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The Energy Balance of Corn Ethanol: An Update

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Abstract

Studies conducted since the late 1970s have estimated the net energy value (NEV) 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 NEV of corn ethanol has been rising over time 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 output:input ratio of 1.34.

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

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Summary

Ethanol production in the United States grew from just a few million gallons in the mid-1970s to over 1.7 billion gallons in 2001, spurred by national energy security concerns, new Federal gasoline standards, and government incentives. Production of corn-ethanol is energy efficient, in that it yields 34 percent more energy than it takes to produce it, including growing the corn, harvesting it, transporting 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 increasing farm income and reducing farm program payments, while helping the U.S. economy decrease its dependence on imported oil. Increasing ethanol production induces a higher demand for corn and raises the average corn price. Higher corn prices can result in reduced farm program payments.

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 energy efficiency 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 been improving significantly over time. The estimated net energy value (NEV) of corn ethanol was 21,105 Btu/gal under the following assumptions: fertilizers are produced by modern processing plants, corn is converted in modern processing 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 in the United States came when the 1970s 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. In the 1980s, ethanol established a role as an octane enhancer as the Environmental Protection Agency began to phase out lead in gasoline. Later, 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 oxygen requirements mandated by the act. Methyl tertiary butyl ether (MTBE), the only other oxygenate used in the United States, may soon be substantially reduced or eliminated, because of its propensity to contaminate ground and surface water. The elimination of MTBE could increase the demand for ethanol significantly.

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Introduction

Ethanol production in the United States grew from just a few million gallons in the mid-1970s to over 1.7 billion gallons in 2001. 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 production of ethanol made from corn (Hohmann and Rendleman, 1993). The initial impetus for ethanol commercialization came during the 1970s. The oil embargo of 1973 and the Iranian revolution of 1978 caused oil prices to increase rapidly, creating much concern over the security of national energy supplies. Fuel ethanol became attractive as a gasoline extender and was considered a means of increasing the U.S. gasoline supply. About the same time, the Environmental Protection Agency (EPA) was looking for a replacement for lead additives to gasoline used to boost the octane level. Because of its high octane content, ethanol soon established a role as an octane enhancer (Lee and Conway).

In 1990, ethanol production received a major boost with the passage of the Clean Air Act Amendments (CAA) of 1990. Provisions of the CAA established the Oxygenated Fuels Program and the Reformulated Gasoline (RFG) 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. Blending ethanol with gasoline has become a popular method for gasoline producers to meet the new oxygen requirements mandated by the CAA. Methyl tertiary butyl ether (MTBE), the only other oxygenate used in the United States, may soon be substantially reduced or eliminated, because of its propensity to contaminate ground and surface water (Blue Ribbon Panel, 1999). At least 18 States, including California, the State with the largest consumption of MTBE in the country, are considering a phase-out of MTBE. There is also proposed legislation to eliminate it nationwide and mandate a renewable fuels standard (RFS). An RFS would increase the demand for ethanol significantly because corn ethanol is the only viable renewable fuel sold in the U.S. market today.

Public policies aimed at encouraging ethanol development are largely motivated by the 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 can result in reduced farm program payments.

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, stating that corn-ethanol has a negative energy value (Ho, 1989; Pimentel, 1991; Pimentel and Pimentel, 1996; Pimentel, 2001). That is, according to critics, the non-renewable energy required to grow and convert corn into ethanol is greater than the energy value present in the ethanol fuel. Thus, they claim that corn ethanol is not a fossil 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 (U.S. Department of Energy, 1980; Anderson et al., 1988). In other words, abundant domestic feedstocks 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 fossil fuels used in the production of corn-ethanol. We use both approaches in our analysis.

The energy balance issue first surfaced in the mid-1970s when ethanol began to receive attention as a gasoline extender. Studies during that time that analyzed the energy benefits of substituting ethanol for gasoline generally concluded that the net energy value (NEV, defined as energy content of ethanol minus fossil energy used to produce ethanol) of corn ethanol was slightly negative (Ethanol Study Committee, 1979; Chambers et al., 1979). In the late 1980s, the U.S. desire to reduce air pollution placed ethanol in the spotlight once again and energy balance studies resurfaced. About the same time, studies estimating the emissions of greenhouse gases from ethanol began to appear in the literature (DeLuchi, 1991; Ho, 1989; Marland and Turhollow, 1990). Although these studies focused on estimating the greenhouse gases associated with ethanol relative to gasoline, some of these studies also reported the NEV of ethanol. 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 various researchers used data from different time periods. Studies using older data tended 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 paper is to identify the methodological differences creating the inconsistencies among study results and provide a more consistent estimate for the NEV of corn ethanol.

Table 1 shows the wide variation in the NEV estimates of several studies. Some studies use lower heating values (LHV) for measuring energy and others use higher heating values (HHV). Higher heating value, also called gross heating value, is the standard heat of combustion referenced to water in combustion exhaust as liquid water. Lower heating value, also called net heat of combustion, is the standard heat of combustion referenced to water in combustion exhaust as water vapor. In other words, the difference between HHV and LHV is the energy associated with condensation of the water vapor in the combustion products. Although these two methods can produce slightly different results, either approach can be used. However, once a method is chosen, it should be used consistently throughout the study for all energy calculations.

Table 1—Energy input assumptions of corn-ethanol studies

Study/year	Corn yield	Nitrogen fertilizer application rate	Nitrogen fertilizer production	Corn ethanol conversion rate	Ethanol conversion process	Total[1] energy use	Coproducts[1] energy credits	Net[1] energy value
	Bu/acre	*lb/acre*	*Btu/lb*	*gal/bu*	*Btu/gal*	*Btu/gal*	*Btu/gal*	*Btu/gal*
Pimentel (1991)	110	136	37,551	2.50	73,687	131,017 (LHV)	21,500	-33,517
Pimentel (2001)	127	129	33,547	2.50	75,118	131,062 (LHV)	21,500	-33,562
Keeney and DeLuca (1992)	119	135	37,958	2.56	48,470	91,196 (LHV)	8,078	-8,438
Marland and Turhollow (1990)	119	127	31,135	2.50	50,105	73,934 (HHV)	8,127	18,154
Lorenz and Morris (1995)	120	123	27,605	2.55	53,956	81,090 (HHV)	27,579	30,589
Ho (1989)	90	NR	NR	NR	57,000	90,000 (LHV)	10,500	-4,000
Wang et al. (1999)	125	131	21,092	2.55	40,850	68,450 (LHV)	14,950	22,500
Agri. and Agri-Food Canada (1999)	116	125	NR	2.69	50,415	68,450 (LHV)	14,055	29,826
Shapouri et al. (1995)	122	125	22,159	2.53	53,277	82,824 (HHV)	15,056	16,193
This study (2002)	125	129	18,392	2.66	51,779	77,228 (HHV)	14,372	21,105

NR: Not reported

LHV: Low heat value = 76,000 Btu per gallon of ethanol. Keeney and DeLuca used 74,680 Btu per gallon of ethanol.

HHV: High heat value = 83,961 Btu per gallon of ethanol. Lorenz and Morris used 84,100 Btu per gallon of ethanol.

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

Among past studies, Pimentel (1991) reported the lowest NEV for corn-ethanol. Based on a lower heating value of energy items, he reported that it requires a total energy input of about 131,000 British thermal units (Btu) to produce 1 gallon of ethanol. Compared with the LHV of 76,000 Btu for ethanol, this results in a net energy loss of 55,000 Btu per gallon. Even when coproducts were considered, Pimentel still estimated a net energy loss of about 33,500 Btu/gal. Pimentel reported identical results in a 1996 publication (Pimentel and Pimentel, 1996). Pimentel made some minor adjustments in a 2001 publication, but most of the data appeared to come from the 1991 study and the NEV remained about the same (table 1). Keeney and DeLuca (1992) also reported a negative NEV, but their energy deficit was only about 8,440 Btu/gal. Keeney and DeLuca did not consider corn-processing byproducts, but they showed that a positive energy balance could be attained with low-input corn production. Marland and Turhollow (1990) reported that it required almost 74,000 Btu (HHV basis) to produce a gallon of ethanol assuming that conversion took place in the best ethanol facilities available then. When energy use is allocated to ethanol from the coproducts made during the ethanol conversion process, such as gluten meal, gluten feed, and corn oil, they concluded that the NEV of corn ethanol was over 18,000 Btu/gal. Results from the Shapouri et al. (1995) study were very similar to the results of the Marland and Turhollow study. Lorenz and Morris (1995) derived the most favorable NEV estimate. When adding energy coproduct credits, they estimated a net energy gain of about 30,500 Btu/gal. Agriculture and Agri-Food Canada (AAFC) (1999) and Wang (1999) also found relatively high net energy values for corn ethanol.

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 64,000 Btu/gal difference in the results of Pimentel (1991) and Lorenz and Morris. With respect to growing the corn, Pimentel reports that it requires 56,720 Btu/gal (LHV) compared with Lorenz and Morris's 27,134 Btu/gal (HHV). Both studies used the same basic inputs, such as fertilizer, pesticides, and fuel, but Pimentel also included the energy value embodied in farm machinery, though he did not present any details on how he derived embodied energy in farm machinery.

Another factor that makes Pimentel's estimates higher is the use of a national average corn yield of only 110 bu/ac, which is characteristic of corn yields seen in U.S. agriculture in the early 1980s. Lorenz and Morris used 120 bu/ac, which is based on data from more recent years. Although Pimentel increased corn yield in his 2001 report, the NEV remained about the same as reported in the 1991 study (table 1).

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 reported the highest energy estimate for fertilizer, almost 38,000 Btu/lb, using source data from a 1980 study (Dovring and McDowell). More recent studies, such as Wang et al. (1999), reported about 21,000 Btu/lb, and Lorenz and Morris (1995) reported about 27,600 Btu/lb.

Fertilizer application rates can also make a difference in energy use estimates. For example, Pimentel's (1991) nitrogen requirement was 136 pounds per acre, which is 7 pounds per acre higher than the average nitrogen rate of the studies reported in table 1. Pimentel (1991) also reported the highest phosphorus application rate – 67 pounds per acre compared with 40, 48, 50, and 57 pounds per acre in AAFC (1999), Lorenz and Morris (1995), Marland and Turhollow (1990), and Keeney and DeLuca (1992), respectively.

Energy used in ethanol conversion facilities differs greatly among the studies. For example, the energy estimate for ethanol conversion in Pimentel's 1991 and 2001 studies are over 30,000 Btu per gallon higher than the Wang et al. estimate. Much of this difference may be related to the data collection periods used. Estimates used in the Pimentel studies for ethanol conversion came from data collected in the 1980s (Energy Research Advisory Board, 1980; and National Advisory Panel, 1987). Wang et al. used estimates that 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. Another major difference between the Pimentel studies and most other studies is that his 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 most other studies. Pimentel also used a lower ethanol conversion rate—2.50 gal/bu. With the exception of Marland and Turhollow (1990), the other studies use a conversion rate of 2.53 gal/bu or higher.

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. Distiller's 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 Lorenz and Morris (1995) are the only authors to estimate a CO_2 coproduct credit. Some studies, including Wang et al. (1999), Lorenz and Morris (1995), and Shapouri et al. (1995), used both wet-and dry-milling coproducts and weighted coproduct energy credits based on the industry average mix of wet- and dry-milling plants. Pimentel (1991) and AAFC (1999) used only DDGS, Keeney and DeLuca (1992) used only a credit for stillage, and Marland and Turhollow (1990) used coproducts from wet milling. Ho (1989) gave energy credits for fusel oil, aldehydes, and DDGS. In addition to using different coproducts, various researchers also used 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 nonrenewable 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, farm vehicles, and transportation equipment are extremely difficult to quantify. Moreover, secondary inputs related to the ethanol plant would account for very little energy on a per gallon basis. This is because the energy embodied in fixed inputs, such as the cement used to build the plant, would have to be distributed over total production (including coproducts) during the lifetime of the plant. In the case of farm production, the energy embodied in farm equipment would have to be distributed over all crops (including crops not used for ethanol production) for which the equipment was used over the lifetime of the equipment. Of the studies listed in table 1, only Pimentel attempted to quantify the energy embodied in the materials used to construct an ethanol plant and farm machinery. His estimates are based on a plant making ethanol from sugarcane in 1979 (Slesser and Lewis) and farm equipment manufactured in 1976 (Doering). However, few details are given in Pimentel's study on the method used for estimating the energy embodied in construction materials and farm equipment.

Data Trends

Reliable data are required to estimate the NEV of corn ethanol. This analysis uses farm production data from USDA to estimate energy values for farm inputs such as gasoline and diesel fuel use, fertilizers, and other chemicals. It is important that the most current data available 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 20 years. Higher corn yields, lower energy use per unit of output in the fertilizer industry, and advances in corn-to-ethanol conversion technologies have greatly enhanced the economic and technical feasibility of producing ethanol.

Total energy used in U.S. agriculture, including pesticides, fertilizers, other chemicals, liquid fuels, natural gas, and electricity, increased from 1,545 trillion Btu in 1965 to a peak of 2,244 trillion Btu in 1978, and then steadily declined to a low of 1,548 trillion Btu in 1989 (USDA, 1997). Since 1989, there has been a slight upward movement in energy use, but still well below the peak levels that occurred in the 1970s. Agricultural energy use was about 1,800 trillion Btu in 1999, but 2000 energy use dropped to about 1,600 trillion Btu when higher energy prices caused farmers to conserve. The decline in agricultural energy use since 1978 is largely attributed to the replacement of gasoline-powered farm machinery with more fuel-efficient diesel engines (Uri and Day, 1991).

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 farm resources are being used more efficiently.

Fertilizer use in grain production rose for many years, peaking in the early 1980s when it began to decline. Nitrogen use per planted acre of corn declined from

140 pounds in 1985 to 132 pounds in 2000 (Taylor, 1994; USDA/NASS). Phosphate use declined from 60 to 47 pounds per acre, and potash use declined from 84 pounds to 51 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 20 years, and U.S. farmers have gained substantial real energy-saving benefits in terms of nitrogen and phosphorus (Bhat et al., 1994). Energy savings in nitrogen production has been especially important since it has a much higher average energy requirement than phosphorous and potash fertilizers. Bhat et al. (1994) reported that the energy consumed in producing nitrogen fertilizers declined about 11 percent from 1979 to 1987.

Making ethanol from corn also has become more energy efficient. Hohmann and Rendleman (1993) 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 also resulted in substantial energy savings. Modern plants are conserving energy by utilizing cogeneration units that produce steam and electricity simultaneously. Advances in alcohol dehydration have also resulted in considerable energy savings (Hohmann and Rendleman, 1993).

Estimating Energy of Farm Inputs

Estimates of farm energy use in this study are based on data from the 1996 Agricultural Resource Management Survey (ARMS), the most recent data available from USDA. ARMS (formerly called the Farm Costs and Returns Survey (FCRS)), is conducted every 5 years and provides data from selected States on fuel, electricity, natural gas, fertilizer, and chemicals used on the farm and activities of moving farm products to initial storage facilities (Ali and McBride, 1994). We focused our analysis on the major corn-producing States: Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin. These nine States account for about 80 and 91 percent of U.S. corn and ethanol production, respectively. We weighted farm input use by corn acreage planted in each State to estimate an average input level for corn production.

There is a considerable amount of variation in State energy use estimates between survey years. This variation illustrates the unpredictable effect that weather has on energy use and other aspects of production agriculture. For example, the 1991 FCRS data used in the Shapouri et al. (1995) study were considerably different from the data collected by the 1996 ARMS (tables 2 and 3). The 1991 corn crop was hampered by dry weather during the summer months, resulting in lower yields. Production totaled 7.5 billion bushels, about 6 percent below the 1990 crop. The U.S. average yield was about 109 bushels per harvested acre, down

Table 2—Energy-related inputs used to grow corn in nine States and nine-State weighted average, 1991

		IL	IN	IA	MN	NE	OH	MI	SD	WI	Nine-State weighted average
Yield (1990-92)	*Bushels/acre*	128	120	130	119	130	120	110	79	114	121.9
Seed	*Kernels/acre*	25,384	24,827	25,150	26,804	26,546	26,185	25,274	22,115	26,310	25,502
Fertilizer:											
Nitrogen	*Pounds/acre*	156	143	119	79	142	122	127	68	107	124.5
Potash	*Pounds/acre*	78	64	47	55	23	59	47	26	63	52.77
Phosphate	*Pounds/acre*	90	108	49	57	3	91	63	11	45	58.17
Lime	*Pounds/acre*	480	340	280	40	0	140	680	0	120	242.18
Energy:											
Diesel	*Gallons/acre*	4	5	4	5	18	5	7	6	8	6.85
Gasoline	*Gallons/acre*	4	4	3	3	4	3	3	3	3	3.4
LPG	*Gallons/acre*	2	2	5	4	4	4	3	5	2	3.42
Electricity	*kWh/acre*	12	28	5	28	97	10	11	86	69	33.59
Natural gas	*Cubic ft/acre*	60	10	0	0	1,610	10	50	0	10	245.97
Custom work	*Dol./acre*	8	6	7	5	6	5	4	4	16	6.68
Chemicals	*Dol./acre*	23	28	24	21	23	21	21	14	21	23
Custom drying	*Dol./acre*	1	2	2	2	2	1	2	0	1	1.79

Source: USDA, Economic Research Service and Office of Energy Policy and New Uses

Table 3—Energy-related inputs used to grow corn in nine States and nine-State weighted average, 1996

		IL	IN	IA	MN	NE	OH	MI	SD	WI	Nine-State weighted average
Yield (1995-97)	*Bushels/acre*	126	120	133	126	129	123	115	94	119	125
Seed	*Kernels/acre*	25,384	24,827	25,150	26,804	26,546	26,185	25,274	22,115	26,310	25,495
Fertilizer:											
Nitrogen	*Pounds/acre*	160	134	128	117	137	148	118	78	80	129.38
Potash	*Pounds/acre*	102	87	58	46	5	89	99	7	48	59.25
Phosphate	*Pounds/acre*	71	54	44	50	25	74	48	27	33	48.16
Lime	*Pounds/acre*	20	20	20	0	0	20	20	0	60	15.35
Energy:											
Diesel	*Gallons/acre*	7	5	7	8	18	6	8	5	9	8.6
Gasoline	*Gallons/acre*	3	3	3	3	4	3	3	2	2	3.09
LPG	*Gallons/acre*	5	8	7	10	4	15	5	3	3	6.36
Electricity	*kWh/acre*	15	101	154	91	82	41	51	16	20	77.13
Natural gas	*Cubic ft/acre*	150	550	50	0	560	0	250	10	270	200
Custom work	*Dol./acre*	14	14	14	15	17	14	15	17	15	15.07
Chemicals	*Dol./acre*	29	29	29	26	19	29	26	19	26	26.00

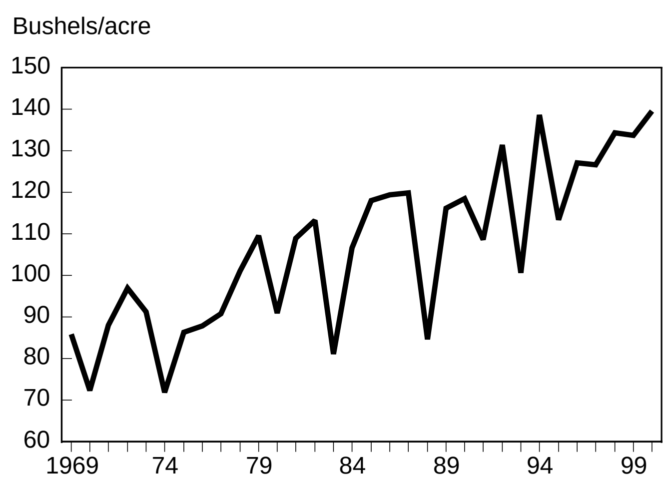
Source: USDA, Economic Research Service and Office of Energy Policy and New Uses.

10 bushels from 1990 and 30 bushels lower than the record yield of 1994. Although yield was down in 1991 due to poor summer weather, the corn crop was aided by good maturing and harvesting weather during the fall. Dry ground conditions in the fall allowed farmers to get their equipment in the fields at the ideal time, and 93 percent of the corn crop was harvested by November 1. In addition to good harvest conditions, the dry weather reduced the moisture content of the 1991 corn crop. This helped the NEV of ethanol, because a relatively small amount of energy was needed for drying corn in 1991.

When the survey was conducted again in 1996, the U.S. corn yield was about 127 bushels per acre, up 13.6 bushels from 1995, but 11.5 bushels below the record of 1994. A cool wet spring across the Corn Belt in 1996 slowed corn growth and many farmers delayed planting until the end of spring. To lengthen the growing season, the corn harvest was slowed in the Midwest to give the crop more time to mature and dry. Although the season ended later than usual in most States, the 1996 corn crop had a high moisture content, and the energy needed for drying was abnormally high. This is reflected in the increase in electricity, liquefied petroleum gas (LPG), natural gas, and diesel fuel use in some States from 1991 to 1996 (tables 2 and 3). Thus, using the 1996 farm survey data may overestimate the average energy used on the farm in recent years. Ideally, we would prefer to use annual average energy use during the last several years, but such data are not available.

Yield is a critical part of the NEV calculation—for every 1 percent increase in yield, the NEV of ethanol increases 0.37 percent, ceteris paribus. Although yield has been generally rising over time, the annual variation is very volatile (fig. 1). Therefore, we used a 3-year average yield instead of the average yield for the survey year. The 1990-92 average corn yield, weighted by corn production in each State, was used to convert farm inputs from a per acre basis to a per bushel basis (table 2). The farm energy use estimates for 1996 are based on the nine-State 1995-97 average corn yield (table 3).

Figure 1
U.S. corn yield



Source: National Agricultural Statistics Service, USDA.

Nebraska had the highest energy use in both survey years, primarily due to the energy used for irrigation. More than 78 percent of the corn acres harvested in Nebraska required irrigation in 1996. In contrast, only 5 percent of the corn acreage was irrigated in Iowa and no corn acreage was irrigated in Indiana, Illinois, and Wisconsin. The impact of irrigation requirements on energy use in Nebraska was especially apparent during 1991's extremely dry summer. Over 1,600 cubic feet of natural gas, used to power irrigation pumps, were required per acre of corn in Nebraska in 1991 (table 2). This was almost three times more natural gas than was required in 1996 (table 3). Electricity, another energy source for irrigation pumps in Nebraska, was also unusually high in 1991. The relatively high electricity use estimate in South Dakota in 1991 was also probably the result of increased irrigation needs–almost all irrigation pumps in South Dakota are powered by electricity. In 1996, when less irrigation water was required, the amount of electricity used to grow a bushel of corn in South Dakota decreased significantly.

Other major factors that caused variation in the State energy use estimates were drying requirements and fertilizer use. There was a significant rise in total energy use in 1996 in Indiana, Iowa, Minnesota, and Ohio, largely because of the increased use of LPG, electricity, and natural gas required for drying crops. Minnesota and Ohio corn acreage also required significantly more energy in the form of nitrogen fertilizer in 1996. On the other hand, Wisconsin reduced energy consumption in 1996 because of significantly less fertilizer use and lower electricity requirements for irrigation.

Table 4 reports farm energy-related inputs on a Btu per bushel of corn basis for each State and a nine-State weighted average for 1996. The inputs are first converted to Btu/bu of energy by multiplying each input by its high heat energy value, e.g., a gallon of diesel fuel has 137,200 Btu, a gallon of gasoline has 125,070 Btu, and a cubic foot of natural gas has 1,020 Btu. One kilowatthour of electricity has 8,625 Btu, after adjusting for the U.S. average Btu loss during electricity generation. Estimates for electricity generation are based on a weighted average of all sources of power, including coal, natural gas, nuclear, and hydroelectric. 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 measured on a higher heating value basis. The energy required for hauling these inputs to the farm from local retailers was also estimated (table 4). Estimates for transporting the corn from farms to the first storage facilities are included in the diesel fuel estimate in table 4. Electricity used on the farm is adjusted for transmission loss by a factor of 1.087, according to data on electricity losses during transmission and distribution from the Energy Information Administration (Wang et al., 1999).

The amount of fertilizer applied to corn is provided by the ARMS and converted to Btu. The actual amount of

Table 4—Total energy requirements of farm inputs for nine States and nine-State weighted average, 1996

	IL	IN	IA	MN	NE	OH	MI	SD	WI	Nine-State weighted average
					Btu to produce one bushel of corn					
Seed	227	245	220	259	225	286	290	268	287	242
Fertilizer use:										
Nitrogen	23,372	20,579	17,660	17,118	19,491	22,091	18,872	15,297	12,303	19,082
Phosphate	1,154	911	679	805	401	1,222	852	578	559	789
Potassium	3,024	2,700	1,642	1,367	133	2,720	3,236	275	1,525	1,776
Lime	117	123	111	0	0	120	128	0	371	90
Energy:										
Diesel	8,887	6,171	8,884	10,953	22,697	7,502	11,520	8,657	12,856	11,175
Gasoline	3,181	4,143	4,065	3,958	4,251	4,168	4,566	3,752	2,925	3,859
LP gas	4,285	6,744	5,233	7,922	2,840	12,247	4,713	3,160	2,213	5,200
Natural gas	1,292	4,973	408	0	4,710	0	2,359	115	2,462	1,768
Electricity	1,125	7,895	10,849	6,798	5,929	3,146	4,117	1,642	1,540	5,665
Chemicals	4,251	4,899	3,633	3,160	3,381	4,823	4,022	3,237	3,053	3,797
Custom work	3,146	3,303	2,981	3,236	3,634	3,223	3,545	4,987	3,426	3,366
Input hauling	920	808	619	556	427	884	815	393	609	663
Total energy	54,980	63,494	56,984	56,133	68,120	62,433	59,034	42,360	44,128	57,476

Source: USDA, Economic Research Service and Office of Energy Policy and New Uses.

pesticides (herbicides and insecticides) applied to corn acreage is not provided by the ARMS, but the survey does collect information on pesticide expenditures. These expenditures were converted to pounds of pesticides based on the number of acres treated and prices in that year. Pounds of pesticides were then converted to Btu. Table 5 shows energy used to produce agricultural fertilizers and pesticides. The data for energy use of manufacturing fertilizers and pesticides are from Argonne's Green House Gases Regulated Emissions and Energy Use in Transportation (GREET) model. Argonne has developed this full fuel-cycle model to estimate energy use and emissions from transportation fuel/vehicle technology systems. The model includes detailed information on corn farming and chemical manufacturing. The model and its documents are posted at *http://greet.anl.gov*. Energy estimates for manufacturing nitrogen fertilizer and phosphoric acid were derived from the Fertilizer Institute Production Cost Surveys (2000). Energy used for producing lime is 620 Btu/lb (Blankenhorn et al., 1985).

Energy use for transporting fertilizers and pesticides was calculated with the following assumptions. We assumed that the transportation energy is diesel fuel (table 4). A transportation distance of 400 miles for barge and 750 miles for rail was assumed for transporting chemicals from manufacturing plants to bulk terminals. A transportation distance of 50 miles was assumed for Class 8 trucks to transport from bulk terminals to mixing centers. A transportation distance of 30 miles was assumed for Class 6 trucks to transport from mixing centers to corn farms. With these assumptions, we applied Argonne's GREET model to calculate a transportation energy use of 301 Btu/lb for chemical transportation.

The energy value of growing seed is assumed to be equal to 150 percent of the energy required to grow corn. The nine-State weighted average kernels per acre is 25,495 (table 3). 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, is included in the total farm fuels and electricity estimates (table 4).

The estimates in table 4 also include the energy used to mine, extract, and manufacture the raw materials into the final energy product. The sum of these energy values was included in the estimates to derive the total energy associated with each farm input required to produce a bushel of corn. Input efficiencies for fossil energy sources, which were estimated with Argonne's GREET model, were used to calculate these additional energy input values. In particular, GREET estimated the energy efficiency of gasoline (80.5 percent), diesel fuel (84.3 percent), LPG (89.8 percent), natural gas (94.0 percent), coal (98.0 percent), and electricity (39.6 percent). After adjusting the inputs by these energy efficiencies, the total energy required to produce a bushel of corn in 1996 was 57,476 Btu (table 4).

Estimating Energy for Corn Transport

We made the following assumptions to calculate energy use for transporting corn from farms to ethanol plants:

- A distance of 40 miles for class 8 trucks from collectors to terminals,
- A distance of 350 miles for barges from terminals to ethanol plants,
- A distance of 400 miles for rail from terminals to ethanol plants.

As mentioned earlier, the farming survey data already included energy use for transporting corn from farms to initial storage facilities, typically a local grain elevator. The energy associated with transporting the corn from local storage facilities to ethanol plants was estimated by the GREET model. The average energy

Table 5—Energy used to produce fertilizers, herbicides, and insecticides

	Nitrogen[1]	Phosphoric acid[1]	Potash[2]	Herbicides[2]	Insecticides[2]
Diesel (Btu/lb)	0	0	642	67,310	69,299
Natural gas (Btu/lb)	16,857	56	559	25,802	26,564
Electricity (kWh/lb)	0.094	0.215	0.255	5.589	5.755

[1] Fertilizer Institute, 2000.
[2] GREET model, Agonnne National Laboratory, 2001

used for transporting a bushel of corn was 6,020 Btu or about 2,263 Btu per gallon of ethanol (table 6).

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 mills are "corn refineries," producing a host of high-value 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 55 percent of U.S. ethanol production, and dry milling accounts for about 45 percent.

Thermal and electrical power are the main types of energy used in both types of milling plants. Currently, most wet-milling plants generate both electrical and thermal energy from burning natural gas and coal. Most dry-milling plants generate only steam, requiring that they purchase electricity from a utility. Electricity is used mostly for grinding and running electric motors. Thermal energy is used for fermentation, ethanol recovery, and dehydration. Flue gas is used for drying and stillage processing.

Estimates of the energy used to convert corn to ethanol is based on a U.S. industry survey conducted in September 2001 by BBI International. The survey was commissioned by the Office of Energy Policy and New Uses, USDA. BBI International collected information from ethanol plants on thermal and electrical energy used per gallon of ethanol for both dry and wet ethanol plants. The survey was conducted by telephone interviews with 17 dry-mill ethanol plants. The number of wet-mill ethanol plants cannot be disclosed in order to protect the confidentiality of the wet-mill producers in the survey. The total production capacity of the plants in the survey is over 1.3 billion gallons or about 65 percent of industry's current capacity.

On average, dry-mill ethanol plants used 1.09 kWh of electricity and over 36,000 Btu of thermal energy per gallon of ethanol. With energy losses to produce electricity and natural gas considered, the average dry-mill ethanol plant consumed about 48,772 Btu of primary energy per gallon of ethanol produced (table 6). Wet-mill ethanol plants participating in the survey used an average 51,060 Btu per gallon of coal and natural gas (with more plants using natural gas) to produce the steam and electricity used in the plants. After adjustments for energy losses to produce coal, natural gas, and electricity, on average, a wet-mill ethanol plant used 54,239 Btu of primary energy to make a gallon of ethanol (table 6). The average conversion rate for dry mills is 2.64 gallons per bushel and 2.68 gallons per bushel for wet mills.

Table 6—Energy use and net energy value per gallon without coproduct energy credits, 1996

	Milling process		
Production phase	Dry	Wet	Weighted average
	Btu per gal		
Corn production	21,803	21,430	21,598
Corn transport	2,284	2,246	2,263
Ethanol conversion	48,772	54,239	51,779
Ethanol distribution	1,588	1,588	1,588
Total energy used	74,447	79,503	77,228
Net energy value	9,513	4,457	6,732
Energy ratio	1.11	1.04	1.08

Energy for Ethanol Distribution

We made the following assumptions for calculating energy use to transport ethanol from ethanol plants to refueling stations. A distance of 80 miles was assumed for trucks to transport ethanol from ethanol plants to collection terminals; a distance of 520 miles for barge from collection terminals to fuel distribution terminals; a distance of 800 miles for rail from collection terminals to distribution terminals; and a distance of 25 miles for trucks from distribution terminals to refueling stations. With the GREET model, we estimated an energy use of 1,588 Btu per gallon of ethanol transported for both wet and dry milling (table 6).

Estimating Energy Credits for Coproducts

The coproducts used in this analysis include distiller's dried grains (DDGS) with solubles from dry milling, and corn oil, corn gluten meal (CGM), and corn gluten feed (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 could be assigned to the ethanol and 52 percent to coproducts. The problem with this method is that the 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 required to produce a substitute for the ethanol coproduct. In this analysis, we used soybean meal as the substitute for distiller's grain with solubles, corn gluten meal and corn gluten feed, and soybean oil was used as the substitute for corn oil. Data from the 1991 FCRS soybean survey was used to help estimate the energy value of the soybean coproducts (Ali and McBride, 1994). Using this method, about 19 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 non-energy units. Also, since energy replacement values result in less energy credits than the other methods, it can be considered a conservative estimate.

Results

Table 6 summarizes input energy requirements by phase of ethanol production on a Btu per gallon basis for 1996 without coproduct credits. It includes energy losses from line loss, venting losses at the ethanol plant, and energy associated with mining, refining, and transporting raw materials used in energy production. Energy estimates are provided for both wet and dry milling, as well as a weighted average of these two ethanol production processes. In each case, corn ethanol has a positive energy balance, even before adding coproduct energy credits. Table 7 presents the final NEV results with coproduct energy credits. 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. The NEV estimate for corn ethanol produced from wet milling is 19,262 Btu per gallon, the NEV estimate for dry milling is 22,629 Btu per gallon, and the weighted average is 21,105 Btu per gallon (table 7). The energy ratio is 1.30 and 1.37 for

Table 7—Net energy value per gallon of ethanol and energy ratio with coproduct energy credits, 1996

	Energy allocation						
	Ethanol	Coproduct	Energy use	Coproduct credit	Energy use with coproduct credit	NEV with coproducts	Energy ratio
	Percent		*Btu/gal*				
Output weight basis:							
Wet mill	48	52	79,503	40,516	38,987	44,974	2.15
Dry mill	49	51	74,447	37,158	37,289	46,672	2.25
Weighted average	48	52	77,228	39,333	37,895	46,066	2.22
Energy content:							
Wet mill	57	43	79,503	33,503	46,000	37,961	1.83
Dry mill	61	39	74,447	28,415	46,032	37,929	1.82
Weighted average	58	42	77,228	31,769	45,459	38,502	1.85
Market value:							
Wet mill	70	30	79,503	23,374	56,129	27,832	1.50
Dry mill	76	24	74,447	17,486	56,961	27,000	1.47
Weighted average	72	28	77,228	21,179	56,049	27,912	1.50
Replacement value:							
Wet mill	81	19	79,503	14,804	64,699	19,262	1.30
Dry mill	82	18	74,447	13,115	61,332	22,629	1.37
Weighted average	81	19	77,228	14,372	62,856	21,105	1.34

wet and dry milling, respectively, and the weighted average energy ratio is 1.34.

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 fossil fuels used to grow corn and produce ethanol are considered in the analysis. On a weighted average basis, about 83 percent of the total energy requirements come from non-liquid fuels, such as coal and natural gas. The liquid fuels, which include gasoline, diesel, and fuel oil, account for about 21,700 Btu per bushel. Calculations based on liquid fuel use provide an estimate of the petroleum displacement value of ethanol. Comparing the energy input value of liquid fuels to the total Btu output value of ethanol indicates a net energy gain of about 70,600 Btu for every bushel of corn used in the production of ethanol. In other words, one Btu of liquid fossil fuel, used in combination with other forms of energy, can produce 6.34 Btu of fuel ethanol.

Discussion

When comparing this study with the other studies in table 1, the results are similar to those of Marland and Turhollow (1990) and Wang et al. (1999). The NEV estimates from these three studies range from about 18,000 Btu/gal to almost 23,000 Btu/gal. The NEV estimated in this study is almost 5,000 Btu per gal greater than the NEV estimated by Shapouri et al. (1995), which used 1991 ARMS data to estimate the energy used in farm production. The higher NEV in this study is partly due to a higher average corn yield that lowered the energy input used per acre. Moreover, increased energy efficiency in fertilizer production and other agricultural chemicals, and the adoption of energy-saving technologies in corn ethanol conversion, increased the NEV in the latter study (table 1).

Lorenz and Morris's NEV estimate is over 9,000 Btu/gal greater than our NEV, 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. Only a few ethanol facilities are selling carbon dioxide today, so we did not include it in our analysis. The Keeney and DeLuca study reported a negative NEV, but they reported 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 NEV estimate 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 likely result in a positive NEV. Ho (1989) also reported a negative NEV, but his energy deficit is only 4,000 Btu/gal. Ho used an unusually low corn yield of 90 bushels per acre. Looking at figure 1, it is apparent that this yield would represent 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 have been significantly higher.

Pimentel reported the lowest NEVs by far, about -33,500 Btu/gal. There is a difference of more than 50,000 Btu between Pimentel's NEV and the estimate derived in this study (table 1). Many factors contributed to Pimentel's low estimate. For example, with the exception of Ho, Pimentel's 1991 study used the lowest corn yield among the studies. His 1991 study used the highest fertilizer application rate and the lowest corn ethanol conversion rate. He increased corn yield and reduced fertilizer application rate in his 2001 study, but oddly, the NEV in the latter study went down. His estimate for energy used for nitrogen fertilizer processing was extremely high and appears not to reflect technology used by modern facilities. The amount of energy required for ethanol conversion in Pimentel's studies also appears outdated. Conversion estimates used by the other studies ranged between 40,850 Btu/gal (LHV) and 57,000 Btu/gal (LHV), while Pimentel's studies calculated about 75,000 Btu (LHV) to convert a gallon of ethanol. In addition, he is the only author to include an energy value for steel, cement, and other materials used in the production of equipment, farm vehicles, and the ethanol plant.

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, and farmers achieve average corn yields. Our NEV estimate of over 21,000 Btu per gallon could 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 1.34; that is, for every Btu dedicated to producing ethanol there is a 34-percent energy gain. Furthermore, producing ethanol from domestic corn stocks achieves a net gain in a more desirable form of energy, which helps the United States to reduce its dependence on imported oil. Ethanol production utilizes abundant domestic energy feedstocks, such as coal and natural gas, to convert corn into a premium liquid fuel. Only about 17 percent of the energy used to produce ethanol comes from liquid fuels, such as gasoline and diesel fuel. For every 1 Btu of liquid fuel used to produce ethanol, there is a 6.34 Btu gain.

When looking at past NEV studies, it appears that energy requirements for producing a gallon of ethanol are falling over time. One of the primary factors for this increase in energy efficiency is the increase in U.S. corn yields. When ethanol first emerged as a gasoline extender in the 1970s, corn yield was averaging about 90 bushels per acre. This study used 1995-97 average corn yield of 125 bushels per acre, which is about 39 percent greater than the yields of the 1970s. Corn yields continue to rise in the United States—the average corn yield per acre for the past 3 years (1999-2001) was about 135 bushels per acre. If the 1999-2001 average corn yield were used in this analysis, the total energy used to produce a bushel of corn would decline by more than 4,200 Btu. As corn yields increase over time, we can expect the energy balance of corn ethanol to increase, as well. Other major factors causing this increase in energy efficiency are related to the energy-saving technologies adopted by ethanol producers and manufacturers of fertilizers and other farm inputs. Higher energy costs will likely continue to provide incentives for these industries to become more energy efficient, which will continue to push the NEV of corn ethanol higher.

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Glossary

AAFC	Agriculture and Agri-Food Canada
ARMS	Agricultural Resources Management Survey
Btu	British thermal units
CAA	Clean Air Act Amendments
CO	Carbon monoxide
CO_2	Carbon dioxide
CGF	Corn gluten feed (21 percent protein)
CGM	Corn gluten meal (60 percent protein)
DDGS	Distiller's dried grains with solubles
EPA	U.S. Environmental Protection Agency
FCRS	Farm Costs and Returns Survey
GHG	Greenhouse gases
GREET	Greenhouse gases, regulated emissions, and energy use in transportation
HHV	High-heat value
HFCS	High-fructose corn syrup
KWh	Kilowatthour
LHV	Low-heat value
LPG	Liquefied petroleum gas
MTBE	Methyl tertiary butyl ether
NASS	National Agricultural Statistics Service
NEV	Net energy value
RFG	Reformulated gasoline
USDA	U.S. Department of Agriculture