of energy. Ethanol production uses abundant domestic supplies of coal and natural gas to convert corn into a premium liquid fuel that can displace petroleum imports.

The initial impetus for ethanol commercialization came when the 1970's oil embargoes exposed the vulnerability of U.S. energy supplies. Fuel ethanol was seen as a gasoline extender; mixing it with gasoline was considered a means of extending the Nation's gasoline supply. Later, ethanol established a role as an octane enhancer as the Environmental Protection Agency (EPA) began to phase out lead in gasoline. More recently, ethanol production received a major boost with the passage of the Clean Air Act Amendments of 1990. Blending ethanol with gasoline has become a popular method for gasoline producers to meet the new oxygen requirements mandated by the act.

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Introduction

Ethanol production in the United States grew from just a few thousand gallons in the mid-1970's to over 1 billion gallons in 1994. National energy security concerns, new Federal gasoline standards, and government incentives have been the primary stimuli for this growth (Lee). In addition, government and privately sponsored research has resulted in new technologies that lowered the cost of large-scale production of ethanol made from corn (Hohmann and Rendleman). The initial impetus for ethanol commercialization came during the 1970's. The oil embargoes of 1973 and 1979 created much concern over the security of our Nation's energy supplies. Fuel ethanol became attractive as a gasoline extender and was considered as a means of extending the Nation's gasoline supply. About the same time, the Environmental Protection Agency (EPA) was looking for a replacement for lead additives used as octane boosters in gasoline. Because of its high octane content, ethanol soon established a role as an octane enhancer (Lee and Conway).

More recently, ethanol production received a major boost with the passage of the Clean Air Act Amendments (CAA) of 1990. Blending ethanol with gasoline has become a popular method for gasoline producers to meet the new oxygen requirements mandated by the CAA (see box). Provisions of the CAA established the Oxygenated Fuels Program and the Reformulated Gasoline Program in an attempt to control carbon monoxide (CO) and ground-level ozone problems. Both programs require certain oxygen levels in gasoline: 2.7 percent by weight for oxygenated fuel and 2.0 percent by weight for reformulated gasoline.

Public policies aimed at encouraging ethanol development are largely motivated by the Nation's desire to improve air quality and enhance energy security. In addition, agricultural policymakers see the expansion of the ethanol industry as a means of stabilizing farm income and reducing farm subsidies. Increasing ethanol production induces a higher demand for corn and raises the average corn price. Higher corn prices reduce farm commodity program payments and the participation rate in the Acreage Reduction Program.

Energy Balance Issue

While the Government's commitment to ethanol has been welcomed by agricultural interests and the ethanol industry, critics question the rationale behind policies that promote ethanol for energy security benefits, often citing that corn ethanol has a negative net energy value (Pimentel and Ho). That is, the liquid fuel and other energy sources required to grow and convert corn into ethanol are greater than the energy value present in the ethanol fuel. This implies that corn ethanol is not an energy substitute and that increasing its production does little to displace oil imports and increase energy security.

Others argue that although energy balance is of some concern, it is not the major issue for addressing energy security. What really matters is that the production of ethanol can achieve a net gain in a more desirable form of energy (Department of Energy; and Anderson et al.). In other words, abundant domestic energy supplies, such as coal and natural gas, can effectively be used to convert corn into a premium liquid fuel that replaces imported petroleum. This approach reduces the energy balance issue to just looking at the energy value of the liquid fuels used in the production of corn ethanol. However, some researchers prefer a comprehensive approach and include all the energy sources used to

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Clean Air Act Amendments of 1990

The Clean Air Act Amendments of 1990 (CAA) target automobile fuel emissions as a major source of air pollution. The Act mandates the use of cleaner burning fuels in the smoggiest U.S. cities. The oxygen requirements of CAA spurred a market for oxygenates and created new market opportunities for ethanol. The Oxygenated Fuels Program targets 39 cities that do not meet National Ambient Air Quality Standards for carbon monoxide (CO). CAA mandates the addition of oxygen to gasoline to reduce CO emissions. It requres an oxygen level in gasoline of 2.7 percent by weight. Control periods vary by city because most CO violations occur during the winter. The average control period is about 4 months. The most widely used oxygenate in the market today is a methanol-derived ether, MTBE, which is made mostly from natural gas. However, most major gasoline refiners are also using ethanol to meet gasoline oxygenate content requirements. In 1993, about 300-350 million gallons of ethanol were blended with gasoline and sold in markets covered by the Oxygenated Fuels Program.

The CAA also requires the use of oxygenated fuels as part of the reformulated gasoline (RFG) program for controlling ground-level ozone formation. This program requires an oxygen level in gasoline of 2.0 percent by weight. Beginning in January 1995, reformulated gasolines were required to be sold in nine ozone nonattainment areas year round. Other provisions in the Act allow as many as 90 other cities with less severe ozone pollution to “opt in” to the RFG program. Under a total opt-in scenario, as much as 70 percent of the Nation’s gasoline could be reformulated.

produce ethanol in their energy use estimates. They argue that conclusions about potential domestic energy gains from ethanol production would be incomplete if only a part of the total energy system is assessed (Pimentel). We use both approaches in our analysis.

The energy balance issue first surfaced in the mid-1970’s when ethanol began to receive attention as a gasoline extender. Studies at that time that analyzed the energy benefits of substituting ethanol for gasoline generally concluded that the net energy value (NEV) of corn ethanol was slightly negative (Ethanol Study Committee; and Chambers, Herendeen, and Penner). In the late 1980’s, environmental concerns placed ethanol in the spotlight once again and energy balance studies resurfaced. However, there was a considerable amount of variation in the findings of these reports. This wide variation relates to various assumptions about farm production and ethanol conversion. Furthermore, the researchers used data from different time periods. Studies using older data may tend to overestimate energy use because ethanol manufacturing and farm production technologies have become increasingly energy efficient over time. To make matters worse, it is often difficult to determine why results differ from study to study because the reports often lack certain details on their calculation procedures. The purpose of this report is to identify the methodological differences creating the inconsistencies among study results and provide a more consistent estimate for the NEV of corn ethanol.

Review of Recent Studies

Table 1 shows the wide variation in the NEV estimates of several recent studies. Since some studies use low heating values (LHV) and others use high heating values (HHV), the energy estimates for ethanol conversion are not always directly comparable due to scale differences. High heating value, also called gross heating value, is the standard heat of combustion referenced to water of combustion as liquid water. Low heating value, also called net heat of combustion, is the standard heat of combustion referenced to water of combustion as water vapor. Energy balance calculations may be made using either basis as long as the basis is consistently applied. Moreover, NEV estimates are comparable regardless of the heating value used. Pimentel reports the lowest NEV for corn ethanol among the studies: based on a low heating value scale, he calculated that the total energy input to produce 1 gallon of ethanol is 131,017 British thermal units (Btu). Compared with the LHV of ethanol, 76,000 Btu, this is a net energy loss of 55,017 Btu per gallon. Even when coproducts were considered, Pimentel still estimated a net energy loss of around 33,517 Btu/gal. Keeney and DeLuca also reported a negative NEV for an average farm, but the energy deficit was only 8,431 Btu/gal. Keeney and DeLuca do not consider corn processing byproducts, but they show that a positive energy balance can be attained with low-input corn production. Marland and Turhollow reported that it requires 73,934 Btu (HHV basis) to produce a gallon of ethanol assuming conversion takes place in the best ethanol facilities available today. When energy use is allocated to the

Table 1--Energy input assumptions of recent corn-ethanol studies

Study/year	Corn yield	Nitrogen fertilizer application rate	Inputs for nitrogen fertilizer	Corn ethanol conversion rate	Ethanol conversion process	Total energy use[1]	Coproducts' energy credits[1]	Net energy value[1]
	bu/acre	*lb/acre*	*Btu/lb*	*gal/bu*	- - - - - - - - - - - - - *Btu/gal* - - - - - - - - - - - - -			
Pimentel (1991)	110	136.0	37,551	2.50	73,687 (LHV)	131,017	21,500	-33,517
Keeney and DeLuca	119	135.0	37,958	2.56	48,434 (LHV)	91,127	8,072	-8,431
Marland and Turhollow (1991)	119	127.0	31,135	2.50	50,105 (HHV)	73,934	8,127	18,324
Morris and Ahmed (1992)	120	127.0	31,000	2.55	46,297 (LHV)	75,297	24,950	25,653
Ho (1989)	90	NR	NR	NR	57,000 (LHV)	90,000	10,000	-4,000
This study (1995)	122	124.5	22,159	2.53	53,277 (HHV)	82,824	15,056	16,193
Average	113	129.9	31,961	NA	NA	NA	NA	2,373

NR: Not reported
NA: Average values ar enot appropriate in this case because studies using high heat values cannot be directly compared with studies using low heat values. This study and the Marland and Turhollow study used high heat values and the others used low heat values.
LHV: Low heat value--76,000 Btu per gallon of ethanol.
HHV: High heat value--83,961 Btu per gallon of ethanol.

[1] The midpoint is used when studies report a range of values.

coproducts made during the ethanol conversion process, such as gluten meal, gluten feed, and corn oil, they conclude that the NEV of corn ethanol is 18,324 Btu/gal. The most favorable NEV estimate was derived by Morris and Ahmed. They found a positive net energy balance of 703 Btu/gal for their average case, even without including energy from coproducts. When adding energy coproduct credits, they estimated a net energy gain of 25,653 Btu/gal.

Differences among these studies are related to various assumptions about corn yields, ethanol conversion technologies, fertilizer manufacturing efficiency, fertilizer application rates, coproduct evaluation, and the number of energy inputs included in the calculations. For example, there is about a 60,000 Btu/gal difference in the results of Pimentel and Morris and Ahmed. With respect to growing the corn, Pimentel reports that it requires 57,330 Btu/gal compared with Morris and Ahmed's 28,917 Btu/gal. Both studies use the same basic inputs, such as fertilizer, pesticides, and fuel, but Pimentel also includes the energy value embodied in farm machinery. Another factor that makes Pimentel's estimates higher is that he uses a national average corn yield based on pre-1989 data of only 110 bu/ac. Morris and Ahmed use 120 bu/ac, which is based on data from more recent years. Yields have been increasing over time, so it is important to use current data to estimate average yield.

The time period for which information was collected on fertilizer plants makes a difference in energy requirements among the studies. For example, Keeney and DeLuca report the highest energy estimate for fertilizer, almost 38,000 Btu/gal, and their source of data is a 1980 study by Dovring and McDowell. The more recent studies by Marland and Turhollow and Morris and Ahmed report just over 31,000 Btu/gal.

Fertilizer application rates can also make a difference in energy use estimates. For example, Pimentel's nitrogen requirement is more than 5 million Btu/acre—more then 1 million Btu/acre higher than Morris and Ahmed's nitrogen estimate. Pimentel's application rate for phosphorus is 67 pounds per acre compared with 48, 50, and 57 pounds per acre for Morris and Ahmed, Marland and Turhollow, and Keeney and DeLuca, respectively.

Assumptions about ethanol conversion facilities differ greatly among the studies. For example, Pimentel's fuel processing estimate is 27,390 Btu/acre higher than Morris and Ahmed's estimate. Much of this difference may be related to the data collection periods of the two studies. Although Pimentel's report was published in 1991, his energy use estimates for processing come from studies conducted in the early and mid-1980's (Energy Research Advisory Board and National Advisory Panel). Morris and Ahmed's estimates reflect today's ethanol facility which uses far less energy than the typical ethanol plant of 10 years ago. Most ethanol plants in production today have been extensively modernized and represent near-state-of-the-art technology. The second major difference between the two studies is that Pimentel's estimates include energy expended on capital equipment. Pimentel's estimate for converting ethanol is about 7,000 Btu/gal higher because it includes energy for steel, cement, and other materials used to construct the ethanol plant, components not included in the Morris and Ahmed study. Pimentel also uses a lower ethanol conversion rate—Pimentel uses 2.50 gal/bu compared with Morris and Ahmed's 2.55 gal/bu.

The large variation in coproduct energy credits listed in table 1 is related to the specific coproducts included in each analysis. Coproducts depend on the milling process used for the analysis. Distillers' dried grains with solubles (DDGS) is a dry milling coproduct, while corn oil, corn gluten meal (CGM), and corn gluten feed (CGF) are derived from wet milling. Both dry and wet-milling emit carbon dioxide (CO_2), but Morris and Ahmed are the only authors to include it in their analysis. Some studies (Morris and Ahmed and this study) include both wet and dry milling coproducts and weight coproduct energy credits based on the industry average, i.e., wet milling accounts for about two-thirds and dry milling one-third of total ethanol output (Hohmann and Rendleman). Pimentel uses only DDGS, while Keeney and DeLuca and Marland and Turhollow use just the coproducts from wet milling. Ho gives energy credits for fusel oil (boiler fuel), aldehydes, and DDGS. In addition to using different coproducts, authors also use different methods for estimating coproduct values, which have a major influence on the results. Options for estimating coproduct values are discussed in more detail below.

Estimating Net Energy Value

Estimating the energy input for determining the NEV of corn ethanol involves adding up all the energy required to grow corn and to process it into ethanol. Most studies, including this one, include only primary energy inputs in their NEV estimates. Secondary inputs, such as energy required to build ethanol facilities and produce transportation equipment are extremely difficult to quantify. For example, collecting data on the energy embodied in an ethanol plant would require a tremendous amount of data on a wide range of building materials. It would be necessary to allocate this energy among all the products manufactured in the plant over its lifetime. After going through all this trouble, the final result would add very little to the total energy value of a gallon of ethanol.

Data Trends

Reliable data are required to estimate the NEV of corn ethanol. This analysis uses farm production data from USDA's 1991 Farm Costs and Returns Survey (FCRS) to estimate energy values for farm inputs such as gasoline and diesel fuel use, fertilizers, and other chemicals (Ali and McBride). It is important that the most current data be used to estimate the NEV of ethanol because the efficiency of growing corn and converting it to ethanol has improved significantly over the past 10 years. Higher corn yields, lower energy use per unit of output in the fertilizer industry, and advances in fuel conversion technologies have greatly enhanced the economic and technical feasibility of producing ethanol.

Total energy used in agriculture including pesticides, fertilizers, other chemicals, liquid fuels, natural gas, and electricity increased from 1,499 trillion Btu in 1965 to 2,155 trillion Btu in 1978, and then declined to 1,550 trillion Btu by 1989. The decline in energy use in agriculture since 1978 is largely attributed to the replacement of gasoline-powered farm vehicles with more fuel-efficient diesel engines.

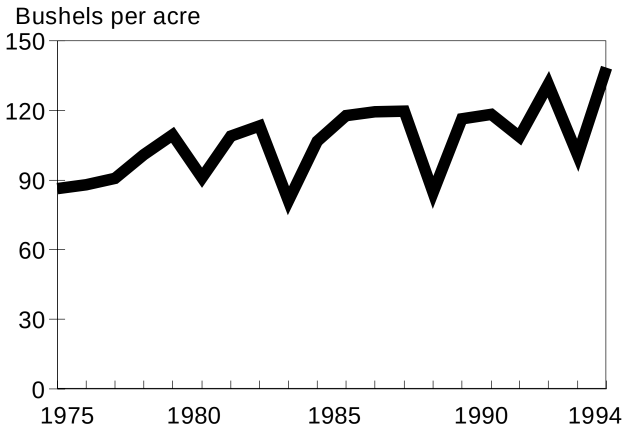
While energy use has been declining, there has been a rising trend in corn yields. Figure 1 shows that with the exception of a few bad years, annual corn yields have been increasing since 1975. The large downward spikes in 1983, 1988, and 1993 were caused by adverse weather. Droughts caused unusually low yields in 1983 and 1988, and in 1993 the Midwest experienced a devastating flood. Higher yields without corresponding increases in energy use indicate that resources are being used more efficiently. The farm energy use index, an efficiency measurement for fuel and electricity used on U.S. farms, has improved significantly in recent years: it fell from a high of 125 in 1978 to 93 in 1989 (fig. 2).

Fertilizer use in grain production rose for many years but lately has appeared to be in decline (Taylor). Nitrogen use per planted acre of corn declined from 140 pounds per acre in 1985 to 123 pounds per acre in 1993. Phosphate use declined from 60 to 56 pounds per acre, and potash use declined from 84 pounds per acre to 79 pounds per acre during the same period.

In addition, the manufacture of agricultural chemicals has become more energy efficient. The fertilizer industry, for example, has undergone a major technological advancement in the last decade, and U.S. farmers have gained substantial real energy-saving benefits in terms of nitrogen and phosphorus (Bhat et al.). Energy saving

Figure 1

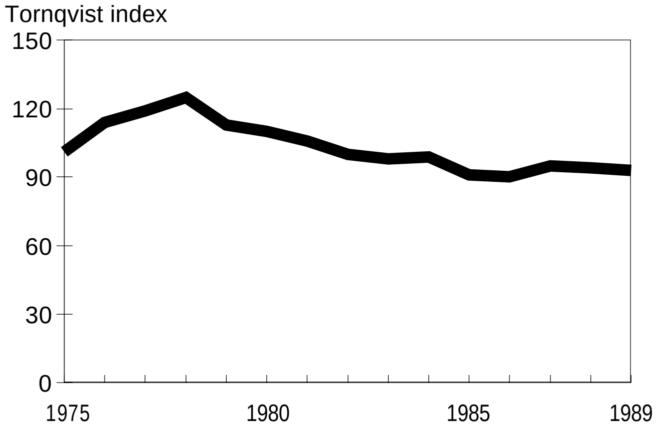
U.S. corn yield, 1975-94



Source:USDA, National Agricultural Statistics Service.

Figure 2

Energy use index for U.S. farms, 1975-89



Source:USDA, Economic Research Service

for producing nitrogen has been especially important since it has a much higher average energy requirement than phosphorous and potash fertilizers. Bhat et al. reported that from 1979 to 1987, the energy consumed in producing nitrogen fertilizers declined about 11 percent.

Making ethanol from corn also has become more energy efficient. Hohmann and Rendleman reported that a shift in production to larger plants and the adoption of energy-saving innovations reduced the processing energy required to produce a gallon of ethanol from 120,000 Btu in 1981 to 43,000 Btu in 1991. Efforts by the industry to conserve electricity have resulted in substantial energy savings. In 1980, for example, ethanol plants used 2.5 to 4.0 kilowatthours (kWh) of electricity per gallon of ethanol versus 0.5 kWh used by today's modern facilities. Modern facilities conserve energy by utilizing cogeneration facilities that produce steam and electricity simultaneously. Advances in alcohol dehydration have also yielded considerable energy savings (Hohmann and Rendleman).

Estimating Energy of Farm Inputs

Estimates of farm energy use are based on data from the 1991 Farm Costs and Returns Survey. The FCRS provides State data on diesel, gasoline, electricity, and natural gas used on the farm. This study focuses on the major corn-producing States: IL, IA, IN, NE, MN, OH, MI, WI, and SD (Ali and McBride). These nine States account for about 82 and 93 percent of U.S. corn and ethanol production, respectively. Focusing on these States is an improvement over many past studies that included data from every State to estimate farm energy use. Using a U.S. average distorts results because it includes farm production data from States that do not produce grain for ethanol use. We weighted farm input use by corn acreage planted in each State to estimate an average energy input level for corn production (table 2). The 1990-92 State average corn yield of 122 bu/ac was used to convert farm inputs from a per-acre basis to a per-bushel basis.

Table 3 shows the energy used by farm inputs to produce a bushel of corn for each State and a 9-State weighted average. The inputs are first converted to Btu/bu of energy by multiplying each input by its high energy heat value, e.g., a gallon of diesel fuel has 137,202 Btu, a gallon of gasoline has 125,073 Btu, a cubic foot of natural gas has 1,021 Btu and a kilowatt hour of electricity has 12,456 Btu. Data for electricity are based on coal generation. We then determined how much energy is required from each input to produce a bushel of corn. All thermal inputs and outputs in this study are made on a gross high heat value basis. The choice of basis, as long as it is applied in a consistent fashion, does not affect the overall results. The energy required for hauling these inputs to the farm from local retailers is included in the values in table 3. Electricity used on the farm is adjusted for transmission loss by a factor of 1.203 (EPA).

The actual amount of chemicals (e.g., pesticides and herbicides) applied to corn acreage is not provided by the FCRS, but the survey does collect information on chemical expenditures. These expenditures were converted to pounds of herbicides and insecticides based on number of acres treated and chemical prices. Pounds of chemicals were then converted to energy using Pimentel's Btu estimates of chemicals used in corn production. Estimates of the primary feedstocks used to manufacture farm chemicals are 60 percent oil, 23 percent natural gas, and 17 percent electricity. Electric power was assumed to be produced from coal. It requires about 180,000 Btu to produce a pound of insecticide or herbicide, including transportation energy.

Energy used for manufacturing nitrogen fertilizer, potash, and phosphate is based on information provided by the Fertilizer Institute. It requires 22,159 Btu to produce a pound of nitrogen, 1,245 Btu for a pound of potash, and 4,175 Btu for a pound of phosphate. More than 90 percent of the energy in the applied fertilizer is in the form of nitrogen, which is manufactured almost completely from natural gas. The energy embodied in phosphate includes 47 percent electricity, 27 percent diesel, and 26 percent natural gas. The energy invested in potash is 42 percent electricity, 31 percent diesel fuel, and 27 percent natural gas. Energy used for producing lime is 620 Btu/lb (Blankenhorn et al.).

The energy value of growing seed is assumed to be equal to 150 percent of the energy required to grow corn. Corn seed uses more energy than regular corn because there is an additional storage and packaging cost. Also, it takes more energy to haul the seed from a local seed farm to retailers and from retailers to corn farmers. Energy used for planting the seed and other farm activities such as land preparation, plowing, weeding, distribution of fertilizer and chemicals, irrigating, harvesting, and drying, are included in the total farm fuels and electricity estimates.

Table 2--Energy-related inputs used to grow corn in 9 States and 9-State weighted average

Item	Unit	9-State weighted average	IL	IN	IA	MN	NE	OH	MI	SD	WI
Seed	Kernels/acre	25,501.86	25384	24827	25150	26804	26546	26185	25274	22115	26310
Fertilizer:											
Nitrogen	Pounds/acre	124.50	156	143	119	79	142	122	127	68	107
Potash	Pounds/acre	52.77	78	64	47	55	23	59	47	26	63
Phosphate	Pounds/acre	58.17	90	108	49	57	3	91	63	11	45
Lime	Pounds/acre	242.18	480	340	280	40	0	140	680	0	120
Energy:											
Diesel	Gallons/acre	6.85	4	5	4	5	18	5	7	6	8
Gasoline	Gallons/acre	3.40	4	4	3	3	4	3	3	3	3
LPG	Gallons/acre	3.42	2	2	5	4	4	4	3	5	2
Electricity	kWh/acre	33.59	12	28	5	28	97	10	11	86	69
Natural gas	Cubic ft/acre	245.97	60	10	0	0	1610	10	50	0	10
Custom work	Dol./acre	6.68	8	6	7	5	6	5	4	4	16
Chemicals	Dol./acre	23	23	28	24	21	23	21	21	14	21
Custom drying	Dol./acre	1.79	1	2	2	2	2	1	2	0	1
Avg. yield	Bushels/acre	121.90	128	120	130	119	130	120	110	79	114

Energy used in transporting production inputs to the farm is based on an average distance of 500 miles by river and 150 miles by truck. This translates into 274 Btu per river-ton-mile, and 2,000 Btu per highway-ton-mile (DeLuchi). Barge transportation is a common upstream mode of transportation for delivering fuels, fertilizers, and agricultural chemicals. Trucks are used to haul these materials from river ports to wholesalers where they are sold to farmers. We assumed that trucks and barges are able to haul other products on their return trip, so those miles are not entered into the calculations.

The total energy required per bushel of corn by State and the weighted average of the nine States are shown on the bottom of table 3. Total Btu of energy per bushel of corn varies from about 41,000 Btu in Minnesota to over 81,000 Btu in Nebraska. Corn production in Minnesota, Iowa, and Ohio requires less energy than in other States because they can achieve relatively high yields without irrigation. In contrast, direct energy use (gasoline, diesel, electricity, natural gas, and LPG) for corn production in Nebraska accounts for about 48,000 Btu per bushel. More than 75 percent of the area planted to corn in Nebraska requires irrigation.

The estimates up to this point do not consider the energy inputs required to mine, extract, and manufacture the raw materials into the final energy product. The sum of these energy values must be added to the values in table 3 to estimate the total energy associated with each farm input required to produce a bushel of corn. Input efficiencies for fossil energy sources, which have been developed by EPA and adjusted for this study, were used to calculate these additional energy input values. For example, the energy efficiency of gasoline is 1.349 (table 4). Multiplying 1.349 by 3,493 Btu, the gasoline energy requirements shown in table 3, results in the total energy input requirement for gasoline (table 4). In addition, the energy contents of fertilizer and other farm inputs are adjusted by the energy efficiencies for the fossil fuels used in their production. Since a number of fuels may be required to manufacture the various farm inputs, the input efficiencies are weighted by each energy source or feedstock. Adjusting all the inputs in table 3 results in a 9-State weighted average of 59,765 Btu/bu (table 4).

Estimating Energy for Corn Transport

We assumed that 25 percent of the corn was delivered directly from the farm to ethanol plants, with the remaining 75 percent transported from farms to ethanol plants via grain elevators. The estimated trucking distance from elevator to plant is 100 miles round-trip. The diesel fuel requirement is about 2,000 Btu per ton-mile for a loaded truck and 1,000 Btu per ton-mile to return the empty truck. It requires 3,150 Btu per bushel to haul corn to the plant. Each gallon of ethanol produced in a dry mill uses 1,212 Btu of diesel fuel for hauling corn to the plant. A wet mill uses 1,260 Btu of diesel fuel for each gallon of ethanol produced.

Estimating Energy for Ethanol Conversion

Ethanol production facilities include both wet milling and dry milling operations. Dry mills are usually smaller and are built primarily to manufacture ethanol. Wet mill facilities are “corn refineries,” producing a host of high-valued products such as high-fructose corn syrup (HFCS), dextrose, and glucose syrup. Since both wet and dry milling are used to convert corn to ethanol, our energy conversion estimates are weighted accordingly. Wet milling accounts for about two-thirds of U.S. ethanol production and dry milling accounts for about one-third.

Thermal and electrical power are the main types of energy used in both types of milling plants. Currently most corn processing plants generate both electrical and thermal energy from burning coal. A few plants generate only steam; electricity is purchased from a utility. Electricity is used mostly for grinding and drying corn. Thermal energy is used for fermentation, ethanol recovery, and dehydration. Flue gas is used for drying and stillage processing.

Modern wet milling plants are able to produce 1 gallon of ethanol with 35,150 Btu of thermal energy and 2.134 kWh of electricity per gallon of ethanol production. If molecular sieves are used, the thermal input drops to 32,150 Btu per gallon. DeSpiegelaere reported that of the total thermal energy, 7,000 Btu/gal and 1.16 kWh were related to drying high-grade germ, fiber, and gluten. On average, wet mills produce 2.5 gallons of ethanol per bushel.

Table 3--Energy requirements of farm inputs for 9 States and 9-State weighted average

Item	IL	IN	IA	MN	NE	OH	MI	SD	WI	Weighted average
					Btu per bushel					
Seed	170	189	141	148	271	162	217	290	211	186
Fertilizer:										
Nitrogen	26,995	26,356	20,322	14,671	24,228	22,382	25,719	19,163	20,828	22,631
Potash	757	660	452	576	218	609	529	411	693	539
Phosphate	2,936	3,743	1,580	2,011	85	3,142	2,390	588	1,635	1,992
Lime	2,331	1,757	1,335	208	0	721	3,839	0	654	1,232
Energy:										
Diesel	4,793	5,843	4,686	5,427	18,881	5,131	8,620	10,650	9,184	7,713
Gasoline	3,439	3,710	3,281	3,019	4,301	2,723	3,530	4,846	2,802	3,493
LPG	1,515	1,619	3,292	3,287	2,510	2,780	2,654	5,705	1,578	2,575
Electricity	1,207	2,927	511	2,907	9,270	1,011	1,209	13,627	7,537	3,432
Natural gas	479	85	0	0	12,632	85	464	0	90	2,058
Custom work	1,480	1,213	1,289	1,131	1,106	981	927	1,271	3,619	1,371
Chemicals	5,635	7,176	5,730	5,380	5,448	5,433	5,936	5,723	5,784	5,766
Custom drying	902	1,153	1,463	1,321	1,153	764	1,654	39	964	1,134
Input hauling	1,062	1,062	1,062	1,062	1,062	1,062	1,062	1,062	1,062	1,062
Total energy	53,702	57,493	45,144	41,148	81,165	46,986	58,750	63,375	56,641	55,184

Table 4--Total energy requirements per bushel of corn, 9-State weighted average

Item	Primary energy requirements	Feedstock share	Natural gas	Diesel	Coal	Gasoline	Oil	Input efficiency factor	Total energy
	Btu/bu	*Percent*	- - -- - - - - - - - - - - - - *Btu/gal*	- - - - - - - - - - - - - - -					
Chemicals	5,766	23,60,17	1,326		980		3,460	1.065	6,142
Fertilizer:									
Nitrogen	22,631	90,10	20,368	2,263				1.012	22,911
Phosphate	1,992	25.9,26.7,47.4	516	532	944			1.088	2,168
Potash	539	26.7,31.3,42.0	144	169	226			1.095	590
lime	1,232	26.7,31.3,42.0	329	386	517			1.095	1,349
Diesel*	10,146			10,146				1.154	11,708
Gasoline	3,493					3,493		1.349	4,712
Natural gas and LP**	5,767		5,767					1.112	6,413
Electricity	3,432				3,432			1.038	3,563
Seed	186		97	43		11	11	1.126	209
Total	55,184		28,547	13,539	6,125	3,504	3,471		59,765

* Includes custom work and input hauling.
** Includes custom drying

A new dry milling plant requires 37,000 Btu of thermal energy and 1.2 kWh of electricity per gallon of ethanol. The typical dry mill facility produces 2.6 gallons of ethanol per bushel of corn. The total energy used for converting ethanol, weighted by milling process and adjusted by EPA's input efficiency factor for the energy used to mine and transport coal, is 53,277 Btu/gal.

The conversion estimates developed for this analysis represent modern facilities that use cogeneration. The use of cogeneration for steam appears to be absent from other studies, although it has become common for modern wet and dry mill ethanol plants to employ cogeneration technology to produce steam and in-house power. In addition, in many operations, flue gas drying of products is practiced. In our analysis, we coupled a modern coal-based cogeneration system to wet and dry mill facilities to supply power and steam from coal.

We used engineering design specifications reported by the industry when available, and, when necessary, we contacted plant operators to obtain additional information. Detailed information on dry milling plants is provided by Katzen et al. Similar information on wet milling operations is reported by DeSpiegelaere and by Wood. Sophisticated cogeneration facilities can be economically justified for plants with thermal and electrical needs of 30 million gallons per year and greater. For example, a 30-million-gallon-per-year plant requires 150 million Btu per hour of steam for all needs, the equivalent of a 15-megawatt coal plant. Such scale facilities typically produce relatively high-quality steam for cogeneration. The wet mill estimates are based on a plant with a capacity of 100 million gallons per year, and dry mills have a capacity of 30 million gallons per year. See Conway et al. for a further description of the engineering details and energy specifications of equipment used in plant operations.

Estimating Energy for Ethanol Distribution

Energy requirements to distribute and dispense ethanol were developed by EPA (1993). Energy requirements for shipping to the terminal and the retailer are both included. Further, to be consistent, the energy distribution charge recommended by EPA was increased in proportion to the relative energy densities of gasoline and ethanol. Ethanol is shipped to the wholesaler by truck and/or barge. The average trip from an ethanol plant to a terminal requires 2,501 Btu of diesel fuel. Ethanol is blended with gasoline at the terminal and delivered to retailers by truck. It is generally blended with 90-percent gasoline and 10-percent ethanol (E10). The energy used for blending along with the electricity used for dispensing the fuel from the pump is 672 Btu per gallon of ethanol.

Estimating Energy Credits for Coproducts

The coproducts used in this analysis include DDGS from dry milling, and corn oil, CGM, and CGF from wet milling. There are basically four ways to estimate energy credits for coproducts. First, the energy content of coproducts can be used to estimate energy credits. For example, a pound of corn gluten meal or corn gluten feed has a caloric content of 8,000 Btu. This results in about a 40-percent coproduct energy credit. The disadvantage of this method is that calories are a measurement of food nutritional value and are not a good proxy for energy in a fuel context.

A second method of estimating coproduct energy values is to use the relative market values of ethanol and its coproducts. For example, if energy used to produce ethanol is allocated between ethanol and coproducts based on their 10-year average market values, about 30 percent of energy used to produce ethanol should be assigned to the coproducts. The problem with this method is that prices of ethanol and ethanol coproducts are determined by a large number of market factors that are unrelated to energy content.

Third, one can allocate energy use among multiple products on an output weight basis, regardless of the operation's purpose or the coproducts' economic values. If energy used to produce ethanol is allocated between ethanol and coproducts based on the output weight, about 48 percent of energy used to produce ethanol should be assigned to the ethanol and 52 percent to coproducts. The problem with this method is that weight of a product is not always a good measurement of its energy value.

A fourth method, based on the replacement value of coproducts, is the method chosen for our final results. Energy credits are assumed to be equal to the energy value of a substitute product which the ethanol coproduct can replace. For example, in the case of corn gluten meal and corn gluten feed, soybean meal can be used as a substitute, and soybean oil can replace corn oil.

Using this method, about 20 percent of the energy used to produce ethanol would be assigned to coproducts. This method has appeal because the coproduct value is measured by energy units unlike the other methods that use calories, economic value, and weight to represent energy value. Also, since energy replacement values result in fewer energy credits than the other methods, it can be considered a conservative estimate.

Results

Table 5 summarizes the energy requirements by phase of ethanol production on a Btu-per-gallon basis. It includes energy losses from line loss, venting losses at the ethanol plant, and losses associated with mining, refining, and transporting raw materials. Also presented is the NEV of corn ethanol without coproduct credits for wet-milling, dry-milling, and a weighted average of wet and dry milling. The weighted average is based on production capacity, that is, two-thirds of U.S. ethanol capacity is from wet-milling and one-third from dry-milling. The average conversion rate for the two processes is 2.525 gallons per bushel. The NEV for dry-milling was the highest, 5,880 Btu per gallon. The NEV for wet-milling was slightly negative, -1,199 Btu per/gal, but the weighted average of the two processes has a positive net energy balance, 1,137 Btu/gal. The energy ratio, which is the ratio of energy-out to energy-in, is close to 1 in all three cases. In other words, the Btu in a gallon of ethanol is about equal to the energy required to produce a gallon of ethanol even when energy coproducts are not considered.

Table 5—Net energy value of corn-ethanol without coproduct energy credits

Production phase	Milling process: Dry	Milling process: Wet	Weighted average
		Btu/gal	
Corn production	21,225	22,074	21,793
Corn transport	1,212	1,260	1,244
Ethanol conversion	47,425	53,273	51,343
Ethanol distribution	3,173		
Energy losses	5,046	5,380	5,271
Total energy used	78,081	85,160	82,824
Net energy value[1]	5,880	-1,199	1,137
Energy ratio	1.08	0.99	1.01

[1] A gallon of ethanol contains 83,961 Btu on a high heat value basis.

Table 6--Net energy value per gallon of ethanol with coproduct energy credits

Item	Energy allocation: Ethanol	Energy allocation: Coproducts	Energy use	Energy use with coproduct credit	NEV with coproducts	Energy ratio
	- - -*Percent* - - -		- - - - - - - - - - - - - - - - -*Btu/gal* - - - - - - - - - - - - - - - - -			
Energy content:						
Wet mill	57	43	85,160	50,082	33,879	1.68
Dry mill	61	39	78,081	49,027	34,934	1.71
Weighted average	58	42	82,824	49,543	34,418	1.69
Market value:						
Wet mill	70	30	85,160	60,687	23,274	1.38
Dry mill	76	24	78,081	60,202	23,759	1.39
Weighted average	72	28	82,824	60,637	23,324	1.38
Replacement value:						
Wet mill	81	19	85,160	69,660	14,301	1.21
Dry mill	82	18	78,081	64,671	19,290	1.30
Weighted average	81	19	82,824	67,768	16,193	1.24
Output weight basis:						
Wet mill	48	52	85,160	42,740	41,221	1.96
Dry mill	49	51	78,081	40,087	43,874	2.09
Weighted average	48	52	82,824	41,619	42,342	2.02

Table 6 presents the NEV results for corn ethanol when energy credits are added to the estimates. Three conversion processes are considered: wet mill, dry mill, and a weighted average of wet and dry mill. For comparative purposes, the coproduct energy values are shown for each of the four methods described above. However, from this point forward, we will limit our discussion to the replacement value case, which is our preferred method for measuring coproduct energy value.

When coproduct energy credits are added to the calculations, the NEV of corn ethanol is positive regardless of the type of milling used. Dry-milling results in the highest NEV, 19,290 Btu, but wet-milling NEV differs by only 4,989 Btu per gallon. The NEV for the weighted average case is 16,193 Btu per gallon. Adjusting for coproduct credits also increases the energy ratio significantly. The energy ratio is 1.21 and 1.30 for wet- and dry-milling, respectively, and the weighted average energy ratio is 1.24.

As discussed earlier, some researchers prefer addressing the energy security issue by looking at the net energy gain of ethanol from a liquid fuels standpoint. In this case, only the liquid fuels used to grow and produce ethanol are considered in the analysis. Table 7 shows the energy required for making corn ethanol by energy supplies for dry-milling, wet-milling, and a weighted average. On a weighted average basis, about 85 percent of the total energy requirement comes from non-liquid fuels—coal accounts for 137,750 Btu per bushel and natural gas and liquefied petroleum (LP) account for 28,547 Btu per bushel. The liquid fuels, which include gasoline, diesel, and fuel oil, account for 29,998 Btu per bushel. Comparing the energy input value of these liquid fuels to the Btu output value of ethanol indicates a net energy gain of 182,676 Btu for every bushel of corn used in the production of ethanol. Thus, from a liquid fuel utilization perspective, ethanol can extend U.S. domestic crude reserves by a factor of 7 or similarly reduce U.S. import requirements.

When comparing this study with the other studies in table 1, we have similar results to the Marland and Turhollow study. Their NEV estimate was only about 2,000 Btu/gal greater than ours. Morris and Ahmed's NEV estimate is 9,460 Btu/gal greater, but much of this difference can be explained by the large value they use for coproduct energy credits. They are the only authors to use carbon dioxide as an energy coproduct, which adds 4,460 Btu/gal to their NEV. Information to determine how many modern ethanol facilities are selling carbon dioxide is not readily available, thus we did not include it in our analysis. The Keeney and DeLuca study reported a negative NEV, but they report a very low value for energy coproducts. They used only a stillage credit and did not include processing coproducts, such as CGF, CGM, and corn oil. Adding these coproduct credits to their analysis would raise their NEV estimate significantly. They also appear to have used an outdated estimate for the energy used for manufacturing nitrogen fertilizer. Adjusting their nitrogen fertilizer estimate to reflect modern technology and adding processing coproducts to their calculations would result in a positive NEV. Ho also reports a negative NEV, but his energy deficit is only 4,000 Btu/gal. Ho uses an unusually low corn yield of 90 bushels per acre. Looking at figure 1, it is apparent that this yield represents only very poor years, like 1988 when U.S. agriculture experienced a serious drought. If Ho had used a yield that reflected a normal year, his NEV estimate would likely be positive.

Pimentel reports the lowest NEV by far, -33,500 Btu/gal (LHV). There is about a 36,000 Btu difference

Table 7—Energy requirements by feedstock and petroleum replacement value of ethanol

Item	Dry mill	Wet mill	Weighted average
		Btu/bu	
Coal:			
Ethanol plant	123,305	133,183	129,923
Ethanol distribution	1,747	1,680	1,702
Corn production	6,125	6,125	6,125
Total	131,177	140,987	137,750
Natural gas & LP:			
Chemicals & fertilizers	22,780	22,780	22,780
Corn production	5,767	5,767	5,767
Total	28,547	28,547	28,547
Liquid fuels:			
Diesel			
Corn production	13,538	13,538	13,538
Corn delivery	3,150	3,150	3,150
Ethanol distribution	6,503	6,253	6,335
Gasoline	3,504	3,504	3,504
Fuel oil	3,471	3,471	3,471
Total	30,167	29,915	29,998
Total Btu-input	189,890	199,449	196,294
Total Btu-output	218,299	209,903	212,674
Petroleum replacement factor	7.24	7.02	7.09

between Pimentel's NEV and the average estimate of the studies shown in table 1. Many factors contribute to Pimentel's low estimate. For example, with the exception of Ho, Pimentel used the lowest corn yield among the studies. He used the highest fertilizer application rate and the lowest corn ethanol conversion rate. His energy estimate for energy used for nitrogen fertilizer processing is extremely high and appears not to reflect technology used by modern facilities. The amount of energy required for ethanol conversion in Pimentel's study also appears outdated. Conversion estimates used by the other studies ranged between 46,000 Btu/gal and 57,000 Btu/gal, while Pimentel reported that it required almost 74,000 Btu to produce a gallon of ethanol. In addition, he is the only author to include an energy value for steel, cement, and other plant materials in the ethanol-processing estimate.

Conclusions

We conclude that the NEV of corn ethanol is positive when fertilizers are produced by modern processing plants, corn is converted in modern ethanol facilities, farmers achieve normal corn yields, and energy credits are allocated to coproducts. Our NEV estimate of 16,193 Btu/gal can be considered conservative, since it was derived using the replacement method for valuing coproducts, and it does not include energy credits for plants that sell carbon dioxide. Corn ethanol is energy efficient, as indicated by an energy ratio of 1.24, that is, for every Btu dedicated to producing ethanol, there is a 24-percent energy gain. Moreover, producing ethanol from domestic corn stocks achieves a net gain in a more desirable form of energy. Ethanol production utilizes abundant domestic energy supplies of coal and natural gas to convert corn into a premium liquid fuel that can extend petroleum imports by a factor of 7 to 1.

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