Fossil Energy Use in the Manufacture of Corn Ethanol

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Executive Summary:

Ethanol is a liquid fuel produced primarily from corn that is used as a gasoline additive. Over the last several years, there has been considerable discussion in government, the fuels industry, and the environmental and agricultural sectors regarding the expansion of ethanol production. In particular, environmentalists and policy makers have expressed concern about the energy efficiency of corn ethanol production and its potential impact on petroleum use. Energy efficiency is important to climate change as well. The main purpose of this analysis is to quantify the total fossil energy and petroleum energy used to produce ethanol from corn for the current industry as well as the future industry that would result from an expansion from the current 2 Billion gallons per year to 5 billion gallons per year of ethanol in 2012. The report has been peer reviewed by scientists affiliated with the Department of Energy and Agriculture. Their comments were addressed where necessary and are included as appendix 11.

In any such analysis, the energy basis chosen impacts the result. In this study, the basis chosen is the total net heating value, or total lower heating value (LHV) per gallon of 200 proof ethanol. The primary LHV represents the useful energy that can be extracted from fuel in conventional combustion systems. The total LHV energy includes the primary energy plus the extraction, manufacturing and transportation energy required to bring it to its end use. Only fossil energy is considered in the energy analysis. Thus, energy supplied by solar and nuclear sources is not included, but the fossil energy to recover and process uranium is included. Solar sources include energy captured by corn, as well as hydroelectric and biomass fired electric power.

The energy inputs can also be categorized as “variable” and “capital”. Variable inputs are those that are used directly and are proportional to the quantity of ethanol produced. An example is the quantity of coal used in an ethanol plant to produce a gallon of ethanol. The capital energy is the prorated energy to manufacture equipment and facilities used to grow corn and produce ethanol over the useful life. In this analysis, the variable energy use is estimated. The possible effect of capital energy is examined using a semi-quantitative technique. Some analysts also consider human energy inputs, but these are not evaluated in this analysis.

In carrying out this study, extensive use has been made of public data bases related to agricultural inputs, energy contents of fuels and fuel extraction, refining and transportation efficiencies. Data on the efficiency of manufacturing sectors including fertilizer components and ethanol conversion were collected through industry surveys. Some researchers distrust industry surveys; thus where possible the survey data are validated by testing against other public information. The quality of the data is evaluated, and a propagation of errors analysis is made to establish confidence in the results.

The corn-producing region studied includes 9 states where the vast majority of the corn and ethanol are now produced. These states are also the scene of the majority of industry expansion currently underway. They are Illinois, Indiana, Iowa, Minnesota, Michigan, Nebraska, Ohio, South Dakota and Wisconsin. State level data for agricultural inputs are aggregated by planted acreage to estimate the total inputs for corn production for the base year 2000 as well as 2012.

The total fossil energy input to corn accounts for about one-third of the total fossil energy in ethanol. In corn agriculture, fertilizers, particularly nitrogen, account for more than 40% of the total energy input per acre of corn harvested. The US fertilizer industry trade group has recently reported the aggregated energy input for US fertilizer manufacture. The input is consistent with data reported by EU countries that indicates that the US industry average and the EU average energy input per pound of nitrogen produced are essentially the same.

Farm fuels including diesel, gasoline, LPG, natural gas and electricity make up almost 50% of the energy inputs. USDA in two separate surveys has reported the quantity of fuels used in the 9-state area. The difference in the total energy in farming using the two surveys was approximately 20%. The higher energy input was for a particularly wet year, 1996 and might represent an upper bound on farm inputs, while the lower value was for a more normal year, 1991. The average of these inputs were adjusted for yield to estimate the year 2000 input for fuels.

Ethanol is produced in wet mills and dry mills. In 2000, wet mills accounted for about 54% of the grain based capacity in the US. Since the vast majority of new capacity is in the form of dry mills, it is projected that dry mills will account for 80% of US capacity in 2012 under a 5 billion gallon per year scenario.

Ethanol conversion is the most significant energy input to the total energy input. Only small amounts of energy are required for corn and ethanol transportation and distribution.

The energy inputs to dry mills was established using industry survey data collected by a USDA contractor. The author conducted separate surveys of the corn wet milling industry and of ethanol plant constructors to establish energy use in new grassroots dry-mill plants. These data were compared to those disclosed in the literature. The datasets were all consistent providing confidence in the assigned inputs for the study.

Corn and soybean meal are the primary protein containing components in livestock diets. The system considered includes ethanol production, vegetable oil and beef output. When producing ethanol, only starch is converted. The protein, fiber, oil and micronutrients in the corn are recovered as co products. Dry mills produce a feed called DDGS that contains the protein and oil. Wet mills produce two feeds, 60% protein corn gluten meal and 20% protein corn gluten feed as well as corn oil. In order to value the co products, yields from wet and dry mills were established. Using a beef-feeding model provided by the National Research Council, the quantity of corn and soybeans avoided by using co products produced by ethanol plants that produced the same average daily gain for beef finishing was estimated and the avoided energy of growing corn and soybeans and processing soybeans to meal and oil was established.

The following table provides a summary of the results of this study. The net (variable) energy is the sum of the energy content of ethanol and avoided energy related to co products less the energy of all inputs. The energy ratio is the output energy in ethanol divided by the input energy corrected for the co product credit. A positive net energy indicates a process that contains more product energy than inputted fossil energy. A net energy ratio greater than one suggests a process that produces more energy out in liquid fuel than is consumed as fossil fuel.

Study Results
Energy per gallon of 200 Proof Ethanol

Parameter	2000	2000-2004 Incremental Industry	2012
Wet Mills, MM gal/yr	982	123	1,105
Dry Mills, MM gal/yr	846	890	4,777
Corn Production, BTU/gal	19,472	19,625	16,109
Corn Transportation, BTU/gal	1,743	1,757	1,489
Ethanol Production, BTU/gal	55,049	47,937	45,768
Ethanol Distribution, BTU/gal	1,233	1,233	1,113
Byproduct credit, BTU/gal	(14,829)	(12,880)	(10,062)
Total BTU/gal	62,668	57,671	54,417
Energy In Ethanol, BTU/gal	76,000	76,000	76,000
Net Energy, BTU/gal	13,332	18,329	21,583
Energy Ratio	1.21	1.32	1.40
Lower 95% confidence, net energy, BTU/gal	8,136		
Barrels Crude Saved/Barrel of ethanol	0.58		

The following conclusions were developed from the study:

- The energy ratio for corn production in 2000 is about 7.4. Thus, the energy embodied in corn is more than seven times the fossil energy inputs required for growing.

- The ethanol industry exhibited a variable energy ratio[1] of 1.21 and a net energy of 13,332 BTU/gallon in 2000 considering total energy inputs on a lower heating value basis.

- A detailed propagation of errors analysis indicates that the lower 95% confidence limit for the net energy is 8,136 BTU/gallon. Since the lower 95% confidence limit is a large positive energy value, it is extremely unlikely that the net energy could actually be negative.

- Currently there is a billion gallon capacity increase in design and under construction. The estimated energy ratio for new capacity is estimated to be 1.32 and the net energy is 18,329 BTU/gallon.

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[1] Energy ratio refers to the energy in ethanol divided by the fossil energy inputs related to ethanol production. Net energy is the energy in ethanol and co products less the energy in the inputs.

- In the 2002 to 2004 timeframe when the current round of construction is completed, the industry energy ratio may be 1.25 with a corresponding net energy of 15,114 BTU/gallon.

- In 2012, the industry will consist of 80% dry mills. The energy ratio of the industry may be 1.4 with a corresponding net energy 21,583 BTU/gallon.

- The total energy in petroleum used to produce ethanol is approximately 7% of the energy in the ethanol.

- Each barrel of ethanol produced directly takes the place of 0.58 barrels of crude oil and adds about 214,000 barrels per day of gasoline supply, an amount equal to the output of two world scale refineries.

- The makeup of the energy sources for a gallon of ethanol based upon the current industry is approximately 7.3% petroleum, 75.2% coal and natural gas and 17.5% solar energy captured by corn.

- Using coal and natural gas as feedstocks for ethanol plants is a more efficient way to convert coal and natural gas to transportation fuel. The energy ratio for conversion of coal and natural gas to transportation fuel is typically 0.4 and 0.65 respectively, while it is 1.21 for the base ethanol case.

- The total “capital energy” is estimated to be on the order of 1% of the energy in the ethanol.

The results of this study are in good agreement with recent similar studies, and improve upon the quantification of the ethanol energy balance through the use of a considerable amount of new and up to date data. One exception is the recent published work of Dr. David Pimentel that suggests that corn ethanol exhibits a very negative net energy. A critique of Dr. Pimentel’s analysis is included as Appendix 5. Generally, his results do not characterize the current ethanol industry. He has made his analysis based upon old data that considerably overstate energy use in agriculture and ethanol production and made a number of poor assumptions including a zero energy credit for corn co products.

1. Study Bases and Overview

1.1 Objectives:

The main purpose of this analysis is to quantify the total fossil energy and petroleum energy used to produce ethanol from corn. The analysis follows the accepted "life cycle" approach of evaluating the total "variable energy" inputs required to produce ethanol including agricultural inputs, ethanol manufacture, transportation and distribution. The energy analysis includes not only losses in the individual processing steps, but also losses associated with the extraction, refining and distribution of the energy to the system. The "capital energy" contribution resulting from depreciation of equipment and machinery used to produce ethanol is also quantified.

The analysis considers current wet and dry mills as a baseline, examines the incremental efficiency of plant capacity being added and projects industry performance in 2012 when the corn to ethanol industry has grown to 5 billion gallons per year.

In 2000, the US consumed 129 Billion gallons of gasoline. About 2 billion gallons of ethanol was blended into gasoline generally at 10% by volume. Ethanol was added primarily to satisfy federal clean air regulations, increase gasoline octane, and extend the volume of gasoline. The practical impact that corn based ethanol can have on fuel supply is limited. USDA has estimated that about 7 billion gallons of ethanol could be produced from agricultural products in the near future without disrupting food markets[2]. Under current legislative proposals, ethanol production could have a mandated floor of 5 billion gallons per year in 2012. EIA[3] has projected that gasoline demand will increase to near 165 billion gallons per year by 2012. Assuming that the increase in ethanol would occur by 2010, ethanol would make up about 3% of the gasoline volume. In order for ethanol to have an impact on petroleum imports, the energy in petroleum used to produce ethanol must be considerably less than the energy in ethanol. A purpose of this analysis is to examine the benefits of ethanol production on petroleum displacement.

According to the USDA[4], corn production may increase from 10.2 billion bushels in 2001 to 11.2 billion bushels in 2011/12 with no change in planted acreage. Currently, about 58% of corn is used for domestic livestock feed, 11% goes to food and industrial uses not including ethanol, and 22% is exported. Only about 7% of US corn is used for ethanol.

Ethanol is produced from cornstarch. The remaining nutrients are dispersed as co products and are primarily used for livestock feeding. An important outcome of this analysis is the examination of both the energy and food by products resulting from ethanol manufacture.

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[2] Private Communication, USDA Office Energy Policy and New Uses.

[3] EIA, "Annual Energy Outlook 2002 with projections to 2020", Table 33., Report DOE /EIA-0383, December 2001.

[4] Interagency Agricultural Projections Committee, USDA Agricultural projections to 201, USDA WAOB-2002-1, Feb 2002.

1.2 Energy Basis:

Energy is defined using two bases. These are higher or gross heating value (HHV) and lower or net heating value (LHV). The higher heating value includes the energy associated with condensation of the water of combustion and is the definition used for selling and purchasing energy. The lower heating value is based upon water of combustion being present in the vapor phase and represents the useful energy that can be extracted in conventional combustion systems. The term primary refers to the fuel or energy in its delivered form. An example of primary energy is the heat content of a unit of natural gas. The LHV basis is adopted in this analysis.

The total energy includes the useful energy plus the energy used in extraction, manufacturing and transportation to bring it to its end use. In this report, solar energy, for example energy accumulated by biomass or extracted by hydroelectric facilities, is not considered. Additionally, since this report is directed at examining fossil energy inputs to ethanol production, the primary electricity generated by nuclear facilities is also not counted. However, energy associated with mining, transportation and processing of uranium is included. The resulting total fossil LHV as reported in this study is useful in analyzing the "life cycle energy" of the system.

Table 1 presents higher and lower heating values used in this analysis[5]. Two primary values are included for electricity. These are the primary energy per kWh and the fossil heat rate that includes primary energy plus generation and transmission losses. The fossil heat rate is discounted for nuclear, hydroelectric and renewable generation. Appendix 1 provides information on the energy content of electricity. The heat rate data are specific to Midwest generation. Appendix 2 summarizes extraction, conversion and transportation loses assumed for the various forms of energy. In Table 1, the Total LHV column lists the total energy values for key fuels used in this analysis.

Table 1 Primary and Total Energy Contents of Fuels, BTU

		HHV	LHV	Total LHV
Ethanol	Gallon	84,262	76,000	-
Crude	Gallon	141,619	133,130	137,669
Diesel	Gallon	138,714	130,719	156,982
Gasoline	Gallon	124,619	116,515	159,225
LPG	Gallon	86,310	79,405	90,695
Electricity	kWh		3,412	
Heat Rate	BTU/kWh	9,385	8,887	9,331
Natural Gas	SCF	1,026	923	1,016
Coal	Ton	20,479,000	19,455,050	19,754,444

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[5] EIA, "Annual Energy Outlook 2001" Appendix H, Table H1 Heat Rates.

1.3 System and Approach Overview:

The energy inputs may be divided into "variable" and "capital" classifications. In the context of this analysis, variable inputs represent the actual inputs of fossil energy to the system derived from fossil fuels including natural gas, petroleum, and coal. Some researchers also consider capital inputs. The capital input is the prorated energy of manufacture including the energy required to extract and refine raw materials per unit of production input.

In comparing the energy efficiency of alternatives, such as ethanol compared to gasoline, it is usually assumed that the capital contribution is small and similar in magnitude for both options so that only the difference in variable energy input need be considered. Since this is how the results of this analysis will generally be used, the variable approach is followed. Because modern agriculture may require a quantity of sophisticated equipment beyond that found in other fuel production processes, the potential impact of the capital contribution is estimated in Appendix 9.

In the analysis, the basis is an undenatured gallon, which is 200-proof, ethanol.

Figure 1 shows the system flow diagram. Throughout the report, intermediate quantities of energy are provided as primary process inputs. In the following discussion, the main data sources used are indicated. The detailed references are provided in the report body. Inputs related to extraction, processing and transportation of primary energy to its final destination for use are denoted with an ♦, and are included in the "tLHV" accounting but not in primary "LHV" and "HHV" totals. Electricity generation and transmission with losses are included in both primary and total accounting totals. The efficiency of extraction, transportation, processing and distribution were taken from USDOE analyses based upon the "GREET" model developed at Argonne National laboratories. USDOE EIA reported the electrical energy generation and transmission efficiency.

In fertilizer and chemical manufacture, the raw materials and process energy inputs are derived from fossil fuels. In the case of nitrogen, natural gas is the main energy and feedstock input. For mineral fertilizers such as potassium (K_2O), no fossil energy is assigned to the mineral in the ground. The system boundary is the mine. The Fertilizer Institute has reported energy use in nitrogen and phosphate fertilizer manufacturing. The energy in potash mining is reported by Statistics Canada.

The transportation energy for farm inputs is estimated based upon the source of supply, destination and transportation energy factors developed by the US Department of Transportation (USDOT). Ammonia pipeline distances were estimated by compounding line of sight distances along the pipeline between terminals. Rail distances were estimated using rail mileage data supplied by CSX and Burlington Northern Railroads. Barge distances were estimated from US Army Corp of engineering maps. Truck mileage was estimated based upon an accounting of major fertilizer terminals in each state.

The area considered is a nine state region including Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, Ohio, South Dakota and Wisconsin where the majority of the corn is grown and ethanol is manufactured. USDA statistics are used to develop production-weighted inputs.

At the farm, the energy use is derived from USDA state level surveys along with yield, planted and harvested acres and crop input data for fertilizers and chemicals supplied by USDA NASS. The state level surveys for corn are conducted every 5 to 8 years and surveys are currently available for 1991 and 1996. The fuel inputs cover all operations related to corn production including field operations conducted by the farmer, use of the farm trucks for pickup and delivery, on-farm corn drying, shelling and storage, and irrigation pumping. Farmers subcontract a portion of their operations to outside entities; this is commonly termed custom work and includes field operations like spraying and harvesting as well as contract drying. The energy contribution for custom operations was estimated from custom operation contract price data and energy consumption for various operations developed by the University of Illinois and Mississippi State University. The energy content of hybrid seed corn was established through communications with seed companies and a designer/constructor of seed processing plants.

The state level data include fuel costs to move corn to the first site of use. This is not necessarily the ethanol plant. It was assumed that the additional distance to move corn from storage to the mill was the same as from the farm to the mill based upon an analysis done by the Iowa Transportation Department and validated by conversations will several Midwest mills. The energy use is estimated using a USDOT factor. This may double count some transportation energy. However, it is likely that most corn transport covered in the state level survey is to local elevators, and not processing mills.

The composition of corn supplied to the ethanol plants is based on an annual survey of corn quality carried out in Indiana by Purdue University. The ethanol yield and energy inputs are based upon recent surveys of the ethanol industry carried out by USDA and the author of this study. USDA conducted a cost of production survey in 1998 and an energy use survey in 2001 that provided a capacity averaged thermal and electrical input for wet and dry mills. Industry participation in both surveys was high. The USDA 2001 energy survey did not discriminate between total electricity used in manufacture and net electricity purchased by the ethanol manufacturer. The difference is important for cogenerators because they produce some or all of their electricity from purchased coal and natural gas resulting in double counting of some energy. This is especially true for wet mills. The author conducted a separate survey of corn-wet millers producing ethanol to insure that thermal inputs were not double counted.

Currently, there is considerable activity related to construction of ethanol plants. The author surveyed the major plant constructors to establish the guaranteed energy use for new plants under construction to establish the energy efficiency of new capacity coming on stream.

The compositions of the feed grain co products were established from vendor specification sheets. Based upon the assumed corn composition, ethanol yield, and co product specifications, the mass yield of the co products was established for average wet and dry mills by material balance and survey data.

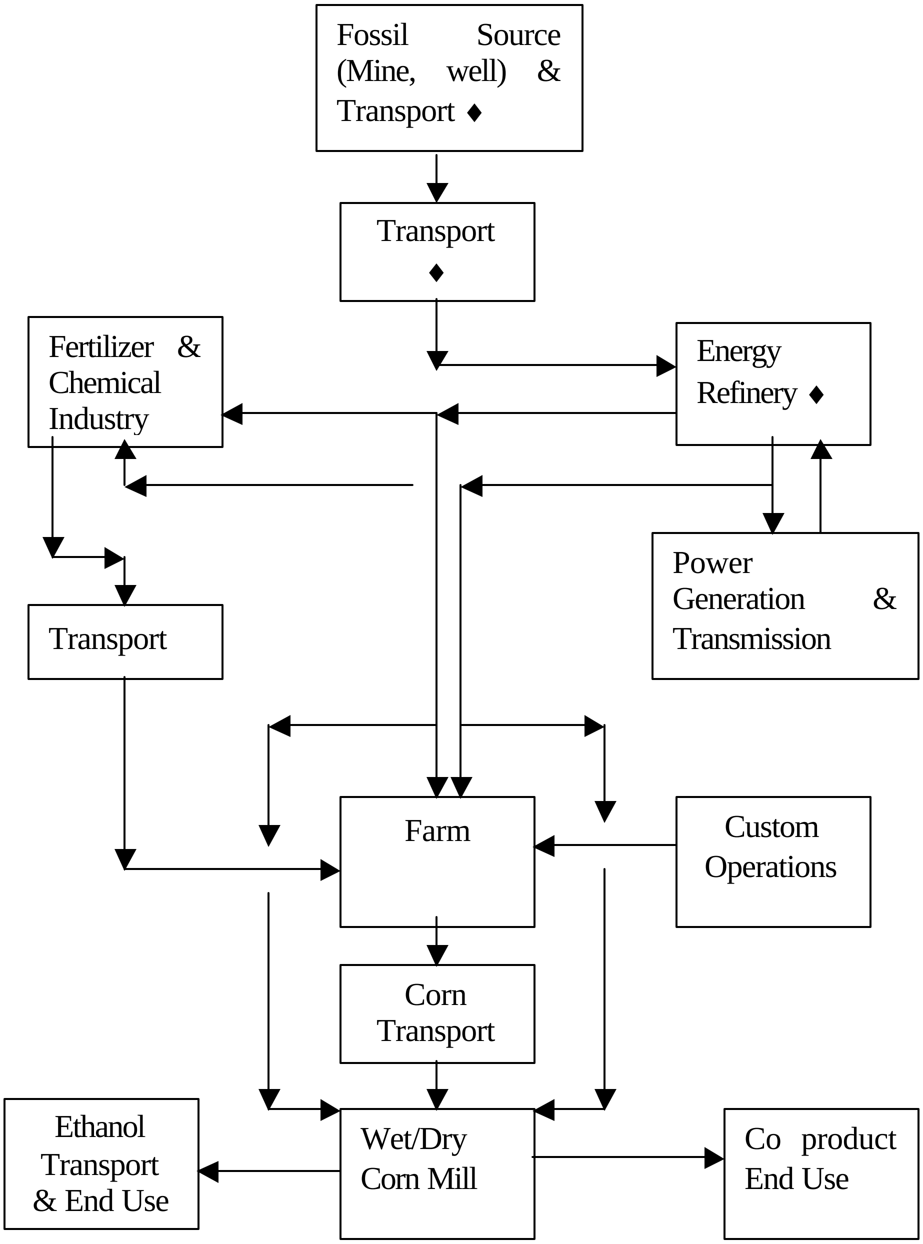
The energy content of co products was estimated based upon their feed value in the livestock industry. Feeding formulas are generally established based upon least cost subject to diet constraints. In the feed marketplace, the relative value of all feed components is generally based upon their protein content. To conduct this analysis, economics were not employed to establish the appropriate substitutions. Instead diet substitutions were established based upon the likely replacement of corn and soybean meal by co products in the animal diet using a feeding model developed by the National Research Council. Once a substitution was established, the energy avoided by not having to supply grain is assigned to the co product.

For dry mills, the main co product is termed DDGS and it is assumed that DDGS is fed to beef cattle. The co product protein is significantly more effective than protein in corn or soybean meal for ruminant animals. Also, since DDGS contains all of the oil in the corn, it has a higher energy content than either corn or soybean meal.

The main feed products for wet mills are corn oil, corn gluten feed and corn gluten meal. In wet mills, the corn oil is recovered as a separate product; thus the feed materials are essentially oil free. To establish an energy value for the co products, crude vegetable oil production was constrained.

The energy for transportation and distribution of ethanol was based upon an estimate of the use of ethanol in each PADD. Rail distances to main cities in each PADD were established using CSX and Burlington Northern data and transportation energy was estimated using USDOT efficiency. The energy used to load and unload and distribute the ethanol has been estimated by USEPA.

Figure 1 System Flow Diagram
(¨ - Included in tLHV)



2 Background

2.1 Previous Studies

Table 2 presents a time line for recent energy balance studies. In the table, the net energy is the energy available in ethanol at its point of use plus the energy credits for co products less the total energy used in its production less. The energy ratio is the energy content of ethanol divided by the total energy required to produce the ethanol adjusted for co products. In either case, renewable energy is not included. A positive net energy or an energy ratio greater than unity signifies that the production of ethanol produces more energy than is consumed in its production.

The current study tries to examine how ethanol energy efficiency is changing. The baseline is the "2000 industry", inclusive of all operating facilities. Two cases are examined. These are the incremental energy efficiency of new production, and the industry efficiency projected to 2012.

Studies conducted in the late 1980's and early 1990's yielded mixed results; except for Pimentel, the older studies show that ethanol production was nearly energetically neutral. In recent years, four studies have reached the conclusion that ethanol from corn is net positive in fossil energy. The exact magnitude varies primarily because of the energy basis chosen, the year the study was completed, the data sources used, and the assumption regarding allocation of co products. The Agriculture Canada study may not be applicable to the US ethanol industry as it applies to Canadian agriculture.

The recent studies all rely upon USDA data for agricultural inputs for point in time estimates generally based upon data collected in the early to mid 1990's. In this analysis, estimates of the farming inputs are made specifically for the Corn Belt region where ethanol plants are being located. The estimates are made not only for 2000 but also extrapolated to 2012. The estimates provided in this study may be more complete than in the other analyses. For example, the energy input for hybrid seed production is analyzed in detail. Shapouri et al. and Wang significantly underestimated the inputs to grow seed. Methods were developed to estimate the energy use in custom operations based upon reported cost data. Shapouri et al. employed an undocumented rule of thumb in their analysis.

The most important energy input is for ethanol manufacture. In this analysis, new up to date plant input data were established via multiple surveys. The other analyses are based in part on older energy input data. USDA conducted a 2001 energy use survey that is reasonably accurate for dry mills that may overestimate the energy input by not properly accounting for cogeneration. The author conducted surveys of the wet milling industry and the Engineering and Constructors involved in new dry mill plant construction. The types of fuels used including waste fuels were identified in the studies conducted by the author. These data permit four estimates to be made. These are:

- The current industry
- The 2002-2004 under construction incremental industry
- The industry in 2002-2004
- The industry in 2012

As such, unlike previous studies, this analysis tries to examine the impact of the changing structure of the industry over time to determine how energy efficiency may change.

In general, the more recent studies of Wang, Lorenz and Morris and Shapouri et al. use a replacement approach to value co products based upon their crude protein content. Kim and Dale[6] have formalized this approach to expand the system boundaries to encompass the production of co product substitutes. The current study follows the approach of Kim and Dale so that food value and oil are balanced with and without ethanol. Thus, equal mass of beef and vegetable oil are produced with and without ethanol. The differences in feeding quality of the various co products are considered using an accepted publicly available feed model available from the National Research Council.

In this analysis, energy required to grow and refine replacements is considered. In the Shapouri et al study, soybeans were assumed to replace co products and agricultural inputs were considered but not the energy to extract and process vegetable oil and meal. It is not known how Wang and Lorenz and Morris developed the replacement energy. However, the co product credits reported in those studies are much larger than those reported here.

This analysis employs the National Research Council beef-feeding model that allows feeds to be developed that satisfy the complete nutrient requirement of the livestock. The likely replacements for co products are corn and soybeans. In this work, feeding formulas were developed that attempted to maximize use of corn compared to soybeans because the relative cost per bushel of these feed alternatives will favor use of corn as the protein supplement. This approach tends to produce a smaller co product energy credit compared to that based upon a high soybean diet.

The previous analyses present snapshots of the energy efficiency of the industry. Lorenz and Morris and Shapouri et al present energy inputs on a HHV basis. In this analysis, we follow the approach of Wang and present data on an LHV basis. Importantly, the impact of the quality of the data on the outcome is explored.

David Pimentel has published several studies reaching the opposite conclusion regarding energy efficiency; that is, ethanol production in fact uses more energy than it produces. Pimentel's analyses are critically reviewed in Appendix 5 and are shown to be faulty.

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[6] Kim, S., Dale, B., "Allocation Procedure in Ethanol Production System from Corn grain I. System Expansion", J LCA (2002).

Table 2 Net Energy and Energy Ratio of Recent Corn-Ethanol Studies

Study/Year	Basis	Corn Yield, Bu/Acre	Ethanol Yield, Gal/Bu	Ethanol Plant, BTU/Gal	Total Energy Use BTU/Gal	Co product Credits BTU/Gal	Net Energy BTU/Gal	Energy Ratio
This Study, 2000 Baseline	LHV	140	2.65	55,049	77,497	14,829	13,332	1.21
This Study, 2002-2004 New Plants	LHV	140	2.73	47,937	70,551	12,880	18,329	1.32
This Study, 2002-2004 Industry	LHV	140	2.68	52,513	75,020	14,134	15,114	1.25
This Study, 2012 Industry	LHV	154	2.80	45,768	64,479	10,062	21,583	1.40
Pimentel[7] (2001)	LHV	127	2.50	69,330	130,725	0	(54,725)	0.58
Wang[8] (2001)	LHV	125	2.58	39,067	66,564	14,333	23,769	1.45
Agriculture & Agri-Food Canada[9] (1999)	HHV	116	2.69	50,415	68,190	14,055	30,127	1.56
Shapouri, Duffield,, Graboski, [10] (1995)	HHV	122	2.53	53,277	82,824	15,056	16,494	1.20
Lorenz and Morris[11](1995)	HHV	120	2.55	53,956	81,090	27,579	30,751	1.57
Keeney and Deluca[12] (1992)	LHV	119	2.56	48,434	91,127	8,072	(8,451)	0.92
Marland and Turhollow[13] (1990)	HHV	119	2.50	50,105	73,934	8,127	18,455	1.28
Ho[14] (1989)	HHV	90	NR	57,000	90,000	10,000	(4,262)	0.95

NR: Not reported LHV: 76,000 Btu per gallon of ethanol. HHV: 84,262 Btu per gallon of ethanol.

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

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[7] Pimentel, D., "The Limits of Biomass Energy", Encyclopedia of Physical Sciences and Technology, Academic Press 2001. See also "Ethanol Fuels: Energy Security, Economics and Environment", J Ag and Environmental Ethics (4), pp1-13, 1991. Also see same title, International Sugar Journal, (103) #1235, p491-494, 2001.

[8] Wang, M. 2001, Development and Use of greet 1.6 Fuel Cycle Model for transportation Fuels and Vehicle Technologies", ANL-ESD-TM-163. Table entries provided by M Wang, provate communication 2002.

[9] Levelton Engineering, Ltd. and (S&T)^2 Consulting Inc. 1999. Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario. Canada.

[10] Shapouri, H., Duffield, J., Graboski, M.S. "Estimating the Net Energy Balance of Corn", USDA AER-721, 1995.

[11] Lorenz, D., Morrris, D., "How Much Energy Does it take to make a Gallon of Ethanol", Institute for Self Reliance, Wash DC, 1995.

[12] Keeney, D.R. DeLuca, T.H., "Biomass as an Energy Source for the Midwestern U.S.", American Journal of Alternative Agriculture (7), p137-143 (1992).

[13] Marland, G., Turhollow, A. F. "CO2 Emissions from the Production and Combustion of Fuel Ethanol from Corn", ORNL, USDOE, Feb 1991.

[14] Ho, S.P., "Global Warming Impact of Ethanol Versus Gasoline", presented at Clean Air Issues and America's Motor Fuels Business, Wash DC, Oct. 1989.

2.2 Corn Production:

Agricultural productivity has increased dramatically in the last several decades. The sustainability of agriculture and ethanol production should be examined in the context of time dependent increases in productivity.

Production of corn has made great strides in energy efficiency since its introduction as a fuel. Ahearn et al[15] report that the inputs of energy, predominantly fuels and electricity, track the overall USDA input index, declining about 15% since 1980 while the total farm output has increased by 33% due to increased farming efficiency. For this analysis, the 9 major corn producing states responsible for more than 80% of U.S. corn production where essentially all grain based ethanol is currently or likely to be produced (Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, Ohio, South Dakota, Wisconsin) are considered. Since 1980 in this region, an annual average of 53,200,000 acres ± 2,176,000 at the 95% confidence level have been harvested for grain corn. The harvested acres are not correlated with time over this period. The 3-year average yield in bushels per acre rose from 109 for 1980-1982 to 140 in 1998-2000. In more recent years, the three-year average yield increased (significant at the 95% confidence level, p=0.031) for the period 1991-1993 to 1998-2000 from 115.3 to 140.2 bushels/acre.

The type of tillage system employed has an impact on energy use. Conservation tillage is defined as leaving at least 30% of the field covered with residue. Under some conditions, no and low tillage reduce yield and generally, reduced tillage systems require additional herbicides for weed control. Reduced tillage reduces runoff of nitrogen reducing the need for fertilizer application and adds organic carbon to the soil. From 1990 to 2000, the use of conventional tillage in the Corn Belt dropped from 68% to 64% of the planted acres. The fraction of conventional tillage land leaving 15% to 30% residues held constant at 38% compared to land where 0 to 15% residues were left. No-till increased from 7.5% of the acres to 17.3%.

While yield has increased, inputs of N, P and K fertilizers have declined per bushel of corn. The three-year average nitrogen, phosphate and potassium inputs have declined (significant using Student-t at the 95% level, p = 0.021,0.013,0.018) from 1.18, 0.46, 0.56 pounds per bushel in 1991-93 to 0.94, 0.34, 0.42 pounds per bushel in 1998-2000. Similarly, total herbicide and insecticide use has declined from 3.22 to 2.48 pounds of active ingredient per acre (significant at the 99% level, p=0.004).

2.3 Ethanol Production Technologies:

Ethanol is produced using two distinct processes. These are termed dry milling and wet milling. Wet mills process large amounts of corn and are generally designed to produce 100 million or more gallons per year of ethanol. Dry mills are smaller in scale; typical dry mills are designed to produce 30 to 50 million gallons per year of ethanol.

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[15] Ahearn, M., Yee, J., Ball, E., Nehring, R., "Agricultural Productivity in the United States", Agricultural Bulletin 740, USDA, January 1998.

2.3.1 Wet Mills:

The wet milling process, depicted in Figure 2, is designed to separate the corn into a number of useful products including starch, corn oil, and specialty feed ingredients called gluten feed and gluten meal. The shelled corn is steeped in a dilute sulfur dioxide solution for 30 to 50 hours at 130F to soften the kernels. The corn germ is removed and processed to recover the oil. At this point, the de-germed corn slurry is screened to remove the bran. The steep water is concentrated and combined with germ residue and bran to yield gluten feed. The typical analysis of CGF, widely used as a feed component for dairy and beef cattle, poultry, swine and pets, is 18% protein, 2% fat, 8% fiber. The screen overflow contains starch and gluten protein. These are separated in a centrifuge and the gluten protein is dried to yield gluten meal. CGM is typically 60% protein, 2% fat and 1% fiber. It is widely used as poultry feed and is an excellent cattle feed because of its high bypass protein content. The starch is then continuously hydrolyzed and the resulting sugars are fermented to ethanol. The ethanol is concentrated to 95% azeotropic alcohol by distillation and the azeotropic water is removed using molecular sieve dryers that are much more efficient than the older technology that employed an azeotropic distillation step. The fuel grade alcohol product, which contains fusel oils produced in the fermentation step, is denatured with 5% gasoline prior to shipping.

2.3.2 Dry Mills:

In the dry mill, depicted in figure 3, shelled corn is hammer-milled. In the mashing step, the ground corn is first mixed with water to produce slurry. The slurry is adjusted to 5 to 6 pH, 180F to 195F and treated with an enzyme to promote hydrolysis and liquefy the starch. After liquefaction, the corn mash is cooked to sterilize the mixture. The mash is then cooled and fermented. The corn protein provides a major source of nitrogen absorbed by the yeast during fermentation. The portion of the protein broken down is converted to nutritionally valuable amino acids. The corn oil and fiber are unchanged during fermentation. The fermenter “beer” is distilled to remove the 190 proof azeotropic alcohol. The azeotropic water is removed using molecular sieves. The fuel grade alcohol is then denatured with 5% gasoline for shipping. The whole stillage, containing fiber, fat, protein and yeast are collected from the base of the distillation tower. The stillage is centrifuged to concentrate the solids. The thin stillage overflow is thickened in an evaporator and the syrup is combined with the solids. The mixture is then dried to yield corn distillers dried grains with solubles (DDGS). On a dry matter basis, DDGS typically contains 27% protein, 11% fat, and 9% fiber as well as amino acids, trace minerals and vitamins

2.4 The Importance of Capital Energy

Capital energy associated with ethanol manufacture is discussed in appendix 9. It is difficult to directly estimate the energy associated with the manufacture of equipment associated with production of corn and ethanol. Instead, the approach taken examines the prorated energy use per unit of purchase price for portions of the total system to infer the importance of the capital energy contribution. The estimated capital contribution of farming and ethanol manufacture is on the order of 1% of the total energy input to ethanol production. Including the manufacture of other inputs such as fertilizers, chemicals and refined fuels will not change this estimate much since those industries have very small capital charges compared to variable charges in their costs of production.

Figure 2 Corn Wet Milling Process

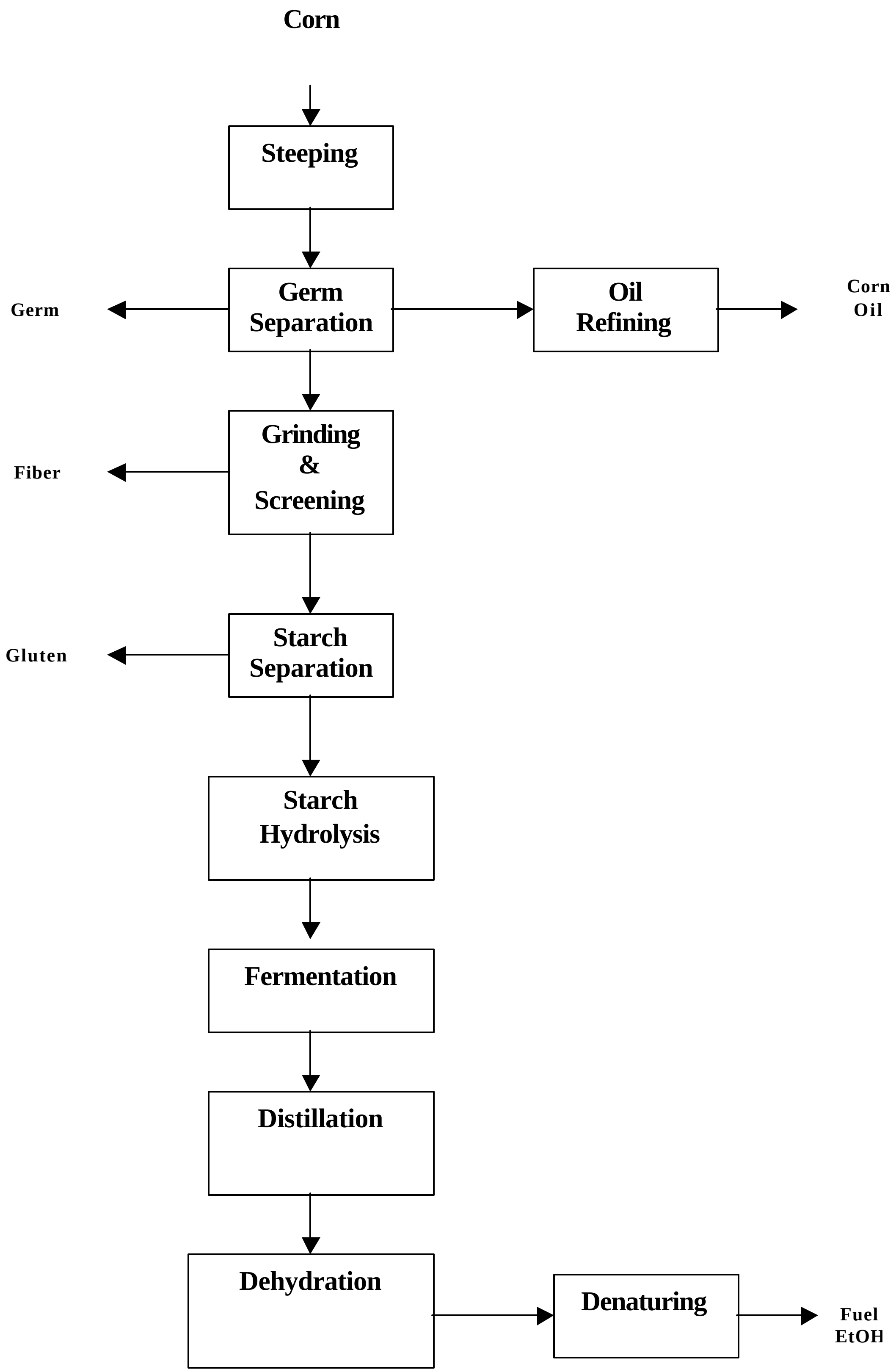
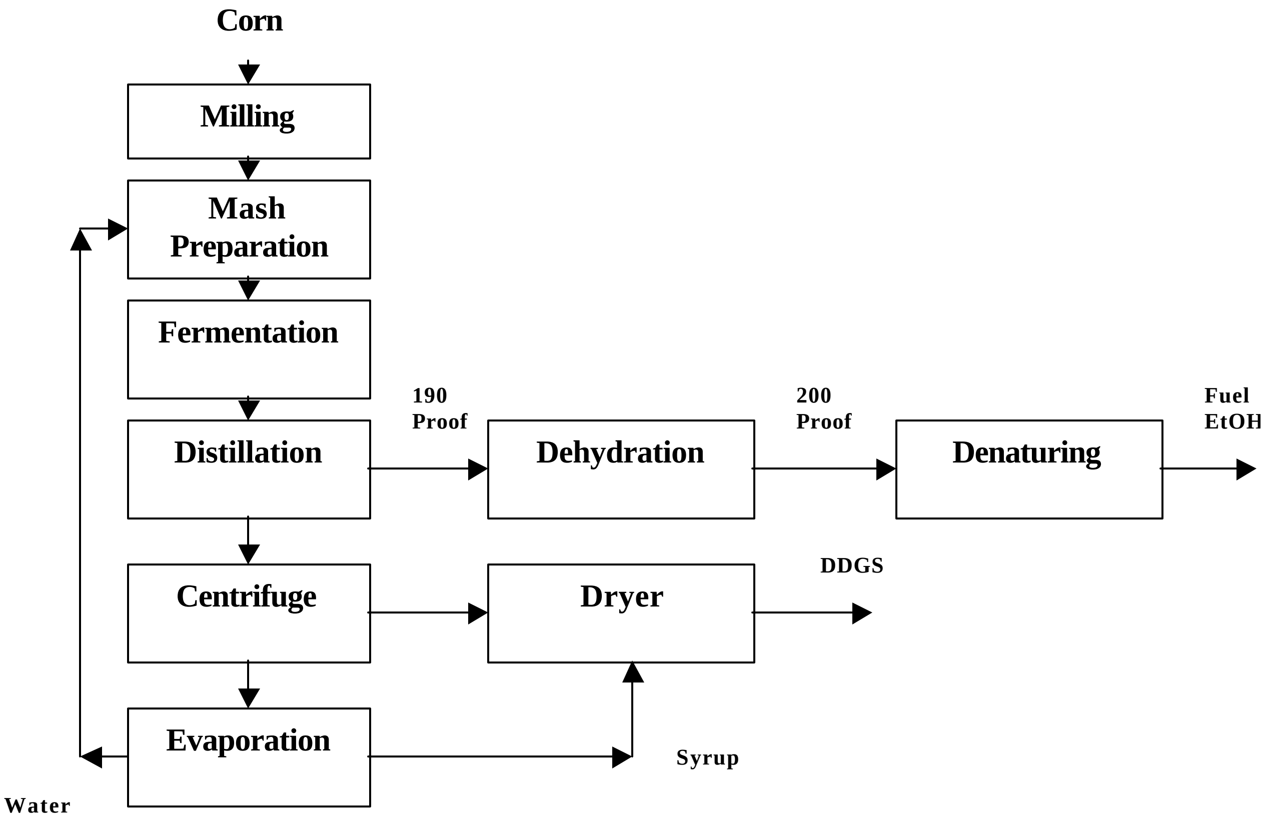


Figure 3 Corn Dry Milling Process



3 Energy Use in Corn Agriculture:

USDA has reported comprehensive surveys of corn production costs for 1991 and 1996[16] which can be used to estimate certain energy inputs to corn farming. These include energy inputs for on-farm fuel use, energy included in farm services (custom drying and field work) and energy in purchased irrigation water. The fuels cover farm energy uses related to corn production including fieldwork, harvesting, shelling, any on-farm transport of grain and materials, on-farm grain drying, and irrigation energy. Transportation energy of corn to the first point of sale or storage is also included. The 1991 survey provides a detailed breakdown of farm fuel use by state and type. The 1996 survey provides only total fuel cost and use by region. Considerable information is available to check the energy data reported in the surveys. An alternative accounting is made where possible to validate the energy inputs.

USDA NASS maintains a historical database that provides yield, planted and harvested acreage, fertilizer and chemical input data at the state level. In this analysis, survey data by NASS are weighted according to acreage in each state. The year 2000 is selected for the analysis.

The 1991 survey provides data for individual states. The 9-major corn producing states covered in the survey are Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, Ohio, South Dakota, and Wisconsin. All weighting is done based upon harvested acres for grain in the states for the appropriate year. The 1996 survey breaks costs only into regions. Based upon the 1996 region definitions, South Dakota is in the Northern Great Plains Region, Michigan and Wisconsin are in the Northern Crescent, Nebraska is in the Prairie Gateway and the remainder of the states is in the Heartland. USDA has provided appropriate state-weighted farm fuel inputs derived from the database. The regional definitions were applied to farm services to develop those energy estimates.

Historically, plants were located near adequate corn supply and transportation infrastructure primarily in states with incentive programs. If the location of plants in the future were known, the most appropriate weighting would be by plant capacity in each state. Instead, it is assumed that ethanol capacity will ultimately be related to local corn supply and thus the weighting will be the same.

3.1 Corn Production:

The nine state production area yields over 80% of corn produced in the United States and contains most of the grain-based ethanol plants in operation and currently under construction. Table 3 provides corn production data for 2000 from the USDA NASS database. Approximately 95% of the acres planted in corn were harvested for grain. Less than 1% was not harvested for grain or silage.

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[16] Ali, M.B., McBride, W.D., "Corn- State-Level Production Costs, Characteristics, and Input Use, 1991", ERS Statistical Bulletin 891, September 1994. Foreman, L. , "Characteristics and Production Costs of U.S. Corn Farms", USDA Statistical Bulletin 974, August 2001.

While the reference year is 2000, normalization per bushel is based upon the three-year average yield for 1998-2000 to minimize weather and other related impacts. The three-year average yield is 140 Bu/acre, the same for 2000.

3.2 Fertilizer and Chemical[17] Application Rates:

Fertilizer use for 2000 is summarized in Table 4. Since NASS tabulates fertilizer use per state for all corn, it was assumed that the fertilizer and chemical application rates were the same for both grain and silage. Use of nitrogen for corn represented about 90% of farm based nitrogen use for the four major crops planted in the nine states (corn, soybeans, sugar beets, wheat). The principle nutrients are nitrogen, phosphate and potash. The mass basis for these is pounds of nitrogen in nitrogen fertilizers, P_2O_5 in phosphate fertilizer and the K_2O equivalent of potash fertilizer.

Limestone is widely used as a soil conditioner and other micronutrients are applied in small amounts. USDA has not characterized the average application rate of micronutrients. The energy in sulfur and micronutrients is not included in the analysis.

Major chemical inputs are tabulated in Table 4. Some BT was used, but the quantity was small and the energy required for production is uncharacterized.

Table 3 Corn Production Data for Nine States for 2000

	Planted	Yield	Harvested Acres			
		Bu/Acre	Grain	Silage	Total	Bushels
	1,000 Acres			1,000 Acres		
IL	11,200	151	11,050	115	11,165	1,691,200
IN	5,700	147	5,550	130	5,680	837,900
IA	12,300	145	12,000	250	12,250	1,783,500
MI	2,200	124	1,970	220	2,190	272,800
MN	7,100	145	6,600	425	7,025	1,029,500
NE	8,500	126	8,050	290	8,340	1,071,000
OH	3,550	147	3,300	180	3,480	521,850
SD	4,300	112	3,850	420	4,270	481,600
WI	3,500	132	2,750	720	3,470	462,000
Total	58,350	140	55,120	2750	57,870	8,151,350

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[17] These data are tabulated by Cornell University, Ithaca NY. The web site is http://usda.mannlib.cornell.edu/reports/nassr/

Table 4 Fertilizer Input Data for 2000

	Million Lbs			Lb/Bushel		
	N	P2O5	K2O	N	P2O5	K2O
IL	1,798	739	1,029	1.066	0.439	0.610
IN	865	366	626	1.036	0.438	0.750
IA	1,533	503	631	0.863	0.283	0.355
MI	240	97	154	0.884	0.357	0.568
MN	786	404	378	0.772	0.397	0.371
NE	1,261	243	22	1.200	0.231	0.020
OH	573	224	287	1.120	0.438	0.561
SD	419	154	36	0.876	0.321	0.075
WI	301	121	161	0.656	0.263	0.351
Total	7,775	2,851	3,323	0.962	0.352	0.410

Table 5 Chemical Input Data for 2000

	Thousand Pounds		Lb/acre		
	Herbicide	Insecticide	Herbicide	Insecticide	Total
IL	28,190	3,131	2.525	0.280	2.805
IN	15,460	797	2.722	0.140	2.862
IA	24,518	635	2.001	0.052	2.053
MI	5,658	131	2.584	0.060	2.643
MN	10,597	369	1.508	0.053	1.561
NE	16,862	1,470	2.022	0.176	2.198
OH	10,339	603	2.971	0.173	3.144
SD	5,790	44	1.356	0.010	1.366
WI	6,410	365	1.847	0.105	1.952
Totals	123,824	7,545	2.159	0.133	2.293

3.3 Farm Fuels:

Farm fuels are used for a variety of operations including field operations, on-farm hauling, grain drying and storage, and irrigation. By conducting appropriate large surveys, USDA accurately characterizes all of the energy inputs for grain production. Data are analyzed in this section for 1991 and 1996 to estimate farm fuel use in 2000.

Table 6 summarizes cost and energy inputs by fuel type for the 1991 survey.

Table 6 1991 Farm Fuel Input Worksheet

State	Acres	Fuel	Diesel Gal	Gasoline Gal	LPG Gal	Electricity Kwh	Natural Gas MCF
Illinois	11,000	$11.64	4.46	3.51	2.11	12.4	0.060
Indiana	5,550	$13.14	5.11	3.56	2.12	28.2	0.010
Iowa	12,200	$11.33	4.44	3.41	4.67	5.3	-
Michigan	2,300	$14.95	6.9	3.10	3.18	10.7	0.050
Minnesota	6,000	$12.42	4.72	2.88	4.28	27.9	-
Nebraska	7,800	$38.56	17.89	4.47	3.56	96.8	1.610
Ohio	3,400	$11.05	4.5	2.62	3.65	9.8	0.010
South Dakota	3,250	$18.59	6.11	3.05	4.90	86.1	-
Wisconsin	3,200	$17.32	7.62	2.55	1.96	68.9	0.100
Weighted		$ 16.50	6.85	3.40	3.42	33.59	0.251

The 1996 survey cost data are analyzed in Table 7. The total weighted fuel cost was adjusted to 1991 using the USDA Farm Fuel Cost Index for each year for the period April through September. The indicated *increase* in farm fuels for 1996 compared to 1991 is 39.3%. Table 8 compares the itemized fuel inputs for 1991 and 1996[18]. The BTU input ratio of 1.41 in Table 8 is in agreement with the energy input developed from survey cost data in Table 7. This indicates that the information referenced in note 18 is accurate.

Table 7 1996 Fuel Worksheet

	Acres	Fraction	Fuels
Heartland	38,400	69%	$ 22.35
Northern Crescent	5,250	9%	$ 20.82
Northern Great Plains	3,650	7%	$ 20.82
Prairie Gateway	8,250	15%	$ 43.17
	55,550		$ 25.20
Farm Fuel Index			
1991			93.5
1996			102.5
Adjusted Cost to 1991			$ 22.98
Energy Input Ratio, acre basis			1.393

Diesel is used for tillage and other field applications, as well as irrigation. Between 1991 and 1996, diesel fuel use increased substantially. Diesel fuel use is more dependent on tillage type and soil conditions than yield. Soil type, moisture content and compaction affect implement power requirement (draft) and traction. Tillage induced compaction of

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[18] . Energy inputs for 1996 costs were provided by the USDA OEPNU. These are published in a USDA report, Shapouri, H., Duffield, J. , Wang, M., "Update on the Energy Balance of Corn Ethanol", Office of Chief Economist, USDA, 2002.

wet soils increases diesel fuel use[19]. Decreasing tillage intensity reduces fuel consumption. The use of diesel fuel increased from 1991 to 1996 even though more land was moved into conservation tillage. Part of the increase is apparently due to replacement of gasoline-powered equipment with diesel equipment.

The increase in electricity and LPG suggests that more on-farm corn drying was required in 1996 than 1991.

Table 8 Comparison of 1991 and 1996 Per Acre Fuel Inputs

Fuel	1991	1996
Diesel, Gallons	6.85	8.60
Gasoline, Gallons	3.40	3.09
LPG, Gallons	3.42	6.36
Electricity, KWH	33.59	77.13
Natural Gas, SCF	251	200
HHV BTU	2,368,552	3,343,262
Ratio		1.412

One possible reason for the higher energy use in 1996 was weather. According to VEGrains[20] the average harvest moisture content was 22.6% compared to an average of 18% for the other years between 1995 and 2000. Depending on timing, wet weather would increase energy for fields operations and grain drying. Diesel, gasoline and electricity for field operations and irrigation should depend primarily on acreage and not crop size. Electricity and LPG used for drying on an acre basis will depend on moisture and yield. Part of the energy increase for drying is due to increased yield. On the farm, some corn is air dried without fuel, while in other cases a fuel assist is employed. Based upon moisture content, the thermal input in heated dryers is approximately 2.8 times as much to dry corn from 22.6% initial moisture compared to 18% initial moisture to final moisture of 15.5%. The electrical energy required to dry a bushel without thermal assist is about 1.5 times as much[21].

Since there is a lack of historical data for weather effects on field operations, farm drying costs and harvested moisture, it is not possible to assign an average energy consumption with a high degree of certainty. In this analysis, since the apparent energy use in 1996 is substantially higher than 1991, these fuel values are adopted as a tentative upper bound for the year 2000 estimate of farm inputs. The year 1991 data adjusted for yield are adopted as a tentative lower bound. The average of the 1991 and 1996 inputs are then

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[19] www.gov.on.ca/OMAFRA/english/crops/facts/88-082.htm, McBride, R.A., Martin, H., Kennedy, B., "Soil Compaction", Ontario Mininstry of Agriculture and Food, 1/97.

[20] Developments in VEC Market, www.VEGRAINS.org, "Summary of Findings from 527 Multiple Year Producer Respondents"

[21] Maier, D., Saksena, V., "Low-Temperature Drying of Corn in Southwest Indiana", Purdue University Grain Quality Task Force, Fact Sheet 30, Jan, 1997.

used. Because drying energy inputs depend on the quantity of corn, the LPG and electrical inputs are adjusted for yield differences between 1991 or 1996 and 2000.

3.4 Custom Operations:

Farmers often contract outside services to assist in planting, fertilizing and harvesting. In the USDA surveys, the cost, but not energy consumption, related to these services is reported. In this section, we estimate energy inputs due to custom operations.

3.4.1 1991-Field Operations:

The 1991 survey reported the combined cost of custom operations for cultivation, planting, fertilizing and harvesting for each of the 9-states. It is assumed that all of the energy used for these operations is in the form of diesel fuel. The cost of commercial drying is treated separately. The University of Illinois[22,23] reports the use of energy for a variety of custom operations for the year 2000. These data suggest that the fraction of the cost of energy for all custom operations is relatively constant and near 10% of the total cost of that operation. Thus, the overall energy use in custom operations is not highly dependent on which custom operations were actually purchased. The conversion of 1991 survey costs for custom operations to energy inputs based upon the U of I 2000 data are detailed in Table 9. The basis is 2000 machinery and labor, 99.5-cent per gallon diesel fuel, and 10% profit. Using the USDA Farm Service and Fuel Indices, these cost data are adjusted to a 1991 basis to provide an estimate of the BTU input from diesel fuel per dollar of custom services.

Using the 1991 survey, the weighted energy input for custom operations is shown in Table10.

Table 9 Custom Operation Worksheet

	Cost of Custom Operations, 2000		
	Total Cost/Acre	Fuel Cost /Acre	
Average of 4 operations	$ 13.82	$ 1.37	
	USDA Cost Index Data		
Index Year	Farm Services	Diesel	Diesel Cost
1991	99	802	$0.769
2000	120	1,037	$0.995
	Adjusted Energy Cost to 1991		
1991 Total Cost	$11.40	By farm services index	
1991 Energy Cost	$1.06	By diesel index	
Diesel Gallons/acre	1.06	Using 1991 diesel cost	

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[22] Schnitkey, G., Lattz, D., Siemens, J., “Machinery Cost estimates; Field Operations”, U Ill Farm Business Management Handbook, FBM0201, April 2000.

[23] See item FBM0203 from note 3.

Table 10 Weighted Energy Input for Custom Field Operations for 1991

	Total $/acre	Fuel $/acre	Acres	t-LHV
Illinois	$ 7.56	$0.70	11,000	111,564
Indiana	$ 5.82	$0.54	5,550	85,887
Iowa	$ 6.70	$0.62	12,200	98,873
Michigan	$ 4.07	$0.38	2,300	60,062
Minnesota	$ 5.40	$0.50	6,000	79,689
Nebraska	$ 5.75	$0.53	7,800	84,854
Ohio	$ 4.79	$0.44	3,400	70,687
South Dakota	$ 4.00	$0.37	3,250	59,029
Wisconsin	$ 16.48	$1.53	3,200	243,199
Weighted	$ 6.69			98,696

3.4.2 1991-Custom Drying:

The Mississippi State University (MSU) Extension Service[24] reports that for 1999, energy costs for commercial drying were typically 10 cents per bushel and they represented 32% of the typical custom drying charge. For the analysis, MSU reported that LPG cost 8.5 cents per bushel and was priced at 50 cents per gallon. MSU also assumed a slightly different heating value for LPG compared to USDOE/EIA reported in Appendix 1. The remainder of the energy cost was 1.5 cents of electricity. A US average commercial electricity price for 1999 of 6.9 cents per Kwh was used to convert the cost to energy. Table 11 shows the adjustment to a 1991 basis using the USDA farm cost indices. Table 12 provides the weighted energy input for custom drying.

Table 11 Worksheet for Custom Drying

LPG, LHV BTU/Gallon, MSU assumption	83,260	
1999 Total Drying Cost per bushel	$0.313	
Farm Services Index Ratio, 1991/1999	0.825	
Adjusted 1991 Total Cost per bushel	$0.258	By Farm Services Index Ratio
1999 LPG Cost for drying	$0.085	
1999 Electricity Cost for drying	$0.015	
MSS LPG basis, $/gallon	$0.50	
Gallons LPG/Bu	0.17	
MSS, Electricity cost, $/Kwh	$0.069	1999 EIA commercial cost
Kwh/ Bu	0.217	
1991 LPG Price	$0.769	1991 Farm Average Price, USDA
1991 Electricity Price	$0.084	1991 EIA commercial cost
1991 Energy Cost for drying	$0.149	
Energy as % of 1991 cost	57.8%	

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[24] MSU Extension Service, “Corn Harvesting, Drying and Storage”, www.msucares.com.

Table 12 Energy Input for Custom Drying, 1991

	Total $/acre	Fuel $/acre	Acres	t-LHV Btu/acre
Ill	$1.49	$0.86	11,000	100,616
In	$1.79	$1.03	5,550	103,638
Ia	$2.46	$1.42	12,200	142,430
Mi	$2.35	$1.36	2,300	136,061
Mn	$2.04	$1.18	6,000	118,113
Ne	$1.94	$1.12	7,800	112,323
Oh	$1.19	$0.69	3,400	68,899
SD	$ 0.04	$0.02	3,250	2,316
Wi	$1.42	$0.82	3,200	82,216
Weighted	$1.79			106,439

3.4.3 1996- Custom Operations Energy Input:

The 1996 survey does not break out custom operations into field operations and drying. Furthermore, the data are not presented by state, but rather by area. Based upon the 1996 definitions, the 9-state area, South Dakota is in the Northern Great Plains Region, Michigan and Wisconsin are in the Northern Crescent, Nebraska is in the Prairie Gateway and the remainder of the states is in the Heartland. A custom operations cost for the Northern Great Plains was not included. It was assumed to be the same as the Northern Crescent. Table 13 provides the worksheet.

Table 13 1996 Custom Operations Worksheet

			t-LHV
1991 Total custom op + drying			$8.48
BTU/acre			229,910
BTU/$			27,123
	1996 Custom Operations		
	Acres	Fraction	
Heartland	38,400	69%	$ 10.75
Northern Crescent	5,250	9%	$ 9.33
Northern Great Plains	3,650	7%	$ 9.33
Prairie gateway	8,250	15%	$ 14.28
	55,550		$ 11.05
	Farm services Index		
1991			99
1996			116
Adjusted 1996 Cost to 1991			$9.43
1996 Energy BTU/ acre, scaled from 1991			228,157
1996 Energy BTU/Bushel			1,780

3.4.4 2000 Custom Operations:

The energy input per bushel for 2000 for field operations per acre is assumed to be the average of 1991 and 1996. The averaged custom energy for drying is assumed to be the same per bushel. Yields were 110 and 125 for 1991 and 1996 respectively. The resulting input is 241,170 BTU/acre.

3.5 Purchased Irrigation Water:

Most irrigation energy is embodied in diesel, LPG and electricity use on the farm. A detailed analysis of farm irrigation energy is provided in Appendix 6 that demonstrates that there is adequate energy in the farm surveys to accommodate the required irrigation energy reported as a result of USDA survey data on irrigation. The only states in the nine-state area that use on farm produced or purchased irrigation water were Nebraska and South Dakota. The weighted 1991 cost per acre was 38 cents. Most if not all of this water was supplied from gravity flow surface collection and diversion systems that would require very low energy inputs; here, the energy content of this water is neglected. The energy to distribute the water on the farm is included in total on-farm fuels.

3.6 Energy in Seed Corn:

One bushel of corn (56 pounds at 15% moisture) contains 80,000 kernels. The average seed planting rate per acre 27,315 kernels per acre was 1996, approximately 0.3 bushels per acre.

In production of hybrid seeds, “male” plants are interplanted with “female” plants in staggered rows so the male can cross-pollinate the female. The mechanical field operations as well as chemical inputs per acre are essentially the same as for production agriculture. In addition to mechanical operations, the field is manually “rouged” to remove volunteers and off-type plants and the plants designated as female are manually detasseled to eliminate self-pollination. The major difference between seed production and corn production is that the yield is considerably lower. According to one report, the yield is 45 bushels per acre[25] compared to 140 bushels per acre.

There is a considerable amount of electrical energy used to process the seed corn. Processing typically includes drying, shelling, grading, cleaning, size and shape separation, bagging and storage. The average electrical requirement for these steps is estimated to be 152.5 kwh/tonne[26].

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[25] According to Garst Seed Company, the inputs for seed production per acre are about the same as for production corn. However, the yield is about 45 bushels per acre compared to 140 for production corn in 2000.

[26] Bratney Company personal communication.

Seed corn is harvested with a high moisture[27] content and dried to typically 12.5% MC. The total heat duty required to dry 35% MC corn on the cob to 12.5% is estimated to be about 49,586 BTU/Bu HHV[28].

In addition, there is negligible energy associated with development of the hybrid[29].

Based upon these data, the energy required for growing and processing seed corn, presented in Table 14, is approximately 4.7 times that required for production corn.

Table 14 Energy required to Produce Seed Corn

Inputs/acre	t-LHV
Production Corn w/o seed (next section)	7,169,132
Custom Drying adjustment	(137,467)
Adjusted Inputs, BTU/acre	7,031,665
Yield	45
Inputs/Bu	156,259
Cleaning, husking, drying and bagging	
Electrical (152.2 kwh @ fossil heat rate)	36,169
Drying (35% to 12.5% @ 2000 BTU/lb)	49,126
Total, BTU/bu	241,554
Ratio to corn production	4.67

3.7 Inputs and Energy Estimate for 2000:

Table 15 provides a summary of the energy inputs to corn production. The energy content of items such as fertilizer, chemicals and transportation are discussed in appendices 7, 8 and 10.

Because weather is a variable, and insufficient survey data are available to characterize energy use in an average year, the average farm fuel inputs were based upon the 1991 and 1996 survey. The drying energy was scaled by yield while the field and irrigation energy per acre was not adjusted for yield. The seed input is assumed constant with increased yield coming from greater productivity per plant.

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[27] Garst Seed Company harvests at 22% to 30%. According to the Bratney Company, a supplier of seed corn processing plants, seed corn can be harvested at up to 35% moisture.

[28] According to Campbell,G., "Estimating the Value of Wet Ear Corn", University of Wisconsin Extension, Bulletin 3410, (1987) there are 20.743 bushels of 15.5% MC shelled corn in a ton of 35% corn on the cob. This results in a water removal requirement of 514.3 pounds per ton. At a typical drying heat rate of 2000 BTU HHV per pound of water, the energy requirement is 49,586 BTU/bu.

[29] According to Garst Seed Company, about 75% of R&D breeding costs are labor. Breeding energy is amortized over a very large quantity of seed ultimately grown and sold. The majority of the energy used in R&D is in field trials. These are typically carried out in farmer's fields on small plots, say 20 acres, and the product is turned over to the farmer as payment.

The gross heating value of bone-dry shelled corn is reported to vary between 8,000 and 8,500 BTU/lb. At 15% MC, the gross heating value is approximately 6,800 BTU/lb[30]. The energy ratio for corn agriculture considering only primary energy is estimated to be 7.4.

Table 15 Estimated Inputs to Corn Production for 2000

Energy Basis		Quantity	Energy/unit	t-LHV
Seed	Bu/acre	0.34		82,477
N (as N)	Lb/acre	134.35	21,893	2,941,372
P (as P2O5)	Lb/acre	49.27	824	40,601
K (as K2O)	Lb/acre	57.42	2,059	118,219
Limestone	Tons/acre	1.32	107,435	141,814
Micronutrients				N.A.
Chemicals	Lb/acre	2.27	130,192	295,544
Diesel	Gallons/acre	7.73	159,225	1,230,259
Gasoline	Gallons/acre	3.25	152,470	495,108
LPG	Gallons/acre	5.54	90,695	521,026
Electricity	KWh/acre	62.6	9,331	602,943
Natural Gas	CF/acre	225.62	1,016	229,332
Custom Work & Drying	BTU/acre			241,170
Inputs Transportation	Fertilizer			283,451
Inputs Packaging	Fertilizer			28,294
Total				7,251,609
Yield	Bu/acre	140.18		
BTU/Bu				51,731

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[30] See energy.cas.psu.edu/energycontent.html.

4 Corn Transportation and Storage:

Shelled corn at 15% nominal moisture content is moved from the farm to the elevator or the processor. The elevator network involves county, sub-terminal, terminal, river and port elevators, and grain may be handled several times. In the case of ethanol production, farmers will deliver a portion of the crop directly to the mill. The mill may also contract or spot purchase corn from local elevators.

Gervais and Baumel[31] reported how Iowa corn was transported in the 1994-1995 season. Of the 1.5 billion bushels hauled off of the farm, 35.8% was moved in semi's, 33.3% in wagons and 30.9% in single and tandem axle trucks. The hauling distance was 37.2 miles by semi, 4.9 miles by wagon and 9.1 miles by single and tandem axle vehicles. 71% was delivered to county elevators and 29% was delivered directly to other markets including processors. The average hauling distance to county elevators was 7.5 miles and to processors was 49.7 miles. Semi trucks accumulated the majority of the ton-miles required for corn transported to the mill. Several Minnesota corn millers who indicated that the maximum radius of supply for their mills was 65 to 80 miles; these data validate the Iowa hauling distance. In this analysis, it was assumed that the trucks returned unloaded. Since the weight of the payload is approximately equal to the empty weight of the truck, the return fuel cost was assumed to be half of the fully loaded transport energy cost. The energy for transport is therefore estimated for the effective 74.6 mile round trip (1.5 times 49.7 miles).

There is a minor energy requirement involved with corn storage and handling. Corn supplied to local elevators and storage systems at the mill must be aerated and treated with insecticide and fungicide to preserve the grain. There is also energy consumption for loading and unloading the grain.

The work to lift the corn into the elevator and unload it is small. For a typical bucket elevator, the energy use is about 0.05 hp-hr/ton. For an auger load out, the energy is approximately 0.2 hp-hr/ton. For each loading and unloading, the energy would be approximately 44 BTU/bushel accounting for electrical generating efficiency. For winter storage, Maier[32] indicates that 1200 cubic feet of air movement are required per bushel for cooling to a temperature sufficiently low for a long storage life. Assuming 50% efficiency for the fan, the energy required to ventilate each bushel is approximately 40 BTU.

USDA NASS reported post harvest use of fungicide and insecticide for stored corn[33] for the period September 1 1997 to August 31, 1998. The predominant insecticides were Malathion and Aluminum Phosphide and the main fungicide was Captan. For Illinois, Indiana, Iowa, Minnesota, Nebraska and Ohio, the total application of active ingredients

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[31] Gervais, J., Baumel, C.P., "The Iowa Grain Flow Survey: Where and How Iowa Grain Producers Ship Corn and Soybeans", CTRE, Iowa State University, 19XX.

[32] Maier, D., "Shifting from Corn Drying to Corn Storage", Purdue University Cooperative Extension, Grain Quality Fact Sheet #6, 1992.

[33] USDA NASS, "Post Harvest Chemical Use Estimates for Corn and Wheat", March 1999.

were 54,100 pounds of insecticide and 34,100 pounds of fungicide to a crop of 5,930 MM bushels. Assuming energy content of 200,000 BTU/lb for these chemicals, the energy in all post harvest chemicals is approximately 3 BTU/bushel.

The total input for transportation, storage and handling is estimated to be 4,631 BTU/Bu total LHV.

5 Ethanol Manufacture

In 2000, 92% of all the existing corn/milo based ethanol production resided in the nine-state region of the Corn Belt[34]. Table 16 is a summary of estimated capacity by type and state. Approximately 46% of the capacity is in dry mills. The table also shows how the crop was distributed over the 9-state region. It is evident that weighting by either ethanol plants or corn production will give essentially the same result.

Recent new plant construction is based upon dry mills. Existing wet mills have undergone expansion to provide new ethanol capacity. However, construction of grass roots wet mills is not likely in the future because of their higher capital cost and due to the fact that the market for corn sweetener, a high valued swing product also made from corn starch, is saturated. Considering plants in planning and under construction, total corn based capacity may rise to 2,841 MM gallons/year in the next few years. The incremental capacity will include 890 MM gallons per of dry mills and 123 MM gallons per year of wet mills.

In the more distant future, the "marginal" ethanol plant will be the dry mill. Thus, in the future, assuming 5 billion gallons per year envisioned in recent Federal legislation proposals, with a 85% plant operating factor, the quantity of dry milling capacity would rise to 4.8 billion gallons.

Table 16 Summary of Grain based Ethanol Capacity in 2000
MM Gallons per Year

	Total	Wet	Dry	% Capacity	% Crop
IL	639	406	233	35.0%	31.7%
IN	85	0	85	4.6%	4.8%
IA	385	361	24	21.1%	25.6%
MI	0	0	0	0.0%	0.0%
MN	272	40	232	14.9%	15.2%
NE	384	175	209	21.0%	19.2%
OH	0	0	0	0.0%	0.0%
SD	59	0	59	3.2%	3.3%
WI	4	0	4	0.2%	0.2%
Subtotal	1,828	982	846		
Other States	122				
Total	1950				

5.1 Material Balance:

Yields of ethanol and co products depend on corn composition. Data for the composition of corn have not been reported for the whole nine-state region. Data have been reported

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[34] See www.RFA.org for a listing of plants and plant capacities.

by Purdue University for extensive sampling of Indiana corn for 1995 through 1997[35]. These data are used as the basis for wet and dry mill overall material balances. A standard bushel is 56 pounds of corn at 15% moisture content. Generally, this specification applies to corn delivered to ethanol plants. Table 17 presents the analysis for corn assumed for this study as well as the results of the 1997 survey.

Table 17 Corn Analysis, Bushel Basis

Component	Assumed		1997 Indiana Survey	
	%	Pounds/Bu	Average	Range
Starch	61.9%	34.7	61.9	55.3-64.9
Corn oil	3.3%	1.85	3.3	2.5-7.2
Protein	7.9%	4.4	7.9	4.5-11.9
Fiber	11.9%	6.7		
Moisture	15.0%	8.4	15.0	
Total	100.0%	56		
Dry matter		47.6		

5.1.1 Ethanol Yield:

A recent survey conducted by the USDA[36] has found that the yield of ethanol in dry and wet mills currently achieved is 2.63 and 2.68 Gallons per bushel respectively. According to Engineers &Constructors currently developing projects, new dry mill facilities are expected to achieve 2.73 Gallons/ Bu. The best new plants under construction may achieve 2.8 gallons/Bu.

In either wet or dry milling, starch is converted to ethanol by fermentation. Starch is a polysaccharide (complex sugar) with the formula $(C_6H_{10}O_5)_n$. To produce ethanol, the starch is first hydrolyzed to glucose ($C_6H_{12}O_6$) by addition of one molecule of water per glucose (MW 180). The glucose is fermented according to the following formula:

$$\tfrac{1}{2}\ C_6H_{12}O_6 \text{ (Glucose)} \Rightarrow C_2H_5OH \text{ (Ethanol)} + CO_2 \text{ (Carbon Dioxide)}$$

The approximate formula relating ethanol yield from starch is given by the following:

$$\text{Yield, gallons/bushel} = \text{Starch Converted, lbs}^{*}\ (180/162)^{*}(46/90)/6.61$$

The ratio 180/162 accounts for hydrolysis of starch to glucose while the ratio 46/90 is the weight fraction of ethanol yielded from fermentation of glucose. The remainder, 44/90, is carbon dioxide. The density of ethanol is 6.61 lbs/gallon. For the cornstarch fraction assumed, the theoretical yield of ethanol is about 2.97 gallons per bushel.

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[35] Maier,D., Reising,J., Briggs,J., Gann,R., “1997 Indiana Corn Composition Data”, Grain Quality Task Force, Purdue University.

[36] Shapouri, H., Gallagher, P., Graboski, M.S., “USDA’s 1998 Ethanol Cost of Production Survey”, Agricultural Economic Report 808, USDA, January, 2002. USDA Survey

5.1.2 Dry Mill Co Products:

In the dry mill, the protein, corn oil, unconverted starch, and non-reactive dry matter are combined to produce a feed supplement termed DDG (Distillers Dried Grains). Often, this is combined with a second residue called thin stillage to produce DDGS (Distillers Dries grains with Solubles). Many dry mills are shipping Distillers grains wet to minimize drying costs. The USDA survey reports that about 16% are shipped as WDGS.

DDGS is a market commodity with a specification[37]. Typical composition data were used in this study to constrain the calculated composition and yield of DDGS based upon ethanol yield and assumed corn composition[38]. Table 18 shows the estimated output data from the dry mill. These are determined by material balance from the assumed corn composition and the ethanol yield. Based upon material balance data and actual reported outputs for plants, 4% loss is assumed.

Table 18[39] DDGS Production and Quality
10% Moisture Basis

Ethanol Yield , gallons/Bu		2.63	
DDGS	Lb/bu	Protein	Fat
	17.87	23.8%	9.9%

Table 19 compares the data of Spiehs et al[40] with the assumed analysis to be used in this investigation. It was not possible to match the protein and fiber content without a significant change in protein and starch from the Indiana analysis. The DDGS used in this study is lower in quality than that reported by Spiehs et al.

Table 19 DDGS Comparison

	% Wet Basis	
	This Analysis	Spiehs et al
Protein	23.8%	27.2%
Fat	9.9%	9.8%

5.1.3 Wet Mill Products:

In the wet mill, corn oil and two feed grain products, corn gluten meal (CGM) and corn gluten feed (CGF) are typically recovered. The Corn Refiners Association[41] report that typical yields from wet mills producing 2.5 gallons of ethanol per bushel are 1.6 pounds of corn oil, 13.5 pounds CGF and 2.5 pounds of CGM. The yield of CGF depends on the corn composition and ethanol yield. Table 20 presents the material balance co product

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[37] See for example the Williams Energy website for their specifications for various feed materials.

[38] See www.Ingredients101.com/dgrains.htm

[39] The excel solver tool was used to force the material balance to be satisfied.

[40] Spiehs, M.J., Whitney, M.H., Shurson, G.C., "Nutrient Base for Distillers Dried Grains with Solubles Produced from New Ethanol Plants in Minnesota and South Dakota", University of Minnesota.

[41] www.corn.org/web/faq.htm

yields based upon Indiana corn composition, when constraining CGM before processing losses to 2.5 pounds. A processing loss of 4% is assumed for CGF and CGM based upon a comparison of survey data and material balance calculations.

Table 20 Wet Mill Co-Products
Per Bushel 15% MC Corn

	Weight, lbs	Protein	Fat	Moisture
Corn Oil	1.52			
Gluten feed	13.43	20.9%	2.0%	10%
Gluten meal	2.40	60.0%	2.0%	10%

5.2 Plant Energy Use:

Data on plant energy use are detailed in Appendix 4. Table 21 presents the capacity weighted purchased energy inputs for wet and dry mills.

Table 21 Energy Inputs for Ethanol Plants

Energy Input	Dry Mill	Wet Mill
Thermal, HHV BTU/gallon	39,031	55,328
Electricity, Kwh/gallon	1.07	0.74
Total LHV Input BTU/gallon	48,539	60,658

5.2.1 Dry Mill Energy Consumption:

Shapouri et al.[42] report energy costs for 18 dry mills. The plants are mainly fueled using natural gas and coal; a small quantity of steam is also purchased. The by-state average price for coal and natural were estimated and the approximate thermal input by plant was established. The (arithmetic) average fraction of the primary energy on a steam free basis is 87% natural gas and 13% coal.

To convert electricity to total energy, it is appropriate to use the Corn-Belt average fossil energy to electricity efficiency reported in Appendix 1 for electricity. Because purchased energy is reported, the inputs include all plant stack losses and inefficiencies.

The dry mill inputs are in good agreement with reported modern designs based upon molecular sieve dehydration yielding DDGS. Madsen [43] reported a process input of 34,000 LHV BTU/gallon and 1.2 Kwh/gallon. Assuming 90% LHV boiler efficiency with natural gas results in a total LHV input of 48,500 BTU/gallon adjusted for boiler efficiency. For WDGS, Madsen estimated a total LHV input of 38,685 BTU/gallon.

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[42] Shapouri, H., Gallagher, P., Graboski, M., “Ethanol Plant Operation Analysis”, Presented at the Dry Mill Ethanol Plant Conference, Normal Illinois, May 3, 2001.

[43] Madsen, p., “Energy Utilization in Fuel Ethanol Production”, 1991 Fuel Ethanol Workshop, South bend Indiana, June 10-12, 1991.

Assuming 16% of the co product is delivered wet, the weighted input is estimated to be 46,930 BTU/gallon suggesting that future design targets identified in 1991 are being met by the current industry.

Based upon survey data of Engineers and Constructors currently building new plants, the total LHV input for a natural gas fired dry mill without cogeneration producing DDGS is about 46,176 BTU/gallon or 5 % below the energy input identified by Madsen.

5.2.2 Wet Mill Energy Consumption

Modern wet mills employ cogeneration to produce a substantial part of their electric power. Of the current wet mill capacity, it is estimated that 90% of the production capacity uses at least some cogeneration. The major wet-millers use coal and natural gas as their energy sources.

Table 21 indicates that current wet mills require about 60,658 BTU/gallon of total LHV input. DeSpiegelaere (see appendix 4) reported that the best-wet mills could require 50,802 BTU/gallon at 2.68 Gallons/Bu yield. It would appear that the current wet milling operations are achieving efficiencies somewhat lower than those reported in the literature.

5.3 The Energy Value of Co Products:

Inputs and outputs are summarized in Table 22 for 5 billion gallons per year of ethanol production. Table 23 shows the potential for feeding DDGS and corn gluten feed and meal at typical rates to livestock.

Table 22 Input and Output Data
For 5 Billion Gallons/Year Production

Corn	1,786	Million Bu
DDGS	36,289,058	Tons per year
CGF	6,307,332	Tons per year
CGM	1,127,100	Tons per year
Oil	1,425,964,522	Pounds per year

Table 23 Potential Livestock Feed Market for DDGS, CGF, and CGM

Potential Uses	Herd	Rate, lb/day	Tons/yr
Dairy	9,200,000	10	16,790,000
Beef	97,309,000	10	177,588,925
Swine	96,991,000	0.5	9,195,949
Poultry Broilers	8,150,000,000	0.0330	49,142,346
			252,717,220

At the time the ethanol market is 5 billion gallons per year, DDGS and WDGS production may increase to about 36 MM tons per year. The largest market is beef finishing followed by poultry production. Because of the quantity of co products, most feeding will not be integral with the dry mill. Thus, the likely co product form will be DDGS in order to minimize transportation cost. This will result in an increase in energy use on-average in future plants due to the drier load.

The co product is credited in terms of its value as a livestock feed. Therefore, the energy used to produce alternate feed formulations with and without co products must be evaluated.

5.4 Use of DDGS and WDGS as Livestock Feed:

Because of the market size, it is assumed that WDGS and DDGS will be used completely in the beef market. The most likely formulation provides the minimum cost of the finished feed per unit weight gain of animal. In the future, WDGS and DDGS will have to be priced to provide economic incentive for its use.

The performance of D and WDGS as feed supplements depends on the type of animal. The key element in the diet is protein. For ruminants, bypass protein escapes less useful digestion in the rumen and is digested in the abomasums and small intestine. Thus, feeding efficiency is dependent on the bypass protein. The bypass protein content of DDGS has been reported[44] to be 40 to 74% of the crude protein compared to about 31% for soybean meal. Aines et al also report that the bypass value of WDGS and DDGS ranges from 129% to 408% of soybean meal with a likely value of 200%. Thus, less protein is required in diets when W or DDGS is substituted for soybean meal. In the case of non-ruminants, WDGS or DDGS is valued on its crude protein content.

The energy content of the feed is also important. Generally, the net energy, that is the portion of the energy not excreted or used in the metabolic and digestive processes is relevant. Three net energies are cited. These are net energy for maintenance of weight, net energy available for gain of weight, and net energy for lactation of dairy cows. W and DDGS contain three times the fiber in corn, are very low in starch and are very high in fat compared to corn. Lalman[45] reports that energy values for feeds are a function of the dietary mixture. The effective energy content of grains like corn used in significant quantity in feed formulations are overstated because of the high starch level (the so called negative associative effect). Co products like DDGS and CGF provide most of the energy in the form of highly digestible fiber instead of starch. Boyles[46] indicates that corn grain depresses forage digestibility where as highly digestible feeds do not. The typical feedlot diet contains about 85% corn. Ham et al[47] show that the effective energy of DDGS when used to replace 40% of the corn in the finishing diet decreased the feed to gain ratio by

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[44] Aines, G., Klopfenstein, T., Stock, R., “Distillers Grains”, University of Nebraska Cooperative Extension, report MP 51, 1986.

[45] Lalman, D., “Alternative Feeds for Beef Cows and Stockers”, Ag Pub G2076, UMo-Columbia, Jan 1996.

[46] Boyles, S., “Corn Gluten Feed”, Ohio State University Extension-Beef Information page, beef.osu.edu/library/gluten.html. CGF has an apparent energy of 102% of corn in high silage diets.

[47] Ham, G.A., Stock, T.J., Klofenstein, T., Larson, E.M., Shain, D.H., Huffman, R.P., “Wet Corn Distillers Byproducts Compared with Dry Corn Distillers Grains with Solubles as a Source for Protein and Energy for Ruminant”, J Animal Sci, (72), page 3246, 1994.

13% suggesting that the effective energy of the DDGS in that diet was on the order of 1.2 times corn. The corresponding ratio for WDGS is 1.5. Trenkle[48] carried out a 137-day feeding trial for 154 steers was conducted on diets based upon cracked corn, and corn supplemented with 10% soybean meal, 16% DDGS, and 16%, 28% and 40% WDGS. The control diet was a mixture of corn, alfalfa, molasses, urea and minerals. Generally, soybean meal, DDGS or WDGS were substituted for corn and urea was adjusted. The equivalent energy for DDGS was 92% of corn while WDGS was found to have an energy equivalent of 150% of corn. Aines et al report a summary of 1980's literature that shows that DDGS has an effective energy of 109% on average and up to 124% of corn. There are mixed results for DDG and DDGS in the older literature, primarily due to feed quality. Older ethanol dry mills often produced a colored dry solid that had been scorched in the drier; this feed has been degraded and is of lower quality than dry solid produced in modern plants. Williams and Corners[49] recently fed 63 Angus heifers with a silage-based feed that included a soybean meal or DDGS supplement. The difference in the mean gain/feed ratio was significant at the 80% level and the indicated energy of DDGS was 1.2 relative to corn. Gordon et al[50] conducted a 153 day trial with 345 heifers where DDGS was varied in finishing diets based on steam flaked corn at levels of 0%, 15%, 30%, 45%, 60% and 75%. The best DDGS feed-level was 15%. The effective energy of DDGS was estimated to be 1.26. In addition, the beef quality was superior to the control diet with 29% of the herd grading as prime using 155 DDGS compared to 15%. Both feeds produced the same fraction as select grade beef.

The relative energy content of 44% soybean meal under similar circumstances is 98% to 100%. On average it appears that DDGS is superior to corn and soybean meal in terms of energy content for ruminant feeding. In the case of non-ruminants, the energy density is lower because non-ruminants have a limited ability to utilize fiber as an energy source[51].

The third major feeding consideration is essential amino acids, of which Lysine is most important and generally limiting. The Lysine concentration in DDGS is relatively low, especially compared to soybean meal. Thus, in substituting DDGS at high levels in the diet especially for non-ruminants, Lysine must either be balanced or supplemented. Most feeding formulations limit the fraction of DDGS in the feed. Limited amounts of synthetic lysine are made commercially by fermentation from cornstarch.

5.4.1 Wet Mill Products:

Today, most of the wet mill byproducts are exported. The wet mill products CGF and CGM are used as a protein source for livestock feed and are interchangeable with a

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[48] Trenkle, A., "Evaluation of wet Distillers Grains for Finishing Cattle", As Leaflet R1342, Iowa State University, 1995.

[49] Williams, J., Corners, B., "Final Report to Dakota Commodities and Northeast Missouri Grain", see www.dakotagold.org, 2002.

[50] Gordon, C.M., Drouillard, J.S., Gosch, J., Sindt., J.J., Montgomery, S.P., Pike, J.N., Kessen, T.J., Sulpizio, M.J., Spire, M.F., Higgens, J.J., "Dakota Gold-Brand Dried Distillers Grains with Solubles: Effects of Finishing Performance and Carcass Characteristics", page 27, Cattlemen's Day, 2002.

[51] Oba, M., Allen, M., "Utilization of Corn Distillers Grains as a Livestock Feed", Michigan State University. See www.micorn.org/research/dried%20distillers%20grain.htm.

mixture of shelled corn and soybean meal. The bypass protein value of CGM is much higher than for soybean meal while the bypass value for CGF is lower. CGF like DDGS contains little starch energy. While CGF has a lower energy value than corn, Boyle reports that the effective value of CGF in feed can be 102%.

Since oil is a byproduct of both wet milling and soybean meal production, it is also important to balance oil net production. Corn oil and soybean oil are interchangeable in the marketplace. Oil is also required to balance feed energy. In the analysis, sufficient soybean oil is produced to replace wet mill corn oil and balance feed energy. This defines the quantity of soybeans and soybean protein required to replace the wet mill products.

5.4.2 Soybean Agriculture:

Soybean farming and processing inputs were obtained from Tyson et al[52] and are presented in table 24. Soybeans yielding 37.1% protein and 17.7% oil on a 13% moisture basis are grown[53] to replace the co products. The yield was adjusted to 38 Bu/acre for the year 2000. Table 25 summarizes the processing energy required to produce oil and meal.

Table 24 Soybean Energy Inputs
BTU/Acre

		Input	T-LHV
Seed			
N	Lb/acre	9.89	216,518
P (as P2O5)	Lb/acre	31.02	23,325
K	Lb/acre	52.8	114,544
Limestone	Tons/acre	0	
Chemicals	Lb/acre	4.06	473,918
Diesel	Gallons/acre	5.29	
Gasoline	Gallons/acre	3.11	842,302
LPG	Gallons/acre	0.38	474,181
Electricity	KWh/acre	4.6	34,464
Natural Gas	MCF/acre	70	41,511
Custom Work & Drying	Gal Diesel/acre	0.96	71,153
Inputs Transportation			152,856
Total			229,402
Processing			2,674,175
Total w Processing			2,197,074
			4,871,249
Btu/Bu	Bu/acre	38	131,403
2012 BTU/Bu	Bu/acre	44.5	117,563

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[52] Tyson, S., Sheehan, J., Duffield, J., Shapouri, H., Graboski, M., Camobreco, V., “Life Cycle Inventory of Biodiesel and Petroleum Diesel in an Urban Bus”, USDOE/USDA, 1998.

[53] Maier, D., Reising, J., Brigs, J., Gann, R., “1997 Indiana Soybean Composition Data”, Grain Quality Task Force, Purdue.

Table 25 Soybean Processing
Per Bushel of Soybeans

Bean Proximate	Weight %	Pounds	% Protein
Protein	37.10%	22.26	
Moisture	13%	7.80	
Oil	17.70%	10.62	
Hulls	9.11%	5.46	
Oil free Meal, dry		36.12	
Total		60.00	
Total Dry Matter		52.20	
Oil in Hull	2.0%	0.12	
Oil in Meal	1.4%	0.56	
Net meal, 10% MC	46.9	40.75	53.3%
Net Hulls, 10% MC		6.21	9.89%
Net Oil	9.94		

Table 25 Continued Processing Energy per Bushel of Soybeans

	Power Kwh/Bu	Steam BTU/Bu	Natural gas BTU/Bu	Total NG BTU/Bu	Diesel	BTU/Bu
Transport					73.5	
Processing, HHV	1.876	23,776	14,100	43,820		
LHV tot	17,509			43,413	108.3	61,030 or 6,123 BTU/lb Oil

5.4.3 Co Product Credit:

The co product credit was estimated using the National Research Council (NRC) model for cattle feeding[54]. In the analysis, feed supplements were compared on the basis of total useful protein[55] and energy for growth for the total pool of production weighted co products. The replacement feed cost was "minimized"[56], generally meaning that diets are protein limited if possible and use the maximum amount of corn. Feedstocks considered are as follows: shelled corn, whole soybeans, 44% soybean meal, for the protein supplement, corn cobs and soybean hulls for fiber and energy and urea to balance degradable protein. NRC data were used except for DDGS where the energy was increased by 20% relative to corn. The percentage of DDGS in the diets was generally

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[54] National Research Council, "Nutrient Requirements for Beef Cattle", Seventh Revised Edition, Update 2000, National Academy of Sciences Press, Washington DC, 1996. A "level 1" approach is followed .

[55] The NRC model considers both degraded and undegraded protein.

[56] The level 1 NRC diet model provides diagnostic tools to ensure that the diet predicted is realistic. However, the model is not readily integrated into an optimization routine. Because soybean products are more expensive to use than corn products, "minimized" means to use the least soybean and soybean meal possible.

limited to 15% based upon literature recommendations. The animal unit chosen was taken from Trenkle[49].

Table 26 provides the diet analysis. In the ethanol case, the co product mix was weighted by corn use as 54% to wet mills. In the replacement case, the quantity of soybean meal was established by oil required to replace corn oil (1.52 lb/Bu * 54%). Table 27 presents the co product replacement energy analysis.

Table 26 Diets Based Upon NRC Model

Diet Component	Lbs/day With Ethanol	Lbs/day with Replacement	Difference Per Bushel 15% MC
Cracked corn	7.200	14.20	17.198
Urea	0.000	0.10	0.246
Corn cob	1.550	2.00	1.106
Soybean hulls	2.750	0.55	(5.405)
Minerals	0.300	0.30	0.000
DDGS	3.000	0.00	(7.370)
CGM	0.476	0.00	(1.169)
CGF	2.667	0.00	(6.552)
Corn Silage	0.000	0.00	0.000
Soy bean meal, 44%	0.000	1.418	3.483
Soybean whole	0.000	0.00	0.000
DMI	18.000	18.57	
ADG-E	3.50	3.56	
ADG-P	4.61	3.50	
DIP bal	14	5	
eNDF bal	0.00	0.00	
Soybean Oil			0.823

ADG is average daily gain by Energy (E) or Protein (P), DMI is dry matter intake
eNDF is fiber from roughage, DIP, degradable intake protein refers to microbial protein

Corncobs and soybean are considered as waste products. They have essentially zero processing and agricultural energy as these are assumed to be embodied in the grain.

Table 27 Co Product Energy per Bushel of Processed Corn to Ethanol

Component	Difference lb/Bu to EtOH, wet basis	Energy/ Unit	T-LHV, BTU/Bu
Cracked corn	20.23(0.361)	51,731 BTU/Bu	18,690
Urea	0.25	11,260 BTU/lb	2,766
Corn cob	1.301	0	0
Soybean hulls	(6.006)	0	0
Minerals	0	-	0
DDGS	(8.67)	-	0
CGM	(1.38)	-	0
CGF	(7.71)	-	0
Soy bean meal, 44%	4.00 (0.098 Bu)	131,403 BTU/Bu	12,098
Oil	0.876	6,119 BTU/lb	5,034
Total BTU/Bu			39,398
Total BTU/Gal			14,829

In both cases, the ADG assumed is 3.50 pounds per day per animal unit. In the ethanol diet, average daily gain is energy limited and there was “protein giveaway”. Considerable effort was expended examining feed formulations based upon the feed stuffs available in the NRC library that could bring energy and protein based weight gains more in agreement for co product based feeds without success. It was possible to balance energy and protein requirements in the replacement case. Urea was required to balance DIP in the replacement case. Based upon the replacements, the estimated credit is 14,829 BTU/gallon. It is estimated that it would require 0.72 acres/acre of corn for ethanol to provide the feed replacements. The “protein giveaway” reduces the value of the co product credit.

Similarly, Table 28 shows the diets found for the 200-2004 incremental industry under and for the industry in 2012. In 2000-2004, the reported ethanol yield of new wet and dry plant capacity will be 2.73 gallons/Bu, while in 2012 it increases to 2.80. Table 29 shows the replacement energy. In table 29, the soybean farming efficiency was adjusted to reflect an increased yield to 44.5 Bu/acre based upon the USDA soybean baseline.

The energy replacement value of the wet mill co products is significantly higher than the dry mill co products. In the base case, 72% of the land supplying corn to wet and dry mills would need to be planted in the absence of ethanol production for ruminant feeding and corn oil replacement. Thus, while the apparent yield of ethanol per harvested acre is currently 372 gallons, the actual yield when replacement is taken into account is approximately 1,300 gallons per acre.

Table 28 Diet Summary for 200-2004 and 2012

	2000-2004		2012	
Diet Component				
Cracked corn	9.22	11.50	9.03	11.40
Urea	0.15	0.00	0.13	0.03
Corn cob	2.10	2.05	2.03	2.13
Soybean hulls	3.00	2.60	3.00	3.20
Minerals	0.30	0.30	0.30	0.30
DDGS	3.00	0.00	3.00	0.00
CGM	0.054	0.00	0.093	0.00
CGF	0.304	0.00	0.519	0.00
Corn Silage	0.00	0.00	0.00	0.00
Soy bean meal, 44%	0.00	0.162	0.00	0.276
Soybean whole	0.00	2.30	0.00	1.78
DMI	18.10	18.91	18.10	19.10
ADG-E	3.5	3.69	3.50	3.69
ADG-P	4.15	3.50	4.19	3.50
DIP bal	10	7.00	4.00	5.00
eNDF bal	0.01	0.00	0.00	0.01

Table 29 Replacement Co product Energy for the Incremental and Future Industries

	2000-2004		2012	
Diet Component				
Cracked corn	12.72(0.23Bu)	11,748	12.19(0.22Bu)	9,820
Urea	(0.71)	(8,008)	(0.44)	(4,923)
Corn cob	(0.28)		0.51	
Soybean hulls	(2.11)		0.97	
Minerals	-		-	
DDGS	(16.73)		(15.43)	
CGM	(0.30)		(0.48)	
CGF	(1.70)		(2.67)	
Soy bean meal, 44%	0.88(0.02Bu)	2,845	1.39(0.03Bu)	4,004
Soybean whole	12.53(0.21Bu)	27,450	8.95(0.15Bu)	17,529
Oil	0.181	1,109	0.285	1,745
Energy, BTU/Bu		35,143		28,174
Energy BTU/Gal		12,880		10,062

6 Ethanol Distribution

Ethanol distribution includes:

- Shipping to distribution terminals primarily by rail
- Distribution to service stations by truck
- Delivery to vehicles via dispensing pumps

An estimate of the use of ethanol by PADD in 2000 and 2012 was made. For 2000, FHWA[57] gasohol use by state was utilized. In 2012, it was assumed that the percentage of gallons treated with ethanol doubled in PADD 2 from about 30% to 60%. The remaining ethanol was distributed uniformly throughout the remaining PADDs.

It was assumed that rail was used for all long distance transportation to distribution terminals. Table 30 shows the assumed weighted rail transportation distances and gallons transported in 2000 and 2012. The miles were obtained by averaging CSX and BN rail distance finders from Chicago to several larger cities in each PADD.

The average distance from the terminal to the service station is assumed to be 25 miles with an empty return. The truck must carry an incremental 0.53 gallons of ethanol for each gallon of gasoline replaced because of the lower energy density of ethanol.

Energy used for loading and unloading ethanol at various locations and dispensing energy is assumed to be 0.8% of the energy content of the ethanol[58].

Table 30 Ethanol Distribution Distance

	2000		2012	
PADD	MM Gal	Miles Rail	MM Gal	Miles Rail
1	65	809	1,232	809
2	1,097	308	2,632	308
3	59	981	435	981
4	111	1,298	107	1,298
5	144	2,119	593	2,119
Totals	1,476	608	5,000	726

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[57] FHWA, 2000 Gasohol data

[58] EPA

7 Net Energy

7.1 Net Energy for Current Technology:

Tables 31, 32 and 33 present results for current dry and wet mills along with the industry average analysis. Table 31 and 32 show the net energy of dry mill and wet mill ethanol plants not considering any co product credit. Without co products, dry mills exhibit a positive net energy while wet mills yield a negative net energy. Table 33 shows that the net energy of the current industry is 13,300 BTU/gallon and the corresponding ratio is 1.21.

Table 31 Energy Analysis for 2000 Vintage Dry Mills

	T-LHV
Corn Production	19,669
Corn Transportation	1,554
Ethanol Production	48,539
Ethanol Distribution	1,238
Sub-total	71,202
Energy in ethanol	76,000
Net Energy w/o Co Product	4,798

Table 32 Energy Analysis for 2000 Vintage Wet Mills

	Total LHV
Corn Production	19,303
Corn Transportation	1,525
Ethanol Production	60,658
Ethanol Distribution	1,238
Sub-total	82,922
Energy in ethanol	76,000
Net Energy w/o Co Product	(6921)

Table 33 Industry Weighted Analysis for 2000

	t-LHV
Corn Production	19,472
Corn Transportation	1,743
Ethanol Production	55,049
Ethanol Distribution	1,233
Byproduct credit	(14,829)
Total	62,668
Energy in ethanol	76,000
Net Energy	13,332
Ratio	1.21

7.2 Propagation of Errors

The industry-weighted analysis was further analyzed in appendix 3 where the quality of data and sensitivity of the net energy to errors in the data are examined using propagation of errors. The expected net energy is 13,332 BTU/gallon. The estimated lower 95% confidence limits for net energy based upon the inputted data is 8,136 BTU/gallon. The analysis demonstrates that the probability that net energy balance could be negative due to compounding of errors in the data set is virtually zero.

7.3 Net Energy of the Incremental Industry:

The current industry represents a mixture of old and new facilities, and may not be characteristic of new production coming on-line. A recent report of plants under design and construction suggests that the new total capacity of grain-based ethanol will be 2,841 MM gallons in the very near future[59]. The increase in capacity over the year 2000 is 890 MM dry mill and 123 MM wet mill gallons per year. The wet mill capacity is a result of debottlenecking existing facilities and should not impact the energy use. The majority of the new dry mill efficiency is based upon data supplied by Engineering and Construction firms for plants currently under construction as reported in Appendix 4. The E&C data may provide a conservative energy estimate because some of the co product may be shipped wet. Table 34 summarizes the results. The estimated total plant energy use is 13% lower than the energy reported to be used by the current operating industry. However, the co product credit is also lower because of the large fraction of dry mills in the new capacity. The net energy ratio is substantially higher than that of the current industry.

Table 34 Net Energy and Energy Ratio of Incremental Ethanol Capacity

Dry Mill Capacity	890 MM GPY
Wet Mill Capacity	123 MM GPY
Corn Production	19,625
Corn Transportation	1,757
Ethanol Production	47,937
Ethanol Distribution	1,233
Byproduct credit	(12,880)
Total	57,671
Energy in ethanol	76,000
Net Energy	18,329
Ratio	1.32

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[59] RFA, "US Fuel Ethanol Production Capacity", 2002.

7.4 The Industry in 2002-2004:

In the time frame 2002-2004 after startup and construction are completed, the capacity will be approximately 2.841 Billion gallons/year of ethanol. Of this, dry mills will account for 1.736 Billion gallons/year. According to the USDA corn baseline, the corn yield is expected to be flat between 2000 and 2004. It is assumed that energy required for corn and soybean farming is therefore constant over this time period. With these assumptions, the data from the two previous sections are production weight resulting in a net energy of 15,114 BTU/gallon of 200 proof ethanol yielding an energy ratio of 1.25.

7.5 The Energy Efficiency in 2012:

By 2012 when 5 billion gallons of ethanol are being produced annually, the energy balance will improve because of a decade of efficiency gains. In this section, *a projection* is made on the impact of key efficiency gains on the energy ratio.

7.5.1 Fertilizer Production:

Between 1987 and 1999, energy use in nitrogen production decreased by 5%. From 2000 to 2012, a 0% reduction *is assumed* applicable to all fertilizer manufacture. In reality, it might be expected that the industry efficiency would increase for one of two reasons. First, some of the less efficient smaller ammonia plants in the Midwest could shut down due to high natural gas prices, increasing the use of imported ammonia. Second, the industry could increase its efficiency as it did in the previous decade. The spread in efficiency of EU producers indicates that there is considerable room for efficiency gains. However, an offsetting effect would be increased transportation energy for imported fertilizer and uncertainty in the future mix of fertilizers used.

7.5.2 Corn Yield:

The USDA projects the corn yield will increase to 151 Bu/acre in 2010 from 135.5 Bu/acre in 2000 for all corn produced. Using the last four-year rate of increase, in 2012, the projected yield is 154.4 Bu/acre. *The 2012-yield is adjusted to 160 Bu/acre* for the Corn Belt based upon the 2000 yield of 140 Bu/acre. The increase in yield can be accomplished without increasing other inputs substantially. Seed producers are working toward improving the genetic purity of seed corn to increase yield. Proper selection of hybrids by farmers for the local growing conditions and type of tillage employed can greatly impact yield. Use of disease and pest resistant genetically modified seed reduces field losses. The use of some precision farming techniques can have a significant impact. For example, it has been shown[60] that by simply controlling plant spacing uniformity using an advanced planting control system, yield can be increased by up to 23.3 Bushels per acre.

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[60] Pioneer H—Bred International, Inc., “The Value of Planter Calibration Using the Metermax System”, Crop Insights, V10, Number 23, and www.pioneer.com.

7.5.3 Fertilizer and Chemical Inputs:

Figure 4 shows inputs for the 9-state area for 1991 through 2000 in pounds per acre, for nitrogen, phosphate, and potash. Figure 5 shows the historical data for chemicals. These data were linearly regressed.

Historical data for fertilizers suggests that nitrogen inputs per acre may be increasing while phosphate and potash may be decreasing; the rates of change are much lower than the increase in yield. Thus fertilizer input per bushel of production will continue to decrease. Inputs were estimated for 2012 from the linear models. The majority of the variance is due to the year-to-year variability. However, the regression models yield significant slopes at the 90% level for N (0.52± 0.27 lb/yr, slope p =0.11) and P (-0.29 ± 0.17 lb/yr, slope p=0.12). The K-model slope (-0.16 ± 0.13 lb/yr) exhibited a p-value of 0.26; it was assumed that the K application rate doesn't change and thus the average use from 1991 to 2000 was assumed.

The most important difference observed from historical data was a very large reduction in chemical active ingredient input. While USDA does not project future chemical use, the agency reports that chemical use is declining for several reasons. These are better management of chemicals through field surveying, the development of more effective chemicals whose recommended application rates are much lower and the switch to genetically modified insect and disease resistant corn hybrids. As corn farming moves toward reduced tillage systems, herbicide use increases relative to cultivation for weed control. The data on chemical use includes the significant shift to conservation tillage discussed in the next section. In the case of chemical inputs the regression explained 81.5% of the variance (adjusted R-square) with a slope of –0.099± 0.016 and the p-value of the slope is 0.0002. The inputs are projected in Table 35.

Table 35 Projected Inputs in 2012 Compared to 2000, Pounds/Acre

	2000	2012
N	134.4	136.8
P	49.3	43.5
K	57.4	59.1
Chemicals	2.27	1.23

7.5.4 Farm Fuels and Conservation Tillage:

The definition of conservation tillage is any tillage/planting system that leaves at least 30% residue coverage on the field after planting is completed. McCarthy[61] reports that 30% coverage requires about 0.5 tons per acre of mulch. For corn, the total quantity of residue available is about 60 pounds per bushel, or in excess of four tons per acre that could provide 95% initial coverage and as much as 80% coverage after planting

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[61] McCarthy, J., "Conservation Tillage and Residue Management to Reduce Soil Erosion", U Missouri Extension, Publication G1650, 1993.

compared to 15% of that for bare soil. Less intensive tillage results in lower consumption of diesel fuel but higher consumption of herbicide.

The attributes of tillage systems used are as follows:

- **No-till:** The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is in narrow seedbeds created by specialized equipment. Weed control is accomplished primarily with herbicides.
- **Ridge-till:** The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is in seedbeds prepared as ridges. Residue is left on the surface between ridges. Weed control is accomplished by herbicides and cultivation. The ridges are rebuilt after cultivation.
- **Mulch-till:** The soil is disturbed prior to planting. Weed control is accomplished by herbicides and cultivation.
- **Reduced-till:** Tillage types that leave 15% to 30% residue cover after planting to minimize wind erosion in the early season. Weed control is accomplished by herbicides and cultivation.
- **Conventional-tillage:** Tillage types that leave less than 15% residue cover after planting to minimize wind erosion in the early season and employs plowing. Weed control is accomplished by herbicides and cultivation.

Historical data for gasoline and diesel use suggest that gasoline usage has leveled out but diesel use continues to decline. A reason for the decline in diesel is the movement to conservation tillage. Table 36 summarizes the change in Midwest corn farming operations between 1990 and 2000. Diesel fuel use for four tillage systems have been reported[62]. Linearly extrapolating the conservation tillage trend suggests that 29% of the corn acres may be no till in 2012.

Table 36 Midwest Corn Tillage System by Acreage[63]

Tillage System	1990	2000	2012	Diesel Fuel, gal/acre
No Till/Strip Till	7.5%	17.3%	29.0%	1.65
Ridge Till	3.1%	2.3%	1.3%	4.75
Mulch Till	21.6%	16.6%	10.5%	5.95
Conservation Till Total	32.2%	36.7%	40.8%	
Reduced Till (15-30% cover)	25.9%	24.3%	22.4%	6.30[1]
Conventional Till	41.9%	39.6%	36.8%	6.60
Fuel Use for tillage	5.95	5.53	5.00	

Note 1 Average of intensive and mulch till

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[62] Energy requirements for Four Tillage Planting Systems, National Corn handbook.

[63] CTIC National Crop Residue Management Survey, 2000.

7.5.5 Fuel Efficiency Gains:

EIA[64] projects that gasoline and diesel engines will be about 15% and 10% more efficient respectively in 2012. These efficiency gains were used in the 2012 projection to relate fuel use in the current fleet with fuel use in the future fleet. While the fleet of diesel and gasoline engines turns over slowly, the more or less uniform creep in fuel efficiency gain with time benefits the entire fleet. The change in efficiency of electrical generating systems is less clear. Older nuclear and coal plants will be retired and replaced with very

Figure 4 Historical Use of Fertilizer

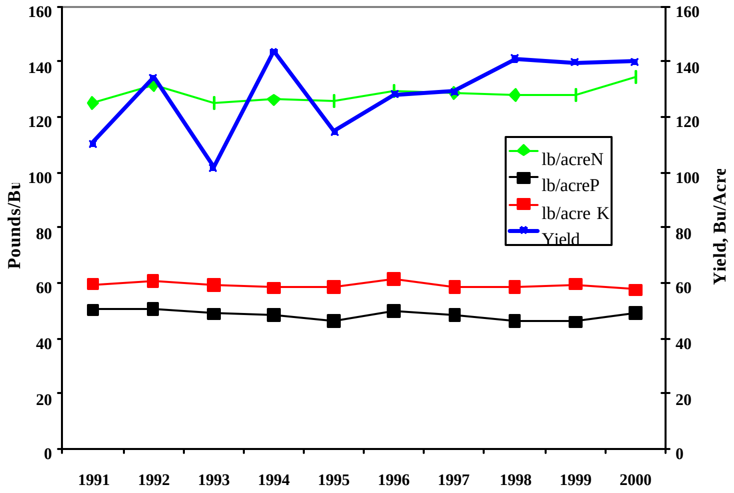
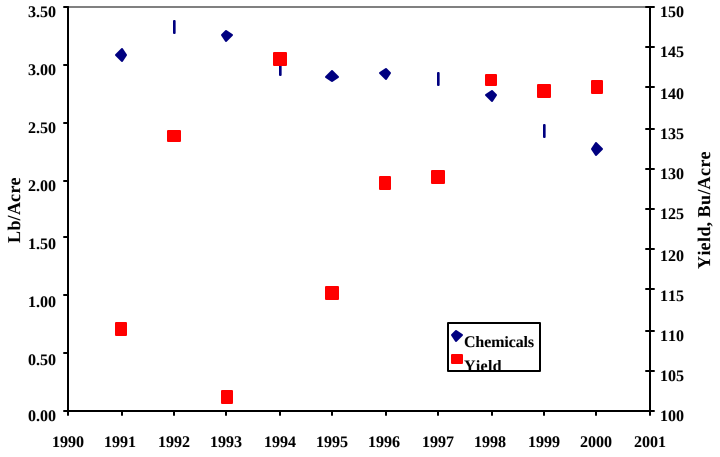


Figure 5 Historical Chemical Usage



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[64] See footnote 2.

high efficiency coal and gas power plants. The heat rates of the replacement plants are similar to the heat rate of the national mix of generators. Thus, it is assumed that there are no future benefits in terms of fossil energy efficiency.

Farm LPG and electricity use are assumed to remain the same. While some increase in efficiency may result from a shift away from heated corn drying to natural air-drying, electricity (natural gas and diesel) use may increase on irrigated farms due to receding water table levels.

7.5.6 Industry Profile:

After the current round of wet mill expansions is completed, all new capacity is assumed to be added as dry mills. In 2012, the industry nameplate capacity is assumed to be 1,105 MM wet mill and 4,777 MM dry mill GPY. These plants will produce 5 billion GPY of ethanol when operating with an 85% stream factor.

7.5.7 Ethanol Plant Energy:

Current dry mill energy usage is comparable to the best industry designs. There may be some changes in designs related to improving dry mill economics such as germ separation and recovery. These changes should improve dry mill economics, but will not materially alter energy use. Improved enzymes that permit lower cooking temperature could reduce energy use somewhat. Replacement of some natural gas with biomass crops or field residues would have a significant impact on fossil energy use; however, such a shift is not likely because of the difficulty and cost associated with collecting and burning such fuels. In the future, because of the large volumes of co products, there may not be a substantial move to wet distillers grains due to transportation costs. Thus, it is assumed that the energy use by 2012 dry mills will be the same as today. No implementation of biomass conversion technology for corn fiber is assumed. The theoretical yield of ethanol based on cornstarch is about 2.97 gallons per bushel. Ethanol yield across the industry might match today's best practice of 2.80 gallons per bushel.

In the future, the ethanol yield in wet mills will also increase; it is assumed that the increase keeps pace with the dry mills and reaches 2.80 gallons per bushel in 2012. No conversion of corn fiber to ethanol is implemented.

7.5.8 Co Products:

In 2012, the mass of co products will fall slightly as additional starch is converted to ethanol. Since there is no loss of nutrients with greater ethanol conversion, the feed value of the co products will be relatively unchanged. However, the increased efficiency in corn production will be paralleled by a similar increase for soybeans.

Other co products of higher value may be generated. For example, dry mills may start to produce corn oil. Corn gluten meal may also become more widely used as a natural herbicide. Recovery of specific high valued nutrients for human use may occur.

No co product credit for CO_2 recovery was claimed. In the future, CO_2 recovery could become more widespread.

7.5.9 Results:

Tables 37 projects the performance of the industry in 2012. By 2012, the fraction of dry milling capacity is expected to increase to 81%. At that time, the energy efficiency ratio based upon total LHV for the industry is expected to be 1.40.

Table 37 Industry Weighted Analysis for 2012

	t-LHV
Corn Production	16,109
Corn Transportation	1,489
Ethanol Production	45,768
Ethanol Distribution	1,113
Byproduct credit	(10,062)
Total	54,417
Energy in ethanol	76,000
Net Energy	21,583
Energy Ratio	1.40

8 Petroleum Displacement:

Based upon the energy balance for 2000, an accounting of crude oil use was made for ethanol manufacture. Each gallon of petroleum used as gasoline, diesel and fuel oil was adjusted to its crude oil volume equivalency using the heat content and refining and extraction efficiency data provided in Appendix 2. The consumption is detailed in Table 38.

Table 38 Crude Oil Equivalents Used in Ethanol Manufacture, Total LHV Basis

Step	Gallons/acre
N	0.137
P (as P2O5)	0.030
K	0.036
Limestone	0.039
Chemicals	0.350
Diesel	8.299
Gasoline	3.212
LPG	0.055
Electricity	0.084
Natural Gas	0.007
Custom Work & Drying	0.720
Inputs Transportation	1.907
Corn Transportation	0.029
Ethanol Manufacture	0.000
Ethanol Distribution	0.022
Total, Gallons Crude/Acre	14.928
BTU/acre	2,055,075
BTU/Gallon Ethanol	5,518

The total crude oil input to ethanol production is estimated to be 5,518 BTU/gallon of ethanol.

Ethanol will be produced whether MTBE is phased out or not. Table 39 shows that the transportation energy available from ethanol is approximately 70,482 BTU/gallon as adjusted for crude oil consumed in ethanol production. Using the approximate refining and extraction efficiency from Appendix 2 for gasoline, each gallon of ethanol used for transportation fuel is shown to be equivalent to saving 0.58 gallons of crude.

Each barrel of ethanol produced directly takes the place of 0.58 barrels of crude oil and adds about 214,000 barrels per day of 115-octane gasoline supply.

The makeup of the energy sources for a gallon of ethanol based upon the current industry is approximately 7.3% petroleum, 75.2% coal and natural gas and 17.5% solar energy captured by corn. The majority of the energy inputs are coal and natural gas. Converting coal via gasification and natural gas by reforming to transportation fuels including methanol and Fischer-Tropsch liquids is inefficient. The energy ratio is typically 0.4 for coal and 0.65 for natural gas, while it is 1.21 for the base ethanol case. Using coal and natural gas as feedstocks for ethanol plants is thus a more efficient way to convert coal and natural gas to transportation fuel. As the energy ratio increases in the future due to the inclusion of more efficient ethanol plants, ethanol production becomes an even more attractive way to convert domestic coal and natural gas to liquid fuel.

Table 39 Crude Oil Savings from Ethanol Production

	Energy Data	
	BTU	Gallon
Ethanol, energy per gallon	76,000	1
Crude Oil in manufacturing	(5,518)	
Available/gallon EtOH produced for transportation	70,482	
Gasoline Energy required[1]	70,482	
Distribution	300	
Refining	8,447	
Crude Extraction	756	
Total	79,985	0.58

[1] These values are the energy that result from refining a unit of crude necessary to produce gasoline with the same energy content as the net transportation energy available from ethanol.

9 Discussion and Conclusions:

The energy consumed in corn agriculture was estimated based primarily upon recent USDA survey reports for 1991 and 1996 surveys along with annual mass input data for chemicals and fertilizers reported by USDA. The accounting included all of the energy directly used in farming as well as the energy used to produce and transport the inputs to the farm. Energy estimates were made on a "total" basis. The estimate for the energy embodied in fertilizers was estimated from industry survey data. The energy in chemicals was based on published data. An estimate of the energy required to grow a bushel of corn in a region that includes 9 corn-producing states where ethanol is produced was developed for the year 2000. The analysis shows that the energy ratio for corn production relative to fossil fuel inputs on a primary HHV basis is about 7.4.

The net energy of ethanol to corn was examined for three different scenarios. These are the baseline industry in the 2000 time frame just prior to the recent expansion underway that anticipates the phase out of MTBE, the incremental industry now under construction, and the industry in 2012 with a 5 billion gallon production rate.

The energy input to ethanol plants was based upon industry surveys of the existing wet and dry mill industries. It was found that the industry exhibited a total energy ratio (energy produced as ethanol/fossil energy inputs) of 1.21 and a net energy of 13,332 BTU/gallon of ethanol (energy in ethanol-fossil energy inputs) in 2000. Considering propagation of errors, the lower 95% confidence level for the energy ratio is 1.12 with a corresponding net energy of 8,136 BTU/gallon.

Currently there is over a billion gallon capacity increase in design and under construction. The majority of that expansion is based upon dry mill technology. The energy input to those plants was established by surveying Engineers and Constructors who are currently building those facilities. The estimated energy ratio on a total LHV basis for new capacity is estimated to be 1.32 with a net energy of 18,329 BTU/gallon.

At the end of the current round of construction, the industry capacity will be about 2.84 BGPY. The energy ratio will be 1.25, and the net energy will be 15,114 BTU/gallon.

In 2012, the energy ratio on a total BTU basis may rise to 1.40 with a net energy of 21,583 BTU/gallon primarily through increased energy efficiency in the wet mill sector of the industry and new capacity additions in the form of dry mills. A part of the increase in efficiency in wet mills will be the result of increased ethanol yield, but the major improvement must come from investments in heat integration. If the wet mill efficiency remains static, the industry energy ratio is estimated to be 1.34.

The total energy in petroleum used to produce ethanol is approximately 7% of the energy in the ethanol. Each barrel of ethanol produced directly takes the place of about 0.58 barrels of crude oil. This results in an equivalent production of 214,000 Barrels per day of 115-octane number gasoline.

The makeup of the energy sources for a gallon of ethanol based upon the current industry is approximately 7.3% petroleum, 75.2% coal and natural gas and 17.5% solar energy captured by corn. Converting coal via gasification and natural gas by reforming to transportation fuels including methanol and Fischer-Tropsch liquids is inefficient. The energy ratio is typically 0.4 for coal and 0.65 for natural gas, while it is 1.21 for the base ethanol case. Using coal and natural gas as feedstocks for ethanol plants is thus a more efficient way to convert coal and natural gas to transportation fuel.

Appendix 1 Electrical Generation

Purchased electricity is a major energy input in all of the process energy inputs including fertilizer manufacture, corn production and ethanol manufacture. In order to appropriately characterize the energy input, data for the Corn Belt region, US electricity production and retail consumption were used[65].

Table A1-1[66] shows the net generation by fuel type and retail consumption for 2000. Net generation refers to electricity available for transmission. The transmission and distribution loss averages 7% nationally[67]. This factor was applied to the Corn-Belt. Since the energy balance is concerned with total fossil energy input, the total heat rate is in effect reduced by the non-fossil percentage. This results in a fossil input heat rate shown in the table including transmission losses. The total LHV considers the fossil energy used to extract, transport and refine uranium.

Table A1-1 Electricity Generation Efficiency

	Generation and Transmission Data		
Distribution efficiency		93%	
	Corn-Belt Net Generation Data		
		MM Kwh	
Coal		657,611	72.92%
Oil		5,295	0.59%
Gas		34,118	3.78%
Nuclear		181,707	20.15%
Hydroelectric		15,283	1.69%
Renewable		7,763	0.86%
Total		901,777	
	Corn-Belt Fossil Energy Inputs		
		Quantity	Trillion BTU, HHV
Coal	MM Tons	358.661	7,345
Oil	MM BBLS	8.695	55
Gas	BCF	462.484	471
			7,871
	Corn-Belt Average Heat rate, BTU/Kwh end user		
HHV Primary	9,385		
LHV Primary	8,887		
LHV Total	9,331		

Appendix 2 Energy Equivalents and Efficiencies

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[65] EIA, "2000 Electric Power Annual"

[66] EIA input factors from Table H1, EIA Annual Energy Outlook 2000.

[67] EIA, "Mitigating greenhouse Gas Emissions-Voluntary Reporting", DOE/EIA-0608 (96), page 14, 1997.

Table A2-1 provides higher heating values used in the analysis[68]. Lower heating values of liquid hydrocarbon fuels were estimated from the HHV[69]. The LHV/HHV ratio for natural gas was estimated from the GPSA Handbook[70]. The LHV/HHV ratio for coal was estimated from the Penn State coal bank and database[71]. Coal used in the Midwest is a mixture of low sulfur western sub-bituminous and higher sulfur local coal. The ratio of LHV/HHV for 20% moisture Wyoming Powder River and Montana Rosebud coals is about 94.1%. The ratio of LHV/HHV for Illinois 6 and Kentucky C coals are 95.4% and 96.5% respectively. A typical ratio of 0.95 is thus assumed.

The ethanol heating values for fuel grade alcohol reported by EIA[72] are shown in the table. The higher and lower heating values for pure ethanol have been reported by NIST[73] as 84,448 and 76,300 respectively. The density of ethanol used to convert NIST data to a per gallon basis was 6.61 lb/gal[74]. Fuel grade alcohol contains a trace of water and up to several percent fusel oils[75] whose heat of combustion is higher than that of ethanol. Thus, the heating value of ethanol could be slightly understated.

Table A2-1 Heat Rates

	Unit	HHV BTU	LHV BTU
Ethanol (undenatured)	Gallon	84,262	76,000
Crude Oil	Gallon	141,619	133,130
Residual Fuel Oil	Gallon	149,690	141,308
Diesel	Gallon	138,714	130,719
Gasoline	Gallon	124,619	116,515
LPG	Gallon	86,310	79,405
Electricity	KWH	9,385	8,887
Natural Gas	SCF	1,026	923
Natural gas (utilities)	SCF	1,019	917
Coal, Dry Basis	Ton	20,479,000	19,455,050

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[68] Data were taken from EIA, Energy Outlook 2000, Appendix H, Table H1, Heat Rates.

[69] National Bureau of Standards Information Miscellaneous Publication 97.

[70] Gas Processors Suppliers Association, "Engineering Data Book", Ninth Edition, 1972. Based on tabulated heating values, a gas with 1026 BTU/CF containing 95% methane, 3.78% ethane and 1.22% inerts has a LHV/HHV ratio of 0.90.

[71] Pennsylvania State University, Coal and Organic Petrology Laboratory. 105 Academics project Building University Park Pa 16802. www.ems.psu.edu/COPL/.

[72] EIA, Annual Energy Review 2000, Appendix A, Thermal Conversion Factors.

[73] NIST Standard Reference Data Program, Enthalpy of Combustion at STP, webbook.nist.gov. The gross heat of combustion of liquid ethanol is –326.99kcal/mole. Using the heat of formation of water for liquid and gas phase yields a net heat of combustion of –295.439 kcal/mol. The molecular weight is 46.07.

[74] API, "Alcohols and Ethers,: A technical Assessment of their Application as Fuels and Fuel Components", Publication 4261, Third Edition, June 2001.

[75] Morrison and Boyd, "Organic Chemistry", Allyn and Bacon, Inc, Boston, 1959 report that fusel oil is a mixture of primary alcohols, mostly isopentyl with smaller amounts of n-propyl, isobutyl, and 2-methyl-1-butanol.

To convert energy to a total BTU basis, additional information is required. Wang has reported estimates of the energy required to extract and refine the primary energy sources [76]. Table A2-2 presents a summary of the relevant factors. These factors show the total fossil energy and the energy input as petroleum per BTU of product output. To estimate the total LHV input for gasoline, for example, use the primary LHV value of 116,515 BTU/gallon times the refining factor of 1.265_4 times the crude oil factor of 1.034_1 to obtain 152,470 BTU/gallon.

The energy ratio factor for uranium is converted into a tLHV heat rate for nuclear power assuming a nuclear generating efficiency of 34%, steam to net electricity yielding 1,189 BTU/Kwh.

In this analysis, no steam is assumed to cross any plant boundary. In fertilizer manufacture, steam imports and exports are reported for individual process steps. Steam is charged at 100% efficiency. That is, there are no energy losses in its manufacture since the steam is typically generated from process waste heat. The process is integrated; it is assumed that all of the steam is used within the plant boundaries. Carrying the steam flow data is important only in estimating the energy involved in manufacturing the various fertilizer products.

Table A2-2 Extraction/Processing Energy Ratios

BTU In /BTU Out

	Fossil	Petroleum	Step
Crude with vent gas	1.034	1.010	Recovery and transport
Coal	1.015	0.014	Mine and transport
Fuel oil	1.074	1.039	Refining
Diesel oil	1.178	1.084	Refining
Gasoline	1.265	1.119	Refining
Natural Gas	1.101	0.005	Recovery and transport
LPG	1.142	0.016	Recovery, refine, transport
Uranium	0.118	0.005	Recovery, refine, transport
Steam	1.000	1.000	Assume heat recovery

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[76] Adapted from Wang, M., Center for Transportation Research Argonne National Laboratory, Greet Model Version 1.5a, Updated 5/25/01.

Appendix 3 Data Quality and Sensitivity

In this analysis, agricultural data were collected from several different sources within USDA, and the energy use on the farm was projected to 2000 and 2012. The purpose of this appendix is to discuss the impact of combine data from separate surveys and examine the order of magnitude of the error in total farm energy use due to sampling error.

Agricultural Survey data:

In the analysis, annual data reported by NASS for fertilizers and chemicals was combined with state or region level data for farm fuels and custom operations collected in 1991 and 1996. In addition, NASS data for yield was used to normalize the energy input to a bushel basis.

According to table 15, of the approximate 7.7 MM BTU/acre input to the farm, 3.4MM BTU/acre were inputted as fertilizer and chemicals and 3.7 MM BTU/acre was in the form of fuels. Thus, approximately 44% of the energy input is based upon NASS data, 49% is based upon ARMS state/region level data and 7% is derived from other sources.

The sampling design for each survey was not examined; however, the quantity of data collected in each case is large, and USDA has considerable expertise in designing and conducting surveys that are representative and unbiased. Since all of the surveys are sampling from the same population of corn farms, differences should be related to sampling errors only.

The basis for data analysis in this study is per-acre. Single year per acre data are summed and then normalized by the overall yield. Because yield varies from year to year due to random effects such as weather, the trailing 3-year average yield is used.

In projecting energy use per acre to 2000, an estimate for 44% of the on-farm energy use can be made directly from NASS survey data. Nitrogen alone accounts for 38% of the energy input. One may question whether NASS data and ARMS survey data produce the same estimates. Table A3-1 demonstrates that the surveys provide essentially the same estimates of fertilizer and chemical inputs for 1991 and 1996. Thus, one can tentatively conclude that combining NASS and ARMS data in any given year will have little effect on the overall farming energy estimate.

Table A3-1 Comparison of Survey Data

	NASS	State Survey
1991 N	124.9	124.6
1991 P	50.2	51.8
1991 K	59.4	59.3
1996 N	129.1	129.4
1996P	49.9	48.2
1996K	61.6	59.3
1996 Chemicals	2.92	2.91

Projecting Fuel and Custom Inputs to 2000:

In the analysis, 49% of the energy use in 2000 is projected from the 1991 and 1996 ARMS survey data. Time, sampling error, and random effects confound the two estimates of fuel use. It is not possible to determine whether one year is more representative than the other.

Time is important because old and gasoline powered farm machinery is being constantly replaced with new diesel equipment; this increases overall fuel efficiency. Also, there is a trend toward less intensive cultivation that will decrease fuel use.

The most important random effect is weather. No substantial database was identified that provided information on the average moisture content of harvested corn. Furthermore, there is no information on how much corn is dried annually on the farm using driers with and without thermal assist. Thus, determining the more correct energy consumption for corn drying is not possible even if it is believed that 1996 was an abnormally wet year.

The total energy embodied in diesel and gasoline was substantially lower in 1991 than 1996 even though one would expect it to be higher based upon the time factor. While the spring of 1996 was wet throughout the Midwest, there appear to be no data that concretely link that observation to an increased quantity of diesel fuel use.

In projecting to 2000, the two years worth of survey data are treated tentatively as upper and lower bounds.

Potential Error Due to Sampling of Agricultural Data:

The estimates for the various energy components are themselves subject to sampling error as well as other issues such as conversion of custom costs to energy use.

The sample is stratified by state. The appropriate weighting factor is harvested acres in each state. From a sampling aspect, one is interested in confidence limits around the global average of a variable, such as the weighted by state nitrogen application rate. The 1991 survey specifically provides by state average and variance for cost of various energy components. Assuming that the cost per unit is essentially constant across all farms allows an estimate of the confidence limits on the global average energy associated with the cost element to be developed. Table A3-2 presents the calculation for 95% confidence limits on average fertilizer cost for the stratified sampling data presented. The second column provides the number of survey samples analyzed for each state. Column 3 and 4 represent harvested acres and weighting factors based upon acreage. Columns 5 and 6 are the reported costs and percent coefficient of variation data for the survey. Column 7 converts CV to variance in $. Column 8 contains the variance of the means data (column 8/ column 2 * column 4^2). The global standard deviation of the mean is the square root of the sum of the elements in column 8. The 95% confidence limit is approximately 1.96 times the global standard deviation. It is found that the cost, and therefore energy associated with the global average fertilizer application rate is 0.96%.

Table A3-2 Global Mean and 95% Confidence Limit for 1991 Fertilizer Cost
1991 Survey

			Strata	Fertilizer	Strata	Strata	Variance, $	STD Dev, $
	# Samples	Acres	Weight	$	CV, %	Variance, $	Calculations	
Ill	85	11,000	0.201097	52.19	6.61	11.9	0.006	
In	60	5,550	0.101463	54.06	9.02	23.8	0.004	
Io	74	12,200	0.223035	36.32	6.68	5.9	0.004	
Mi	43	2,300	0.042048	61.88	11.13	47.4	0.002	
Mn	55	6,000	0.109689	35.16	10.48	13.6	0.003	
Ne	49	7,800	0.142596	44.86	16.51	54.9	0.023	
Oh	51	3,400	0.062157	53.65	11.35	37.1	0.003	
SD	36	3,250	0.059415	26.57	13.18	12.3	0.001	
Wi	55	3,200	0.058501	37.27	10.97	16.7	0.001	
Global		54,700	1	44.03			0.215	0.49%
95% CL							0.422	0.96%

In the same way, the confidence limits on chemicals, fuels, custom operations and custom drying were computed to be 1.0%, 1.6%, 2.1%, and 4.8% respectively.

Potential Errors Due to Derived Energy Factors:

The energy contribution of various components is also related to derived data.

Extraction and refining efficiencies are taken from Greet

The overall efficiency of various refining and extraction industries has been fairly well characterized by EIA/DOE and industries are required to report input and output data on a confidential basis. The energy allocated to specific steps in processing is probably less well understood. For example, refinery-modeling data have been examined to assign specific efficiencies to gasoline and diesel production. These could be in error by ±5%.

Fertilizer Energy

80% of the energy content of fertilizers including packaging and transportation is associated with nitrogen. The energy content of nitrogen fertilizer depends not only on natural gas usage but other component manufacturing efficiencies, the fraction of the various types of fertilizers used, transportation and packaging estimates. Since the energy inputs to convert ammonia to other forms of nitrogen are small, it would seem that the most important factor is the natural gas input to ammonia and the actual fraction of fertilizer used directly as ammonia compared to other types of nitrogen fertilizer.

The amount of natural gas used by US industry is based upon an industry survey and should be accurate. However, the efficiency related to imports is not well understood.

Based upon the EU, the range of manufacturing efficiency for ammonia is about 35% from the best to the worst country. Assuming an average import of 20% of the ammonia from plants operating at the extreme would change the energy in ammonia by about ± 3.5%. In addition, uncertainties associated with other fertilizers could be large. It is assumed that the standard error for these is 10%.

Ethanol Manufacture

The energy input data for ethanol plants obtained from various sources is in good agreement. For example, guaranteed energy use for new dry mill construction agrees within about 5% of capacity averaged dry mill survey data gathered by BBI. Because the survey data and new plant construction data agree well, it is highly unlikely that the survey information has been gamed.

Furthermore, BBI reported energy data for 16 unidentified dry mills. Of these, 15 delivered predominantly DDGS and one WDGS. The number (not capacity based) standard deviation in total energy use of the distribution is 12%. If we assume these individual values represent a sampling of the population of ethanol plants, the estimated standard deviation around the sample mean is $12\%/(15)^{0.5}$ or 3.1%. This value is assumed for the sensitivity analysis.

In addition, the BBI survey data may be biased because of lack of specification of the energy basis (see appendix 4). However, it was assumed that the BBI data were based upon LHV; thus the net energy value is already biased towards its lowest value.

The standard deviation in co products is assumed to be 10%.

Transportation and Distribution

The standard error is assumed to be 10% for these elements.

Energy in Chemicals

The accuracy of the energy content for chemicals reported in the literature is not known but assumed correct. Even if it is assumed that the energy content is correct, only about 2/3 of the chemicals used have been characterized. If it is assumed that the unaccounted for chemicals have an energy content ± 1 standard deviation from the weighted average, the possible uncertainty in chemical energy is ± 20%.

Energy in Fuels

Assuming that the spread in fuels for 1991 and 1996 represents upper and lower bounds for wet and dry years, the ranges were used to estimate the standard deviation for individual fuels. The sampling errors are added to each individual fuel standard deviation.

Energy in Custom Work and Drying

There are no data that suggest the accuracy of the fuel use estimates derived from custom operation and drying costs. It is assumed that the range in energy for these steps is ± 25%.

Yield

The standard deviation in yield for the three-year period is 0.5%. The sampling error in yield is not known but is assumed to be 1%. The standard deviation in ethanol yield is also assumed to be 1.5%

Propagation of Errors

In each case, the estimated error is either the standard error or the maximum error. If it is the maximum error, the standard error is estimated by dividing the one-sided maximum error by three.

The function is linear. That is:

$$\mathbf{E_T = \Sigma\ E_i\ = G * (\ \Sigma\ f_i/\alpha\ + \Sigma\, g_i)}$$

The E_i are the individual energy elements. Each energy element is the product of the primary LHV (f_i for farming and g_i for processing) for the step and its Greet factor (G) that converts the energy into total LHV. Since farm inputs are provided on a per acre basis, these need to be adjusted to a gallon-basis using yield of corn and ethanol. α is the product of the corn yield and the ethanol yield.

Using propagation of errors theory results in the following equation for the percent coefficient of variation. For simplicity, it is assumed that the Greet factor for all energy is approximately a constant. The average Greet factor is found to be 1.07 for the 2000 base case. The Greet standard error is assumed fixed for all energy inputs. For a range of 10%, the standard deviation will be about 1.67%.

$$\mathbf{CV^2{}_T = CV^2{}_G + (G\ \Sigma\ f_i/(\ \alpha\ E_T)^2\,(CV_\alpha)^2}$$
$$\mathbf{+\ \ (G/E_T)^2((\Sigma\,(f_i)^2\ CV_{fi}{}^2)/\ \alpha\ ^2 + \Sigma\,(g_i)^2\ CV_{gi}{}^2)}$$

Table A3-3 presents the calculation for the CV. The propagation of errors suggests that the total energy is known to within about ± 8.3% at the 95% confidence level. The p-value associated with the net energy being equal to or greater than zero is smaller than 0.001.

Because of its magnitude, the most important variable is ethanol plant energy. Doubling the uncertainty increases the 95% confidence limits to 12.5%. No other variable impacts the C_v by more than 0.5% when its uncertainty is doubled. Even in this case, the p-value associated with the net energy being equal to or greater than zero is smaller than 0.001.

Table A3-3 Propagation of Errors Computation

	fi or gi	CV	fi^2 or gi*Cvi^2
Seed	76,843	10%	54,728,436
N	2,677,410	3.5%	8,781,442,350
P (as P2O5)	35,838	11.0%	15,428,071
K	109,067	11.0%	142,891,183
Limestone	131,400	11.0%	207,401,075
Micronutrients	-	-	-
Chemicals	256,245	21.0%	2,895,676,305
Diesel	1,124,185	5.4%	2,969,821,111
Gasoline	360,030	3.2%	147,705,169
LPG	566,343	11.6%	2,819,593,440
Electricity	768,729	14.7%	7,154,059,435
Natural Gas	184,680	5.4%	126,773,857
Custom Work & Drying	220,374	15.2%	1,111,089,646
Inputs Transportation	232,705	10.0%	541,515,099
Inputs Packaging	27,552	10.0%	7,591,402
Total	6,771,401		26,975,716,580
Yield	140.18	1.5%	
Ethanol Yield	2.66	1.5%	
Corn Transportation	1,355	10%	18,347
Ethanol Production	52,152	3%	2,613,798
Ethanol Distribution	1,012	10%	10,244
Byproduct credit	(13,194)	10%	1,740,793
Total	41,325		4,383,182
	58,483		
Greet	1.075	1.67%	
Grand Total	62,880		

	Calculation
CvG^2	2.778E-04
[Sum(fi)]^2*(G/alpha/Et)^2*Cvalpha^2	1.937E-05
Sum((fi)^2(Cvfi)^2)/alpha^2*(Eg/Et)^2	5.686E-05
Sum((gi)^2*(cvgi)^2)*EG^2/Et^2	1.282E-03
Cvtot^2	1.636E-03
Cvtot	4.04%
Confidence Limits, 95%	
Lowest Net Energy	8,136
Lowest Energy Ratio	1.12

Appendix 4 Ethanol Plant Energy Survey Data Analysis

USDA-BBI 2001 Survey[77]

Table A4-1 presents data for dry mills. The questions asked by BBI were the following:

- What is your per gallon thermal energy use?
- What is your per gallon electrical use?

Table A4-1 BBI 2001 Dry Mill Survey

Dry Mill #	Thermal Use, BTU/Gallon	Electrical Use Kwh/gallon
1	48,000	0.96
2	33,782	1.13
3	42,209	1.16
4	33,824	0.93
5	35,200	0.83
6	36,000	1.2
7	36,677	0.93
8	34,873	0.72
9	40,000	1.59
10	42,000	1.91
11	38,500	1.01
12	40,000	0.93
13	47,500	1.1
14	37,000	0.85
15	36,500	1.3
16	16,500	1.28
Capacity Average	35,382	1.07
Number Average	37,410	1.11

There are two issues regarding these results. First, the basis for the thermal energy is not specified. Second, the electrical question does not take into account cogeneration as it did not ask, " What is your net purchased electricity?" At least one dry miller cogenerates some of its electricity and this is not reflected in the table. Furthermore, the type of fuel is not specified.

In the USDA 1998 survey, 87% of the fuel input was gas and 13% was coal. This breakdown was used to establish the ratio of HHV to LHV. Based upon those data, the ratio of LHV/HHV is 0.907. It is assumed that all of the company survey responses were LHV. The thermal input is adjusted to 39,031 BTU/gallon on a HHV basis. No

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[77] USDA, "BBI Survey of Plant Energy Use", Private Communication, 2002.

adjustment is made for dry mill cogeneration. The total LHV energy is therefore estimated to be 48,539 BTU/gallon.

In the 1998 benchmarking survey, USDA indicated that the average cost of energy in dry mills was 13.1 cents per gallon. In 1998, the average price of gas in the Corn Belt was about $2.50 /MMBTU and industrial electricity was 4.5 cents per Kwh. Delivered western coal was about $1.25/MM BTU. Using these energy prices, the estimated cost of energy from for dry mills for the adjusted survey data is $0.139 per gallon. This demonstrates internal consistency in the two surveys and substantiates the energy value used in the analysis.

One thermal input, for plant 16, is very low. However, the data include dry mills that deliver WDGS and DDGS.

Existing Wet Mills

BBI also surveyed wet mill operators. They reported, as shown in Table A4-2, a thermal input of 44,975 BTU/gallon and an electrical input of 1.89 Kwh per gallon. However, since a substantial part of wet mill capacity is based upon cogeneration, the BBI results could double count the electricity input and may not be useful in the context of this study. It is not known how respondents answered the BBI survey questions. Assuming the thermal energy is reported as LHV from coal, the total thermal input from the BBI data is estimated to be 65,706 BTU/gallon.

Table A4-2 BBI 2001 Wet Mill Survey

Wet Mill #	Thermal Use, LHV BTU/gallon	Electrical Use, Kwh/gallon
1	46,670	1.33
2	43,568	1.88
3	45,289	1.91
4	37,000	1.95
Capacity Average	44,975	1.89
Number Average	44,849	1.77
Capacity Based Total Input, LHV	65,706	

In order to quantify wet mill input with more certainty, operators of existing wet mills were surveyed by Dr. Graboski to determine purchased thermal and electrical inputs. Wet mill operators primarily use coal-based cogeneration but also purchase natural gas to supply steam and electricity for their facilities.

A large portion of the wet mill capacity was covered in the survey. It was found that 73.6% of the fossil fuel was inputted as coal and the remainder was natural gas. The capacity weighted HHV thermal input was found to be 55,327 BTU/gallon and the purchased electrical input was 0.74 Kwh/gallon. The resulting total LHV input for the portion of the wet mill industry that responded was 60,658 BTU/gallon.

The ethanol yield was 2.66 gallons per bushel compared to 2.68 reported by USDA for all wet mill producers responding to its survey. The wet mills produced an aggregated 2.4 lb/gallon of CFM on a wet basis. The oil yield was estimated to be 1.68 pounds at 100% recovery. Employing a typical recovery factor that resulted in an oil production of 1.52 lb/gallon, the CGF yield was 13.4 lb/gallon.

The cost of energy reported for wet mills by USDA in 1998 was 10.98 cents per gallon. Based upon the energy inputs from this survey, the estimated energy cost is 12 cents, further substantiating the energy input derived from the survey.

New Construction Dry Mills

According to recent reports, there is approximately 550 MM gal/yr of new dry mill capacity under construction and another 300 MM gal/yr recently started up as new plants and due to debottlenecking/expansion of existing plants. There are about 11 plants that are sized at 40 to 45 MM gallons per year currently under construction.

The engineer/constructors of the new plants under construction were surveyed by Dr. Graboski to determine the energy input. Responses were received from several design firms that covered approximately 600 MM gallons of new and proposed capacity. The capacity is 100% natural gas fired and there is no cogeneration of electricity. The average LHV thermal input is 35,575 BTU/gallon for dry DDGS product. The electrical input is 0.752 Kwh/gallon. The expected weighted total LHV input for these plants is 46,176 BTU/gallon. The yield is 2.74 gallons/Bu and the DDGS yield is 17.95 lb/gal at 10% MC. The total energy required in new dry mills is about 5% less than the total energy reported by the BBI dry mill survey. The energy reduction is proportional to the increase in yield of ethanol suggesting that the majority of the design improvements are related to improving yield and not heat integration. According the E&C’s, this will continue to be the case with guaranteed yield of 2.8 gal/Bu being achieved shortly.

Implications for 2012

In 2012, it is expected that both dry and wet mills will achieve 2.8 gallons per bushel.

For dry mills, it is assumed that the entire industry achieves 2.8 gallons per bushel, and that energy consumption only scales with yield. The total LHV energy use for dry mills will thus decrease to 45,108 BTU/gallon based upon the new plant survey results.

For wet mills, the analysis of Despiegelaere[78] of Process Systems Inc reported that best wet mill processing with azeotropic distillation would require 35,150 BTU/gallon LHV thermal plus 2.134 Kwh/gal electricity. Wood[79], also from PSI indicates that the expected wet mill yield is 2.49 gallons per bushel. Madsen[80] reported that azeotropic systems require about 3000 BTU/gallon more energy than molecular sieve systems. Adjusting the PSI data considering molecular sieves and a yield of 2.8 gallons/Bu yields a best future energy input of 28,590 LHV BTU/gallon thermal and 1.898 Kwh/gallon. Correcting the actual cogenerated electricity for yield results in a purchased electricity of 0.708 Kwh/gallon. Using a typical mechanical efficiency of 75% steam energy to electricity for the turbine generator results in a plant steam energy requirement of 34,000 BTU/gallon LHV. The process inputs and need to be adjusted for boiler efficiency. A typical efficiency of modern non-slagging coal fired and gas fired boilers with good heat recovery is 84% on a HHV fuel input basis. Using the same mix of coal and gas in the future results in a LHV/HHV ratio for fuel of 0.937. Thus, the LHV boiler efficiency is estimated to be 89.7%. The LHV purchased thermal inputs are thus 43,208 (HHV)/40,477 (LHV) BTU/gallon and 0.708 Kwh/gallon. The best future wet mill is thus estimated to require 48,624 BTU/gallon total LHV. This amounts to a 20% reduction in energy input compared to a 4.5% increase in yield and suggests that wet mill operators could improve their thermal efficiency significantly in the next decade. Whether they actually do will depend upon the impact of efficiency improvements on plant income.

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[78] DeSpiegelaere, T., “Energy Consumption in Fuel Alcohol Production for a Corn Wet Milling Process”, IBIS 1992 Fuel Ethanol Workshop, June 1992, Wichita Ks.

[79] Wood, P. , “New Ethanol Process Technology Reduces Capital and Operating Costs for Ethanol Producing Facilities”, Fuel Reformulation, Page 56, July/August, 1993.

[80] Madsen, P., “Energy utilization in Fuel Ethanol Production”, 1991 Fuel Ethanol Workshop, South Bend In, June 1991.

Appendix 5 Critique of Pimentel Energy Balance

Table A5-1 provides a comparison of key assumptions made by Pimentel and used in this report. In Pimentel's analysis, he mixes up higher and lower heating values, and the basis, that is primary or total energy is not defined.

In Pimentel's analysis, he considers the energy supplied by human labor and the energy used to manufacture the equipment used to grow corn and manufacture ethanol. We have not considered these elements in our reported energy values. The impact of energy to manufacture equipment is examined in Appendix 9. The energy consumed by people will be essentially the same whether they are involved in agriculture or some other enterprise. Therefore, there is no energy savings to be had by following a non-ethanol policy. The very limited analyses of energy involved in equipment manufacture has been examined and it was determined that the contribution of these elements is small and not quantifiable. Pimentel estimates that the energy used to construct an ethanol plant is about 3% of the energy input per gallon when prorated over the plant lifetime. There are major difficulties in addressing these energy flows that are related to assigning equipment lifetimes, and the assigning of credits for the recycling materials at the end of the useful life of the equipment.

Pimentel has estimated the energy consumption for corn farming based upon yields and fertilizer inputs consistent with early 1990's farming practice instead of current practice. He also assumes a substantially higher input for production of nitrogen fertilizer. Nitrogen fertilizer represents almost 50% of the energy input to corn farming. The energy input in this analysis is based upon a 1987 survey conducted for DOE, a natural gas input based on a 2000 survey for ammonia manufacture and fertilizer use by type based upon USDA field data (TFI(1987,2000)). Pimentel used the results of a UN FAO analysis of the world fertilizer industry that is clearly not as efficient as US industry.

Pimentel assumed that the energy embodied in corn seed is approximately 21 times his energy estimate for corn production or 58 times the energy from this estimate. Using data from the seed industry, the ratio is closer to 5 times the energy derived in this estimate.

In his estimate of farming inputs, Pimentel found that the energy input for irrigation amounted to almost 30% of the total farming energy. Based upon the 1997 USDA NASS Farm and Ranch Irrigation study, it was found that his estimate is the correct order of magnitude for irrigated acres; however, only 10% of the corn supplied to the 9-state region comes from irrigation. In this analysis, approximately 17% of the current ethanol capacity resides in Nebraska, where15% of the corn is produced.

The energy reductions in ethanol manufacture are even more dramatic than for the fertilizer industry. Pimentel reported that the energy used to manufacture ethanol in 1979 was nearly 70,000 BTU/gal and assumed that value in his analysis. All *new* ethanol today is being produced by dry mills; these now supply more than half of US production. In 2000, the industry average dry mill consumed 45,170 BTU/gallon (USDA(2000)) as primary energy that is very close to the current best designs reported in the literature (see footnote 3 in table 1). He also assumed an ethanol yield of 2.5 gallons per bushel of corn, characteristic of the industry in the 1980's, compared to the industry average of 2.65 gallons per bushel being achieved today in wet and dry mills.

In his analysis, Pimentel ignores any value to the co products. DDGS, CGF and CGM, are priced in the market based upon protein value. Clearly, if these feeds can substitute directly and economically for other sources of protein in livestock feeding, an energy credit should be assigned because they offset the need to supply other protein sources. In this analysis, it was assumed that co products production would reduce the quantity of corn and soybeans fed to livestock..

Table A5-1 Comparison of Key Assumptions

	Pimentel	This Work, dry mill
Energy in machinery and human labor	Yes	No
Corn Yield, Bu/acre	127	140
Energy in N fertilizer, LHV BTU/lb[81]	33,484	22,007
Nitrogen use per Bushel, lb	1.02	0.96
Energy in Irrigation, MM BTU/Acre [82]	4.935	0.422
Energy in Ethanol Manufacture, BTU/gal[83]	69,330	47,637
Ethanol yield, gallons/Bu[84]	2.5	2.65
Co product credit[85]	No	Yes

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[81] Pimentel used an FAO estimate. Our energy input was developed based upon the annual energy survey conducted by an industry trade association, The Fertilizer Institute and considers extraction, refining and shipping of the primary energy sources, manufacture of fertilizer and transport to the point of use.

[82] Pimentel's estimate is apparently based upon Batty, C., Hamad, S., Keller, J., "Energy inputs to irrigation", J Irrigation & Drainage Div. ASCE, p293, Dec 1975. However, the pumping energy reported by Batty agrees with our estimate. We have further reviewed Batty's estimate of energy in irrigation equipment based upon current technology and believe the prorated energy in hardware is less than 15% of the pumping energy. The major difference seems to be that Pimentel has not prorated his irrigation energy for the fraction of corn that is irrigated. For the 9-states considered in our analysis, only 8.73% of the acres are irrigated producing 10.1% of the corn.

[83] We estimate primary net basis energy input as 47,637 BTU/gal for the industry based upon a USDA survey conducted in 2000. This input includes electricity generation and transmission losses based upon the US average heat rate on a net basis of 7,911 fossil energy BTU/kwh. The majority of the thermal energy used in ethanol manufacture comes from natural gas. The total energy input of 52,352 BTU/gal includes extraction, refining and transportation of the fossil energy inputs to the ethanol plant and power plant.

[84] The current yield of ethanol from wet and dry mills is 2.68 gal/Bu and 2.63 gal/Bu based upon the 1998 USDA survey.

[85] In ethanol dry mills, about 32% of the corn input is converted into DDGS. The DDGS contains all of the oil, protein and trace nutrients in the corn and is a very high quality livestock feed especially for ruminants. We have credited ethanol production an amount of energy required to feed livestock with a typical feed formulation based upon whole corn and urea.

Table A5-2 compares the Pimentel energy balance with this one. Based upon the current industry, the energy efficiency ratio is 1.19 compared to Pimentel's ratio of 0.58. In 2012, as production shifts heavily to dry mills the ratio increases to 1.44.

Table A5-2 Comparison of Energy Balances

Pimentel Compared to 2000 and 2012 Industry Average Ethanol Production

This Study result for Total LHV BTU

	Pimentel	2000	2012
Energy in ethanol	76,000	76,000	76,000
Corn Production & Transport	55,800	21,710	17,669
Ethanol Production & Distribution	74,925	53,589	45,161
Co product Credit	0	(11,573)	(9,990)
Total Inputs	130,725	63,726	52,840
Net Energy Difference	(54,725)	12,274	23,160
Energy Ratio	0.58	1.19	1.44

Even if ethanol energetics were not favorable, there is an argument to be made in favor of ethanol. In agriculture and ethanol production, the crude oil inputs are minor; the majority of the fossil energy used to grow corn and produce ethanol comes from natural gas and coal. In this analysis, it is estimated that on an energy basis, 0.073 BTU of petroleum are used to produce a BTU of ethanol. Ethanol should be viewed as an extremely effective way to convert gaseous and solid fuel energy into liquid fuel energy. It is a fact that US ethanol production increases the supply of liquid fuels with the consequence of depressing fuel prices. Because ethanol has a positive energy balance, it necessarily has a positive impact on climate change. Today, neither of these external benefits is properly considered in the pricing of the fuel. To that end, it is the purpose of policy to address such issues.

Appendix 6 Energy Use in Irrigation

In an analysis of the overall impact of irrigation on farming energy to produce corn, the components of irrigation energy use are:

- Fraction of land irrigated for corn.
- Annual pumping energy
- Manufacturing energy of the system

In this section, both the pumping and fixed contributions to irrigation are explored in detail. The basis for the analysis is a comprehensive database generated by USDA NASS, as well as other published or documented data.

The issue of basis for accounting is also important. In this analysis, the energy use estimates based upon both higher and lower heating values[86] are developed.

In 1998, of the 80.165 million acres planted for grain and silage, 2.1% were not harvested or not accounted for in government statistics. In the 9-state Corn Belt area, of the 55.450 million acres planted, only 0.80% was not harvested. The nine states produced 80% of the corn crop.

According to USDA data[87], the total acres harvested for corn for use as grain and seed was 72.589 million acres in 1998 (latest data available). The irrigated land for corn used for grain and seed by all irrigation methods was 9.630 million acres. The yield was134.4 Bu/acre for all acres, 130 Bu/acre for non-irrigated acres and 163 Bu/acre for irrigated acres. 13.3% of the acres were irrigated. Because of the higher yield under irrigation, the fraction of the crop produced with irrigation was 16.1%.

Nebraska accounts for about half of all irrigated acres harvested for grain corn. While irrigated acres for corn increased nationally by 270,000 acres between 1994 and 1998, irrigated corn acres in Nebraska decreased by 60,000 acres.

The nine major corn states are a more appropriate land base to consider. Essentially 100% of US grain based fuel alcohol is manufactured now (and *will* be in the future) from corn produced in these states. Most ethanol production occurs in the non-irrigated states. Nebraska is an exception as tax policy has spurred considerable development of ethanol capacity in that state. Kansas, on the other hand, which also produces a significant quantity of corn via irrigation, produces much less ethanol. Using 50-state data that includes the heavily irrigated southwestern states will bias the energy input estimate for ethanol production. Table A6-1 provides state data for 1998 for corn harvested for grain and seed. Here, 8.7% of the harvested acres were irrigated yielding

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[86] For Diesel, the values used are BTU/gallon: LHV 127,748, HHV 137,150. For Natural Gas LHV 910 BTU/SCF, HHV 1021 BTU/SCF, For coal LHV is 0.95 of HHV.

[87] USDA NASS, "1998 Farm and Ranch Irrigation Study" (see www.usda.nass.gov)

10.1% of the corn production. About 85% of corn irrigation utilized some pumping. Center pivot irrigation was used exclusively on 45.9% of the irrigated land.

Table A6-1 Production of Corn using Irrigation in the 9-State Region

1998 Data from NASS Farm and Irrigation Survey

	Total		Irrigated		Irrigated Portion	
	Thousand Acres Harvested	Thousand Bushels	Thousand Acres Harvested	Thousand Bushels	% Acres Harvested	% Bushels
Illinois	10,450	1,473,450	171	25,609	1.63%	1.74%
Indiana	5,550	760,350	128	20,676	2.31%	2.72%
Iowa	12,200	1,769,000	44	6,280	0.36%	0.36%
Michigan	2,050	227,550	161	23,621	7.84%	10.38%
Minnesota	6,750	1,032,750	139	22,890	2.06%	2.22%
Nebraska	8,550	1,239,750	3,994	659,060	46.72%	53.16%
Ohio	3,340	470,940	2	304	0.06%	0.06%
South Dakota	3,550	429,550	123	19,730	3.47%	4.59%
Wisconsin	2,950	404,150	72	11,540	2.44%	2.86%
9-State	55,390	7,807,490	4,834	789,711	8.73%	10.11%

In the future, it could be argued that substantial new ethanol production will come from new corn production. In this case, it is necessary to determine whether the majority of new corn production comes from irrigated land or the land base in general. Figure A6-1 shows that total land harvested in the 9-state region for grain corn may vary from year to year, but over the last 20 years, there has been no real increase in harvested acres. The figure also shows that Nebraska's share of the harvested acreage increased during the 1980's but has now stabilized. Figure A6-2 compares the yield in Nebraska to the harvested acreage weighted yield of the remaining 8-states. The plot suggests that yield is actually increasing more rapidly in the 8 non-irrigated states than in highly irrigated Nebraska. The 20-year average increase in yield over the 8 non-irrigated states is 1.8%. At least, this suggests that new corn production results from yield increases over all acres due to general farming practices and technology, and not increases in either harvested acres or irrigation. The USDA[88] projects that corn yield will continue to increase by 1.2 percent per year through the projection period ending in 2009/2010 resulting in a national yield of 150.8 Bu/acre in 2009/2010 compared to 135.5 Bu/acre in 2000/2001. There is no change in land use for corn production during the projection period, suggesting that no significant amounts of new irrigated land will be brought into corn production. Thus, it is concluded that current and near future irrigation patterns will be the same, and that new corn will come from yield increases on all acres.

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[88] Interagency Agricultural Projections Committee, "USDA Agricultural Projections to 2009", USDA, 2001.

Figure A6-1 Corn Acreage Harvested for Grain in Nebraska and the 9-State Region
Source USDA NASS Data Base

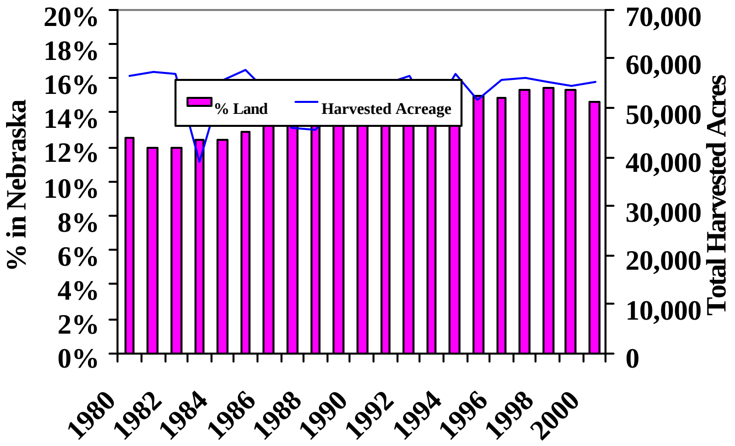
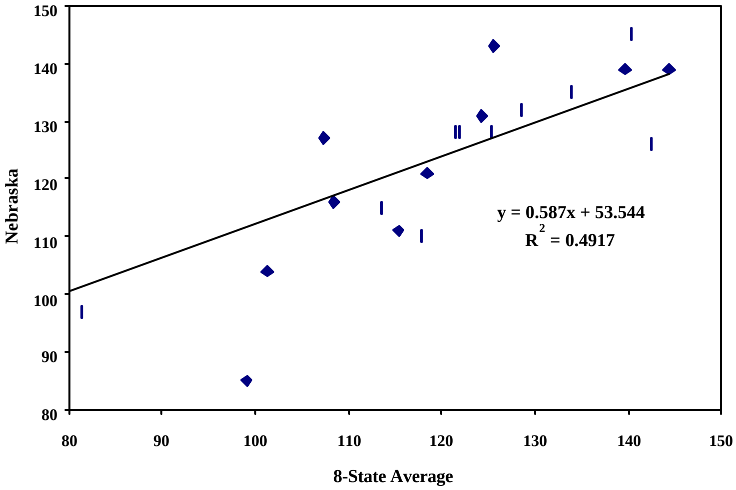


Figure A6-2 Historical Corn Yield Data
Source: NASS Data Base



NASS provides information for irrigation of all crops by method as well as information concerning pumped and artesian wells. More than 99% of the wells are pumped. These data are summarized in Table A6-2. Since 65% of all crop acres irrigated in the 9-state area were planted with corn, it was assumed that these data apply proportionally to corn.

In the 9-state area except for Nebraska, sprinklers are the dominant form of irrigation. In Nebraska, 35% of the irrigated land is watered by gravity flow systems. Thus, assuming that all irrigation work is based on sprinkler irrigation practices is extremely conservative. According to the NASS survey, the majority of center pivot systems employ low and medium pressure nozzles. For the land irrigated under sprinklers (pivot and other), the 9-state average (production weighted) well depth to water is 68 feet. The average well depth is 180.6 ft. The average pump discharge pressure is 42.4 psi. The average annual water application rate is 1.03 feet.

These data can be used to estimate annual average pumping energy for sprinkler-irrigated corn and the weighted energy per bushel of production. The calculation is presented in Table A6-3 assuming that electricity, diesel and gas are used in the 9-state area as 15% electricity, 47% diesel and 37% natural gas[89]. The efficiencies used are appropriate for the three prime movers based upon current technology[90]. In addition the energy data have been adjusted to account for extraction and manufacturing losses yielding the total energy use. For example, the energy embodied in electricity includes coal mining, generation and transmission.

The total energy per harvested sprinkler irrigated acre is estimated to be 1,672,653 LHV kcal/hectare or 1,822,214 HHV kcal/hectare. Considering the entire 9-state corn crop, the energy input for pumping is 147,200 net kcal/hectare or 160,362 gross kcal/hectare assuming all irrigated acres require sprinklers. On a bushel basis, the energy consumption is 936 net Kcal/Bushel (1019 gross kcal/bushel).

It is useful to compare these energies with a value that may be estimated from the Farm Cost Survey Returns. In the SURVEY, total on-farm use of diesel, electricity and natural gas is reported. Table A6-3 demonstrates that assuming the main difference in inputs between Nebraska and the other 8-states is irrigation energy, the approximate input per planted hectare for irrigation is 249,575 gross kcal/hectare. Thus, it is concluded that the survey properly accounts for irrigation pumping energy for corn.

Importance of Capital Energy

The order of magnitude of the pumping energy calculation of 1,828,493 Kcal/irrigated hectare is consistent with the Batty et al[91] who estimated 2,134,000 Kcal/irrigated hectare

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[89] Ali,M, McBride,W, "Corn, State Level Production Costs, Characteristics and Input Use, 1991", USDA ERS Report SB-891, September 1994. From Appendix table 2, we found the difference between diesel, natural gas and electricity use for Nebraska and the other 8 states in the survey. These differences were attributed to irrigation and recast as percentages based upon the energy inputs. See also Table 4.

[90] In all cases, the well pump is motor driven. The efficiency of a typical 75 to 100 hp TEFC motor is 94% (from specification provided by Siemens). Diesel and natural gas generator sets are also used. According to specifications from Elliott Power Systems, 100 KW units operating on diesel and natural gas at ¾ load exhibit heat rates, BTU LHV/kwh of 8011 diesel for Model 100RDand 13,120 for natural gas model 100 RN/L.

[91] On page 302 at the bottom, he shows that for an example irrigation system, the pumping energy input is 1,811,000 Kcal/hectare. In his example his total head is 53 psi and his irrigation depth is 20 inches. Adjusting his value to 12.4 inches of depth and 82 psi pump differential indicated by NASS results in an

using slightly different parameter estimates. However, because Batty overestimates the energy input for manufacturing the system itself, there is an increased discrepancy in the estimates. Thus, while the total annual energy consumption of 1,893,569 Kcal/ irrigated ha, Batty et al estimate 3,093,900 Kcal/irrigated hectare.

In Table 3 of “The Limits of Biomass Energy”, Pimentel estimates the energy use is 3,072,000 Kcal/hectare that is not totally inconsistent with either this estimate or that from Batty et al if it applies to irrigated hectares only. However, Pimentel uses this energy value in Table 4 as if it applies to all corn production instead of 10% of the crop. An appropriate accounting would reduce Pimentel’s energy input to corn by nearly 30%.

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energy of 1,746,000 Kcal/irrigated acre. This compares well with my average of 2,084,000 Kcal/irrigated hectare.

Table A6-2 Summary of NASS 1998 Farm and Ranch Irrigation Survey Data for 9-State Irrigation for All Crops

		Total		Pressure Data, Pivot systems			Water application			Average	Average	Average	Depth +
		Thousand Acres		High	Medium	Low	Total	Wells	Number	Depth to	GPM	Pressure	Losses, ft
	Irrigated	All Sprinklers	Pivot	>60 psi	30-59 psi	<30 psi	acre-ft		Wells	water, ft		psi	Per acre
Illinois	290.8	288.5	275.6	40.7	150.1	84.8	182.6	177.2	2,542	36	854	44	0.61
Indiana	217.2	212.6	189.4	29.7	101.7	58.0	113.1	93.5	1,586	26	651	50	0.44
Iowa	67.9	65.9	64.4	17.7	29.5	17.2	32.1	29.4	693	29	687	51	0.45
Michigan	368.0	354.4	254.1	72.5	142.9	38.6	262.8	142.3	2,953	38	568	71	0.40
Minnesota	322.3	311.6	293.6	65.7	96.5	131.4	195.3	170.4	2,981	35	662	43	0.55
Nebraska	5,692.2	3,686.5	3,612.4	569.9	1,950.1	1,092.4	4,975.3	4,191.3	47,643	75	813	40	1.14
Ohio	12.0	9.7	2.9	0.4	2.2	0.4	5.8	2.4	160	36	275	56	0.25
South Dakota	164.7	121.4	196.3	54.3	94.0	48.0	311.7	90.2	1,216	44	702	46	0.74
Wisconsin	351.0	352.7	307.0	134.1	127.8	45.1	311.7	224.2	2,855	44	797	62	0.64
9-State	7,486.2	5,403.2	5,195.8	985.1	2,694.9	1,515.9	6,390.5	5,121.0	62,629	68.2	796	42.4	1.03

Table A6-3 Pumping Estimate Based Upon NASS Irrigation Data

water depth, mm	26	
Water depth, feet	1.030	
Square feet per acre	43,560	
Q, CF/Acre	44,867	
Q, CF/Hectare	110,821	
Lift, ft	68	
Head lift, psia	30	
Pump Delivery Pressure	42	
Total Head, psi	72	
Total Hea6d, psf	10,361	
Total Pump Work, ft-lbf/hectare	1,148,247,369	
Total Pump Work, BTU/Ha	1,475,896	
Total Pump Work, kcal/Ha	371,926	
Pump Efficiency	75%	
Actual Pump work	495,901	
Motor Efficiency	94%	
Total Pumping Energy	527,554	
Pumping by grid electricity	81,154	15%
Pumping by Diesel	250,425	47%
Pumping by Natural Gas	184,217	37%
Grid Electrical Input Estimate	LHV	HHV
Electrical Generation + Transmission Efficiency	7,911	8,432
Coal Extraction Efficiency	95%	95%
Overall Efficiency	38.3%	36.0%
Total Energy per irrigated Ha, kcal electrical	211,783	222,372
Diesel Input Estimate		
Engine-Generator efficiency (HHV BTU/bhp-hr)	5,968	6,358
% Efficiency	42.6%	40.0%
Crude Extraction efficiency	93.20%	
Refining efficiency	94.97%	
Transportation and distribution	97.91%	
Overall Efficiency	36.92%	
Total Energy per irrigated Ha, diesel	678,321	722,583
Natural Gas Input		
Gas engine heat rate HHV BTU/bhp-hr	9,775	10,967
Gas engine efficiency	26.0%	
Natural Gas extraction efficiency	89.93%	
Overall efficiency	23.4%	
Total Energy per irrigated Ha, kcal gas		
Total Energy Kcal/Ha	1,672,653	1,822,214
Total BTU Energy/Ha	6,637,510	7,231,008
Fraction of Hectares irrigated	8.73%	8.73%
Fraction of acres harvested	99.20%	99.20%
Total Energy per harvested Ha, kcal	147,200	160,362

Table A6-4 Irrigation Energy Estimate Based Upon 1991 SURVEY Data

	8-state Average	Nebraska State Average	Difference	Net BTU/ acre	Gross BTU/acre	Total efficiency	Total per Hectare		bhp/acre	% bhp
Diesel, gallons	4.930	18	13.1	1,686,094	1,793,298	86.7%	4,806,008	5,111,580	286	46.7%
Electricity, kwh	16.433	96.978	80.5	274,900	274,900	38.3%	1,771,949	1,771,949	103	16.8%
Natural gas, scf	17.754	1610	1592.2	1,448,944	1,625,683	89.9%	3,979,726	4,465,166	224	36.5%
Total BTU				3,409,937	3,693,880		10,557,684	11,348,695	612	100%
Kcal/Ha							2,660,536	2,859,871		
Fraction Hectares Irrigated							8.73%	8.73%		
Kcal/Ha All acres							232,180	249,575		

Note: Electricity adjusted for drying on farm at 0.2 kwh/bu.

Appendix 7 Fertilizer Manufacture and Transport

The main inputs to corn farming are nitrogen, phosphate and potash. Limestone is sometimes used as a soil builder. Minor amounts of trace nutrients are also added.

Nitrogen

Sources of Supply

All synthetic nitrogen fertilizer production in the United States is based upon the conversion of natural gas to ammonia. Between 1991 and 2000, the US has imported, on average, less than 20% of its total ammonia consumption[92]. Because of high natural gas prices, ammonia imports rose to 29% in 2001. In 2001, 89% of US ammonia consumption was used for fertilizers. Approximately 58% of US ammonia capacity resides on the Gulf Coast. Imports come primarily from Trinidad/Tobago (50%) and Canada (36%).

Table A7-1 provides sources of supply of nitrogen fertilizer. Some nitrogen fertilizer is manufactured in the 9-state area and shipped by pipeline, barge and rail to the corn-belt. Table A7-1A provides a summary in thousands of tons per year nameplate capacity of active manufacturing facilities in the 9-state region. Table A7-1B shows potential rail and barge sources from outside the region. Table A7-1C shows potential supply of ammonia by pipeline.

Table A7-1 Active Nitrogen Fertilizer Facilities, Thousands of Tons/Year Capacity
Table A7-1A 9-State Plants

State	Facility	Location	Ammonia	Urea	Ammonium Nitrate	Ammonium Sulfate	N-Solutions
Illinois	Royster Clark	East Dubuque	306	146	170	0	390
	Orica	Seneca		0	230	0	0
	LTV	Chicago	0	0	0	6	0
	National Steel	Granite City	0	0	0	9	0
	CP Chemicals	Union	0	0	0	2	0
Indiana	Beth Steel	Burns Harbor	0	0	0	18	0
	USX	Gary	0	0	0	35	0
Iowa	Farmland	Fort Dodge	386	195	243	0	570
	Green Valley	Creston	35	0	0	0	0
	Terra	Port Neal	370	306	319	0	810
Minnesota			0	0	0	0	0
Michigan			0	0	0	0	0
Nebraska	Farmland	Beatrice	292	75	93	0	200
	Agrium	Beatrice	0	0	209	0	0
Ohio	PCS	Lima	598	451	135	0	250
	Royster Clark	North bend	0	0	0	0	23
	LTV	Warren	0	0	0	6	0

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[92] Source: Deborah A. Kramer, dkramer@usgs.gov, annual briefing paper titled "Nitrogen(Fixed)-Ammonia" in USGS, Mineral Commodity Summaries, page 116, January 2002.

	USX	Loraine	0	0	0	22	0
South Dakota			0	0	0	0	0
Wisconsin			0	0	0	0	0
Total			1987	1173	1399	98	2243
Nitrogen			1636	547	490	21	673

Table A7-1B Potential Rail and Barge Sources Thousands Tons per Year

State	Plant	Location	Ammonia	Urea	Ammonium Nitrate
Alberta, Canada	Agrium	Various	0	1900	0
Saskatchewan Canada		Various	0	1353	0
Ontario, Canada	Terra	Courtright	435	254	146
Tennessee	PCS	Memphis	409	451	0
Arkansas	Terra	Blytheville	420	480	0
	El Dorado Chem.	El Dorado	0	0	570
Mississippi	Misschem	Yazoo City	685	196	1330
Louisiana	CF Industries	Donaldsonville	0	0	934
Wyoming	Costal	Cheyenne	192	101	310
Oklahoma	Terra	Verdigris	0	0	858
Total			2141	4735	4148
Total N			1763	2210	1452

Table A7-1C Potential Pipeline Sources Thousands Tons per year

State	Plant	Location	Ammonia
Mapco			
Texas	Agrium	Borger	540
Oklahoma	Farmland	Enid	1025
	Terra	Verdigris	1050
Total			2615
Total N			2154
Gulf Central			
LA	CF Industries	Donaldsonville	2200
	Farmland	Pollock	518
	IMC Phosphates	Donaldsonville	560
	Koch nitrogen	Sterlington	1222
Total			4500
Total N			3706

Ammonia pipelines service the central and western area, and in addition, plants are located adjacent to rail and barge transport to the area. While the exact sources of nitrogen fertilizer imported to the region are not known, the following supply and demand balance provides a reasonable geographical picture.

Table A7-2 provides demand data for nitrogen use in the 9-state area in millions of pounds of nitrogen per year. Sufficient supply is identified to satisfy the agricultural needs of the region. It is assumed that ornamental fertilizer use is small compared to that of agriculture. In Table A7-2, regional production of nitrogen is based upon an assumed 80% stream factor for the operating plants. Imports of nitrogen to each state are shown by difference.

The most current tabulation of the uses of various types of fertilizer is summarized in Table A7-3[93]. It is assumed that this breakdown applies to corn. Almost half of the nitrogen used was in the forms of ammonia and ammonia solutions. The “other” is mostly mono and diammonium phosphates.

Table A7-2 Nitrogen Supply and Demand MM lbs (2000 Use)

	Nitrogen Demand					State Nitrogen Production	Nitrogen Imports
	Corn	Soybeans	Sugar beets	Wheat	Total		
IL	1,798	17	0	80	1,895	942	953
IN	865	11	0	0	876	18	858
IA	1,533	81	0	0	1,614	2438	-824
MI	240	11	26	0	277	0	277
MN	786	10	41	170	1,007	0	1,007
NE	1,261	20	10	77	1,367	712	654
OH	573	22	0	107	702	1350	-648
SD	419	24	0	159	602	0	602
WI	301	7	0	0	307	0	307
Total	7,775	202	76	592	8,646	5,459	3,186

Table A7-3 US Consumption of Nitrogen Fertilizer 1991

Fertilizer Type	Wt % N	Tons	Ton N	%
Ammonia	82.4%	5,066,947	4,172,780	46.24%
Aqueous Ammonia (22% ammonia, 65% ammonium nitrate)	40.9%	336,051	137,781	1.53%
Ammonium Nitrate	35.0%	1,844,144	645,450	7.15%
Ammonium Sulfate	21.2%	819,515	173,837	1.93%
32%Nitrogen Solutions (34.2% Urea, 45.8% Am nitrate, 20% water)	32.0%	7,699,031	2,309,709	25.59%
Urea	46.7%	3,395,512	1,584,572	17.56%
Other (Not used in weighted estimate)		1,146,480	-	-
Totals		20,307,680	9,024,129	100.00%

Assuming this distribution applies to the Corn Belt states, Table A7-4 provides a fertilizer balance and an estimate of the various forms of nitrogen imported to the region. It is evident that urea and ammonium nitrate are imported to produce the required nitrogen solutions. The shortfall in nitrogen solutions are assumed blended in the region from imported ammonium nitrate and urea to 32% N-solutions by adding 20% water. The majority of the urea imported to the region is likely to come from Saskatchewan and Alberta. The closest large sources of ammonium nitrate are in Tennessee, Oklahoma and Mississippi. The ammonium sulfate is likely to come from a large number of unidentified sources. Thus, except for urea, it would appear that U.S. industry efficiency is appropriate

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[93] ERS, “Fertilizer Use and Type”, 1991.

for characterizing fertilizer energy inputs. If Canadian operators are more energy efficient, fertilizer inputs could be slightly overstated.

Table A7-4 Reconciliation of Nitrogen Supply, MM Pounds per year for Corn

	Use	Area	Imports	Total	Source of imports
Ammonia	47.77%	2355	1360	3715	Pipeline
Ammonium Nitrate	7.15%	157	399	556	South US
Ammonium Sulfate	1.93%	30	120	150	
Nitrogen Solutions	25.59%	1989	0	1990	Blended
Urea	17.56%	378	987	1365	Canada
Totals	100.00%	4909	2866	7776	

Energy Consumption in Manufacture of Nitrogen

In 1999, the production of one ton of ammonia in the US required 33.5 million BTU's of natural gas energy on a higher heating value basis. This value is substantiated by data reported in the literature. McKetta and Cunningham[94] state "feed plus fuel (natural gas) consumption for a large (ammonia) plant ranges from 28.5 to 33.3 MM BTU/ton (7.2 to 8.4 MM kcal/ton) which represents essentially the entire energy consumption of the plant". Kirk-Othmer[95] cites an energy consumption of 29 GJ/ton or 27.5 MM BTU/ton for 1980's and 34.0 MM BTU/ton for 1970's natural gas based plants. By way of comparison, they also cite an energy consumption of 46 MM BTU/ton for 1970's coal-based plants. Essentially all ammonia produced in the US and imported to the U.S. is based upon natural gas.

Worell et al[96] have reported that the US fertilizer industry is relatively old. They report, citing TFI data, that in 1996, the primary energy used was 35 MM BTU/ton HHV for ammonia including feedstock. They also indicate that the average US and EU energy consumptions are nearly the same. However in the EU, inputs range from 26.5 MM BTU/ton in Spain to 38 MM BTU/ton in Belgium. Because the plants are newer, it is expected that Canada and Trinidad producers are more energy efficient than U.S. producers. If natural gas prices remain high, it is likely that the less efficient U.S. plants could shutdown and ammonia imports would increase. The consequence of this might be a slightly lower energy input to fertilizer manufacture.

EIA[97] has published data on manufacturing energy used in the "Nitrogenous Fertilizer" industry, Sic Code 2873. SIC 2873 relates to establishments primarily engaged in manufacturing nitrogenous fertilizers including anhydrous ammonia, nitric acid,

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[94] McKetta, J., Cunningham, W.A., Encyclopedia of Chemical Processing and Design, "Ammonia", Volume 3, page 262, Marcel Dekker, Inc, NY, 1977.

[95] Kirk-Othmer Encyclopedia of Chemical Technology, "Ammonia", Fourth Edition, Volume 2, page 655, John Wiley & Sons, 1992.

[96] Worell, E., Phylipsen, D., Einstein, D., Martin, N., "Energy Use and Energy Intensity of the U.S. Chemical Industry", LBLN-44314, April 2000.

[97] Energy Information Agency, DOE, EMEU Website for 1991, 1994 and 1998 total manufacturing energy use.

ammonium nitrate and sulfate, mixed fertilizers, solution fertilizers and urea for 1991, 1994 and 1998. Reference 28 and previous editions provide total US ammonia production by year. From these data, the calculated energy per pound of nitrogen for the fertilizer industrial sector are estimated as follows: 20,142 for 1991, 21,069 for 1994 and 19,472 for 1998 as BTU/Lb N HHV. These values range from –4% to -12% of the HHV estimate provided in Table A7-5. However, industries in SIC code 2873 could be involved in producing and mixing fertilizers from imported ammonia as well as domestically produced ammonia; the imported fraction of ammonia was 14% in 1991, and 19% in 1994 and 1998. Thus, the EIA energy input data could overstate the efficiency of fertilizer manufacture by ignoring energy inputs to produce imported ammonia used for fertilizer.

Production energy requirements for other forms of nitrogen fertilizer including gas, oil, electricity[98] and steam covering 86% of US production capacity have been reported by TFI[99]. Table A7-5 summarizes the energy input for manufacture. The primary gross (HHV) and net (LHV) energy inputs are based upon the distribution of energy inputs to each product. The total LHV energy includes energy for extraction and transportation of raw materials to the manufacturing site. Packaging and transportation of the fertilizer to the point of use is considered separately and shown as entries in Table 15. In downstream processing, for example to make urea, no conversion efficiencies were reported by TFI. 99% conversion efficiency of raw materials was assumed. The feedstock energy input as sulfur to sulfuric acid manufacture was assumed to be zero. In 2000, the last domestic sulfur mine was closed and only 9% of US sulfur was mined[100]. 81% of US sulfur was recovered from pollution control equipment in the elemental form and 10% was byproduct sulfuric acid from smelting operations. Sulfur production from pollution control is ubiquitous and thus transportation energy for sulfur was considered negligible. Production of sulfuric acid is highly exothermic and produces waste energy in the form of process steam resulting in an energy reduction in several downstream steps.

Table A7-5 Energy Use in Nitrogen Fertilizer Production

		BTU/lb N		
	Usage, %	HHV	LHV	Total LHV
Ammonia	46.24%	20,739	18,675	20,548
Aqueous Ammonia	1.53%	21,961	19,777	22,096
Ammonium Nitrate	7.15%	22,374	20,150	22,162
Ammonium Sulfate	1.93%	17,707	15,969	17,872
Nitrogen Solutions	25.59%	23,207	20,970	23,003
Weighted Total	100.00%	22,077	19,928	21,893

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[98] The energy input for purchased electricity is assumed to be 8,432 BTU/kwh on a higher heating value basis including generation and transmission losses. See the appendix for the detailed analysis of fossil energy input for electricity.

[99] The Fertilizer Institute, "Energy Use Survey, 1987".

[100] Ober, Joyce, private communication, USGS Minerals Information Team.

Phosphates

Essentially all US phosphate is strip-mined in Florida. The rock phosphate is beneficiated to improve quality and refined using sulfuric acid to produce phosphoric acid and phosphates. The US is self sufficient in phosphate production. Phosphate fertilizer is reported on a P_2O_5 basis; there are 81.7 pounds of phosphate in phosphoric acid. Much of the phosphate is supplied as mono and diammonium salts. If all phosphate were applied as DAP, the nitrogen contribution would be on the order of 10% of the total chemical nitrogen supplied for corn. In this analysis, the processing energy input used for phosphate manufacture assumes the product is the ammonium salt. The energy embodied in the ammonia is not considered because it is included in the total nitrogen applied.

The Fertilizer Institute has reported energy use for mining, beneficiation and production of phosphoric acid. In 1987, the industry average input for mining, beneficiation, and drying was 706,000 BTU/ton of P_2O_5.

On average, the phosphate content of rock phosphate is 32%[101]. To produce a ton of P2O5, 2.04 tons of sulfuric acid must be added. The energy analysis is provided in Table A7-6. The estimated energy is small because of the energy benefit resulting from the use of recycled sulfur to produce sulfuric acid.

Table A7-6 Total Energy Input MM BTU Per TonP2O5

Input	Quantity	Energy
Rock Mining and Beneficiation	3.13 Tons	1,992
Sulfuric Acid	2.04 Tons	(3,745)
Natural Gas		0
Fuel oil		12
Electricity		657
Steam		2,356
Sub-total to phosphoric acid		915
As ammonium phosphate[102]		1,648

Potash (K_2O)

Canada produces about 92% of North American potash. The United States imports approximately 75% of the potash used; 94% of the imports are from Canada, the vast majority as muriate of potash (MOP) also called potassium chloride[103]. MOP exhibits a 62% K_2O equivalency. Potash in the US is produced primarily in Utah and New Mexico.

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[101] Kirk-Othmer Encyclopedia of Chemical Technology, "Fertilizers", Fourth Edition, Volume 10, page 454, John Wiley & Sons, New York, 1992.

[102] The majority of the phosphate is sold as mono and diammonium salts. The energy includes the processing energy and feedstock phosphate energy but not the energy in the nitrogen feedstock as it is accounted for separately.

[103] USGS Mineral Industry Surveys, "Potash in Crop Year 2000", September 2000.

Because of the large production in Saskatchewan, it is likely that nearly all potash used in the Corn Belt is moved to the area by rail from western Canada.

The two main mining methods used are underground shaft mining and solution mining. In Saskatchewan, about 80% of the production comes from shaft mines. The energy consumption in potash manufacture has recently been reported by Statistics Canada[104] based on a 1997 survey. The relative production of fossil and non-fossil electricity use in Saskatchewan Canada and the US was used to adjust the US electricity heat rate to a Canadian equivalent. Table A7-7 presents the analysis.

As a check, the Fertilizer Institute survey reports that shaft mining of potash required 2,489 MBTU/ton HHV in 1985. Assuming the product is MOP, the energy is 4,015 MMBTU/ton or 2,008 BTU/lb K2O equivalent. MOP is water-soluble and can be removed with hot water. The energy consumption for potash solution mining at a very large facility in Canada[105] was reported as 8,270 MM Btu/ton. The weighted energy input is 2,433 BTU/lb K2O on a HHV basis. The input based upon the Canadian data is approximately 15% lower than the estimate made using the older Fertilizer Institute and solution mining data.

Table A7-7 Energy Inputs to Potash Mining

Total		Quantity	Total LHV BTU
NG	CF	23,419,592,215	23,794,891
Gasoline	Gal	196,266	29,925
Diesel	Gal	1,157,522	184,306
Fuel Oil	Gal	8,072,009	1,285,266
LPG	Gal	779,518	70,698
Power	Kwh	1,648,908,000	16,521,424
			41,886,511
MM Btu/ton	US t K2O	10,172,946	4.117
Btu/lb			2,059

Packaging

The TFI survey provides energy consumption data on granulation and preparation of mixed fluids. The energy varies from zero for ammonia to 2,515 BTU/lb total LHV for ammonium sulfate. The weighted average energy applied to nitrogen fertilizer is 210 BTU/lb N on a Total LHV basis. The energy for ammonium phosphate is for the granular state. No packaging energy is assumed for potash.

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[104] Statistics Canada, “Non-Metal Mines, 1997”, Rpt 26-224-XIB.

[105] Potash Corporation of Saskatchewan, Inc., “Energy Use and Emissions Data for PCS Inc., Patience lake Division”, Canadian Industry Program for energy Conservation., 19XX.

Limestone and Micronutrients

In the corn-belt, sulfur and micronutrients were applied on a small fraction of the acres; the 1991 to 1995 averaged fraction of acres receiving these materials were 10.25%, and 11.25% respectively[106]. The application rate for sulfur was only 12.25 pounds per acre. No data are reported for micronutrients.

There is a large discrepancy in the USDA literature concerning limestone use. While the application rate is reported to be generally 2 tons per acre, the Corn Belt acres receiving limestone vary from less than 10% to 60% depending on the reference. For this analysis, the highest level of limestone application is used. In 1999, limestone was applied to about 60% of the corn-belt acres at a rate of 2.2 Tons/acre[107].

There are deposits of limestone in nearly every state. The lower grade limestones are suitable for agriculture where chemical composition is a limiting factor. USGS[108] reported that in 1999, there were 837 active limestone quarries in the 9-state Corn Belt region. The quantity of limestone sold as agricultural grade is more consistent with treatment of 10% of the acres.

There are no publicly available energy audits reported for limestone mining. Limestone is generally removed from surface deposits using explosives. The rock is ground to agricultural size and transported.

It has been reported[109] that the blasting requirement for one major limestone operation is 0.49 pounds of ammonium nitrate/ton of limestone. The energy to crush limestone to agricultural grade size is estimated to be 10.5 Kwh/ton[110]. A diesel allowance was included for on-site hauling. The input energy for limestone mining, shown in Table A7-8, is very small. It would appear that the majority of energy consumed in limestone use is in transport to the farm.

Table A7-8 Estimated Inputs for Limestone Mining

	Electricity Kwh/ton	Explosive Lb /ton	Diesel	BTU/ton Total LHV
Blasting		0.4889		4,937
Hauling			2000	2,436
Breaking and Crushing	10.50			100,062
BTU/ton				107,435
BTU/lb				53.72

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[106] Padgitt, M, Newton, D., Penn, R., Sandretto, C., "Production Practices for Major Crops in US Agriculture, 1990-1997", USDA Statistical Bulletin 969, Part 3.1 "Nutrients", August 2000.

[107] www.ers.usda.gov/briefing/agchemicals/questions/nmqa3.htm

[108] USGS, "Minerals handbook, 2000".

[109] www.wagnerquarries.com/blasting/html

[110] According to www.penncrusher.com, the energy to reduce stone to 6 inch size is 0.5 hp-hr/ton. To further reduce the stone to 100% 4-mesh, a 55-85 tph mill requires 450 to 550 hp. Private communication gsmith@cecrushers.com

Fertilizer Transportation Energy

In the evaluation of energy use, transportation of feedstock and product are considered. Table A7-9 provides data for various forms of transportation. In each case, the transportation weight was adjusted for the fraction of active ingredient.

Table A7-9 Transportation Inputs, HHV Basis

Method	Operating Energy, BTU/ton-mile	Data Source
Rail Unit Train	352	[111]
Truck	1,995	[19]
Barge, upstream	551	[19]
Barge, downstream	209	[19]
Ammonia Pipeline	280	[112]

Approach

The transportation energy is a small part of the total fertilizer energy input. It is a difficult task to quantify with high accuracy the transportation energy weighted to the entire region. The approach taken is as follows:

- The weight of fertilizers N,P,K and limestone corrected for transport weight not active ingredient by state are used as weighting factors.
- The fertilizers are separated by in-state production and imports
- For imports, rail, pipeline and barge miles are determined from the likely source to a midpoint location in the state.
- All instate material is assumed available at the distribution terminal.
- Material is trucked from each main distribution terminal. A less than complete count of main distribution terminals is used to compute the equal area travel distance based upon the state area. The truck mileage is increased by 1.5 to account for an unloaded return trip.

Total Transportation Energy

The total estimated transportation energy is provided in Table A7-10. More detailed information is provided in Appendix 10. The truck miles are estimated based upon the number of identified terminals handling fertilizer and the state area.

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[111] USDOT Maritime Administration, "Environmental Advantages of Inland Barge Transportation", Final Report, page 7, August 1994. The energy was adjusted to remove energy for refining assuming the refining efficiency to diesel is 95%.

[112] ANL, TAPSEIS.ANL.GOV/documents/docs/section_4_9_may2.pdf, Feb 2001. The energy is based upon crude oil transport as there is no published information on liquid ammonia.

Table A7-10 Summary of Fertilizer transportation Energy

	Made in Region	Imported	Weighted Transport Mileage				BTU/Acre
	Actual MM lbs		Pipeline	River Barge	Rail	Truck	
Ammonia	2879	1631	732	0	0	74	
Ammonium Nitrate	450	1228	0	0	646	66	
Ammonium Sulfate	146	561	0	0	820	74	
Nitrogen Solutions	6217	0	0	0	834	70	
Urea	811	1923	0	0	1085	76	
Phosphate		6980	0	618	1032	83	
Potash		10720	0	0	1337	81	
Limestone			0	0	0	21	
Gross BTU							246,937
Net BTU							232,705
Total LHV							283,451

Appendix 8 Chemicals:

For corn, the primary chemicals used are herbicides and insecticides; no fungicide use is reported. USDA has reported the use of chemicals by active ingredient for 2000 for the nine-state corn belt region[113].

Limited data on the energy required to manufacture chemicals has been reported. Table A8-1 provides data for the manufacturing and feedstock energy in chemicals along with consumption data for 18 states including the Corn Belt. About 94% of the chemicals applied for corn are herbicide. The eight herbicides for which energy data are reported account for 66% of the herbicide applied. Data are available for only two insecticides that account for 8% of the insecticide applied. The range of energy for insecticides and herbicides is similar. The weighted energy input is estimated to be 104,616 HHV BTU/lb of active ingredient. In addition, there is a substantial amount of energy involved in packaging and transporting the active ingredients. The total delivered chemicals have an energy content of 122,266 BTU/lb HHV, 112,880 LHV and 130,192 tLHV.

Table A8-1 Energy Content of Chemicals

Total Herbicide use	153,464	M lbs applied	
	M lbs	BTU/lb HHV Active Ingredient	Reference
2,4,D	2,359	36,570	Helsel, Z[114]
Alachlor	4,748	119,597	Helsel, Z
Atrazine	53,954	81,739	Helsel, Z
Dicamba	4,933	126,920	Green,M.B.[115]
Glyphosate	4,438	195,328	Green,M.B.
Metalochlor	29,615	118,745	Green,M.B.
Paraquat	570	197,894	Helsel, Z
Trifluralin	43	64,531	Helsel, Z
M lbs accounted for	100,660	101,226	
Fraction accounted for	0.66		
Total Insecticide Use	9,811		
Carbofuran	580	195,313	Helsel, Z
Methyl parathion	246	68,833	Helsel, Z
Total	826	157,645	
Fraction accounted for	0.08		
Weighted total, HHV all chemicals		104,616	
Transport& Packaging		17,650	Helsel, Z
Primary energy , HHV delivered to farm		122,266	

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[113] usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0501.txt

[114] Helsel,Z, "Energy and Alternatives for fertilizer and Pesticide Use", In: Fluck, R.C. (Ed), Energy in Farm Production Vol6 in Energy in World Agriculture, Elsevier, New York, p177-201, 1992.

[115] Green, M.B. "Energy in Pesticide Manufacture, Distribution and Use, In: Stout B.A., Mudahar, M.S., Energy in Plant Nutrition and Pest Control, Elsevier, Amsterdam, pp 165-177, 1987.

Appendix 9 Manufacturing Energy of Systems

Pimentel has considered the prorated energy in manufacturing of farming components and ethanol manufacturing facilities. The purpose of this section is to analyze the magnitude of the energy involved in equipment.

Energy in Steel Making

According AISI[116] the energy used in producing a ton of steel has fallen by more than 45% since 1975 primarily due to the recycling of iron and steel. AISI estimates that 19 million BTU/ton, or 4.789 million kcal/ton are consumed. The U.S. DOE[117] has performed a detailed industry survey on energy use in the iron and steel industry. DOE cites a total energy input per ton of steel as 18.135 million BTU/ton (4.57 million kcal/ton) in 1994. The major forms of energy inputted in steel making are electricity (8.1%), natural gas (26.1%), and coal and coke (37.8%). Some residual fuel oil is used for boiler fuel. Losses, especially in coking, presumably represent the difference. Assuming this energy breakdown, the total energy[118] for steel making including extraction, conversion and transportation is estimated to be 19.23 million BTU/ton or 4.85 million Kcal/ton.

Energy in Materials as a Function of Industry Classification

EIA/DOE[119] have reported intensities for industries that produce various products. Intensity is defined as BTU input/$ sales. Table A9-1 provides intensities for several “value added” industries. For a wide range of industries involved in the manufacture of equipment used in farming and ethanol production, the energy input per dollar value of production is nearly constant. The range is from 500 to 1800 BTU/$ with an arithmetic average of 943 BTU/$. The root mean square error in each industry category is typically 5% or less for the survey.

Table A9-1 Value Added Industry Energy Intensities

Electrical equipment	1,000
Semi Conductors	800
Computers	500
Fabricated metals	1,800
Machinery	800
Misc manufacturing	900
Transportation equipment	800
Average value added intensity	943

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[116] www.steel.org/facts/power/energy.htm
[117] www.eia.doe.gov/emeu/efficiency/steel_data.htm
[118] DOE total energy includes transmission and generation efficiencies for electricity.
[119] www.eia.doe.gov/emeu

“Capital” Energy in Machinery

To estimate the order of magnitude of energy in machinery, it is assumed that the majority of the equipment weight is in steel. For a given piece of equipment, the sales price per unit weight then allows an estimate of the total energy input using the energy in steel plus the value added intensity.

Once the capital energy is established, the energy in the machinery is established by its pro-rated use per unit of production plus energy in maintenance. The latter is estimated based upon the annual cost of maintenance as a fraction of the new equipment price and energy.

Farm Equipment

Table A9-2 shows that the price per unit weight for different types of manufactured equipment. Prices were established from vendor quotes. For powered equipment such as farm tractors, medium duty freight trucks, farm combines, engine-generator sets and transit buses, the range is $4.11 to $7.76. The average over all groups is $5.43 per pound. The table also provides some data on farm non-powered farm implements. The average is $3.24 per pound.

Table A9-2 Price per Unit Weight for Equipment

Powered Units			Sale Price	Unit wt	Unit $/lb	Group $/lb
Tractor, 2WD	J Deere	105 hp	$ 44,877	10,750	$4.17	
Tractor, 4WD	J Deere	280 hp	$ 127,365	30,970	$4.11	$4.14
Truck	International	375 hp	$ 71,000	15,000	$4.73	
Truck	Freightliner	375 hp	$ 76,000	16,000	$4.75	
Truck	Kenworth	375 hp	$ 78,000	15,600	$5.00	$4.83
Engine-Generator-4045T	J Deere	81 bhp	$ 11,500	2,185	$5.26	$5.26
Combine, 9650	J Deere	275 hp	$ 161,400	25,762	$6.27	$6.27
Transit Bus	1999 ELDORADO		$ 206,500	29,800	$6.93	
Transit Bus	2000 GILLIG		$ 246,000	39,600	$6.21	
Transit Bus	2000 ORION		$ 267,000	40,600	$6.58	
Transit Bus	2000 ORION		$ 267,000	40,600	$6.58	
Transit Bus	2000 NABI		$ 395,000	66,600	$5.93	
Transit Bus	2001 NEOPLAN		$ 377,000	48,600	$7.76	$6.66
Implements						$5.43
Disk	J Deere 637	26 ft	$ 27,700	9,074	$3.05	
No till drill	J Deere 1560	15 ft	$ 29,000	8,460	$3.43	$3.24
Powered equipment					$5.43	
Implements					$3.24	

Equipment Used in Corn Farming

Based upon a review of agricultural budgets for various size farms producing corn, the fraction of machinery first cost classified as powered units is near 85% with implements accounting for 15% of the cost. Using the factors derived in table A4-2, the first cost per unit weight of farm machinery is $5.10/pound.

In the 1996 survey, USDA reports that the cost of capital recovery for machinery and equipment is about $61.00 per acre of corn. The capital recovery cost of the farm equipment depends primarily upon the interest rate, lifetime, and farm size. The typical farm equipment loan is seven years at 10% resulting in an annualized payment of $0.2054 per dollar of loan. Assuming the equipment has a 15 year useful life, the fraction of depreciation per dollar of capital recovery is 32.5% or $19.80 per acre. Various farm budgets reported in the literature suggest a range of $13 to $30.

The 1996 USDA survey provides a cost of repairs of about $14.50 for equipment. This results in a total equipment related cost of $34.30 per acre. Table A9-3 demonstrates that the "capital energy" energy related to farm equipment is about 0.3% of the energy in ethanol.

Table A9-3 Capital Energy Contribution of Farm Equipment

Total Fixed Cost, $/acre	$34.30
Equipment cost, $/lb	$5.10
Energy in steel, MMBTU/ton	19.23
Prorated Steel, lb/acre	6.72
Energy in Steel, BTU/acre	64,617
Energy in Manufacturing, BTU/acre	32,340
Energy in Equipment, BTU/acre	96,957
Energy in Equipment, BTU/gallon	261
% Energy in ethanol	0.34%

Irrigation Systems

A typical central pivot system consists of a well with submerged turbine pump, diesel engine-generator, PVC header and center pivot system.

Energy In PVC Manufacture

According to recent peer reviewed analysis of the life cycle energy[120], PVC manufacture requires 12.66 MM kcal/ton on a net basis. Of this energy, 5.8 MM kcal/ton comes from crude oil.

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[120] See WWW.ping.be, The Life Cycle of PVC and Alternatives Compared.

PVC pipe exhibits a lifetime of 50 years or more in water systems. In this analysis, 20 years is assumed.

Life Expectancy And Design Aspects Of Central Pivot Systems and Auxiliaries

Central pivot systems are generally constructed of galvanized steel. According to manufacturers of systems and other experts, the life of a system should be 20 years[121].

Typical 125-130 acre center pivot systems weigh 32,000 to 40,000 pounds. In this analysis, a weight of 35,000 pounds is assumed. The University of Arkansas Cooperative Extension, reports that the annual maintenance cost amounts to 1% of the first cost, and thus approximately 1% of the energy of manufacture of a non-towable center pivot unit.

Pimentel cites Batty et al[122] as a source for the estimation of the manufacturing energy in irrigation systems. Batty et al significantly overestimate the energy required to manufacture a center pivot system. First, they assume a lifetime of 10 years. Second, they assumed an energy use for steel production of 67.5 MM BTU/ton or 17 million Kcal/ton.

Based upon NASS data, the average well pump operates at 72 bhp. Allowing a 10% safety factor, the average irrigation pump will be near 80 bhp. The turbine pumps are equipped with an electric motor. Power is supplied by either a motor-generator set or through the electric grid. Based on Ali and McBride[123], it is estimated that in the 9-state area, 15% of irrigation is supplied from the electric grid while the remainder is supplied by diesel (47%) and natural gas (37%).

The usage of a central pivot system, pump, and engine-generator over a 20-year life is only about 16,000 hours. The pump and electric drive should exhibit a lifetime of at least 20 years. The engine-generator set typically has a 10,000-hour lifetime.

For the well header pipe, Batty et al assume that 1300 feet of a 10-inch PVC pipe weighing 6.43 lb/ft with a 20-year life are used. The header requires little or no maintenance. More typically, 8-inch pipe weighing 2.7 lb/ft is used[124]. Thus, instead of

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[121] According to Quality Irrigation, systems in Nebraska with good maintenance and water quality last in excess of 30 years. In areas with exceptionally corrosive water, the life could be as little as 10 years, but here the system would be repiped, not replaced. In those areas, stainless steel or ceramic lined piping are now being used to extend life. Another supplier, T-L Sales indicates a lifetime of 20+ years. Evans, R.G., “Center Pivot Irrigation”, Washington State University suggests the lifetime of systems should be 15 to 20 years. The University of Arkansas Cooperative Extension suggests a depreciable life for accounting purposes of 15 to 20 years for center pivot systems..

[122] Batty, J.C., Hamad, S.A., Keller, J., “Energy Inputs to Irrigation”, J Irrigation and drainage Division ASCE, Page 293, 1975.

[123] Ali, M, McBride, W, “Corn, State Level Production Costs, Characteristics and Input Use, 1991”, USDA ERS Report SB-891, September 1994. From Appendix table 2, we found the difference between diesel, natural gas and electricity use for Nebraska and the other 8 states in the survey. These differences were attributed to irrigation.

[124] According to Quality Irrigation which services Yuma and Washington Counties in Colorado, pipelines for quarter section are 1300 feet long and are designed for 900 GPM using 8 inch 80-psi PVC pipe. JM

4.18 tons of PVC, a more correct estimate is 1.76 tons. Batty el al provided an estimate 26 MM kcal manufacturing energy per ton of PVC.

Table A9-4 summarizes the energy input estimate for the system.

Table A9-4 Capital Energy in Irrigation, 126 Acre System

Center Pivot System	Cost	Weight	Life	Lb/ Acre-yr	Depreciation & Repair
Well	$ 5,000	1,363	20	0.54	$275
PVC Header		3,510	20	1.39	
Pump	$ 7,000	2,500	20	0.99	$490
Power Unit	$ 10,000	2,185	12.5	1.39	$1,000
Center pivot	$ 42,000	35,000	20	13.89	$2,520
	$ 64,000	44,558			$4,285
	MM BTU/ton	Pounds/ Acre	BTU/ Irr.acre	BTU/ Gallon	
Annual Energy in Steel, center pivot	19.23	16.7	182,685	49.2	
Annual Energy in Steel, equipment	19.23	3.7	35,748	9.6	
Annual Energy in PVC	50.238	1.4	34,987	9.4	
Energy in manufacturing		5.1	4,819	1.3	
Total Energy			258,239	69.6	
Total Energy, % energy in ethanol				0.09%	

Note: Center pivot was adjusted by 1.14 to reflect the sum of the primary metal and fabricated intensities to produce pipe.
Manufacturing intensity does not apply to center pivot.
Grid interconnection is assumed to require the same capital energy as the engine generator set.
10% of the corn acres are assumed irrigated.

The annualized energy embodied in the equipment in actuality is considerably less. Today, center pivot units built in the mid-1970's are being replaced with new units. The existing units are being recycled and used in less demanding applications[125]. Electric motors and motor-generators are generally rebuilt and at worst salvaged for scrap metal. The analysis presented here does not consider any salvage value.

Energy in Ethanol Plants

To estimate the possible capital energy in ethanol plants, an installed turnkey price of $1.25 per annual gallon was assumed. The plant life was conservatively estimated at 20 years with an annual maintenance cost of 4% for labor and materials. Table A9-5 provides a breakdown of the installed cost by category.

PVC irrigation pipe rated at 8 inch and 80 psi catalog SDR-51 has a weight of 2.7 lbs/ft (www.jmpipe.com).

[125] Private Communication from Daryl Bowin, Quality Irrigation.

The cost of equipment and materials is estimated to be $0.64 per annual gallon of capacity. Assuming a 20-year life, the depreciation cost is $0.03/gallon. For fluid solid plants, total annual maintenance cost for labor and materials is assumed to be 4% of the first cost. The material cost at 4% of the total plant material investment is, therefore, $0.03 per gallon. Assuming $5/pound for equipment and materials plus a manufacturing intensity of 1,186 BTU/$ results in an energy charge of 181 BTU/gallon or 0.2% of the product heating value.

Table A9-5 Capital Energy per Gallon of Production for a New Dry Mill

		Factors[126]	Cost/ annual Gallon	Materials	Labor + fees
Purchased equipment		100	$0.33	$0.33	$ -
Installation		187	$0.62	$0.31	$0.31
Land		6	$0.02		$0.02
E&C design, management,profit		84	$0.28		$0.28
Total		377	$1.25	$0.64	$ 0.61
Depreciation	20	years		$0.03	
Maintenance labor & materials	4%			$0.03	
Total				$0.06	
Cost, $/lb				$5.00	
Weight/gallon				0.01	
Energy in materials				112	
Energy in manufacturing				68	
Total Energy				181	
Energy, % Ethanol				0.2%	

Capital is $1.25 /annual gallon

Assumes materials and labor are each 50% of installed cost.

Other Capital Energy Considerations

The capital energy in fertilizer and chemical facilities should be on the order of that for ethanol facilities.

The capital energy for transportation and distribution should be similar to or less than the capital energy for farm machinery.

Conclusion

For agriculture and ethanol manufacture, the total "capital" input is on the order of 1% of the energy in the ethanol.

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[126] Peters and Timmerhaus, "Plant Design and Economics for Chemical Engineers", Mcgraw Hill, New York, Third Edition, 1980.

Appendix 10 Transportation of Fertilizers

Ammonia

Imported ammonia is assumed received by pipeline. Figure A10-1 shows the ammonia pipeline layout. Two pipelines exist. These are the Mapco pipeline that originates in Texas and Oklahoma and the Gulf Central pipeline that originates in Louisiana. Most of the production plants in the Corn Belt are also located on the pipelines. In the Corn Belt region, there are approximately 30 terminal locations along the pipelines.

The average pipeline transport distance was found by estimating the distance between individual terminals[127]. If multiple terminals and or pipelines exist in or are adjacent to a state, the average of the shortest and longest distance was used. The transport distance was then production weighted using 2000 nitrogen data by type and by state.

Ammonia is assumed to be 82% nitrogen by weight. All ammonia is trucked to the farm from the terminal.

Ammonium Nitrate:

Imported ammonium nitrate is moved by rail. The assumed sources are Courtright, Ontario and Memphis, Tennessee. Rail mileage was determined using the CSX rail system mileage locator to midpoint cities in each state from the points of origin.

Ammonium nitrate was assumed to be 35% nitrogen. All ammonium nitrate is assumed moved by truck to the farm.

Ammonium Sulfate:

Ammonium sulfate was assumed to come from the same locations as ammonium nitrate.

Urea:

Imported urea was assumed to come from Saskatchewan and Courtright, Ontario (for

Ohio and Michigan). Rail mileage was determined using the Burlington Northern and CSX rail system mileage locators to midpoint cities in each state.

Urea was assumed to be 46.7% nitrogen. All urea was trucked to the farm.

Nitrogen Solutions:

Nitrogen solutions are assumed prepared at the distribution terminal from Urea and Ammonium Nitrate at the 32% nitrogen level and trucked to the farm.

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[127] The zip code for each terminal was inputted to zipfind.com.

Phosphate:

Depending on the state, phosphate is railed from Tampa or barged. For cities west of the Mississippi, the material is off-loaded from the barge and railed to the midpoint of the state.

Phosphate is assumed to be 81.7% P2O5. Phosphate is trucked to the farm.

Potash:

Potash is transported from Saskatchewan by rail to the corn belt. BN and CSX mileage locators are used to establish the distance to the midpoint of each state.

Potash is assumed to be 62% K2O. All potash is trucked to the farm.

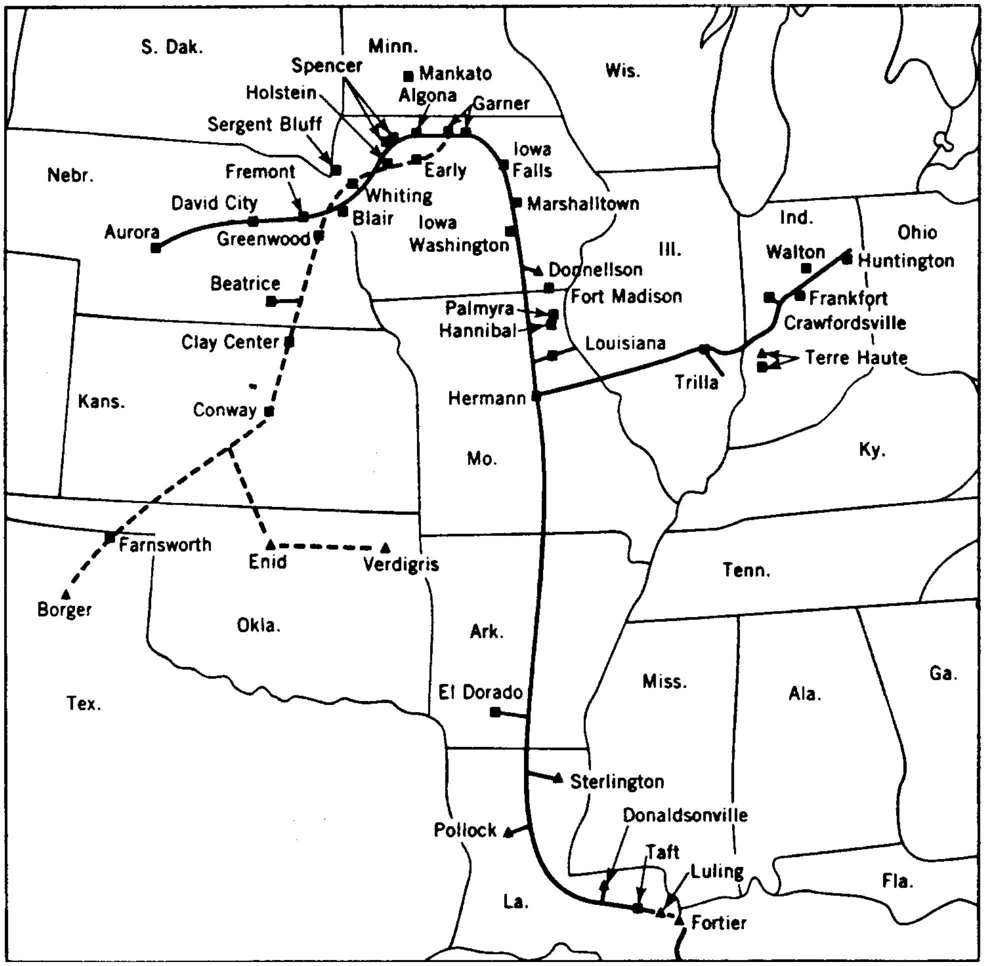
Limestone:

Table A10-1 provides quarry counts and area for the nine-state corn belt region. Limestone is not extensively used in South Dakota and Nebraska because of the alkaline soils found in those states. For the other states, the estimated average one-way hauling distance was estimated by computing the equal area average radius around each quarry. The truck distance was increased by 1.4 to account for road tortuosity. The return trip was counted as half the miles to account for the fuel use difference for empty and loaded trucks.

Table A10-1 Calculation of hauling Distance for Limestone

	Quarries				Transport
	Limestone #	M-Metric Tons/yr	Use tons/yr	Area Sq miles	equal area Miles
Illinois	149	72,100	2,244	55,593	7.7
Indiana	95	59,000	1,480	35,870	7.8
Iowa	212	41,800	1,304	55,875	6.5
Michigan	28	41,800	NA	56,809	18.0
Minnesota	56	10,350	NA	79,617	15.0
Nebraska	11	7,090	NA	76,878	33.4
Ohio	111	72,710	961	40,953	7.7
South Dakota	4	NA	NA	75,896	55.0
Wisconsin	171	29,240	327	54,314	7.1
Total 5 states	837	274,850	6,316		
Average(wo NE,SD)					10.0
Tortuosity					Sqrt(2)
Average with empty return					21.2

Figure A10-1 Ammonia Pipelines



Pipeline systems of transport for anhydrous ammonia within the United States (7), where A represents an ammonia plant location; m, storage terminals; (-), Gulf Central pipeline; and (---), Mapco pipeline.

Appendix 11 Reviews

In the following attachments, reviews provided by DOE, NREL, and USDA are included. Page citations in the reviews apply to the draft version and will not coincide with the current version of the report. Only major comments are included. The reviewers also included editorial comments.

Michael Wang Center for Transportation Research Argonne National Laboratory

This is a very detailed report on ethanol's energy balance, which should put the energy balance debate of ethanol to rest. The level of the technical details will make it a credible study for others to use. I have the following comments on the draft report.

Major Comments

There are a lot of acronyms used in this report, but they are not spelled out. A list of acronyms needs to be created.

There is an executive summary and a summary. I suggest that the summary section is combined with the executive summary to make the newly combined section as the executive summary. There is no need to have both.

p.1, 1st pp. and the 6th bullet. "The second purpose of this analysis is to examine the benefits of ethanol production on petroleum displacement." The analysis is based on the annual use of 5 billion gallons of ethanol in 2012. I expect that the some of this ethanol use is for displacing MBTE, which is a product from natural gas, not petroleum. Thus, displacement of oil by ethanol use could be small. Because of this, the estimated 0.674 barrels of crude oil imports to be displaced by a barrel of ethanol is questionable for two reasons. First, we do not know if ethanol will displace oil. Second, we do not know if the displaced oil will be imported oil.

p.1, 1st bullet. The net energy ratio concept is introduced first time here. Its definition needs to be explained here. Although some readers many know the concept, others may not.

p.1, 4th bullet. The 82% and 18% split between dry and wet mills gives readers the impression that the estimate is very precise. In reality, it may be possible that some may decide to build wet mills in the future. Something like 80% and 20% split is adequate enough for this analysis, considering the uncertainties in new ethanol demand and in types of ethanol plants to be built.

p.3, 1st pp. "Thus, using the primary HHV provides an indication of the benefit of ethanol manufacture weighted according to energy cost." This may sound correct from a company's accounting point of view. But it does not have much meaning in analyzing energy balance. The reason for using HHV in an analysis could be that in reality, some of the steam generated during fuel combustion in facilities could be recovered for use. This is especially true for steam generation units. In such cases, HHV is more adequate to address energy balance issues.

p. 3, Table 1. Besides the two columns (HHV and LHV), another column for total LHV could be added to the table for consistency with the report. In fact, the electricity values in the current table do not belong to HHV and LHV categories (in both cases, the electricity heat value should be 3413 Btu). The values in the table can be put to the newly added column.

p.4, 1st pp. "Electricity generation and transmission with losses are included in all three accounting totals." This is not consistent with the definitions of the three accounting systems. The losses during generation and transmission should be accounted in tLHV, but not in LHV and HHV.

p.6, Figure 1. This chart is confusing. It needs to be reorganized for helping readers understand what are included in this study.

p.7, the bullets are the repeat of those on p.1. If the executive summary section were combined with the summary section, the repeat would be avoided.

p.8, Section 2.1. The review of previous studies needs to be extended. For example, the review could include: what are the main assumptions in each study? Why are the studies different from each other? Readers, especially those who are not familiar with this topic, need a complete account of ethanol energy balance analyses completed in the past so that readers can put the Pimentel study into perspective.

p.10, 2nd pp. "significant at the 95% level, p=0.021, 0.013, 0.018." I am not clear how statistics were conducted here for these results. A little explanation is needed.

p.15, the last pp. Between 1991 and 1996, the switch from gasoline equipment to diesel equipment should help reduce farming energy use, since diesel equipment is generally more efficient than gasoline equipment. On the other hand, 1996 required more energy for drying corn than 1991 did. While the former reflect a real trend (which this study should take into account), the latter reflects climatic fluctuation (which this study should exclude).

p.16, 2nd pp. If you maintain that 1996 is a wet year, you should adjust drying energy need for 2000 for climatic differences between 1996 and 2000.

p.22, Table 15. The numbers for total Btu/bushel appear problematic.

p.23, 2nd pp. U.S. imported nitrogen fertilizer now is much higher than the 20% reported here. Also, the importing origin countries mentioned here might be out of date. You need to use new USDA data to update the information here.

p.26, 2nd pp. The 33.5 mmBtu requirement per ton of ammonia could be too high. Some recent data show that the Fertilizer Institute's data are in the high end of the available data range. The citation of 1980s and 1970s plants does not help, since they are too old to represent today's plants. You need to get some data for later 1990s plants.

p.33, 2nd pp. The USDA farming energy survey data may include some of the energy used for transporting corn from fields to local storage. Check with Hosein Shapouri for this.

p.38, Table 32. The electricity use for wet mills could be double counted, since most wet mills generate electricity themselves. Check with Hosein Shapouri for this.

p.38, 4th pp. "The best modern design inputs for wet mills are reported to be 38,580 Btu/gallon including stack losses and 2.134 Kwh/gallon respectively." What is the source for this statement? Also in the pp., "It would appear that the current wet milling operations are less efficient than possible with current technology and energy integration." If some wet mills are to be built from now to 2012, this issue of efficient wet mills needs to be addressed.

p.41, Table 36. The table is confusing because units are not presented clearly. The table may need to be separated into two tables. How was energy use for alfalfa and urea estimated?

p.42, Table 37 and p.43, Table 39. The tables are confusing because units are not presented clearly. The tables may need to be separated into two tables.

p.46. Section of The Energy Efficiency in 2012. While extrapolation from 1996 to 2000 is done in the report with data support, the extrapolation from 2000 to 2012 is speculative. The report needs to acknowledge this.

p.46, 3rd pp. I did not see discussion of the decrease in energy use for nitrogen production by 5% between 1987 and 1999. Besides, I would expect that the decrease during this period was more than 5%. Furthermore, the 5% reduction between 2000 and 2010 needs some support.

p.51, 1st pp. The assumption of same energy use between 2000 and 2012 for dry mills is questionable. You may need to contact ethanol plant designers such as Phil Madson for some insights. Also, did you use the ethanol yield of 2.8 gallons per bushel for 2012?

p.53, the last pp. and Table 51 on p.54. The conclusion is not definitive. First, we do not know if ethanol will replace gasoline or MTBE. Second, even if we assume that ethanol will displace gasoline, we do not know if ethanol will displace imported oil.

p.55, the section on Discussion and Conclusions. The net energy of 7.4 for corn production does not have much meaning. The net energy of 1.2 for ethanol production stage is less meaningful. The net energy ratio of 1.44 in 2012 is repeated in the 4th pp.

The conclusions regarding petroleum displacement and imported oil reduction are speculative. This section needs to be rewritten completely.

p.56, 2nd pp. and Table A1-1. Some electricity may be consumed by other non-retail channels. The estimated loss of 13% is too high because of this reason.

p.57, 3rd pp. “Beyond EPA, no other references reporting conversion efficiencies of crude oil to various refined products were found.” The GREET model has a table to present the exact information you are looking for.

p.58, Table A2-2. Steam from waste has an efficiency of 100%. Can you explain this more?

p.71, Table A5-2. The approach of using Btu/$ and $/lb for estimating energy use for manufacturing equipment is very crude. A better approach is to get data on energy requirement for manufacturing major equipments (such as tractors).

David Andress, USDOE May 13, 2002

Overall, this is a very good report. The amount of detail is extraordinary. The Pimentel rebuttal is good, and the calculation of the capital energy contribution puts that question to rest.

The key place the report could be improved is the executive summary, which is somewhat terse and could be confusing to a non-technical reader. The main text is excellent, so it is just a matter of borrowing from it could easily beef up the executive summary. A table or two would also help. The format in Table A3-2 would be perfect.

One major result of this study is that the energy balances for wet and dry differ significantly. This was not the case in the 1995 USDA study or in the GREET analysis. I think this is an important conclusion that should be included in the executive study and conclusion section.

In stating the main conclusions and in the key summary tables, I suggest qualifying the energy as Afossil@ energy. Admittedly, this is in the title of the report and the first line of the executive summary states Athe main purpose of this analysis is to quantify the total fossil energy and petroleum energy used to produce ethanol from corn@, but this is apt to get lost and in Asound bites@.

My guess is that Pimentel did not make a distinction between fossil and non fossil inputs for electricity generation in his analysis, which is another factor that may account for Pimentel=s high estimate. (Not a major factor, but a factor.) The USDA analysis assumed all electricity was generated by coal.

Mike=s paper calculates the fossil energy balance. However, some people may take the position that it is the total, not just the fossil, energy inputs are important. Basically, this

> means counting all the electrical energy inputs, not just the fossil share. One can make an argument that nuclear, at least, should be included in the energy balance calculation, since uranium, with the once-through cycle, is a depletable resource. On the other hand, one can argue that the key concern is fossil fuel usage. Take your choice. The only point I want to make here is that it is a factor when comparing different studies.
>
> We can calculate the impact of using the total electricity heating values, i.e., without discounting for the non fossil portion, by adding the non fossil electrical BTUs to the fossil energy calculations in Mike=s report. The report used 8,432 BTUs / kWh for fossil electricity, which includes T&D losses. The fossil share of electricity generation is around 70% nationwide. Therefore, the non fossil BTUs are 3,614 per KWh. To illustrate the impact for wet mills, the worse case, note that 1.89 (Table 32) kWh of electricity are used for each gallon of ethanol. The non fossil electricity accounts for an extra 6,830 BTUs, enough to make the net energy balance from wet mills negative **B** 80,279 BTUs in versus 76,000 BTUs out.

The report uses the term net energy ratio to represent the ratio of the output BTUs (BTUs in the product) to the input BTUs. In other papers, this is referred to as the energy ratio. The term net energy is used to denote the energy gain or loss, i.e., the BTUs ethanol minus the input BTU. In this context, the net energy ratio would be the energy ratio minus one.

Provide the technical distinction between HHV and LHV, i.e., the non useful energy dissipated as water vapor.

The report calculates three energy values, but it is really only the total energy values that are important for energy balances. Suggest stating this up front and in the executive summary, to guide the non technical reader. Moreover, it is not clear why the HHVs are presented. The text notes they are related to costs, but does not pursue this further. Are they calculated for comparison to other studies? In that case, the relevant measure would be total HHV.

Executive Summary
(Italics for Report)

The analysis considers current wet and dry mills as a baseline, *****AND***** *examines the incremental efficiency of plant capacity being added and projects industry performance in 2012 when the corn to ethanol industry has grown to 5 billion gallons per year.*

The energy inputs were divided into Avariable@, that is actual input per unit of production and Acapital@ that is prorated energy from equipment over production during the useful life.

Suggest redoing this statement to reflect the study=s conclusion, i.e., that the capital energy inputs are minor (1%). The study concentrated on the variable energy and the capital energy calculation was relegated to an Appendix. Moreover, it is not clear that the small capital BTU inputs are included in the energy ratios. The text does not show this to be the case, but the statements in the Executive Summary imply that it is.

The report should explain why the following is important:

The net energy ratio for corn production in 2000 on a primary HHV basis is about 7.4.

Why are the above results expressed in terms of HHV, when the key concern is total energy (LHV in the report); all other conclusions in the Executive Summary are expressed in terms of total LHV? Provide the reader some guidance about the significance of the above statement in both the Executive Summary and the text.

Each barrel of ethanol produced directly takes the place of 0.674 barrels of crude equal to the output of two world scale refineries. oil imports and adds about 214,000 barrels per day of gasoline supply, ...

Reword. As it currently reads: Each barrel of ethanol produced ... adds about 214,000 barrels per day of gasoline supply ...

Also, the 214,000 barrels have to be put into context for the reader, i.e., how much ethanol does this correspond to. (Page 55 also)

Main Text

Suggest adding Atotal LHV@ to Table 1. Also adding HHV and LHV for ethanol.

Page 10. Suggest adding the results of this study to Table 2. This would be very helpful to the reader. Also, suggest including a column for the energy ratio and one for total energy used for corn production and transport.

Table 51 on Page 54.

I could not follow the logic and calculation in this table. The text references Appendix 2 for efficiency data, and I could not match the data in Table A2-2 to this data (see comment on Page 58 below) to get the refining loss. The Abarrels COE avoided / barrel COE ethanol@ ratio appears to be the ratio of the Agasoline energy + refinery loss@ to the Agasoline energy@ or the ratio of the BTUs input to the BTUs output for gasoline, which is independent of the amount of petroleum used in ethanol production. I suggest redoing the table on a BTU basis, since this would probably easier for the reader to understand. Although using COE barrel or gallon is equivalent to a BTU basis, the non technical reader will find it more difficult because it involves an adjusted volume concept.

The LHV of gasoline in Table 51 is 112,925 BTUs, as opposed to 116,515 used in other tables.

To illustrate what I think the calculation should be. GREET estimates 1.09 BTUs of oil input for each BTU of gasoline and 0.09 BTUs input for each BTU of ethanol. Therefore, one BTU of ethanol displaces 1.0 BTU of oil (1.09 - 0.09).

Using what I think is the data in Table 51. 1.179 BTUs of oil (assuming all refinery loss is oil) are input for each BTU of gasoline, and 0.074 BTUs of oil are input for each BTU of ethanol. Therefore, each BTU of ethanol replaces 1.125 BTUs of oil.

Note: the report calculates oil displacement on a BTU basis, but does not calculate fossil displacement.

Page 56 Electricity Data

Most of the report uses very detailed state-level data. The percent of electricity that is fossil based is a notable exception. The following table presents this information for the ethanol producing regions, from the EIA Electric Power Annual 2000 Volume I.

Million kWhr for 2000

	Total	coal	pet	gas	nuclear	hydro	other	fossil
ENC	617	442	3	26	137	4	5	471
WNC	285	215	2	8	45	12	3	225
ENC +WNC	902	657	5	34	182	16	8	696

Fossil is sum of coal, petroleum and gas. Fossil percent is 77%. This is greater than the 70.7% nationwide fossil percent used in the report.

ENC -- East North Central
  Illinois
  Indiana
  Michigan
  Ohio
  Wisconsin
WNC -- West North Central
  Iowa
  Kansas
  Minnesota
  Missouri
  Nebraska
  North Dakota
  South Dakota.

Page 57

Part of Footnote 82 on page 57 belongs with Footnote 84

Page 58

Using individual process efficiency data, an independent and very rough estimate of the gasoline conversion efficiency was near 88%, somewhat greater than EPA=s 81.6%.

Table A2-2 Extraction/Processing Thermal efficiencies per BTU of Energy

	BTU In /BTU Out	*Source*	*Step*
Crude with vent gas	*1.073*		*Recovery and transport*
Coal	*1.038*	*Oil*	*Mine and transport*
Fuel oil	*1.000*	*Crude*	*refining*
Diesel oil	*1.053*	*Crude*	*refining*
Gasoline	*1.225*	*Crude*	*refining*
Natural Gas	*1.112*	*Gas*	*recovery, transport*
LPG	*1.112*	*Gas*	*recovery, transport*
Steam	*1.000*	*Waste*	*Assume heat recovery*

Title of the table should be energy ratios not efficiencies, as they are the inverse of the efficiencies. The sentence above the table is confusing. It implies that the gasoline conversion efficiency of 88% is used for gasoline, but the energy ratio of 1.225 in the Table A2-2 corresponds to the EPA 81.6% conversion ratio.

It appears the thermal efficiencies (or energy ratios) are all fossil inputs, not just petroleum. However, the crude oil savings calculation on page 54 references the data in this table. Suggest showing both the fossil and oil inputs for gasoline.

From Table 22 below, I added the Aratio@ column to get the multipliers used in the report. Suggest that Table A2-2 should show consistent thermal numbers.

Table 22 Energy Inputs to Potash Mining,

			HHV	LHV	total LHV	ratio
NG	CF					111%
Gasoline	Gal	196.266				131%
Diesel	Gal					113%
Fuel Oil	Gal					113%
LPG	Gal	779.518				111%
Power	Kwh					106%
						109%

I think combining the crude and refinery thermal efficiencies in Table A2-2 should do it.

Table A2-2

	BTU In /BTU Out	Source	Step	BTU in / BTU out with crude
Crude with vent	1.073		Recovery and transport	
Coal	1.038	Oil	Mine and transport	
Fuel oil	1	Crude	refining	1.073
Diesel oil	1.053	Crude	refining	1.129869
Gasoline	1.225	Crude	refining	1.314425
Natural Gas	1.112	Gas	recovery, transport	
LPG	1.112	Gas	recovery, transport	
Steam	1	Waste	Assume heat recovery	

John Sheehan National Renewable Energy Laboratory June 1, 2002

Included in this note are general comments on the draft study prepared by Dr. Michael Graboski for the National Corn Growers Assoication. I am also providing an electronic copy of the full report with specific, more detailed, comments inserted throughout the report.

Positive aspects of the study

The purpose of peer review is typically to provide criticisms and identify areas for improvement. But I think it is worthwhile taking a little time up front to point out the positive contributions that this report will make in the debate on renewable energy. In fact, I would argue that the report does not do enough to point these out.

Greater rigor in system definition and handling of coproducts

By far the greatest contribution this study makes is its choice of the system boundaries for ethanol production. By including both the animal feed and fuel ethanol end uses in the calculation of the net energy of fuel ethanol, the study addresses the Achilles heel of all previous analyses for corn ethanol. These previous studies use “allocation formulas” to arbitrarily remove some of the energy burden from the corn ethanol system. This study looks at the net energy consumed by the combination of animal feed production and ethanol production by allowing coproducts from ethanol production to displace existing supplies of animal feed on an equivalent nutritional basis. These kind of “displacement” calculations are now the preferred approach in the field of life cycle analysis.

Capital energy impacts

I’m glad to see the analysis of farm and other equipment manufacture in this study. I, for one, typically ignore it. At least now I can point to an analysis that quantifies the relative impact of equipment.

The study builds on industry data for ethanol production

The report complements the earlier 1995 study Mike Graboski conducted with USDA on the net energy balance of corn ethanol as a motor fuel. The earlier study took an approach dominated more by material and energy balance calculations. This study relies more on survey data from the industry to fill in more detail on the performance of corn ethanol facilities. Taken together, the 1995 study and this new analysis provide a very comprehensive energy analysis of corn ethanol.

Major improvements in the characterization of the farm

The report uses the most up to date statistics from USDA to estimate energy use on the farm. I particularly like the analysis done for seed production and its impact. Seed production has often been estimated in the past by simply assuming a percentage of the total corn production impacts.

Fertilizer characterization is the best I've seen yet

Nitrogen fertilizer is the biggest contributor to corn production's energy budget. This study provides the best analysis of what fertilizers are used, how they are produced, and where they are produced today. The analysis of transport tied specifically to locations of current production facilities adds a new level of rigor.

Areas for Improvement

Most of my comments for changes or improvement can be found in the electronic copy of the report that I am including with this critique. Here, I lay out some general concerns, many of which show up as specific examples in the annotated version of the report.

Provide more background on previous studies

This study really improves a lot on previous studies. It would be worthwhile to spend more time discussing how the various studies cited at the beginning of the report relate to this one in terms of completeness and/or approach. Otherwise, one is left with the impression that this and all other efforts to understand the energy balance are meaningless since the numbers you show point out that anyone can get any answer they want.

Net energy ratios

Net energy ratio should be more explicitly defined. For example, some folks might not get that a ratio of 1.32 is a good thing! Explain that this means that we get 32% more energy out than we have to put in as fossil energy to make the fuel.

The ratio of 7.4 for corn production needs more explanation, or perhaps needs to be removed from the study all together. Including it in the executive summary without a clearer explanation is especially problematic. If I understand it right, this ratio reflects the heat of combustion for corn to the total fossil energy inputted to make the corn. I question the usefulness of this number, and definitely think that many people will misuse or misunderstand it.

Energy terminology

I like the use of the HHV, LHV and tLHV terminology, but it is not applied explicitly enough throughout the report. Terminology such as "the energy in chemicals" or "embodied energy" are confusing. The former term I mistook initially to mean that the energy impact of farm chemicals was estimated by the heat of combustion of the chemicals. I take it that this is not the case. If it is, I have concerns about that.

thermal and electrical inputs Many of the worksheet tables presented to show how calculations were done (particularly the ones related to custom operations on the farm) are very hard to follow.

Sustainable agriculture issues

In several places of the report, there are discussions of corn farming's sustainability. I think most of these discussions are unnecessary, especially the ones related to soil erosion. Sustainability is a very complex issue. This report has a very narrow focus on energy use, which is only one (and perhaps the simplest) aspect of sustainable agriculture. The comment that really bothered me was the statement on page 8: "It is hard to envision that corn production is not sustainable in light of these dramatic gains in yield." It's a bit of a non sequitur at best. Increasing yields is not evidence of sustainability. Such statements will only take away from the impression of objectivity that the study deserves.

As far as the discussions of tilling practices and soil erosion go, I think these discussions should be limited as much as possible to the energy implications associated with them. I have spent the past year and a half looking at both soil carbon and soil erosion effects of various tilling practices as part of our study on stover use for ethanol, and I can tell you that even the definitions of tilling practices are vague and misunderstood. Let alone making claims about what their impacts or benefits are.

Oil displacement assumptions

When you describe crude oil savings, you always talk in terms of oil imports. I'm not at all comfortable with the implicit assumption you are making that all oil savings will come from foreign supply.

USDA COMMENTS

The Fossil Energy Use in the Manufacture of Corn Ethanol report by Michael Graboski is a very detailed report on net energy balance of corn ethanol. The paper attempts to show that the net energy value (NEV) of corn ethanol was positive in 2000, and that the NEV will increase over time.

The paper includes a good detailed description of the corn ethanol production process, but in general, there is nothing new in the paper and the methodology is questionable. Major problems with report include: 1) the author uses data and analysis from upcoming USDA report without citation; 2) the author says that the USDA data is from the Farm Cost and Returns Survey when it is actually from the Agricultural Resource Management Survey (ARMS); 3) the methods used to generate 2000 data produce very unreliable estimates; 4) it is inappropriate to combine data on corn production from the ARMS with corn data from other National Agricultural Statistics Service (NASS) surveys because data for each NASS survey is collected from different samples for different purposes and there are definitional differences among the surveys; and 5) invalid assumptions, based on 1996 weather conditions, are used to characterize the 2000 corn crop. Specific comments are provided below:

- The 9-State weighted average corn yields in 1996 and 2000 were 128 and 140 bushels per acre respectively. Diesel consumption per acre is directly related to corn yield, therefore, using 1996 energy inputs for corn production in 2000 underestimates energy use per acre and per bushel of corn.

- ARMS data are used to estimate quantities of fuel used in corn production per acre. Energy inputs used on the farm includes fuel used to transport corn from the farm to first point of sale or storage. In addition, when farmers deliver corn directly to ethanol plants, the fuel use is included in the ARMS fuel estimates. Thus, the report double counts inputs used in corn transport, resulting in an overestimation of the energy used to haul corn from farm to ethanol plants.

- Weather was unusual in 1996, wet during the planting season and wet during the harvest season. As a result, a large amount of energy was used to remove excess moisture from corn. The 2000 crop year was a fairly normal year, so using 1996 data to represent the 2000 corn crop over estimates the energy used in corn production in 2000.

- Energy inputs used in corn production such as gasoline, diesel, natural gas, electricity, etc. are the most critical data in estimating the net energy balance for corn ethanol. These data are from the ARMS and are not published, however, through a special request to the Economic Research Service (ERS), the 1991 and 1996 estimates were provided to the Office of Energy Policy and New Uses (OEPNU). The 1991 estimates were reported in the 1995 ERS report *Estimating the Net Energy Balance of Corn Ethanol* by Shapouri, Duffield, and Graboski. The 1996 estimates will soon be released by the Office of the Chief Economist in a report called *Update On The* Energy Balance of Corn Ethanol by Shapouri, Duffield, and Wang. A summary of this report was presented at the 7th Annual National Ethanol Conference: Policy & Marketing, San Diego, California, February 27 – March 1, 2002. Graboski used the 1996 fuel estimates presented in San Diego in his report, but fails to reference the work by Shapouri, Duffield, and Wang. In addition, Graboski's description on page 4 on how ERS estimates fuel used by farmers is incorrect.

- The OEPNU will release its latest report on the net energy value of corn ethanol in June using data from the 1996 ARMS. We believe that using actual survey data for 1996 is far superior than the 2000 data generated by Graboski. Dr Graboski generates the 2000 ARMS data, which is not yet available, using other data from NASS collected in 2000 on corn production, yield per acre, planted and harvested acreage, fertilizer use, and chemical use. His estimates are based on a combination of past work done by USDA and the latest estimates from the San Diego presentation to derive 2000 estimates. Without complete data for 2000, Graboski had to make numerous assumptions about energy inputs used by farmers, with little basis or justification. The various calculations used in the paper to estimate the energy used by corn farmers in 2000 are subject to a large amount of error and uncertainty, resulting in unreliable estimates. For example, in 1996, in IA, Il, IN, SD, MI, more than 80 percent of corn crop was dried by farmers – the amount of moisture removed from 1996 corn crop for the above States ranged from 5 to 7 percent. USDA did not report the moisture removed from the 2000 corn crop, so there is no way of knowing the energy required for drying.

$ Energy used to convert corn to ethanol by wet mill is overestimated in the report. Based on the 2001 USDA survey of ethanol plants, wet mill ethanol plants participating in the survey used an average 51,060 Btu of coal and natural gas to produce the steam and electricity used in the plants. After adjusting for energy losses to produce coal, natural gas and electricity, on average, a wet mill ethanol plant used 54,239 (HHV) Btu of total energy to make a gallon of ethanol.

$ Energy allocated to byproduct credits for the wet mill is underestimated in the report when it is compared with byproduct credits for dy mill. In the USDA study byproduct credits for wet mill per gallon of ethanol is higher than dry mill. In the report by Graboski there are more energy credits assigned to dry mill and less to wet mill. This difference could be related the assumptions on the weight of byproducts for dry and wet mill (17.98 pounds of DDG versus16.94 pounds of CGF, CGM and corn oil) and the procedures Graboski used to allocate total energy used to produce corn, transport corn to ethanol plants, and convert corn to ethanol and byproducts.

The ARMS for corn is conducted every 5 years and the data from the 2001 survey will be available next year. The OEPNU plans to ask ERS to provide them with the detailed ARMS data as soon as it becomes available, so they can update the USDA net energy balance report. With the completion of the 2001 survey, there will be 3 data points, 1991, 1996 and 2001 to measure the net energy balance of corn ethanol over time. Ideally the data would be available every year, but the ARMS is conducted for just one crop each year in order to collect detailed data on individual crops. The ARMS provides a very unique data set for corn production every five years and annual estimates cannot be approximated with any degree of accuracy by extrapolating proxy data. Thus, even when the actual ARMS data is a few years old, it is still preferable to using estimates that have been manipulated to approximate newer data.

While the paper provides descriptive detail that is not found in past reports, the basic results are nothing new. Since1990, eight studies (including three from USDA) have shown that the net energy value of corn ethanol is positive. Much of the information found in this report duplicates past USDA studies, so the results were not surprising.