How Much Energy Does It Take to Make a Gallon of Ethanol?

David Morris and Irshad Ahmed

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One of the most controversial issues relating to ethanol concerns the question of what environmentalists call the "net energy" of ethanol production. Simply put, is more energy used to grow the raw material and process it into ethanol than is contained in the ethanol itself?

Our analysis concludes that the answer to this question is no. The production of ethanol from corn is a positive net energy generator. More energy is contained in the ethanol and the other by-products than is used to grow the corn and convert it into ethanol and the other by-products. If corn farmers use state-of-the-art energy efficient farming techniques and ethanol plants integrate state-of-the-art production processes, then the amount of energy contained in a gallon of ethanol and the other by-products is twice the energy used to grow the corn and convert it into ethanol.

Finally, as the ethanol industry expands, it will increasingly rely on more abundant and potentially lower cost cellulosic crops(i.e. fast growing trees, woody plants like Bermuda grass, yard waste, etc.). When that occurs, the net energy of producing ethanol will become even more attractive.

This report describes in detail the methodology we used to arrive at these conclusions.

The first step to answering the question about the net energy of ethanol is to realize that three separate sub-questions must be addressed.

1. How much energy is used to grow the raw material?
2. How much energy is used to manufacture the ethanol?
3. How do we allocate the energy used in steps one and two between ethanol and the other co-products produced from the raw material?

Answers to these three questions are presented in Table 1, Energy Used to Make Ethanol from Corn and Cellulose.

Table 1 is divided into three sections that parallel the three questions: feedstock energy; processing energy; co-product energy credits.

We focus on corn because corn accounts for over 90 percent of the current feedstock for ethanol production in the U.S. and because corn derived ethanol has been at the center of the controversy about the energetics of ethanol.

The data are presented from four different cases.

The first column presents the energetics of ethanol based on the current energy efficiency of corn farming and ethanol production. Assuming the national average for energy used in growing corn and for energy used in the manufacture of ethanol, about 33 percent more energy is contained in the ethanol and other products produced in the corn processing facility than is used to grow the corn and make the products. In other words, the net energy ratio is 1.33:1.

The second column presents the energetics of ethanol based on the assumption that the most energy efficient existing corn growing operation provides the corn for the most energy efficient ethanol production facility. In this case, almost two BTUs of energy would be produced for every one BTU of energy used. The net energy ratio is 1.87:1.

The third column presents the energetics of ethanol based on the assumption that corn farmers and ethanol facilities use state-of-the-art practices. This is a best-case and hypothetical scenario. If farmers and industry were to use all the best technologies and practices the net energy ratic would be 2.21:1.

The fourth column, for comparative purposes, presents the energetics of cellulosic crop derived ethanol. If ethanol becomes a primary transportation fuel it will probably be made primarily from cellulosic crops like fast growing trees or woody plants. The data in column four is from the forest products industry and from biomass based ethanol facilities in the planning stages. The net energy ratio is 2.45:1.

The reader can "mix and match" components from Table 1. For example, assume that an average efficiency corn farm provided the feedstock for the most efficient ethanol plant. The entire process would use 29,431 BTUs in the growing of corn plus 36,232 BTUs for the processing into various products for a total of 65,663 BTUs. Assuming the lower co-product credits of 24,950 BTUs in column one, the total energy output would be, 100,950 BTUs and the net energy increase is thus 35,287 BTUs. In this case the energy output/input ratio comes to 1.54:1.

Table 1. Energy Used to Make Ethanol from Corn and Cellulose (BTUs per Gallon of Ethanol)

		Corn Ethanol (Industry Average)	Corn Ethanol (Industry Best)	Corn Ethanol (State-of-the-Art)	Cellulosic Crop-Based Ethanol
FEEDSTOCK PRODUCTION	Fertilizer	14,800	7,760	4,360	6,200
	Pesticide	715	715	715	350
	Fuel	3,196	3,088	2,992	5,870
	Other (feedstock)[1]	10,720	10,184	9,650	4,150
	Total (feedstock)	**29,431**	**21,747**	**17,717**	**16,570**
PROCESSING ENERGY INPUT	Process Steam	38,500	32,150	28,000	49,075
	Electricity	5,100	1,700	1,700	8,925
	Bulk Transport[2]	1,330	1,100	800	1,330
	Other (process)[3]	1,450	1,282	1,050	2,100
	Total (processing)	**46,380**	**36,232**	**31,550**	**61,430**
TOTAL ENERGY INPUT		**75,811**	**57,979**	**49,267**	**78,000**
ENERGY OUTPUT	Energy in Ethanol	76,000	76,000	76,000	76,000
	Co-product Credits[4]	24,950	32,693	32,693	115,400
	Total Energy Output	**100,950**	**108,693**	**108,693**	**191,400**
NET GAIN	**Net Energy Gain**	**25,139**	**50,714**	**59,426**	**113,400**
	Percent Gain	**33%**	**87%**	**121%**	**145%**

1 Includes energy for average crop irrigation, drying, seed, lime, on-farm electricity, machinery, and bulk crop transportation.

2 Bulk transport of ethanol is primarily by truck except for large plants which employ more energy efficient rail transportation.

3 Process (other) includes energy required for local delivery transportation of ethanol, energy for process water, herbicides, and other minor plant energy needs like waste water recycling and treatment.

4 Co-product energy credits for corn-based ethanol in wet-milling are from corn oil, 21% protein feed, 60% gluten meal, and carbon dioxide. In dry-milling, corn processing to ethanol produces corn oil, distillers dry grain with solubles (DDGS), and carbon dioxide. Credits for cellulose-based ethanol are primarily for the energy content of lignin by-product as a boiler fuel when ethanol is made from wood. Greater quantities of lignin are produced when ethanol is made from virgin wood than from wood waste streams such as sulfite liquor from paper mills. Lignin refined further into phenolic chemicals can contribute more toward energy credits available to ethanol.

SOURCES: "Farmers Fueling America: A Special Report on Ethanol, "Farm Journal Custom Publishing Co., 1991; High Plains Corporation, Wichita, Kansas, June 1992; Keeney, D. R., and Deluca, T. H., "Biomass as an Energy Source for the Midwestern U.S.," *American Journal of Alternative Agriculture*, draft copy, in press, 1992; "Annual Report on Fuel Ethanol," Solar Energy Research Institute, Golden, Colorado, 1990; "Agricultural Chemical Usage: 1991 Field Crops Summary," U.S. Department of Agriculture, ERS, Washington, D.C., 1992.

1. How much energy is used to grow the corn?

This is a complicated question because of the wide variations in farming practices and farming conditions.

Corn is grown in a variety of ways and in a variety of climatic and soil conditions. All of these affect the amounts and kinds of energy used.

For example, the single largest component of on-farm use is for nitrogen fertilizer, representing about 40 percent of all energy used in corn planting, cultivation and harvesting. The use of nitrogen fertilizer varies dramatically. Corn planted in rotation with soybeans or other legumes uses much less fertilizer than corn grown continuously.[1]

Corn farmers nationwide make 1.3-2.2 applications of nitrogen per year. Those who monitor the existing nitrogen in the soil before additional applications reduce the amount of nitrogen used as well.[2]

The National Research Council notes, "Within a given region for a specific crop, average production cost per unit of output on the most efficient farms are typically 25 percent less, and often more than 50 percent less, than the average cost on less efficient farms." The study concluded that in 1987 the most efficient Minnesota corn farms used about 40 percent less fertilizer and pesticide per bushel than the least efficient farm.[3]

A Missouri study of 1,000 farms concluded that a 40 percent reduction in nitrogen applications is possible even among farmers using corn/soybean rotation systems if they adopt alternative growing techniques.[4]

Large farms tend to use continuous corn planting and higher nitrogen fertilizer applications. Smaller farm operations tend to rotate corn and soybeans or other legumes, lowering nitrogen fertilizer applications. From year to year large variations might occur even on the same farm due to weather conditions. Pennsylvania nitrogen fertilizer use, for example, ranged from 113 pounds per acre in 1988 to over 140 pounds in 1989 and 1990 to 84 pounds in 1991.

Our conclusions related to on-farm energy use are contained in Table 2, Agricultural Energy Use for Corn Production in the United States. This Table is the basis for the Feedstock Production data in Table 1.

Table 2. Agricultural Energy Use for Corn Production in the United States

	Average			Best Existing			State-of-the-Art		
	lbs/acre (corn)	BTU/acre[1] (corn)	BTU/gal[2] (ethanol)	lbs/acre (corn)	BTU/acre[1] (corn)	BTU/gal[2] (ethanol)	lbs/acre (corn)	BTU/acre[1] (corn)	BTU/gal[2] (ethanol)
Nitrogen[3]	127	4,023,900	13,150	71	2,130,000	6,830	38	1,178,000	3,850
Phosphorus	48	263,160	860	36	198,000	630	15	83,400	272
Potash	57	241,740	790	22	935,000	300	17	72,760	238
Pesticide	1.58	218,790	715	1.58	218,790	715	1.58	218,790	715
Fuel[4]	6.67(gal)	977,976	3,196	6.45(gal)	944,930	3,088	6.25(gal)	915,700	2,992
Other	—	3,280,320	10,720	—	3,116,300	10,184,	—	3,010,800	9,650
Total Energy	—	9,005,886	29,431	—	7,543,020	21,747	—	5,479,450	17,717

1 The average energy content of nitrogen fertilizer is 31,000 BTUs per pound, phosphorus fertilizers contain 5,580 BTUs per pound, and potash fertilizers 4,280 BTUs per pound.
2 Acre (corn) to Gallon (ethanol) conversion is based on average corn crop yields of 120 bushels per acre and 2.55 gallons of ethanol per bushel.
3 National average for nitrogen application (1991) was 127 pounds per acre. South Dakota achieved the lowest state average application of 71 pounds per acre.
4 Fuel efficiency of newer machinery accounts for the difference between these entries.

SOURCES: Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1990; "Farmers Fueling America: A Special Report on Ethanol," Farm Journal Custom Publishing Company, 1991; Keeney, D. R., and Deluca, T. H., "Biomass as an Energy Source for the Midwestern U.S." *American Journal of Alternative Agriculture*, draft copy, in press, 1992; "Agricultural Chemical Usage: 1991 Field Crops Summary," U.S. Department of Agriculture, ERS, Washington, D.C., 1992.

The national average for nitrogen fertilizer application for corn production in 1991 was 127 pounds per acre. South Dakota farmers used the least amount. South Dakota is the ninth largest producer of corn in the U.S., with a 1991 production of 240.5 million bushels. The state has 19, 448 mostly smaller farms that primarily rely on corn/soybean rotations. South Dakota has traditionally been below the national average in nitrogen fertilizer application. In 1989 it used 131 pounds per acre, dropping to 82 pounds in 1990 and 71 pounds in 1991.

Aside from fertilizers, energy is used for on farm vehicles and for crop drying, seed, on-farm electricity, bulk crop transportation and for crop irrigation. The use of irrigation in particular makes a significant difference in the energetics of corn. Only 16 percent of all corn grown in the U.S. comes from irrigated farms. Thus in the first column of Table 1 under Other(Feedstock) we have assigned a weighted average of 16 percent in our calculations.

The average farm used about 6.67 gallons of diesel fuel per acre in 1990-91. Estimates for industry best are based on more fuel efficient vehicles.

The state of the art column assumes that farmers use low input agricultural practices and new hybrid varieties, like Pioneer Hi-Bred International's new tropical corn.

Although the state of the art column intends to represent a hypothetical best case we have identified at least one farmer who has already achieved similar results. Since 1987, the Thompson farm, located in Central Iowa, has been using 35 percent less energy than the national average while achieving yields 30 percent above the national average. Its total energy input is about 5 million BTUs per acre of corn compared to our state of the art estimates of 5.479 million BTUs and the national average of 9 million BTUs. Translated into energy input per gallon of ethanol, the Thompson farm contributes about 16,800 BTUs per gallon of ethanol produced compared to our low input figures of 17,700 BTUs per gallon.[5]

Our conclusion is that, for corn production, farmers use 29,431 BTUs per gallon of ethanol. The most energy-efficient farms use 21,747 BTUs while the state of the art is 17,717 BTUs per gallon. For comparative purposes, we also include the energy used to raise wood, 16,570 BTUs per gallon of ethanol produced.

2. HOW MUCH ENERGY IS USED TO MAKE THE ETHANOL?

The data in Table 1 for ethanol production are contained in the section titled, Processing Energy Input. They are arrived at by taking the weighted average of both wet and dry milling operations that produce at least 10 million gallons per year. Wet milling accounts for 70 percent of all ethanol produced.

The ethanol industry is only 15 years old. Early plants were very inefficient. Indeed, in 1980 a typical ethanol plant did consume more energy than was contained in a gallon of ethanol. Some plants used as much as 120,000 BTUs to produce a gallon of ethanol that contained only 76,000 BTUs of energy.

In the last decade ethanol plants have become much more energy efficient. This has occurred in many plant operations. In 1980, for example, ethanol plants used 2.5 to 4.0 kWh of electricity per gallon of ethanol produced. Today they use as little as 0.5 kWh. The majority of ethanol producers still purchase electricity from outside, but newer facilities generate electricity from process steam within the plant.

In the late 1970s, ethanol plants did not recover waste heat. Today they do. Old energy intensive rectification and solvent extraction systems required 12,000 BTUs per gallon of ethanol produced. Newer molecular sieves need only 500 BTUs.[6] Larger producers have been using molecular sieves for several years. Now smaller plants(20 million gallons per year and less) are starting to incorporate it.

We conclude that the ethanol industry, on average, uses 49,380 BTUs per gallon to manufacture ethanol. The best existing plants use 36,232 BTUs per gallon. Next generation plants will require only 31,550 BTUs per gallon of ethanol produced.

3. How do we divide the energy used among the products produced?

If we add the amount of energy used in growing corn on the average farm today to the amount of energy used to make ethanol in the average processing plant today, the total is 75,811 BTUs per gallon (Table 1, Column 1). Since ethanol itself contains only 76,000 BTUs per gallon, one might be tempted to conclude that ethanol is not a net-energy product, that is, that it takes as much energy to make a gallon of ethanol as is contained in a gallon of ethanol.

That would be incorrect because the energy used to grow the corn and much of the energy used to process the corn into ethanol is used to make other products as well. In wet mills, these products include corn oil, 21 percent protein feed, 60 percent gluten meal, germ, sometimes carbon dioxide and several grades of refined starches and corn sweeteners. In dry milling co-products can include corn oil, distillers dry grain with solubles(DDGS) and carbon dioxide.

Thus we need to allocate the energy used in the cultivation and production process over a variety of products. This can be done in several ways.

One is by taking the actual energy content of the co-products to estimate the energy credit. For example, 21% protein feed has a calorie content of 16,388 BTUs per pound. The problem with this method is that it puts a fuel value on what is a food and thus undermines the true value of the product.

Another way to assign an energy value to co-products is based on their market value. This is done by adding up the market value, in dollars, of all the products from corn processing, including ethanol and then allocating energy credits based on each product's proportion of the total market value. For example, Table 3 shows the material balance and energy allocation based on market value for a typical wet milling process. Here the various co-products account for 43 percent of the total value derived from a bushel of corn, and thus are given an energy credit of 32,511 BTUs per gallon of ethanol.

The replacement value method is a third way to determine co-product energy credits. Here we determine the nearest competitor to corn products and calculate how much energy it would require to raise the feedstock and process it into that product. For example, it requires 1.6 pounds of soybean oil to replace 1.6 pounds of corn oil. The energy required to raise the soybeans and extract the oil comes to 10,616 BTUs. The nearest feeding equivalent to the 13.5 pounds of 21% corn protein feed is 13.45 pounds of barley. The energy required for growing the barley and drying it is 1,336 BTUs per pound, which translates into 7,047 BTUs per gallon of ethanol equivalent. The carbon dioxide replacement value is based on the energy intensity of other fermentation processes that produce it as a by-product.

Table 3. Market Value Method for Allocating Energy for Corn Wet Milling
(1 bushel=56 pounds)

Products	Amount Produced (pounds)	Market Value (dollars per pound)	Total Value (dollars)	Energy Allocation (BTUs per gallon ethanol)
Corn Oil[1]	1.6	0.35	0.58	8,164
21% Gluten Feed[2]	13.5	0.05	0.68	9,914
60% Gluten Meal	2.6	0.12	0.31	4,519
Carbon dioxide	17.0	0.04	0.68	9,914
Total Co-Products	34.7	—	2.23	32,511
Ethanol[3]	16.5	0.18	2.97	43,300
Total Products	51.2	—	5.20	75,811

1 The market value for corn oil presented here is for refined oil. Crude corn oil has a market value of 27 cents per pound.
2 The 21% protein feed includes 1.0 to 1.5 pounds of germ meal that is produced during the extraction of corn oil from germ.
3 Average ethanol yield is 2.56 gallons per bushel with a 6.6 pounds per gallon density. A gallon of ethanol currently sells for $1.20.
SOURCES: Corn Refiners' Association, Washington, D.C., 1992; National Corn Growers Association, Saint Louis, Mo., 1992; *Chemical Marketing Reporter, 1992.*

Table 4. Co-Product Energy Credit Methodologies for Corn Wet Milling

(BTUs/Gallon of Ethanol)

Method	Corn Oil	60% Gluten Meal	21% Protein Feed	Carbon dioxide	Total Co-Products
Actual Energy Value	9,960	3,404	16,388	—	29,752
Market Energy Value	8,164	4,519	9,914	9,914	32,511
Replacement Value[1]	10,616	2,827	7,047	4,460	24,950

1 Replacement value of corn oil is based on a one-to-one replacement of soybean oil. 13.5 pounds of 21% protein gluten feed is replaced by 13.45 pounds of barley (on a protein equivalent basis) with an energy value of 1,336 BTUs per pound of barley for production and drying. The carbon dioxide replacement value is based on the energy intensity of other fermentation processes that produce it as a by-product. There is no actual energy value for carbon dioxide since it is not classified as a feed or a fuel.

SOURCES: Macgregor, C.A., "Directory of Feeds and Feed Ingredients," W.D. Hoard & Sons, Milwaukee, Wisconsin, 1989; Handbook of Energy Utilization in Agriculture, D. Pimentel (ed.), CRC Press, Boca Raton, Florida., 1980; CRC Handbook of Chemistry and Physics, D. Lide (ed.), CRC Press, Boca Raton, Florida., 1992.

Table 4 provides a comparative overview of all three methodologies. The first two rows are based on corn products. The third row is based on non-corn equivalents. Carbon dioxide has no actual energy value because it is not classified as a food(calorific value) or a fuel(combustion value).

The last column in Table 4 shows the variation depending on which methodology is used. For Table 1 we chose to use the replacement value energy estimates, which come to 24,950 BTUs per gallon.

We have chosen a higher value of 32,693 BTUs per gallon for the best existing and state of the art cases. Each of the co-products produced with ethanol competes with and replaces a variety of alternate products. For example, 21% corn protein meal competes with conventional feed products like hay, grain straw, soybean protein, barley, etc, many of which are not clearly defined in terms of energy value. Currently 21% corn protein competes with all of these and partially replaces all of them. If it were to completely replace barley alone, it would have a higher energy credit. The higher energy credits in the second and third columns of Table 1 are calculated based on potential products that have a higher energy replacement value and which are only partially replaced currently by corn-ethanol co-products.

CONCLUSION

Assuming an average efficiency corn farm and an average efficiency ethanol plant, the total energy used in growing the corn and processing it into ethanol and other products is 75,811 BTUs. Ethanol contains 76,000 BTUs per gallon and the replacement energy value for the other co-products is 24,950 BTUs. Thus the total energy output is 100,950 BTUs and the net energy gain is 25,139 BTUs for an energy output-input ratio of 1.33:1.

The best existing operations, assuming the corn is grown on the most energy efficient farms and the ethanol is produced in the most energy efficient plants, the net energy gain would be over 50,000 BTUs for a net energy ratio of 1.87:1. Assuming state of the art practices, the net energy ratio could be as much as 2.21:1. Cellulosic crops, based on current data, would have a net energy ratio of 2.45:1.

Although we did not explore the following in detail in this report, one could also offer a worst case scenario for ethanol production. This would assume that the most energy inefficient farms supply the most energy inefficient production facilities. Some corn farmers may use as much as 47,000 BTUs per gallon of ethanol produced, assuming irrigation and continuous corn planting. Inefficient ethanol production facilities may consume an additional 55,000 BTUs per gallon. Assuming 76,000 BTUs per gallon of ethanol and co-product energy credits of 24,950 BTUs per gallon, the end result would be a slight energy loss. Very few plants operating in the U.S. are this inefficient. We estimate that less than 1 percent of total ethanol capacity in the U.S. is produced in this manner.

We think it reasonable to look at least to columns one and two for the answer to our initial question. Based on industry averages, we use less energy to grow the corn and make ethanol than is contained in the ethanol. Moreover, we think it is a safe assumption that as the ethanol market expands, new facilities will tend to incorporate state-of-the-art processing technologies and techniques so that each new plant is more energy efficient than the one before. It is a less safe assumption that farmers will continue to become more energy efficient in their operations because of the many variables involved. Nevertheless, it does appear that growing numbers of farmers are reducing their farm inputs and that this trend will continue.

A final word about cellulose. If annual ethanol sales expand beyond 2 billion gallons, cellulosic crops, not starch, will probably become the feedstock of choice. The data in the last column suggest a very large energy gain from converting cellulosic crops into ethanol. Cellulosic crops, like fast growing tree plantations, use relatively little fertilizer inputs and use less energy in harvesting than annual row crops. The crop itself is burned to provide energy for the manufacture of ethanol and other co-products. A major co-product of cellulosic crops is lignin, which currently is used only for fuel but which potentially has a high chemical value. Were it processed for chemical markets the net energy gain would be even greater.

Our conclusion is that under the vast majority of conditions, the amount of energy contained in ethanol is significantly greater than the amount of energy used to make ethanol, even if the raw material used is corn. If ethanol should become a significant transportation fuel, increasing its market share far above its present 1 percent share, the raw material will probably be cellulosic crops which have much better than a two to one net energy production.

NOTES

[1] *Agriculture Chemical Usage: 1991 Field Crops Summary.* U.S. Department of Agriculture. ERS. Washington, D.C. 1992.

[2] Keeny, D.R. and DeLuca, T.H. "Biomass as an Energy Source in the Midwestern U.S.", *American Journal of Alternate Agriculture,* in press. 1992.

[3] *Alternative Agriculture.* Committee on the Role of Alternative Farming Methods in Modern Production Agriculture. Board on Agriculture. National Research Council. National Academy Press. Washington, D.C. 1989.

[4] Research conducted by the Department of Agricultural Economics. University of Missouri-Columbia, Columbia, Missouri.

[5] Personal conversation with Richard Thompson, November, 1992.

[6] DeSplegelaere, T.J. "Energy Consumption in Fuel Ethanol Production for a Corn Wet-Milling Process", paper presented at IBIS 1992 Fuel Ethanol Workshop. Wichita, Kansas. June 9-11, 1992.