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Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower

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Energy outputs from ethanol produced using corn, switchgrass, and wood biomass were each less than the respective fossil energy inputs. The same was true for producing biodiesel using soybeans and sunflower, however, the energy cost for producing soybean biodiesel was only slightly negative compared with ethanol production. Findings in terms of energy outputs compared with the energy inputs were: • Ethanol production using corn grain required 29% more fossil energy than the ethanol fuel produced. • Ethanol production using switchgrass required 50% more fossil energy than the ethanol fuel produced. • Ethanol production using wood biomass required 57% more fossil energy than the ethanol fuel produced. • Biodiesel production using soybean required 27% more fossil energy than the biodiesel fuel produced (Note, the energy yield from soy oil per hectare is far lower than the ethanol yield from corn). • Biodiesel production using sunflower required 118% more fossil energy than the biodiesel fuel produced.

KEY WORDS: Energy, biomass, fuel, natural resources, ethanol, biodiesel.

INTRODUCTION

The United States desperately needs a liquid fuel replacement for oil in the future. The use of oil is projected to peak about 2007 and the supply is then projected to be extremely limited in 40–50 years (Duncan and Youngquist, 1999; Youngquist and Duncan, 2003; Pimentel and others, 2004a). Alternative liquid fuels from various sources have been sought for many years. Two panel studies by the U.S. Department of Energy (USDOE) concerned with ethanol production using corn and liquid fuels from biomass energy report a negative energy return (ERAB, 1980, 1981). These reports were reviewed by 26 expert U.S. scientists independent of the USDOE; the findings indicated that the conversion of corn into ethanol energy was negative and these findings were unanimously approved. Numerous other investigations have confirmed these findings over the past two decades.

A review of the reports that indicate that corn ethanol production provides a positive return indicates that many inputs were omitted (Pimentel, 2003). It is disappointing that many of the inputs were omitted because this misleads U.S. policy makers and the public.

Ethanol production using corn, switchgrass, and wood, and biodiesel production using soybeans and sunflower, will be investigated in this article.

CORN ETHANOL PRODUCTION USING CORN

Shapouri (Shapouri, Duffield, and Wang, 2002; Shapouri and others, 2004) of the USDA claims that ethanol production provides a net energy return. In addition, some large corporations, including Archer, Daniels, Midland (McCain, 2003), support the production of ethanol using corn and are making huge profits from ethanol production, which is subsidized

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by federal and state governments. Some politicians also support the production of corn ethanol based on their mistaken belief that ethanol production provides large benefits for farmers, whereas in fact farmer profits are minimal. In contrast to the USDA, numerous scientific studies have concluded that ethanol production does not provide a net energy balance, that ethanol is not a renewable energy source, is not an economical fuel, and its production and use contribute to air, water, and soil pollution and global warming (Ho, 1989; Citizens for Tax Justice, 1997; Giampietro, Ulgiati, and Pimentel, 1997; Youngquist, 1997; Pimentel, 1998, 2001, 2003 NPRA, 2002; Croysdale, 2001; CalGasoline, 2002; Lieberman, 2002; Hodge, 2002, 2003; Ferguson, 2003, 2004; Patzek, 2004). Growing large amounts of corn necessary for ethanol production occupies cropland suitable for food production and raises serious ethical issues (Pimentel, 1991, 2003; Pimentel and Pimentel, 1996).

Shapouri (Shapouri, Duffield, and Wang, 2002; Shapouri and others, 2004) studies concerning the benefits of ethanol production are incomplete because they omit some of the energy inputs in the ethanol production system. The objective of this analysis is to update and assess all the recognized inputs that operate in the entire ethanol production system. These inputs include the direct costs in terms of energy and dollars for producing the corn feedstock as well as for the fermentation/distillation process. Additional costs to the consumer include federal and state subsidies, plus costs associated with environmental pollution and degradation that occur during the entire production system. Ethanol production in the United States does not benefit the nation's energy security, its agriculture, the economy, or the environment. Also, ethical questions are raised by diverting land and precious food into fuel and actually adding a net amount of pollution to the environment.

Energy Balance

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 of ethanol from 2.69 kg of corn grain (Pimentel, 2001).

The production of corn in the United States requires a significant energy and dollar investment (Table 1). For example, to produce average corn yield of 8,655 kg/ha of corn using average production technology requires the expenditure of about 8.1 million kcal for the large number of inputs listed in Table 1 (about 271 gallons of gasoline equivalents/ha). The production costs are about $917/ha for the 8,655 kg or approximately 11¢ /kg of corn produced. To produce a liter of ethanol requires 29% more fossil energy than is produced as ethanol and costs 42¢ per l ($1.59 per gallon) (Table 2). The corn feedstock alone requires nearly 50% of the energy input.

Full irrigation (when there is little or no rainfall) requires about 100 cm of water per growing season. Only approximately 15% of U.S. corn production currently is irrigated (USDA, 1997a). Of course not all of this requires full irrigation, so a mean value is used. The mean irrigation for all land growing corn grain is 8.1 cm per ha during the growing season. As a mean

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).

value, water is pumped from a depth of 100 m (USDA, 1997a). On this basis, the mean energy input associated with irrigation is 320,000 kcal per ha (Table 1).

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. Note the largest energy inputs are for the corn feedstock, the steam energy, and electricity used in the fermentation/distillation process. The total energy input to produce a liter of ethanol is 6,597 kcal (Table 2). However, a liter of ethanol has an energy value of only 5,130 kcal. Thus, there is a net energy loss of 1,467 kcal of ethanol produced. Not included in this analysis was the distribution energy to transport the ethanol. DOE (2002) estimates this to be 2¢/l or approximately more than 331 kcal/l of ethanol.

In the fermentation/distillation process, the corn is finely ground and approximately 15 l of water are added per 2.69 kg of ground corn. After fermentation, to obtain a gallon of 95% pure ethanol from the 8% ethanol and 92% water mixture, the 1 l of ethanol must come from the approximately 13 l of the ethanol/water mixture. A total of about 13 l of wastewater must be removed per l of ethanol produced and this sewage effluent has to be disposed of at both an energy and economic cost.

Although ethanol boils at about 78°C, whereas water boils at 100°C, the ethanol is not extracted from the water in just one distillation process. Instead, about 3 distillations are required to obtain the 95% pure ethanol (Maiorella, 1985; Wereko-Brobby and Hagan, 1996; S. Lamberson, pers. comm. Cornell Univ. 2000). To be mixed with gasoline, the 95% ethanol must be processed further and more water removed requiring additional fossil energy inputs to achieve 99.5% pure ethanol (Table 2). The entire distillation accounts for the large quantities of fossil energy required in the fermentation/distillation process (Table 2). Note, in this analysis all the added energy inputs for fermentation/distillation process total $422.21, including the apportioned energy costs of the stainless steel tanks and other industrial materials (Table 2).

About 50% of the cost of producing ethanol (42¢ per l) in a large-production plant is for the corn feedstock itself (28¢/l) (Table 2). The next largest input is for steam (Table 2).

Based on current ethanol production technology and recent oil prices, ethanol costs substantially more to produce in dollars than it is worth on the market. Clearly, without the more than $3 billion of federal and state government subsidies each year, U.S. ethanol production would be reduced or cease, confirming the basic fact that ethanol production is uneconomical (National Center for Policy Analysis, 2002). Senator McCain reports that including the direct subsidies for ethanol plus the subsidies for corn grain, a liter costs 79¢ ($3/gallon) (McCain, 2003). If the production costs of producing a liter of ethanol were added to the tax subsidies, then the total cost for a liter of ethanol would be $1.24. Because of the relatively low energy content of ethanol, 1.6 l of ethanol have the energy equivalent of 1 l of gasoline. Thus, the cost of producing an equivalent amount of ethanol to equal a liter of gasoline is $1.88 ($7.12 per gallon of gasoline), while the current cost of producing a liter of gasoline is 33¢ (USBC, 2003).

Federal and state subsidies for ethanol production that total more than 79¢/l are mainly paid to large corporations (McCain, 2003). To date, a conservative calculation suggests that corn farmers are receiving a maximum of only an added 2¢ per bushel for their corn or less than $2.80 per acre because of the corn ethanol production system. Some politicians have the mistaken belief that ethanol production provides large benefits for farmers, but in fact the farmer profits are minimal. However, several corporations, such as Archer, Daniels, Midland, are making huge profits from ethanol production (McCain, 2003). The costs to the consumer are greater than the

$8.4 billion/yr used to subsidize ethanol and corn production because producing the required corn feedstock increases corn prices. One estimate is that ethanol production is adding more than $1 billion to the cost of beef production (National Center for Policy Analysis, 2002). Because about 70% of the corn grain is fed to U.S. livestock (USDA, 2003a, 2003b), doubling or tripling ethanol production can be expected to increase corn prices further for beef production and ultimately 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 pay significantly higher meat, milk, and egg prices in the market place.

Currently, about 2.81 billion gallons of ethanol (10.6 billion l) are being produced in the United States each year (Kansas Ethanol, 2004). The total automotive gasoline delivered in the U.S. was 500 billion l in 2003 (USCB, 2004). Therefore, 10.6 billion l of ethanol (equivalent to 6.9 billion l of gasoline) provided only 2% of the gasoline utilized by U.S. automobiles each year. To produce the 10.6 billion l of ethanol we use about 3.3 million ha of land. Moreover significant quantities of energy are needed to sow, fertilize, and harvest the corn feedstock.

The energy and dollar costs of producing ethanol can be offset partially by the by-products produced, similar to the dry distillers grains (DDG) made from dry-milling. From about 10 kg of corn feedstock, about 3.3 kg of DDG can be harvested that has 27% protein (Stanton, 1999). This DDG has value for feeding cattle that are ruminants, but has only limited value for feeding hogs and chickens. The DDG generally is used as a substitute for soybean feed that has 49% protein (Stanton, 1999). Soybean production for livestock production is more energy efficient than corn production because little or no nitrogen fertilizer is needed for the production of this legume (Pimentel and others, 2002). Only 2.1 kg of 49% soybean protein is required to provide the equivalent of 3.3 kg of DDG. Thus, the credit fossil energy per liter of ethanol produced is about 445 kcal (Pimentel and others, 2002). Factoring this credit in the production of ethanol reduces the negative energy balance for ethanol production from 29% to 20% (Table 2). Note that the resulting energy output/input comparison remains negative even with the credits for the DDG by-product. Also note that these energy credits are contrived because no one would actually produce livestock feed from ethanol at great costs in fossil energy and soil depletion (Patzek, 2004).

When considering the advisability of producing ethanol for automobiles, the amount of cropland required to grow sufficient corn to fuel each automobile should be understood. To make ethanol production seem positive, we use Shapouri's (Shapouri, Duffield, and Wang, 2002; Shapouri and others, 2004) suggestion that all natural gas and electricity inputs be ignored and only gasoline and diesel fuel inputs be assessed; then, using Shapouri's input/output data results in an output of 775 gallons of ethanol per ha. Because of its lower energy content, this ethanol has the same energy as 512 gallons of gasoline. An average U.S. automobile travels about 20,000 miles/yr and uses about 1,000 gallons of gasoline per yr (USBC, 2003). To replace only a third of this gasoline with ethanol, 0.6 ha of corn must be grown. Currently, 0.5 ha of cropland is required to feed each American. Therefore, even using Shapouri's optimistic data, to feed one automobile with ethanol, substituting only one third of the gasoline used per year, Americans would require more cropland than they need to feed themselves!

Until recently, Brazil had been the largest producer of ethanol in the world. Brazil used sugarcane to produce ethanol and sugarcane is a more efficient feedstock for ethanol production than corn grain (Pimentel and Pimentel, 1996). However, the energy balance was negative and the Brazilian government subsidized the ethanol industry. There the government was selling ethanol to the public for 22¢ per l that was costing them 33¢ per l to produce for sale (Pimentel, 2003). Because of serious economic problems in Brazil, the government has abandoned directly subsidizing ethanol (Spirits Low, 1999; Coelho and others, 2002). The ethanol industry is still being subsidized but the consumer is paying this subsidy directly at the pump (Pimentel, 2003).

Environmental Impacts

Some of the economic and energy contributions of the by-products mentioned earlier are negated by the environmental pollution costs associated with ethanol production. These are estimated to be more than 6¢ per l of ethanol produced (Pimentel, 2003). U.S. corn production causes more total soil erosion that any other U.S. crop (Pimentel and others, 1995; NAS, 2003). In addition, corn production uses more herbicides and insecticides than any other crop produced in the U.S. thereby causing more water pollution than any other crop (NAS, 2003). Further, corn production uses more nitrogen fertilizer than any crop produced and therefore is a major contributor to groundwater and river water pollution (NAS, 2003). In some Western U.S. irrigated corn acreage, for instance, in some regions of Arizona, groundwater is being pumped 10 times faster than the natural recharge of the aquifers (Pimentel and others, 2004b).

All these factors suggest that the environmental system in which U.S. corn is being produced is being rapidly degraded. Further, it substantiates the conclusion that the U.S. corn 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. Corn is raw material for ethanol production, but cannot be considered to provide a renewable energy source.

Major air and water pollution problems also are associated with the production of ethanol in the chemical plant. The EPA (2002) has issued warnings to ethanol plants to reduce their air pollution emissions or be shut down. Another pollution problem is the large amounts of wastewater that each plant produces. As mentioned, for each liter of ethanol produced using corn, about 13 l of wastewater are produced. This wastewater has a biological oxygen demand (BOD) of 18,000–37,000 mg/l depending on the type of plant (Kuby, Markoja, and Nackford, 1984). The cost of processing this sewage in terms of energy (4 kcal/kg of BOD) was included in the cost of producing ethanol (Table 2).

Ethanol contributes to air pollution problems when burned in automobiles (Youngquist, 1997; Hodge, 2002, 2003). In addition, the fossil fuels expended for corn production and later in the ethanol plants amount to expenditures of 6,597 kcal of fossil energy per 1,000 l of ethanol produced (Table 2). The consumption of the fossil fuels release 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, Rosencranz, and Niles, 2002). When all the air pollutants associated with the entire ethanol system are measured, ethanol production contributes to the serious U.S. air pollution problem (Youngquist, 1997; Pimentel, 2003). Overall, if air pollution problems were controlled and included in the production costs, then ethanol production costs in terms of energy and economics would be significantly increased.

Negative or Positive Energy Return?

Shapouri (Shapouri and others, 2004) of the USDA now are reporting a net energy positive return of 67%, whereas in this paper, I report a negative 29% deficit. In their last report, Shapouri, Duffield, and Wang (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 the past 2 yr (USDA, 2002, 2003a)? Shapouri results need to be examined.

(1) Shapouri (Shapouri and others, 2004) omit several inputs, for instance, all the energy required to produce and repair farm machinery, as well as the fermentation-distillation equipment. All the corn production in the U.S. is carried out with an abundance of farm machinery, including tractors, planters, sprayers, harvesters, and other equipment. These are large energy inputs in corn ethanol production, even when allocated on a life cycle basis.
(2) Shapouri used corn data from only 9 states, whereas we use corn data from 50 states.
(3) Shapouri reported a net energy return of 67% for the co-products, primarily dried-distillers grain (DDG) used to feed cattle.
(4) Although we did not allocate any energy related to the impacts that the production of ethanol has on the environment, they are significant in U.S. corn production. (Please see our previous comments on this subject).
(5) Andrew Ferguson (2004) makes an astute observation about the USDA data. The proportion of sun's energy that is converted into useful ethanol, using the USDA's positive data, only amounts to 5 parts per 10,000. If the figure of 50 million ha were to be devoted to growing corn for ethanol, then this acreage would supply only about 11% of U.S. liquid fuel needs.
(6) Many other investigators support our type of assessment of ethanol production. (Please see our previous comments on this subject).

Food Versus Fuel Issue

Using corn, a human food resource, for ethanol production, raises major ethical and moral issues. Today, malnourished (calories, protein, vitamins, iron, and iodine) people in the world number about

3.7 billion (WHO, 2000). This is the largest number of malnourished people and proportion ever reported in history. The expanding world population that now number 6.5 billion complicates the food security problem (PRB, 2004). More than a quarter million people are added each day to the world population, and each of these human beings requires adequate food.

Malnourished people are highly susceptible to various serious diseases; this is reflected in the rapid rise in number of seriously infected people in the world as reported by the World Health Organization (Kim, 2002).

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. Cereal grains make up 80% of the food of the people worldwide. During the past 10 years, U.S. corn and other grain exports have nearly tripled, increasing U.S. export trade by about $3 billion per yr (USBC, 2003).

Concerning the U.S. balance of payments, the U.S. is importing more than 61% of its oil at a cost of more than $75 billion per yr (USBC, 2003). Oil imports are the largest deficit payments incurred by the United States (USBC, 2003). Ethanol production requires large fossil energy input, therefore, it is contributing to oil and natural gas imports and U.S. deficits (USBC, 2003).

At present, world agricultural land based on calories supplies more than 99.7% of all world food (calories), while aquatic ecosystems supply less than 0.3% (FAO, 2001). Already worldwide, during the last decade per capita available cropland decreased 20%, irrigation 12%, and fertilizers 17% (Brown, 1997). Expanding ethanol production could entail diverting valuable cropland from producing corn needed to feed people to producing corn for ethanol factories. The practical aspects, as well as the moral and ethical issues, should be seriously considered before steps are taken to convert more corn into ethanol for automobiles.

SWITCHGRASS PRODUCTION OF ETHANOL

The average energy input per hectare for switchgrass production is only about 3.8 million kcal per yr (Table 3). With an excellent yield of 10 t/ha/yr, this suggests for each kcal invested as fossil energy the return is 11 kcal—an excellent return. If pelletized for use as a fuel in stoves, the return is reported to be about 1:14.6 kcal (Samson, Duxbury, and Mulkins, 2004). The 14.6 is higher than the 11 kcal in Table 3, because here a few more inputs were included than in Samson, Duxbury, and Mulkins, (2004) report. The cost per ton of switchgrass pellets ranges from $94 to $130 (Samson, Duxbury, and Mulkins, 2004). This seems to be an excellent price per ton.

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]	2,755	$230[j]
	40 million kcal yield	input/output ratio	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.

However, converting switchgrass into ethanol results in a negative energy return (Table 4). The negative energy return is 50% or slightly higher than the negative energy return for corn ethanol production (Tables 2 and 4). The cost of producing a liter of ethanol using switchgrass was 54¢ or 9¢ higher than the 45¢ per l for corn ethanol production (Tables 2 and 4). The two major energy inputs for switchgrass conversion into ethanol were steam and electricity production (Table 4).

WOOD CELLULOSE CONVERSION INTO ETHANOL

The conversion of 2,500 kg of wood harvested from a sustainable forest into 1,000 l of ethanol require an input of about 9.0 million kcal (Table 5). Therefore, the wood cellulose system requires slightly

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.

Table 5. Inputs Per 1000 l of 99.5% Ethanol Produced From U.S. wood cellulose

Inputs	Quantities	kcal × 1000[a]	Costs
Wood, harvest (fuel)	2,500 kg[b]	400[c]	$ 250[n]
Machinery	5 kg[m]	100[m]	10[o]
Replace nitrogen	50 kg[c]	800	28[o]
Transport, wood	2,500 kg[d]	300	15
Water	125,000 kg[e]	70[f]	20[o]
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 wood	2,500 kg	100[h]	8[h]
Sulfuric acid	118 kg[b]	0	83[p]
Steam production	8.1 tons[b]	4,404	36
Electricity	666 kWh[bl]	1,703	46
Ethanol conversion to 99.5%	9 kcal/L[i]	9	40
Sewage effluent	20 kg (BOD)[j]	69[k]	6
Total		8,061	$575

Note. Requires 57% more fossil energy to produce 1 l of ethanol using 2 kg wood than the energy in a liter of ethanol. Total cost per liter of ethanol is 58¢. A total of 0.2 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 467 kcal.
[a]Outputs: 1000 l of ethanol = 5.13 million kcal; [b]Arkenol (2004) reported that 2 kg of wood produced 1 l of ethanol. We question this 2 kg to produce 1 l of ethanol when it takes 2.69 kg of corn grain to produce 1 l of ethanol. Others are reporting 13.2 kg of wood per kg per l of ethanol (DOE, 2004). We used the optimistic figure of 2.5 kg of wood per l of ethanol produced; [c]50 kg of nitrogen removed with the 2,500 kg of wood (Kidd and Pimentel, 1992); [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]95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, pers. comm., University of California, Berkeley, 2004); [j]20 kg of BOD per 1,000 l of ethanol produced (Kuby, Markoja, and Nackford, 1984); [k]4 kWh of energy required to process 1 kg (Blais and others, 1995); [l]Illinois Corn, 2004; [m]Mead and Pimentel, 2004; [n]Samson, Duxbury, and Mulkins, 2004; [o]Pimentel, 2003; [p]Sulfuric acid sells for $7 per kg. It is estimated that the dilute acid is recycled 10 times.

more energy to produce the 1,000 l of ethanol than using switchgrass (Tables 4 and 5). About 57% more energy is required to produce a liter of ethanol using wood than the energy harvested as ethanol.

The ethnaol cost per liter for wood-produced ethanol is slightly higher than the ethanol produced using switchgrass, 58¢ versus 54¢, respectively (Tables 4 and 5). The two largest fossil energy inputs in the wood cellulose production system were steam and electricity (Table 5).

SOYBEAN CONVERSION INTO BIODIESEL

Various vegetable oils have been converted into biodiesel and they work well in diesel engines. An assessment of producing sunflower oil proved to be energy negative and costly in terms of dollars (Pimentel, 2001). Although soybeans contain less oil than sunflower, about 18% soy oil compared with 26% oil for sunflower, soybeans can be produced without or nearly zero nitrogen (Table 6). This makes soybeans advantageous for the production of biodiesel. Nitrogen fertilizer is one of the most energy costly inputs in crop production (Pimentel and others, 2002).

The yield of sunflower also is lower than soybeans, 1,500 kg/ha for sunflower compared with 2,668 kg/ha for soybeans (USDA, 2003a). The production of 2,668 kg/ha of soy requires an input of

Table 6. Energy Inputs and Costs in Soybean Production Per Hectare in the U.S.

Inputs	Quantity	kcal × 1000	Costs $
Labor	7.1 h[a]	284[b]	92.30c
Machinery	20 kg[d]	360[e]	148.00[f]
Diesel	38.8 L[a]	442[g]	20.18
Gasoline	35.7 L[a]	270[h]	13.36
LP gas	3.3 L[a]	25[i]	1.20
Nitrogen	3.7 kg[j]	59[k]	2.29[l]
Phosphorus	37.8 kg[j]	156[m]	23.44[n]
Potassium	14.8 kg[j]	48[o]	4.59[p]
Lime	4800 kg[v]	1,349[d]	110.38[v]
Seeds	69.3 kg[a]	554[q]	48.58[r]
Herbicides	1.3 kg[j]	130[e]	26.00
Electricity	10 kWh[d]	29[s]	0.70
Transport	154 kg[t]	40[u]	46.20
Total		3,746	$537.22
Soybean yield 2,668 kg/ha[w]		9,605	kcal input: output 1:2.56

[a]Ali and McBride, 1990; [b]It is assumed that a person works 2,000 h 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]Machinery is prorated per hectare and a 10 yr life of the machinery. Tractors weigh from 6 to 7 tons and harvestors from 8 to 10 tons, plus plows, sprayers, and other equipment; [f]College of Agri., Consumer and Environ. Sciences, 1997. [g]Input 11,400 kcal per l; [h]Input 10,125 kcal per l; [i]Input 7,575 kcal per l; [j]Economic Research Statistics, 1997; [k]Patzek, 2004; [l]Hinman and others, 1992; [m]Input 4,154 kcal per kg; [n]Cost 62¢ per kg; [o]Input 3,260 kcal per kg; [p]Costs 31¢per kg; [q]Pimentel and others, 2002; [r]Costs about 70¢ per kg; [s]Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity; [t]Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km; [u]Input 0.83 kcal per kg per km transported; [v]Kassel and Tidman, 1999; Mansfield, 2004; Randall and Vetsch, 2004; [w]USDA, 2003a, 2003b.

about 3.7 million kcal per ha and costs about $537/ha (Table 6).

With a yield of oil of 18% then 5,556 kg of soybeans are required to produce 1,000 kg of oil (Table 7). The production of the soy feedstock requires an input of 7.8 million kcal. The second largest input is steam that requires an input of 1.4 million kcal (Table 7). The total input for the 1,000 kg of soy oil is 11.4 million kcal. With soy oil having an energy value of 9 million kcal, then there is a net loss of 32% in energy. However, a credit should be taken for the soy meal that is produced and this has an energy value of 2.2 million kcal. Adding this credit to soybean oil credit, then the net loss in terms of energy is 8% (Table 7). The price per kg of soy biodiesel is $1.21, however, taking credit for the soy meal would reduce this price to 92¢ per kg of soy oil (Note, soy oil has a specific gravity of about 0.92, thus soy oil value per liter is 84¢ per l. This makes soy oil about 2.8 times as expensive as diesel fuel). This makes soy oil expensive compared with the price of diesel that costs about 30¢ per l to produce (USBC, 2003).

Table 7. Inputs Per 1,000 kg of Biodiesel Oil From Soybeans

Inputs	Quantity	kcal × 1000	Costs $
Soybeans	5,556 kg[a]	7,800[a]	$1,117.42[a]
Electricity	270 kWh[b]	697[c]	18.90[d]
Steam	1,350,000 kcal[b]	1,350[b]	11.06[e]
Cleanup water	160,000 kcal[b]	160[b]	1.31[e]
Space heat	152,000 kcal[b]	152[b]	1.24[e]
Direct heat	440,000 kcal[b]	440[b]	3.61[e]
Losses	300,000 kcal[b]	300[b]	2.46[e]
Stainless steel	11 kg[f]	158[f]	18.72[g]
Steel	21 kg[f]	246[f]	18.72[g]
Cement	56 kg[f]	106[f]	18.72[g]
Total		11,878	$1,212.16

Note. The 1,000 kg of biodiesel produced has an energy value of 9 million kcal. With an energy input requirement of 11.9 million kcal, there is a net loss of energy of 32%. If a credit of 2.2 million kcal is given for the soy meal produced, then the net loss is 8%. The cost per kg of biodiesel is $1.21.
[a]Data from Table 6; [b]Data from Singh, 1986; [c]An estimated 3 kWh thermal is needed to produce a kWh of electricity; [d]Cost per kWh is 7¢; [e]Calculated cost of producing heat energy using coal; [f]Calculated inputs using data from Slesser and Lewis, 1979; [g]Calculated costs from Pimentel, 2003.

Sheehan and others (1998, p. 13) of the Department of Energy also report a negative energy return in the conversion of soybeans into biodiesel. They report "1 MJ of biodiesel requires an input of 1.24 MJ of primary energy."

Soybeans are a valuable crop in the United States. The target price reported by the USDA (2003a) is 21.2¢/kg while the price calculated in Table 6 for average inputs per hectare is 20.1¢/kg. These values are close.

SUNFLOWER CONVERSION INTO BIODIESEL

In a preliminary study of converting sunflower into biodiesel fuel, as mentioned, the result in terms of energy output was negative (Pimentel, 2001). In the current assessment, producing sunflower seeds for biodiesel yields 1,500 kg/ha (USDA, 2003a) or slightly higher than the 2001 yield. The 1,500 kg/ha yield is still significantly lower than soybean and corn production per ha.

The production of 1,500 kg/ha of sunflower seeds requires a fossil energy input of 6.1 million kcal (Table 8). Thus, the kcal input per kcal output is negative with a ratio of 1:0.76 (Table 8). Sunflower seeds

Table 8. Energy Inputs and Costs in Sunflower Production Per Ha in the U.S.

Inputs	Quantity	kcal × 1000	Costs $
Labor	8.6 h[a]	344[b]	111.80[c]
Machinery	20 kg[d]	360[e]	148.00[f]
Diesel	180 L[a]	1,800[g]	93.62[h]
Nitrogen	110 kg[j]	1,760[k]	68.08[l]
Phosphorus	71 kg[j]	293[m]	44.03[n]
Potassium	100 kg[j]	324[o]	34.11[p]
Lime	1000 kg[j]	281[d]	23.00[v]
Seeds	70 kg[a]	560[q]	49.07[r]
Herbicides	3 kg[j]	300[v]	60.00[i]
Electricity	10 kWh[d]	29[s]	0.70
Transport	270 kg[t]	68[u]	81.00
Total		6,119	$601.61
Sunflower yield 1,500 kg/ha[w]		4,650	kcal input: output 1:0.76

[a]Knowles and Bukantis, 1980; [b]It is assumed that a person works 2,000 h per year 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]Machinery is prorated per ha and a 10 yr life of the machinery. Tractors weigh from 6 to 7 tons and harvestors from 8 to 10 tons, plus plows, sprayers, and other equipment; [f]College of Agriculture, Consumer and Environ. Sciences, 1997; [g]Input 10,000 kcal per l; [h]52¢per l; [i]$20 per kg; [j]Blamey, Zollinger, and Schneiter, 1997; [k]Patzek, 2004; [l]Hinman and others, 1992; [m]Input 4,154 kcal per kg; [n]Cost 62¢per kg; [o]Input 3,260 kcal per kg; [p]Costs 31¢per kg; [q]Based on 7,900 kcal per kg of sunflower seed production; [r]Costs about 70¢ per kg; [s]Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity; [t]Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km; [u]Input 0.83 kcal per kg per km transported; [v]100,000 kcal of energy required per kg of herbicide; [w]USDA, 2003a, 2003b.

Table 9. Inputs Per 1,000 kg of Biodiesel Oil From Sunflower

Inputs	Quantity	kcal × 1000	Costs $
Sunflower	3,920 kg[a]	15,990[a]	$1.570.20[a]
Electricity	270 kWh[b]	697[c]	18.90[d]
Steam	1,350,000 kcal[b]	1,350[b]	11.06[e]
Cleanup water	160,000 kcal[b]	160[b]	1.31[e]
Space heat	152,000 kcal[b]	152[b]	1.24[e]
Direct heat	440,000 kcal[b]	440[b]	3.61[e]
Losses	300,000 kcal[b]	300[b]	2.46[e]
Stainless steel	11 kg[f]	158[f]	18.72[g]
Steel	21 kg[f]	246[f]	18.72[g]
Cement	56 kg[f]	106[f]	18.72[g]
Total		19,599	$1,662.48

Note. The 1,000 kg of biodiesel produced has an energy value of 9 million kcal. With an energy input requirement of 19.6 million kcal, there is a net loss of energy of 118%. If a credit of 2.2 million kcal is given for the soy meal produced, then the net loss is 96%. The cost per kg of biodiesel is $1.66.
[a]Data from Table 8; [b]Data from Singh, 1986; [c]An estimated 3 kWh thermal is needed to produce a kWh of electricity; [d]Cost per kWh is 7¢; [e]Calculated cost of producing heat energy using coal; [f]Calculated inputs using data from Slesser and Lewis, 1979; [g]Calculated costs from Pimentel, 2003.

have higher oil content than soybeans, 26% versus 18%. However, the yield of sunflower is nearly one half that of soybean.

Thus, to produce 1,000 kg of sunflower oil requires 3,920 kg of sunflower seeds with an energy input of 156.0 million kcal (Table 9). This is the largest energy input listed in Table 9. Therefore, to produce 1,000 kg of sunflower oil with an energy content of 9 million kcal, the fossil energy input is 118% higher than the energy content of the sunflower biodiesel and the calculated cost is $1.66 per kg of sunflower oil (Table 9) (Note, the specific gravity of sunflower oil is 0.92, thus the cost of a liter of sunflower oil is $1.53 per l).

CONCLUSION

Several physical and chemical factors limit the production of liquid fuels such as ethanol and biodiesel using plant biomass materials. These include the following:

(1) An extremely low fraction of the sunlight reaching America is captured by plants. On average the sunlight captured by plants is only about 01.%, with corn providing 0.25%. These low values are in contrast to photovoltaics that capture from 10% or more sunlight, or approximately 100-fold more sunlight than plant biomass.
(2) In ethanol production the carbohydrates are converted into ethanol by microbes, that on average bring the concentration of ethanol to 8% in the broth with 92% water. Large amounts of fossil energy are required to remove the 8% ethanol from the 92% water.
(3) For biodiesel production, there are two problems: the relatively low yields of oil crops ranging from 1,500 kg/ha for sunflower to about 2,700 kg/ha for soybeans; sunflower averages 25.5% oil, whereas soybeans average 18% oil. In addition, the oil extraction processes for all oil crops is highly energy intensive as reported in this manuscript. Therefore, these crops are poor producers of biomass energy.

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