Ethanol as a Viable Alternative to Petroleum Based Fuels

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There are over 600 million light-duty vehicles (LDV) currently operating in the world. This number is expected to rise to over 1.2 billion by the year 2020.[1] The average LDV in the US travels an average of 20,000 miles a year, consuming around 1,000 gallons of gasoline.[2] This leads to the fact that if current trends do not change drastically, the world will be consuming 1,200,000,000,000 (1.2 trillion) gallons of gasoline a year by the year 2020. While estimates of the amount of oil left in the world vary greatly, it is a limited amount; the rules of supply and demand dictate that as consumption increases and the supply decreases, prices will rise. In addition, it is well known that the use of petroleum derived fuel creates large amounts of greenhouse gases[3]. For all of these reasons, the US has taken a lead in the investigation of alternative fuels and ethanol has emerged as a frontrunner in this search. However, ethanol is not currently a viable alternative due to high energy production costs as well as the effects that mass production would cause on the economy and the environment, despite its many claimed benefits.[4]

The main problem with the use of ethanol as an alternative to gasoline is that it has an extremely high production cost in terms of energy. In order to accurately assess the amount of energy required to produce ethanol, one must consider everything involved in its production. This includes the energy cost of laborers to grow the corn, the energy cost to produce, use, and maintain farm machinery, the energy cost of producing and spreading fertilizer, the energy cost of distilling ethanol and many other inputs as detailed in *table 1* and *table 2*.[2] *Table 1* shows the costs of simply producing the corn while *table 2* shows the costs of turning the corn into usable ethanol fuel.

Table 1. Energy Inputs and Costs of Corn Production Per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs $
Labor	11.4 hrs[a]	462[b]	148.20[c]
Machinery	55 kg[d]	1,018[e]	103.21[f]
Diesel	88 L[g]	1,003[h]	34.76
Gasoline	40 L[i]	405[j]	20.80
Nitrogen	153 kg[k]	2,448[l]	94.86[m]
Phosphorus	65 kg[n]	270[o]	40.30[p]
Potassium	77 kg[q]	251[r]	23.87[s]
Lime	1,120 kg[t]	315[u]	11.00
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[ee]	124.00
Insecticides	2.8 kg[cc]	280[ee]	56.00
Electricity	13.2 kWh[dd]	34[ff]	0.92
Transport	204 kg[gg]	169[hh]	61.20
Total		8,115	$916.93
Corn yield 8,655 kg/ha[ii]		31,158	kcal input: output 1:3.84

[a]NASS, 1999; [b]It is assumed that a person works 2,000 hr per yr and utilizes an average of 8,000 l of oil equivalents per yr; [c]It is assumed that labor is paid $13 an h; [d]Pimentel and Pimentel, 1996; [e]Prorated per ha and 10 yr life of the machinery. Tractors weigh from 6 to 7 tons and harvesters 8 to 10 tons, plus plows, sprayers, and other equipment; [f]Hoffman, Warnock, and Himman, 1994; [g]Wilcke and Chaplin, 2000; [h]Input 11, 400 kcal per l; [i]Estimated; [j]Input 10,125 kcal per l; [k]USDA, 2002; [l]Patzek, 2004; [m]Cost 62¢ per kg; [n]USDA, 2002; [o]Input 4,154 kcal per kg; [p]Cost $62 per kg; [q]USDA, 2002; [r]Input 3,260 kcal per kg; [s]Cost 31¢ per kg; [t]Brees, 2004; [u]Input 281 kcal per kg; [v]Pimentel and Pimentel, 1996; [w]Pimentel, 1980; [x]USDA, 1997b; [y]USDA, 1997a; [z]Batty and Keller, 1980; [aa]Irrigation for 100 cm of water per ha costs $1,000 (Larsen, Thompson, and Harn, 2002); [bb]Larson and Cardwell, 1999; [cc]USDA, 2002; [dd]USDA, 1991; [ee]Input 100,000 kcal per kg of herbicide and insecticide; [ff]Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity; [gg]Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km; [hh]Input 0.83 kcal per kg per km transported; [ii]USDA, 2003a.

Table 2. Inputs Per 1000 l of 99.5% Ethanol Produced From Corn[a]

Inputs	Quantity	kcal × 1000	Dollars $
Corn grain	2,690 kg[b]	2,522[b]	284.25[b]
Corn transport	2,690 kg[b]	322[c]	21.40[d]
Water	40,000 L[e]	90[f]	21.16[g]
Stainless steel	3 kg[i]	12[i]	10.60[d]
Steel	4 kg[i]	12[i]	10.60[d]
Cement	8 kg[i]	8[i]	10.60[d]
Steam	2,546,000 kcal[j]	2,546[j]	21.16[k]
Electricity	392 kWh[j]	1,011[j]	27.44[l]
95% ethanol to 99.5%	9 kcal/L[m]	9[m]	40.00
Sewage effluent	20 kg BOD[n]	69[h]	6.0
Total		6,597	$453.21

[a]Output: 1 l of ethanol = 5,130 kcal; [b]Data from Table 1; [c]Calculated for 144 km roundtrip; [d]Pimentel, 2003; [e]15 l of water mixed with each kg of grain; [f]Pimentel and others, 1997; [g]Pimentel and others, 2004b; [h]4 kWh of energy required to process 1 kg of BOD (Blais and others, 1995); [i]Slesser and Lewis, 1979; [j]Illinois Corn, 2004; [k]Calculated based on coal fuel; [l]7¢ per kWh; [m]95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, pers. commu., University of California, Berkeley, 2004); [n]20 kg of BOD per 1,000 l of ethanol produced (Kuby, Markoja, and Nackford, 1984).

Corn is the foundation upon which the American diet is built. While corn itself is widely considered to be a delicious part of a well balanced diet, only about 10% is consumed by humans. The other 90% is used to feed our livestock, providing meat, milk, eggs, bacon, etc.[5] If corn is this widely used there must be a fairly efficient process to produce it, and there is. The actual production of corn itself (*table 1*) is an efficient process yielding an energy input:output ratio of 1:3.84.[2] The high energy cost comes from the conversion of corn to usable ethanol fuel as seen in *table 2*. First, the ethanol must be ground to a mash and added to a large solution of water. Yeast is then added to this solution and allowed to ferment. Fermentation is the process of the yeast breaking down the sugar molecules into useful ethanol while carbon dioxide is being created as a byproduct. This process typically takes a couple of weeks and yields a solution of mostly water and some ethanol. In order for ethanol to be used as a fuel, nearly all the water must be removed.[3] This is first done through distillation, an extremely energy intensive process due to the fact that water has one of the highest specific heats at 4.814 J/mol K. Further contributing to the high energy cost of this process is the fact that ethanol and water in solution form an azeotrope that requires that the solution be distilled at least three times to reach a maximum of 95% ethanol. Due to the azeotropic effects, the solution can not be distilled beyond this point and so other chemical means must be employed to bring the solution to a usable 99.5% ethanol solution.[3, 6]

The data presented in *table 1* and *table 2*, gives the detailed breakdown of energy consumption, but what it boils down to is that the creation of 1000L of ethanol by the process of growing, fermenting and distilling corn requires around 6,597 kcal. This equates to around 98,000 BTU's of energy per gallon. One gallon of ethanol contains around 76,000 BTU's of energy. This means that the creation of ethanol from corn uses 29% more energy than is contained in the ethanol itself. While the negative net energy value (NEV)[a], [7] is troublesome in and of itself, it would not actually pose a problem if the energy used in the process was created in an environmentally friendly way. Unfortunately, even here in the US, the majority of energy created comes from fossil fuels like natural gas, coal, and oil.[3] So while ethanol itself is much cleaner burning than petroleum fuels, if all the energy used to create it is from fossil fuels, the net pollution will

[a] *It is necessary to point out that the NEV is in contention. Pimentel et al. gives the negative value reported. The United Stated Department of Agriculture report gives a slightly positive NEV. The consensus among the scientific community tends toward Pimentel's NEV.*

actually increase. On the other hand, the negative NEV would not be nearly as large a concern if the majority of energy created was done so using environmentally friendly methods such as solar generation, wind generation, or even nuclear power.[3, 5]

In addition to the problems associated with the negative NEV for the production of ethanol, the price of ethanol fuel is also a deterrent. Currently, the price of a gallon of gasoline is around $3.29 for the average consumer. The cost of a gallon of ethanol is around $3.00 for the consumer. While these two prices are fairly close at the moment, the US government is subsidizing the production of ethanol by over $3 billion a year. If the government were to cut off this funding, the price of ethanol would rise to around $4.70 a gallon. It's possible to see how this could be a reasonable price if gasoline prices continue to rise in the next couple years, but the energy obtained from a gallon of ethanol compared to a gallon of gasoline must also be considered. Recall that a gallon of ethanol contains around 76,000 BTU's of energy. A gallon of gasoline contains around 115,000 BTU's of energy (66% more). What this means is that if a vehicle runs at 25 mpg using gasoline, it will run at 15.625 mpg using ethanol. When this energy difference is factored in, the cost of ethanol rises to around $7.15/gallon. This is simply an economically impossible price for the typical US consumer to pay at the moment.[2, 5]

The use of alternative biomass materials, such as switch grass and wood cellulose, for the production of ethanol has also been investigated.

The use of switch grass was investigated because of its efficient 1:14.6 input:output energy ratio for growth. Unfortunately, the conversion of switch grass to ethanol requires even more energy than the conversion of corn to ethanol, 7,455 kcal/1000L, or 111,000 BTU's of energy per gallon. This means that it requires 49% more energy to create ethanol from switch grass than is contained in the ethanol. The detailed energy inputs for the creation of switch grass can be found in *table 3*. The detailed energy inputs for the conversion of switch grass to ethanol can be found in *table 4*.

A similar methodology was applied to the production and conversion of wood cellulose to ethanol. The end result was that it requires 57% more energy to produce ethanol from wood cellulose than is contained in the ethanol itself.

Table 3. Average Inputs and Energy Inputs Per Hectare Per Year for Switchgrass Production

Input	Quantity	10^3 kcal	Dollars
Labor	5 hr[a]	20[b]	$65[c]
Machinery	30 kg[d]	555	50[a]
Diesel	100 L[e]	1,000	50
Nitrogen	50 kg[e]	800	28[e]
Seeds	1.6 kg[f]	100[a]	3[f]
Herbicides	3 kg[g]	300[h]	30[a]
Total	10,000 kg yield[i] 40 million kcal yield	2,755 input/ output ratio	$230[j] 1:14.4[k]

[a]Estimated; [b]Average person works 2,000 h per yr and uses about 8,000 l of oil equivalents. Prorated this works out to be 20,000 kcal; [c]The agricultural labor is paid $13 per h; [d]The machinery estimate also includes 25% more for repairs; [e]Calculated based on data from David Parrish (pers. comm., Virginia Technology University, 2005); [f]Data from Samson, 1991; [g]Calculated based on data from Henning, 1993; [h]100,000 kcal per kg of herbicide; [i]Samson and others, 2000; [j]Brummer and others, 2000 estimated a cost of about $400/ha for switchgrass production. Thus, the $268 total cost is about 49% lower that what Brummer and others (2000) estimates and this includes several inputs not included in Brummer and others (2000); [k]Samson and others (2000) estimated an input per output return of 1:14.9, but I have added several inputs not included in Samson and others (2000). The input/output returns, however, are similar.

Table 4. Inputs Per 1000 l of 99.5% Ethanol Produced From U.S. Switchgrass

Inputs	Quantities	kcal × 1000[a]	Costs
Switchgrass	2,500 kg[b]	694[c]	$250[o]
Transport, switchgrass	2,500 kg[d]	300	15
Water	125,000 kg[e]	70[f]	20[m]
Stainless steel	3 kg[g]	45[g]	11[g]
Steel	4 kg[g]	46[g]	11[g]
Cement	8 kg[g]	15[g]	11[g]
Grind switchgrass	2,500 kg	100[h]	8[h]
Sulfuric acid	118 kg[i]	0	83[n]
Steam production	8.1 tons[i]	4,404	36
Electricity	660 kWh[i]	1,703	46
Ethanol conversion to 99.5%	9 kcal/L[j]	9	40
Sewage effluent	20 kg (BOD)[k]	69[l]	6
Total		7,455	$537

Note. Requires 45% more fossil energy to produce 1 l of ethanol using 2.5 kg switchgrass than the energy in a liter of ethanol. Total cost per liter of ethanol is 54¢. A total of 0.25 kg of brewers yeast (80% water) was produced per 1,000 l of ethanol produced. This brewers yeast has a feed value equivalent in soybean meal of about 480 kcal.
[a]Outputs: 1000 l of ethanol = 5.13 million kcal; [b]Samson (1991) reports that 2.5 kg of switchgrass is required to produce 1 l of ethanol; [c]Data from Table 1 on switchgrass production; [d]Estimated 144 km roundtrip; [e]Pimentel and others, 1988; [f]Estimated water needs for the fermentation program; [g]Slesser and Lewis, 1979; [h]Calculated based on grinder information (Wood Tub Grinders, 2004); [i]Estimated based on cellulose conversion (Arkenol, 2004); [j]95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, pers. comm., University of California, Berkeley, 2004); [k]20 kg of BOD per 1,000 l of ethanol produced (Kuby, Markoja, and Nactford, 1984); [l]4 kWh of energy required to process 1 kg (Blais and others, 1995); [m]Pimentel, 2003; [n]Sulfuric acid sells for $7 per kg. It is estimated that the dilute acid is recycled 10 times; [o]Samson, Duxbury, and Mulkins, 2004.

In addition to the major problems associated with a negative NEV for the production of ethanol, the use of ethanol as a replacement for petroleum based fuels is simply impossible logistically speaking and brings up serious ethical questions. If all current farm land in the US was used to grow corn for the production of ethanol, it would satisfy about 11% of the country's fuel needs.[2] So the country would be using 11% less oil, but would have nothing to eat. Another way of looking at this is that it requires 0.5 hectares of land to feed the average person in the US. To provide ethanol as a fuel for this person would require 0.6 hectares of land. It would take more land to fuel a person's car than to feed the person themselves. In addition, the World Health Organization estimates that there were about 3.7 billion malnourished people in the world. How can a country morally justify the use of food product as a fuel when so many in the world do not have enough to eat as it is?

The production of ethanol also raises some serious environmental concerns. The production of corn uses more herbicides and pesticides than any other crop in the US, leading to large amounts of water pollution. In addition, the production of corn requires the most nitrogen based fertilizer of any crop produced in the US,[2] again contributing large amounts of water pollution. Further, chemical plant production of ethanol has so far been a fairly unclean process with a number of plants being warned by the EPA to either reduce their air and water pollution or risk being shut down. Lastly, remember that the initial fermentation process yields a solution of mostly water. This water is removed and is considered waste water because of a biological oxygen demand of 18,000-37,000 mg/L. For each L of ethanol produced, 13L of waste water is also produced, and must be treated.

The idea of using ethanol as an alternative fuel to petroleum based fuels is simply impossible. When the viability is examined closely, it is easy to see that factors like the negative NEV, economic and environmental impacts, as well as ethical duty, preclude the use of ethanol as an alternative fuel. However, the world still has an addiction to oil that needs to be broken. There are many other alternatives to be explored, and perhaps one of them will hold the answer.

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