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Ethanol Production: Energy, Economic, and Environmental Losses

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Contents

I. Introduction 25
II. Corn Use in Ethanol Production 26
A. Energy Inputs in Corn Production 26
B. Energy Inputs in Fermentation/Distillation 28
C. Net Energy Yield 29
D. Economic Costs 29
E. Cornland Use 30
F. By-Products 30
G. Sugarcane Use in Ethanol Production 31
III. Ecological Issues 31
A. Cropland Use 31
B. Environmental Impacts 32
C. Negative or Positive Energy Return? 33
D. Food Security 34
E. Food versus Fuel Issue 35
Summary 35
Acknowledgments 36
References 37

I. Introduction

The supply of "conventional" oil is projected to peak before 2010, and its decline thereafter cannot be compensated fully by other liquid fuels (Youngquist and Duncan 2003). The United States critically needs to develop liquid fuel replacements for oil in the near future. The search for alternative liquid fuels has focused on the use of biomass.

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Biomass is green plant material, such as corn, soybeans, sugarcane, and trees. All kinds of biomass convert solar energy into plant material, but this conversion requires suitable soil, nutrients, and freshwater. Then, in the conversion of the biomass into liquid fuel, water, microorganisms, and more energy are required. Andrew Ferguson (2004) makes an astute observation that the proportion of the sun's energy that is converted into useful ethanol, even using very positive energy data, only amounts to 1 part per 1,000, or 0.1% of the solar energy.

Two early studies by the U.S. Department of Energy (USDOE) concerning ethanol production using corn for liquid fuels from biomass reported a negative energy return (ERAB 1980, 1981). These reports were reviewed by 26 expert U.S. scientists independent of the USDOE; their findings concluded that the conversion of corn into ethanol energy was negative, and these findings were unanimously approved. Since then, other investigations have confirmed these earlier findings (Pimentel and Patzek 2005).

In this analysis, the most recent scientific data for corn production and for fermentation/distillation were used. All current fossil energy inputs used in corn production and for the fermentation/distillation were included to determine the entire energy cost of ethanol production. Additional costs to consumers include federal and state subsidies, plus costs associated with environmental pollution and/or degradation that occur during the entire production process. Economic and human food supply issues are discussed. In addition, studies that contrast with the conclusion of this study are evaluated.

II. Corn Use in Ethanol Production

A. Energy Inputs in Corn Production

The conversion of corn and other food/feed crops into ethanol by fermentation is a well-known and established technology. The ethanol yield from a large production plant is about 1 L ethanol from 2.69 kg corn grain (Pimentel and Patzek 2005).

The production of corn in the U.S. requires a significant energy and dollar investment for the 14 inputs, including labor, farm machinery, fertilizers, irrigation, pesticides, and electricity (Table 1). To produce an average corn yield of 8,781 kg/ha [140 bushels/acre (bu/ac)] using up-to-date production technologies requires the expenditure of about 7.5 million kcal energy input, mostly oil and natural gas, as listed in Table 1; this is the equivalent of about 854 L oil equivalents expended per hectare of corn. The production costs total about $892/ha for the 8,781 kg/ha or approximately $0.10/kg ($2.58/ bu) of corn produced.

Full irrigation, when there is insufficient or no rainfall, requires about 100 cm water per growing season. Because only about 15% of U.S. corn

Table 1. Energy inputs and costs of corn production per hectare in the United States.

Inputs	Quantity	kcal ×1,000	Costs ($)
Labor	11.4 hr[a]	462[b]	148.20[c]
Machinery	18 kg[d]	333[e]	68.00[f]
Diesel	88 L[g]	1,003[h]	34.76
Gasoline	40 L[i]	405[j]	20.80
Nitrogen	155 kg[k]	2,480[l]	85.25[m]
Phosphorus	79 kg[n]	328[o]	48.98[p]
Potassium	84 kg[q]	274[r]	26.04[s]
Lime	1,120 kg[t]	315[u]	19.80
Seeds	21 kg[v]	520[w]	74.81[x]
Irrigation	8.1 cm[y]	320[z]	123.00[aa]
Herbicides	6.2 kg[bb]	620[cc]	124.00
Insecticides	2.8 kg[dd]	280[cc]	56.00
Electricity	13.2 kWh[ee]	34[ff]	0.92
Transport	204 kg[gg]	169[hh]	61.20
Total		7,543	891.76
Corn yield 8,781 kg/ha[ii]		31,612 (kcal input : output, 1 : 4.19)	

[a]NASS (2003).
[b]It is assumed that a person works 2000 hr/yr and utilizes an average of 8000 L oil equivalents/yr.
[c]It is assumed that labor is paid $13/hr.
[d]Energy costs for farm machinery that was obtained from agricultural engineers: tractors, harvesters, plows, and other equipment that last about 10 years and are used on 160 ha/yr. These data were prorated per year per hectare (Pimentel and Patzek 2005).
[e]Prorated per hectare and 10-yr life of the machinery. Tractors weigh about 10 t and harvesters about 10 t (International Harvester 2006), plus plows, sprayers, and other equipment.
[f]Hoffman et al. (1994).
[g]Wilcke and Chaplin (2000).
[h]Input 11,400 kcal/L.
[i]Estimated.
[j]Input 10,125 kcal/L.
[k]NASS (2003).
[l]Patzek (2004).
[m]Cost $0.55/kg.
[n]NASS (2003).
[o]Input 4,154 kcal/kg.
[p]Cost $0.62/kg.
[q]NASS (2003).
[r]Input 3,260 kcal/kg.
[s]Cost $0.31/kg.
[t]Brees (2004).
[u]Input 281 kcal/kg.
[v]Pimentel and Pimentel (1996).
[w]Pimentel and Pimentel (1996).
[x]USDA (1997b).
[y]USDA (1997a).
[z]Batty and Keller (1980).
[aa]Irrigation for 100 cm water/ha costs $1,000 (Larsen et al. 2002).
[bb]Larson and Cardwell (1999).
[cc]Input 100,000 kcal/kg of herbicide and insecticide.
[dd]USDA (2002).
[ee]USDA (1991).
[ff]Input 860 kcal/kWhr; requires 3 kWhr thermal energy to produce 1 kWhr electricity.
[gg]Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km.
[hh]Input 0.83 kcal/kg/km transported.
[ii]USCB (2004–2005). There is a need to look at average crop yield over 3–5 years, not record peak years, as a base for fuel policy decisions.

production currently is irrigated (USDA 1997a), only 8.1 cm/ha of irrigation was included for the growing season. On average, irrigation water is pumped from a depth of 100 m (USDA 1997a). On this basis, the average energy input associated with irrigation is 320,000 kcal/ha (see Table 1).

B. Energy Inputs in Fermentation/Distillation

The average costs in terms of energy and dollars for a large (245–285 million L/yr) modern ethanol plant are listed in Table 2. In the fermentation/distillation process, the corn is finely ground and approximately 15 L water is added per 2.69 kg ground corn. After fermentation, to obtain 1 L 95% pure ethanol from the mixture of 8% ethanol and 92% water, 1 L ethanol must be extracted from the approximately 13 L of the ethanol/water mixture.

Table 2. Inputs per 1,000 L 99.5% ethanol produced from corn.[a]

Inputs	Quantity	kcal ×1,000	Cost ($)
Corn grain	2,690 kg[b]	2,314[b]	273.62
Corn transport	2,690 kg[b]	322[c]	21.40[d]
Water	15,000 L[e]	90[f]	21.16[g]
Stainless steel	3 kg[i]	165[p]	10.60[d]
Steel	4 kg[i]	92[p]	10.60[d]
Cement	8 kg[i]	384[p]	10.60[d]
Steam	2,546,000 kcal[j]	2,546[j]	21.16[k]
Electricity	392 kWhr[j]	1,011[j]	27.44[l]
95% ethanol to 99.5%	9 kcal/L[m]	9[m]	0.60
Sewage effluent	20 kg BOD[n]	69[h]	6.00
Distribution	331 kcal/L[q]	331	20.00[q]
Total		7,333	423.18

BOD, biological oxygen demand.
[a]Output: 1 L of ethanol = 5,130 kcal.
[b]Data from Table 1.
[c]Calculated for 144 km round trip.
[d]Pimentel (2003).
[e]15 L water mixed with each kilogram grain.
[f]Pimentel et al. (2004b).
[g]Pimentel et al. (2004b).
[h]4 kWhr energy required to process 1 kg BOD (Blais et al. 1995).
[i]Estimated.
[j]Illinois Corn (2004).
[k]Calculated based on the price of natural gas.
[l]$0.07/kWhr (USCB 2004–2005).
[m]95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, personal communication, University of California, Berkeley, 2004).
[n]20 kg BOD/1,000 L ethanol produced (Kuby et al. 1984).
[p]Newton (2001).
[q]DOE (2002).

Although ethanol boils at about 78°C and water boils at 100°C, the ethanol is not extracted from the water in just one distillation, which obtains 95% pure ethanol (Maiorella 1985; Wereko-Brobby and Hagan 1996; S. Lamberson, personal communication, Cornell University, 2000). To be mixed with gasoline, the 95% ethanol must be further processed and more water removed, requiring additional fossil energy input to achieve 99.5% pure ethanol (Table 2). Thus, a total of about 12 L wastewater must be removed per 1 L ethanol produced, and this relatively large amount of sewage effluent must be disposed of at an energy, economic, and environmental cost.

To produce a liter of 99.5% ethanol uses 43% more fossil energy than the energy produced as ethanol and costs $0.42/L($1.59/gal) (see Table 2). The corn feedstock requires more than 33% of the total energy input. In Table 2, which presents distillation/fermentation processes, the corn grain and transport inputs account for 36% of the total energy spent, and the remaining energy input is 64%. In this analysis, the total cost, including the energy inputs for the fermentation/distillation process and the apportioned energy costs of the stainless steel tanks and other industrial materials, is $423.18/1,000 L ethanol produced (Table 2).

C. Net Energy Yield

The largest energy inputs in corn-ethanol production are for producing the corn feedstock, plus the steam energy and electricity used in the fermentation/ distillation process. The total energy input to produce 1 L ethanol is 7,333 kcal (Table 2). However, 1 L ethanol has an energy value of only 5,130 kcal. Based on a net energy loss of 2,203 kcal ethanol produced, 43% more fossil energy is expended than is produced as ethanol. The energy deficit might be reduced if ethanol producers were able to provide the low-pressure steam required for distillation from cogeneration power facilities or from solar thermal inputs.

D. Economic Costs

Current ethanol production technology uses more fossil fuel and costs substantially more to produce in dollars than its energy value is worth on the market. Clearly, without the more than $3 billion federal and state government yearly subsidies, U.S. ethanol production would be reduced or cease, confirming the basic fact that ethanol production is uneconomical (National Center for Policy Analysis 2002).

Federal and state subsidies for ethanol production that total more than $7 per bushel of corn are mainly paid to large corporations (McCain 2003), while corn farmers are receiving a maximum of only an added $0.02 per bushel for their corn ($6.90/ha or $2.80/A) in the subsidized corn ethanol production system (Pimentel and Patzek 2005). Senator McCain reports that direct subsidies for ethanol, plus the subsidies for corn grain, amount to $0.79/L (McCain 2003).

If the production costs of a liter of ethanol were added to the tax subsidy cost, then the total cost per liter of ethanol would be $1.21. Because of the relatively low energy content of ethanol, 1.6 L ethanol has the energy equivalent of 1 L gasoline. Thus, the cost of producing an equivalent amount of ethanol equal to 1 L gasoline is $1.94 ($7.32/gal gasoline); this is more than $0.53/L, the current cost of producing 1 L gasoline.

Unfortunately, the costs to the American consumer are greater than the $8.4 billion/yr expended to subsidize corn ethanol because diverting the required corn feedstock from livestock increases corn prices for livestock producers. The National Center for Policy Analysis (2002) estimate is that ethanol production is adding more than $1 billion/yr to the cost of beef production for consumers. Given that about 70% of the current corn grain harvest is fed to U.S. livestock (USDA 2003), doubling or tripling ethanol production can be expected to increase corn prices further for beef production and for other livestock products, including milk and eggs, and ultimately to increase costs to the consumer. Therefore, in addition to paying the $8.4 billion in taxes for ethanol and corn subsidies, consumers are expected to face significantly higher meat, milk, and egg prices in the marketplace.

E. Cornland Use

Currently, about 17.0 billion L ethanol (4.5 billion gal) is produced in the U.S. each year (DOE 2005). The total liquid fuels used in the U.S. were about 1,200 billion L in 2003 (Pimentel et al. 2004a; USCB 2004–2005). Therefore, 17.0 billion L ethanol (energy equivalent to 11.2 billion L vehicle liquid fuel) provides only 1% of the liquid fuel utilized by the U.S. each year. To produce this 17.0 billion L ethanol, about 5.1 million ha or 18% of U.S. corn is used. Expanding corn-ethanol production to 100% of U.S. corn production would provide just 6% of the liquid fuel of the U.S.

F. By-Products

The energy and dollar costs of producing ethanol can be offset partially by by-products, such as the dry distillers grains (DDG) made from dry-milling of corn. From about 10 kg corn feedstock, about 3.3 kg DDG with 27% protein content can be harvested (Stanton 1999). This DDG is suitable for feeding cattle, which are ruminants, but has only limited value for feeding hogs and chickens. In practice, this DDG is generally used as a substitute for soybean feed, which contains 49% protein (Stanton 1999). However, soybean production for livestock feed is more energy efficient than corn production because little or no nitrogen fertilizer is needed for the production of this legume (Pimentel et al. 2002). In practice, only 2.1 kg soybean protein provides the equivalent nutrient value of 3.3 kg DDG. Thus, the credit fossil energy/L ethanol produced is about 445 kcal (Pimentel et al. 2002). Factoring this credit for a nonfuel source into the production of ethanol reduces the negative energy balance for ethanol production from 43% to 28% (see Table 2). The high energy credits for DDG given by some are unrealistic because the production of livestock feed from ethanol is uneconomical given the high costs of fossil energy plus the costs of soil depletion to the farmer (Patzek 2004). The resulting overall energy output–input comparison remains negative even with the credits for the DDG by-product.

G. Sugarcane Use in Ethanol Production

Proponents of ethanol point to the production of ethanol in Brazil, which currently is the largest producer of ethanol in the world. Brazil uses sugarcane to produce ethanol, and sugarcane is a more efficient feedstock for ethanol production than corn grain (Pimentel and Pimentel 1996). However, because the energy balance is negative, the Brazilians subsidize their ethanol industry. Initially the government was selling ethanol to the public for \$0.22/L, but it cost the government \$0.33/L to produce (Pimentel 2003). Because of other economic priorities in Brazil, the government has abandoned directly subsidizing ethanol (Spirits Low 1999; Coelho et al. 2001). The ethanol industry is still being subsidized, but the consumer is paying this subsidy directly at the pump (Pimentel 2003). The subsidy is estimated to be about 50% for ethanol production (CIA 2005). In addition, there are serious ecological concerns related to ethanol production in Brazil, which include the removal of mature forests for more sugarcane plantations and increased soil erosion associated with the culture of sugarcane (Azar et al. 2006).

III. Ecological Issues

A. Cropland Use

When considering the advisability of producing sufficient ethanol for automobiles, the availability of cropland required to grow sufficient corn to fuel each automobile is critical. For the sake of argument we use Shapouri's (Shapouri et al. 2002, 2004) optimistic suggestion that all natural gas and electricity inputs be ignored and only gasoline and diesel fuel inputs be assessed. Based on Shapouri's input–output data, 2,929 L ethanol is produced/corn ha. When equated to gasoline, this ethanol has the same energy as 1,890 L gasoline. An average U.S. automobile travels more than 10,000 miles/yr and uses about 1,890 L gasoline/yr (USCB 2004–2005). To replace this gasoline usage with ethanol, about 1 ha corn would have to be grown. Consider that at present 0.5 ha U.S. cropland is used to feed each person a diverse and nutritious diet (USCB 2004–2005). Therefore, even using Shapouri's optimistic energy accounting data, to fuel one automobile with ethanol, as a substitute for the yearly use of gasoline for 1 yr, two times more cropland would be required for corn production and ethanol production than now is required to feed one person!

Worldwide, for ethanol to replace gasoline, about 2.4 billion ha cropland planted to corn would be required, which represents 60% more cropland than exists in the world (A.R.B. Ferguson, personal communication, Optimum Population Trust, November 6, 2005).

B. Environmental Impacts

Some of the economic and energy contributions of the by-products are negated by the widespread environmental pollution problems associated with ethanol production. First, corn production causes more soil erosion than any other U.S. crop (Pimentel et al. 1995; NAS 2003). In addition, corn production uses more herbicides and insecticides and nitrogen fertilizer than any other crop produced in the U.S., and these chemicals may invade groundwater and surface water, thereby causing more water pollution than any other crop (NAS 2003).

As mentioned, the production of 1 L ethanol requires 1,700 L freshwater, both for corn production and for the fermentation/distillation processing of ethanol (Pimentel et al. 2004b). In some Western irrigated corn acreage, e.g., some regions of Arizona, groundwater is being pumped 10 times faster than the natural recharge of the aquifers (Pimentel et al. 2004b).

All these factors confirm that the environmental and agricultural system in which U.S. corn is being produced is experiencing major degradation. Further, it substantiates the conclusion that the U.S. corn production system, and indeed the entire ethanol production system, is not environmentally sustainable now or for the future, unless major changes are made in the cultivation of this major food/feed crop. Because corn is raw material for ethanol production, it cannot be considered a renewable energy source.

Furthermore, pollution problems associated with the production of ethanol at the chemical plant sites are emerging. The EPA (2002) already has issued warnings to ethanol plants to reduce their air pollution emissions or be shut down. Another pollution problem concerns the large amounts of wastewater produced by each ethanol plant. As noted, for each liter of ethanol produced using corn, about 12 L wastewater is produced. This polluting wastewater has a biological oxygen demand (BOD) of 18,000–37,000 mg/L depending of the type of plant (Kuby et al. 1984). The cost of processing this sewage in terms of energy (4 kWhr/kg BOD) was included in the cost of producing ethanol (see Table 2).

Reports confirm that ethanol use contributes to air pollution problems when burned in automobiles (Youngquist 1997; Hodge 2002, 2003, 2005; Niven 2005). The use of both fossil fuels and ethanol releases significant quantities of pollutants to the atmosphere. Furthermore, carbon dioxide emissions released from burning these fossil fuels contribute to global warming and are a serious concern (Schneider et al. 2002). When all the air pollutants associated with the entire ethanol production system are considered, the evidence confirms that ethanol production contributes to the already serious U.S. air pollution problem (Youngquist 1997; Pimentel and Patzek 2005). Investments to control these air pollution problems in the ethanol production plant are possible but will add to the significant production costs of ethanol.

C. Negative or Positive Energy Return?

Shapouri (Shapouri et al. 2004) of the USDA is now reporting a net energy positive return of 67%, whereas in this chapter, we report a negative 43% deficit. In their earlier report, Shapouri et al. (2002) reported a net energy positive return of 34%. Why did ethanol production net return for the USDA nearly double in 2 yr, while corn yields in the U.S. declined 6% during that period (USDA 2002, 2003)? The Shapouri results need to be examined and explained.

1. Shapouri et al. (2004) omit several inputs. For instance, all the energy required to produce and repair farm machinery and the fermentation-distillation equipment is not included. All corn production in the U.S. uses an abundance of farm machinery, including tractors, planters, sprayers, harvesters, and other equipment. These uses contribute substantial energy inputs in corn ethanol production, even when allocated on a life-cycle basis.
2. Shapouri et al. used corn data from only 9 states, compared to this analysis which includes corn data from 50 states most of which have ethanol plants.
3. Shapouri et al. reported a net energy return of 67% after including the co-products, primarily dried distillers grain (DDG) used to feed cattle. These co-products are not fuel! Giampietro et al. (1997) observed that although the by-product DDG may be considered as a positive output in the calculation of the output/input energy ratio in ethanol production, in a large-scale production of ethanol fuel, the DDG would be many times the commercial livestock feed needs each year in the U.S. (Giampietro et al. 1997). It follows then that in a large-scale biofuel production, the DDG could become a serious waste disposal problem and increase the energy costs.

Farrell et al. (2006) report a small positive energy return for corn ethanol but less than half that suggested by Shapouri et al. (2004). The Farrell et al. paper includes the following questionable assumptions:

1. By-products are not the same as “whole corn” for livestock feed.
2. An excessive energy value is allocated for the by-products that would be used to displace the cheaper, more nutritious soybean meal for livestock.

3. Labor of the farmer on the farm was not included.

4. Energy costs for farm machinery were greatly reduced without documentation. These inputs are substantial and were prorated per year per hectare (Pimentel and Patzek 2005).

5. Conservation tillage does save tractor fuel. However, the practice requires the use of significantly more hybrid corn seed, nitrogen fertilizer, herbicides, insecticides, and sometimes rodenticides and molluscicides. All these items require fossil energy for production and application.

6. The only environmental factor mentioned was global warming. Not considered were soil erosion, water use, insecticides, herbicides, and nitrogen fertilizer, which are serious environmental pollutants.

7. We note that Farrell in World Environment News (2006) is quoted saying that it is "possible to put ethanol in a car and run it, but making ethanol using current technology is expensive and contributes to pollution and greenhouse gases." This conclusion is opposite from that of Farrell et al. (2006).

8. In a press release (Jan. 16, 2006, UC Berkeley) one of the authors (Kammen) stated that ethanol could replace 20%–30% of fuel use in the U.S. The 17.0 billion L ethanol currently being produced is using 18% of all U.S. corn production; but this represents less than 1% of U.S. oil use. If 100% of U.S. corn were converted to ethanol it would provide only 6% of current U.S. vehicle fuel use.

In contrast to the USDA and Farrell et al. studies, numerous scientific studies have concluded that corn ethanol production does not provide a net energy balance, that ethanol is not a renewable energy source, and is not an economical fuel; furthermore, its production and use contribute to air, water, and soil pollution and to global warming (Ho 1989; Giampietro et al. 1997; Youngquist 1997; Pimentel 1998, 2001, 2003; NPRA 2002; Croysdale 2001; CalGasoline 2002; Lieberman 2002; Hodge 2002, 2003, 2005; Ferguson 2003, 2004; Patzek 2004; Pimentel and Patzek 2005; Brown 2005; Anthrop 2005; Transportation Research Board 2006; Hassett 2006).

Basically the major problem with corn and all other biomass crops is that they collect on average only 0.1%–0.2% of the solar energy per year. At a fairly typical gross yield of 3,000 L ethanol/ha/yr, the power density achieved is only 2.1 kW/ha, as compared with the gross power density achieved via oil, after delivery for use, which is of the order of 2,000 kw/ha. (A.R.B. Ferguson, personal communication, Optimum Population Trust, November 6, 2005). If all current 28 million ha of corn production were to be devoted only to growing corn for ethanol, this acreage would supply only about 6% of U.S. liquid fuel needs (USDA 2003).

D. Food Security

At present, world agricultural land supplies more than 99% of all world food calories, whereas aquatic ecosystems supply less than 1% (FAO 2001).

Worldwide, during the last decade, per capita available cropland decreased 20% and irrigation land 12% (Brown 1997). Furthermore, per capita grain production has been decreasing, in part due to increases in the world population (Worldwatch Institute 2001). Worldwide, diverse cereal grains, including corn, make up 80% of the food of the human food supply (Pimentel and Pimentel 1996).

The current food shortages throughout the world call attention to the importance of continuing U.S. exports of corn and other grains for human food. During the past 10 yr, U.S. corn and other grain exports have nearly tripled, increasing U.S. export trade by about $3 billion/yr year (USCB 2004–2005).

The expanding world population, which now numbers 6.5 billion, further complicates and stresses the food security problem now and for the future (PRB 2005). Almost a quarter million people are added each day to the world population, and each of these human beings requires adequate food. Currently, malnourished people in the world number about 3.7 billion (WHO 2000), the largest number and proportion ever reported in history. Malnourished people are highly susceptible to various serious diseases, and this concern is reflected in the rapid rise in the number of seriously infected people in the world, with diseases such as tuberculosis, malaria, and Auto-Immune Deficiency Syndrome (AIDS), as reported by the World Health Organization (Kim 2002; Pimentel et al. 2006).

E. Food Versus Fuel Issue

Using corn, a basic human food resource, for ethanol production raises ethical and moral issues (Wald 2006). Expanding ethanol production entails diverting valuable cropland from the production of corn needed to nourish people. The energetic and environmental aspects, as well as the moral and ethical issues, also deserve serious consideration. With oil and natural gas shortages now facing the U.S., ethanol production is forcing the U.S. to import more oil and natural gas to produce ethanol and other biofuels (Pimentel and Patzek 2005).

Furthermore, increasing oil and natural gas imports drives up the price of oil and gas; this is especially critical for the poor in developing countries of the world. The impact is documented by the fact that worldwide per capita fertilizer use has been declining for the last decade (Worldwatch Institute 2001).

Summary

The prime focus of ethanol production from corn is to replace the imported oil used in American vehicles, without expending more fossil energy in ethanol production than is produced as ethanol energy.

In a thorough and up-to-date evaluation of all the fossil energy costs of ethanol production from corn, every step in the production and conversion process must be included. In this study, 14 energy inputs in average U.S. corn production are included. Then, in the fermentation/distillation operation, 9 more identified fossil fuel inputs are included. Some energy and economic credits are given for the by-products, including dried distillers grains (DDG).

Based on all the fossil energy inputs, a total of 1.43 kcal fossil energy is expended to produced 1 kcal ethanol. When the energy value of the DDG, based on the feed value of the DDG as compared to that of soybean meal, is considered, the energy cost of ethanol production is reduced slightly, to 1.28 kcal fossil energy input per 1 kcal ethanol produced.

Several proethanol investigators have overlooked various energy inputs in U.S. corn production, including farm machinery, processing machinery, and the use of hybrid corn. In other studies, unrealistic, low energy costs were attributed to such inputs as nitrogen fertilizer, insecticides, and herbicides. Controversy continues concerning the energy and economic credits that should be assigned to the by-products.

The U.S. Department of Energy reports that 17.0 billion L ethanol was produced in 2005. This represents only less than 1% of total oil use in the U.S. These yields are based on using about 18% of total U.S. corn production and 18% of cornland. Because the production of ethanol requires large inputs of both oil and natural gas in production, the U.S. is importing both oil and natural gas to produce ethanol.

Furthermore, the U.S. Government is spending about $3 billion annually to subsidize ethanol production, a subsidy of $0.79/L ethanol produced. With the subsidy, plus the cost of production, the cost of ethanol is calculated to be $1.21/L. The subsidy for a liter of ethanol is 45-times greater than the subsidy per liter of gasoline.

The environmental costs associated with producing ethanol are significant but have been ignored by most investigators in terms of energy and economics. The negative environmental impacts on cropland, and freshwater, as well as air pollution and public health, have yet to be carefully assessed. These environmental costs in terms of energy and economics should be calculated and included in future ethanol analyses.

General concern has been expressed about taking 18% of U.S. corn, and more in the future, to produce ethanol for burning in automobiles instead of using the corn as food for the many malnourished people in the world. The World Health Organization reports that more than 3.7 billion humans are currently malnourished in the world – the largest number ever in history.

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