This article represents a draft of a chapter in a book on energy (history, present status, future prospects and problems) that the author is writing. It is presented here to provide a more technical treatment of the ethanol issue than was possible in the recent Harvard Magazine article. The material included in the article should not be reproduced or transmitted without prior permission from the author.

Chapter 12

Ethanol from biomass: can it substitute for gasoline?

12.1 Introduction

Present day annual consumption of gasoline in the United States amounts to close to 150 billion gallons, approximately 500 gallons for every man, woman and child in the country. With gasoline prices up by almost a third in 2006, the annualized bill for gasoline for a typical US family of four is now close to $6000, a burden that falls disproportionally on those least equipped to bear it. Not surprisingly, there has been a political reaction. Leaders of the major oil companies have been called to testify in Congress and there are calls for a windfall profits tax. The price of gasoline is linked inevitably, however, to the price of oil and there is little Congress or the oil companies can do about that, at least in the short term. Geopolitical considerations, notably the instability in the Middle East, and international market conditions (increased demand from China and India, political uncertainties in Russia and Venezuela), determine the price of oil, recently at an all time high of more than $75 for a 42-gallon barrel of crude. But there is a solution, some would claim.

Why not replace gasoline with ethanol, the stuff that adds zip to your beer and your gin and tonic, a fuel produced from homegrown corn? After all, more than 40% of the world's corn is grown in the US and the US can legitimately lay claim to its status as the world's most efficient agricultural economy. Corn grows by drawing carbon dioxide from the atmosphere through photosynthesis. That should offset concerns about increasing levels of greenhouse gases and consequences for global warming, should it not?

Brazil has emerged in recent years as an ethanol success story. The feedstock in this case is sugar cane rather than corn. The seeds of Brazil's success date back to the oil crises of the 1970's. The military government in power at that time made a decision to subsidize production of ethanol from sugar cane to reduce their dependence on expensive imported oil. They provided generous subsidies and tax breaks to owners of sugar mills encouraging them to switch from refining sugar to producing ethanol, developing at the same time a distribution system to ensure that the product was readily available to consumers. In 1975, they ordered that all gasoline sold in Brazil should be mixed with 10% ethanol, a percentage increased subsequently to between 20 and 25%. Cars capable of running on ethanol only were introduced in the late 1970's, fruits of a research program funded by the government at a Brazilian Air Force research laboratory. The program fell on hard times, however, in 1990 when the combination of a poor sugar cane harvest and high sugar prices led to a serious shortage of ethanol prompting drivers to switch back to gasoline. The program is now back on track thanks to an innovation that allows computers installed in modern Brazilian cars to be programmed (or reprogrammed) at minimal cost to calculate the ethanol to gas mixture present in the tank of a car at any given time and to adjust the operation of the engine accordingly.

Today, more than 80% of all non-diesel new cars sold in Brazil are flex-fuel. With access to either ethanol or a gasoline-ethanol blend (gasohol, containing up to 25% ethanol) at filling stations, motorists in Brazil have a choice. They can opt for either gasoline or ethanol, or a combination, basing purchasing decisions simply on considerations of price and personal preference. The supply of ethanol is insufficient, however, to totally supplant current demand for gasoline.

Ethanol belongs to the class of chemical compounds known as the alcohols. Molecules in this family are characterized by an OH group bonded to a hydrocarbon framework. Ethanol (CH_3CH_2OH), for example, is equivalent to ethane (CH_3CH_3) with one of the hydrogen atoms replaced by OH (see Figure 12.1). Referred to also as ethyl alcohol, ethanol is a liquid at ambient temperatures with a boiling point of 78 C. The energy content of a gallon of ethanol is equal to 76,000 BTU as compared to about 115,000 BTU for a gallon of conventional gasoline. It follows that to replace the energy equivalent of a gallon of gasoline we would need approximately 1.5 gallons of ethanol or, to put it another way, a gallon of ethanol can contribute the energy equivalence of 0.66 gallons of gasoline

Some 3.4 billion gallons of ethanol were produced from corn in the United States in 2004, sold as a blend with gasoline accounting for about 2% of total gasoline sales in that year by volume, or 1.3% of sales by energy content (Davis and Diegel, 2004). By 2005, production had risen to 3.9 billion gallons accounting for 2.8% of sales by volume or 1.9% by energy content., reaching a level of 4.8 billion gallons per year by mid 2006,with plant under construction expected to add an additional 2.2 billion gallons of capacity over the next few years. Current federal policy in the United States sets a goal for up to 7.5 billion gallons of so-called renewable fuel to be used as an additive to gasoline by 2012 (Farrell et al., 2006). President Bush, in his State of the Union address on January 31, 2006 expressed an objective "to replace more than 75% of our oil imports from the Middle East by 2025".

Brazil is currently the world's largest producer of ethanol (the US is number 2). Some 4 billion gallons were produced in 2004 in Brazil as compared to 3.4 billion gallons in the US. The bulk of this production was consumed domestically, more than 80% in 2004. India is currently Brazil's largest customer for ethanol exports, just ahead of the U.S. with significant exports also to Venezuela and South Korea and prospectively (assuming significant growth in future Brazilian domestic production) to Japan (Lynch, 2006). Domestic demand is growing rapidly, however, in Brazil driven in part by the high price of oil, in part by the growing number of flex-fuel vehicles. Not surprisingly, prices have risen accordingly, by a record 14% in the month of March 2006 alone, raising questions as to the quantity of ethanol that might be available in the immediate future for export. Brazil, like the US, has plans for important future expansion of its ethanol production capacity.

Production of ethanol from either corn or sugar cane poses a dilemma: whether the feedstock should be devoted to food or fuel. With increasing use of corn and sugar cane for fuel, a rise in related food prices would seem inevitable. A potential future option that could avoid this dilemma would involve production of ethanol from cellulose, the ubiquitous component of indigestible grass and wood. Optimists foresee a future where currently idle land could be devoted to cultivation of fast growing grasses (prairie grasses for example) and trees (poplars and willows are mentioned) that could be harvested to produce cellulose to feed a new generation of ethanol factories capable of supplanting as much as 50% of current gasoline use with important savings in terms of emission of greenhouse gases – a great, new, domestically based, energy industry. This would require of course a major commitment of land, perhaps as much as a 75% of the land currently devoted to crops in the US.

Production of ethanol from corn is discussed in Section 12.2. Production from sugar cane is discussed in Section 12.3, with prospects for cellulose treated in Section 12.3. Concluding summary remarks are presented in Section 12.4.

12.2 Ethanol from Corn

Some 73.4 million acres of land were harvested for corn in the United States in 2004, accounting for approximately 23% of the nation's total cultivated land area (the total planted area amounted to 80.9 million acres). The United States is responsible for production of more than 40% of the world's corn. Most of this corn is fed to animals. Corn is traded in units known as bushels: a bushel consists of 25.4 kg or 56 pounds of kernels with a moisture content of about 15% composed of approximately 72.800 kernels. U.S production of corn in 2004 amounted to 11.8 billion bushels corresponding to an average yield of 160.8 bushels per acre (an 18% increase relative to 2003: variations in weather conditions play an important role in determining year-to-year variations in productivity). The fraction of the corn crop used to manufacture ethanol amounted to about 12% of total production in 2004 (1.4 billion bushels)*. Combining the value reported for the total quantity of corn employed in manufacturing ethanol in the United States in 2004 (1.4 billion bushels) with the total quantity of ethanol produced (3.4 billion gallons), we may conclude that 2.4 gallons of ethanol were produced for every bushel of corn consumed by ethanol factories in 2004. Domestic production of ethanol in the U.S. in 2004 fell short of demand by about 160 million gallons (4.5%). Imports - 86 million gallons from Brazil, 39 million from Jamaica, 25 million from Costa Rica and 6 million from El Salvador - made up the deficit.

Use of corn as a feedstock to produce ethanol has been a subject of considerable controversy. Much of the debate has focused on what is referred to as the net energy value (NEV) of corn based ethanol. This is defined conventionally as a measure of the difference between the energy contained in the final ethanol product as compared to the fossil energy consumed in its production. However, even the definition of NEV has been controversial. The question is how one should treat the energy content of products obtained coincidentally in conjunction with the manufacture of ethanol, what is referred

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* Data quoted here were taken from http://www.ethanolmarket.com/corngrains.html

(March 28, 2006). See also, Amber Waves November 2004. US Department of Agriculture: Economic Research Service, Marlow Vesterby and Kenneth S. Krupa.

to in the literature as the co-product credit (see for example the discussion in Farrell et al., 2006). Important co-products of ethanol production include dried distiller grains, corn gluten and corn oil. Should one simply credit the ethanol stream with the caloric energy content of these products? Or would it be more appropriate to estimate first the energy that would be consumed if these products were manufactured in the most efficient manner and to credit the ethanol stream then with the energy costs avoided by substitution of the ethanol co-products for the more conventionally produced alternatives? In estimating the energy input to ethanol production, should one account for the energy embedded in the facility in which the ethanol is produced - the energy consumed to make the steel, concrete and other materials involved in constructing the ethanol processing plant? Should we account also for the energy embedded in the farm machinery employed to plant, tend and harvest the corn in the field or the trucks used to transport the corn to the factory after harvest? Not surprisingly, there has been a tendency for proponents of ethanol to stack the numbers one way – to put their case in its most optimistic light – and for opponents to take the opposite tack. Normally, one might expect this not to matter too much. But in the case of the corn-ethanol issue the differences are large and have come to play an important role in the ensuing public debate. One side claims you have to put in more energy than you get back in the final ethanol product: the other disagrees. We shall attempt in what follows to clarify the essential elements of the controversy.

We shall distinguish from the outset between the energy required to produce the corn and the energy employed subsequently to convert the corn to ethanol. Approximately 30% of the total fossil energy employed in the production of ethanol is associated with planting, growing and harvesting the corn (we exclude from this consideration the solar energy used to grow the corn, the truly renewable input). To achieve the impressive yields of corn realized in the US in 2004 (more than 160 bushels per acre) farmers had to apply copious quantities of fertilizer and significant quantities of pesticides. On an energy basis, nitrogen is the most expensive of the fertilizer inputs. Nitrogen is readily available in the atmosphere. But to be incorporated in living tissue (growing corn for example) the triple bond linking the atoms of N in N_2 (the dominant form of nitrogen in the atmosphere) must be broken. Nitrogen incorporated in living tissue is referred to as fixed nitrogen. Examples of fertilizers delivering fixed nitrogen include ammonia (NH_3), urea ($CO(NH_2)_2$) and ammonium nitrate (NH_4NO_3).

To produce fixed nitrogen from atmospheric N_2 we need to supply energy. Natural gas (methane) is the most common source of the chemical energy used to fix nitrogen. The energy investment required to produce a pound of fixed nitrogen in the US averages 24,500 BTU per pound of N according to Shapouri and McAloon (2004), a little more if we allow for the energy expended in granulating, packaging and transporting the fertilizer. Typical recommended rates for application of nitrogen fertilizer range between about 120 and 140 pounds N per acre, or, assuming the yield for corn achieved in the US in 2004, between 0.8 and 0.9 pounds N per bushel. If we assume that 0.85 pounds of N were applied for every bushel of corn produced in the US in 2004, the energy investment in nitrogen required to produce a bushel of corn would have amounted to 20,825 BTU. Assuming a yield of 2.4 gallons of ethanol per bushel, the energy investment in nitrogen required to produce a gallon of ethanol (corresponding to a nitrogen input of 0.35 pounds N) would be equal to about 8,677 BTU corresponding to a little more than 11% of the energy incorporated eventually in the ethanol. Shapouri and McAloon (2004) quote a figure of 23,477 BTU for the average expenditure in nitrogen required to produce a bushel of corn in the US (reflecting presumably somewhat higher applications of N per bushel than assumed above). With the ethanol yield assumed here, this would imply that the energy investment in nitrogen required to produce a gallon of ethanol would be equal to 9,782 BTU or about 13% of the ultimate energy yield in the ethanol. We shall adopt in what follows the numbers recommended by Shapouri and McAloon (2004).

Growing corn requires an application of not only nitrogen but also phosphate and potassium. To achieve maximum yields we need in addition to apply pesticides and, in some cases, lime to increase the fertility of the soil. Accounting for these added energy investments, the energy associated with the application of N should be increased by about 6,534 BTU per bushel or 2,723 BTU per gallon of ethanol product according to Shapouri and McAloon (2004). We should allow also for the energy consumed by farm machinery, for the energy content of the seed, for the energy expended in drying and hauling the harvest, and for the energy deployed in irrigation (the energy used to pump water from below ground), the latter especially important when the corn is grown in dry environments such as Nebraska. Reflecting these additional expenditures, adopting nationally averaged figures recommended by Shapouri and McAloon (2004), the energy invested in corn production should be increased by a further 19,744 BTU per bushel, or 7,975 BTU per gallon of product. Combining these various components, would imply a total (US average) energy cost for production of a bushel of corn in the US in 2004 of 23,477 + 6,534 + 19,744 = 49,755 BTU, an advance payment of 20,731 BTU for the feedstock converted subsequently to a gallon of ethanol (assuming a yield of 2.4 gallons per bushel) corresponding to about 27% of the energy incorporated eventually in the fuel. The estimate of the fossil energy invested in producing a bushel of corn given by Shapouri and McAloon (2004) is almost a factor of 2 lower than the value reported by Pimentel and Patzek (2005), 94,693 BTU. A breakdown of assumptions implicit in the two analyses is presented in Table 12.1.

The estimates of energy expenditures by Pimentel and Patzek (2005) are systematically higher than those reported by Shapouri and McAloon (2004). Their value for nitrogen, for example, is larger than Shapouri and McAloon's recommendation by 21%. Farrell et al. (2006) suggested that the Pimentel and Patzek (2005) value was based on a numerical error introduced in translating the result presented earlier for nitrogen by Patzek (2004). It should be reduced, they suggest, by a factor of 1.23. Applying this correction, Pimentel and Patzek's value for nitrogen would be in good agreement with Shapouri and McAloon's result. Farrell et al. (2006) were critical also of the application rate for herbicides (6.2 kg per hectare) assumed by Pimentel and Patzek (2005), suggesting that this value may be too high by as much as a factor of 2. They disputed also Pimentel and Patzek's approach to estimating the energy embedded in farm machinery and dismissed out of hand their decision to charge for the energy included in the food consumed by farm laborers. On this latter point, we would agree without question: after all, farm workers have to eat whether or not they are involved in cultivating and harvesting corn! We concur also with their criticism of Pimentel and Patzek's estimate for the energy embedded in farm machinery. Their value is only slightly less than the total energy consumed directly on an annual basis by the machinery. Somewhat arbitrarily, we assign to the energy embedded in farm machinery a value of 2,000 BTU, equal to about 10% of Pimentel and Patzek's result for the annual energy consumed in the form of diesel and gasoline and in pumping water for irrigation. An amended version of Pimentel and Patzek's energy budget is included in Table 12.1.

Table 12.1 Energy (BTU) Required to Produce a Bushel of Corn. Comparison of Estimates by Shapouri and McAloun (2004) and Pimentel (2005).

Shapouri and McAloon (2004)		**Pimentel and Patzek (2005)**		**Pimentel and Patzek (2005) (revised)**	
Inputs	**Energy (BTU)**	**Inputs**	**Energy (BTU)**	**Inputs**	**Energy (BTU)**
Seed	603	Seed	6,005	Seed	6,055
Nitrogen	23,477	Nitrogen	28,507	Nitrogen	23,500
Potash	1,899	Potassium	2,923	Potassium	2,923
Phosphate	1,631	Phosphate	3,144	Phosphate	3,144
Lime	63	Lime	3,668	Lime	3,668
Diesel	7,491	Diesel	11,680	Diesel	11,680
Gasoline	3,519	Gasoline	4,716	Gasoline	4,716
LGG	2,108	Electricity	396	Electricity	396
Electricity	2,258	Irrigation	3,726	Irrigation	3,726
Natural Gas	1,846	Chemicals**	10,481	Chemicals**	5,000
Chemicals	2,941	Transport	1,968	Transport	1,968
Other*	1,919	Machinery	11,855	Machinery	2,000
Total	**49,753**	Labor	5,380	Labor	0
		Total	**94,500**	**Total**	**68,776**

*Other includes contributions from custom work (1581 BTU), purchased water (136 BTU) and input hauling (202 BTU).

**Includes contributions from herbicides (7,220 BTU) and insecticides (3,261 BTU).

The investment in energy required to produce a bushel of corn in our revised version of the Pimentel and Patzek budget is still larger than the value suggested by Shapouri and McAloon (2004) - by 38% - although the discrepancy is reduced significantly in this case relative to the 90% excess associated with the unamended Pimentel and Patzek budget. In an earlier study, Shapouri et al (1995) reported a value of 59.765 BTU for the energy required to produce a bushel of corn, a value intermediate between the more recent Shapouri and McAloon conclusion and our revised version of the Pimentel and Patzek analysis included in Table 12.1. For present purposes, we shall tentatively adopt a value of 55,000 BTU per bushel, slanted to the lower range of the values listed in the Table 12.1.

The first step in converting corn to ethanol involves separation of starch from other components of the corn. Starch accounts for a little more than 60% of the total mass of corn kernels (Graboski, 2002; Shapouri and McAloon, 2004) . The chemical composition of starch may be represented by the formula $(C_6H_{10}O_5)_n$. Glucose is produced from starch by hydrolysis (addition of a water molecule to each unit of the starch):

$$C_6H_{10}O_5 + H_2O \longrightarrow C_6H_{12}O_6 \qquad (12.1)$$

Ethanol is formed subsequently by fermentation, summarized by the net reaction:

$C_6H_{12}O_6$ (1 molecule of glucose) $\rightarrow$ $2C_2H_5OH$ (2 molecules of ethanol) + $2CO_2$ (12.2)

The initial fermentation process yields an ethanol/water mixture with an ethanol content of about 8%. A series of as many as three distillation steps must be carried out subsequently to produce ethanol at a concentration of 95%. Further processing is required to obtain essentially pure ethanol (99.5%). Before shipping, ethanol is denatured (made unsuitable for drinking) by addition of 5% gasoline.

All of this processing requires important inputs of energy. Shapouri and McAloon (2004) estimate that 49,733 BTU are required on average to produce a gallon of ethanol from corn, approximately 80% in the form of thermal energy obtained from a combination of natural gas and coal (mainly the former) with the balance supplied by electricity (a little more than 1 kwh per gallon). Their reconstruction of the total energy budget is summarized in Table 12.2. According to their analysis, before accounting for the energy value of co-products, production of ethanol is associated with a positive energy return: an investment of 72,000 BTU yields a gallon of ethanol with an energy content of 76,000 BTU corresponding to a net gain of 5.2%. Shapouri and McAloon (2004) assumed a yield of 2.66 gallons of ethanol from a bushel of corn. As discussed earlier, the statistical data for 2004 suggests a somewhat lower yield of 2.4 gallons per bushel. If we adopt this lower yield, Shapouri and McAloon's energy balance for ethanol would be slightly negative: production of a gallon of ethanol would require an investment of 3,799 BTU over and above the energy incorporated in the ethanol corresponding to a deficit of 5.0%. With the numbers recommended by Pimentel and Patzek (2005), the energy balance would be distinctly negative as indicated in Table 12.2: an additional 24,602 BTU would be required to produce a gallon of ethanol, a shortfall of 32%. Even taking into account the revisions to the Pimentel and Patzek budget proposed above, the energy balance is still negative, by 14,242 BTU per gallon or 19%. Note the relative agreement between Shapouri and McAloon (2004) and Pimentel and Patzek (2005) with respect to their estimates for the energy expended in converting the corn feedstock to ethanol. Both studies suggest an investment of about 55,000 BTU per gallon. The major discrepancies relate to the differences between their estimates for the energy expended in growing and harvesting the corn. There are important differences also in how they choose to compensate for the energy value of co-products.

Shapouri and McAloon (2004) begin by noting that only 66% of the corn mass (the starch component) is involved in producing ethanol. Most of the balance is converted to animal feed products. Accordingly, they reduce the energy invested in producing a gallon of ethanol by approximately 36%, from 72,052 BTU to 45,802 BTU (they charge only for the 66% represented by the starch component of the corn). The energy balance in this case is markedly positive, by 30,198 BTU per gallon, corresponding to a positive return on the energy investment of 66% (30,198/45,802). Accounting for the lower ethanol yield inferred here for 2004 (the second column in Table 12.2) the energy involved in producing a gallon of ethanol would be increased to 50,726 BTU (allowing for co-products as in Shapouri and McAloon). The return on the energy investment in this case, while still positive, is reduced to 50%. It is difficult, however, to justify Shapouri and McAloon's approach to estimating the energy savings associated with co-products. Implicit in their analysis is an assumption that obtaining animal feedstock by processing corn through an ethanol factory is energy efficient. This seems unlikely. It would seem preferable to estimate first the energy required to produce, by the most efficient (conventional) path, feedstock nutritionally equivalent to that represented by the ethanol co-products. The energy saved in the ethanol production stream should not exceed this limit.

Table 12.2 Energy Required to Produce a Gallon of Ethanol.

	Shapouri and McAloon (2001)		**Pimentel and Patzek (2005)**	
Process	**Energy [a] (BTU/gallon)**	**Energy [b] (BTU/gallon)**	**Energy [c] (BTU/gallon)**	**Energy [c,d] (BTU/gallon)**
Corn production	18,713	20,725	37,870	27,51
Corn transport	2,120	2,348	4,830	4,830
Ethanol production	49,733	55,079	56,415	56,415
Ethanol distribution	1,487	1,487	1,487	1,487
Total	72,052	79,639	100,602	90,242
Net energy value	+3,948	-3,639	-24,602	-14,242
Percent gain or loss	+5.2%	-5.0%	-32%	-19%

a. Corresponding to a yield of 2.66 gallons per bushel.
b. Assuming a yield of 2.4 gallons per bushel rather than the 2.66 gallons per bushel assumed by Shapouri and McAloon (2004).
c. Estimate of energy consumed in ethanol distribution taken from Shapouri and McAloon (2004).
d. Revisions to the Pimentel and Patzek (2005) budget as discussed in the text.

Estimating the energy value of co-products in this manner is referred to in the literature as the displacement method. Accepting the estimate of the displacement value reported by Farrell et al (2006), 14,738 BTU per gallon, the net energy investment required to produce a gallon of ethanol in the Shapouri and McAloon model should be raised to 57,314 BTU, representing a surplus of 18,686 BTU relative to the energy incorporated ultimately in the gallon of ethanol (a positive energy yield of 33%). Results for net energy yields (or deficits) corresponding to the variety of models discussed here are summarized in Table 12.3, with co-product energy values applied as indicated. Considering the uncertainties inherent in all of these analyses, we conclude that the energy balance for corn produced ethanol is marginally positive: the energy captured in the ethanol is greater than the fossil energy employed in its production by about 20 to 30%. The bulk of this fossil energy is supplied in the form of coal and natural gas, 51% . and 38% respectively, with petroleum accounting for as little as 6% according to the Ethanol Today model of Farrell et al. (2006). As indicated earlier, the energy content of a gallon of ethanol is equivalent to the energy content of 0.66 gallons of gasoline. We can think of production of a gallon of ethanol from corn therefore as an opportunity to forgo use of about 0.63 gallons of gasoline (allowing for the petroleum consumed in producing the ethanol). This obviously could be considered a benefit in the United States in terms of reducing demand for imported oil. A separate question is whether substitution of ethanol for gasoline makes sense economically. And we need also to assess the significance of the tradeoffs in terms of the environment, in particular the implications of a switch from gasoline to ethanol for emission of greenhouse gases.

Table 12.3 Estimate of net energy gains or losses associated with production of a gallon of ethanol from corn allowing for the energy value of co-products.

	Case A	Case B	Case C	Case D	Case E	Case F
Energy before allowing for co-products (BTU/gallon)	72,052	79,799	72,052	79,799	90,242	74,417
Co-products allowance (BTU/gallon)	26,250	26,250	14,738	14,738	14,738	14,738
Net energy cost (BTU/gallon)	45,802	53,549	57,314	65,061	75,504	56,679
Net gain or loss (BTU/gallon)	+30,198	+22,451	+18,686	+10,939	+496	+16,321
Percent gain or loss	+66%	+42%	+33%	+17%	+0.7%	+27%

Case A Refers to the original Shapouri and McAloon (2004) budget.
Case B Refers to the Shapouri and McAloon (2004) budget assuming ethanol yield of 2.4 gallons per bushel.
Case C Same as Case A but with co-product allowance reduced as recommended by Farrell et al. (2006).
Case D Same as Case B with Farrell et al. (2006) value for co-product allowance.
Case E Revised Pimentel and Patzec (2005) budget as indicated in Table 12.2 but allowing for energy benefit of co-products following Farrell et al. (2006)
Case F The Ethanol Today model of Farrell et al. (2006)

The wholesale price for neat (pure) ethanol in November 2005 was between $2.06 and $2.16 a gallon (Yacobucchi, 2006). Ethanol in the United States is used as a blend with gasoline, referred to as E10 (10% ethanol, 90% gasoline). Use of ethanol as a blend with gasoline is subsidized in the United States at a level of 51 cents a gallon of ethanol (the subsidy was 52 cents prior to 2004). The subsidy accrues in the form of an income tax rebate to the company that blends the ethanol with gasoline. The effective wholesale price for a gallon of ethanol was reduced therefore to between $1.44 and $1.45 in November 2005, roughly equal on a per gallon basis to the wholesale price of gasoline that prevailed at the same time (between $1.44 and $1.45 a gallon). By May 2006, however, it had risen to $2.65 a gallon. We must allow, however, for the fact that the energy content of a gallon of ethanol is much less than the energy content of a gallon of gasoline: it takes 1.5 gallons of ethanol to provide the energy punch of a gallon of gasoline. The subsidized price for a gallon of ethanol translates therefore on an energy basis to an equivalent wholesale price for a gallon of gasoline of $2.17 to $2.19 in November 2005. The customer was obliged consequently to pay an extra $.90 to $1.06 per gallon of gasoline equivalent on an energy basis as a hidden subsidy for ethanol when filling up his or her car in November 2005. The inequity was even more pronounced a few months later. The wholesale price of gasoline had risen in April 2006 to close to $2.00 a gallon. With ethanol selling at $2.65 a gallon, the energy equivalent price of ethanol was then close to $4.00 a gallon, almost twice the price of gasoline reflecting primarily an increase in demand for ethanol, driven mainly by moves to substitute ethanol for MTBE (methyl tertiary-butyl ether) as an antiknock additive to gasoline (use of MTBE is currently being phased out in the US due to concerns about the chemicals persistent carcinogenic contamination of groundwater). By July 2006 the wholesale price of ethanol had risen to $3.10 a gallon in corn producing states such as Illinois, touching close to $4.00 a gallon in California.

As noted earlier, approximately 4.4% of ethanol consumed in the United States ion 2004 was supplied by imports. Of this, 54% came from Brazil. The United States imposes a tax of 54c per gallon on imported ethanol in addition to a duty equal to 2.5% of the value of the imported product. The price of ethanol loaded on a ship in Brazil averaged 87c a gallon in 2004. Allowing for shipping costs the price per gallon for ethanol arriving at a port in the United States was $1.01. Adding the tax and import duty, the price climbed to $1.58 per gallon, competitive with prevailing, subsidized, prices in the U.S. at the same time. Ethanol imported into the U.S. in 2004 that did not originate in Brazil came mainly from countries in the Caribbean. There is a simple explanation for this. The U.S. Congress in 1984 passed the Caribbean Basin Initiative (CBI) designed to promote economic development in 24 Caribbean and Central American countries. The initiative included a provision that allowed ethanol made or processed in these countries to be imported duty free to the U.S., capped at a limit equal to 7% of U.S. ethanol consumption. In addition to this, a further 35 million gallons can be imported duty free if it is produced using 30% or more of local (CBI country) sugar cane. An additional 35 million gallons can be imported duty free if produced using 50% or more of locally grown sugar cane. U.S. companies are moving aggressively to take advantage of the loopholes available under the CBI. Cargill, for example, is negotiating to build a dehydration facility in El Salvador that would convert Brazilian ethanol to fuel grade product (by removing the residual water) to be imported subsequently duty free to the

U.S. Would it not be better to eliminate all of these barriers to trade at a time when ethanol is in short supply in the U.S. and when prices are at an all time high despite the 51c a gallon subsidy provided to domestic producers by the U.S. tax payer? To do so would provide a welcome break for the U.S. consumer, and at the same time a boon to the economies of developing countries such as Brazil. Everybody would win (except possibly Cargill and other similarly positioned companies). Why have we not done it? Put it down to U.S. domestic politics and the power of special interests.

Table 12.4 provides a list of the top-ten ethanol producers by capacity in the United States in 2006 (Renewable Fuels Association, January 2006). You should not be too surprised therefore when you see advertisements on television from Archers Daniels Midland trumpeting the merits of ethanol as a clean fuel that reduces our dependence on foreign oil, offering at the same time a potential solution to the problem of climate change. Is ethanol a good deal economically for the consumer? The answer is unequivocally no. Senator John McCain (2003) summed it up thus: "Plain and simple, the ethanol program is highway robbery perpetrated on the American public by Congress". Archers Daniel Midland and the other companies listed in Table 12.4 are the winners. Succinctly put, ethanol from corn offers an opportunity to convert coal and natural gas to a liquid fuel that can substitute partially for petroleum. But at the moment the price is unacceptably high. The consumer and the taxpayer are obliged to foot the bill. And the contribution of corn-based ethanol as a solution to the climate problem is marginal at best. The benefits from ethanol produced from sugar cane are more significant as discussed below.

Table 12.4: Major Producers of Ethanol in the U.S., 2006

Company	**Capacity (millions of gallons per year)**
Archer Daniel Midland	1070
VerSun Energy Corporation	230
Aventine Renewable Energy	207
Hawkeye Renewables	200
ASAlliances Bioenergy Corporation	200
Abenoga Bioenergy Corporation	198
Midwest grain Processors	152
U.S. BioEnergy Corporation	145
Cargill	120
New Energy Corporation	102
All Others	3658
Total	**6258**

Source: Renewable Fuels Association, U.S. fuel Ethanol Industry Plants and Production Capacity, January 2006. Includes capacities both for plants in production and under construction. Quoted from Yacobucci (2006).

Combustion of the fossil fuels involved in production of ethanol from corn is associated inevitably with emission of CO_2, the most abundant anthropogenic greenhouse gas. Application of nitrogen fertilizer in growing the corn leads to emission of a second greenhouse gas, nitrous oxide (N_2O), which is even more effective as a greenhouse agent than CO_2, by a factor of 296 on a molecule per molecule basis according to the Intergovernmental Panel on Climate Change (2001). Allowing for emissions of N_2O in addition to CO_2, Farrell et al (2005), in their Ethanol Today model, concluded that the climate impact of a corn-based ethanol-gasoline substitution was comparable to that of a gasoline-only system (a 13% reduction). The impact was somewhat more negative with their CO_2 Intensive model (this model accounts for plans to ship corn from Nebraska to a coal-fired ethanol plant in North Dakota): greenhouse emissions were increased in this case by 2 % relative to the gasoline-only standard.

12.3 Ethanol from Sugar Cane

On an energy basis, sucrose accounts for approximately 30% of the photosynthetic product of sugar cane, with the balance distributed more or less equally between leafy material normally left in the field after harvest (if not previously burnt) and bagasse, the fibrous matter that contains the sucrose (Wikipedea, 2006). The traditional practice for harvesting the cane involves first setting fire to the field in which it is growing. This has a two-fold purpose: first it acts to remove much of the extraneous vegetation; second, it acts to soften the cane, making it easier to harvest the crop. Harvesting cane in the traditional manner is a backbreaking, labor-intensive job. The cane in this case is cut by hand by laborers wielding machetes, not much different from the technique used by the slaves who supplied the labor for the first sugar plantations in the Caribbean. The sucrose content of the cane is concentrated near the base increasing the backbreaking nature of the work involved in its harvest. The worker engaged in this traditional harvesting practice is expected to harvest up to 10 tons of cane per day (Rohter, 2006) for a fraction of the wages earned by agricultural workers in the U.S. Increasingly though, the harvesting process is being mechanized in Brazil eliminating the need to burn the fields prior to harvest, providing higher paying jobs (but much fewer).

After it is harvested, the cane is transported to one of several hundred ethanol factories (distilleries) scattered across the cane-producing region of the country (concentrated in the south near Sao Paulo and in the northeast where climatic conditions are favorable for cultivation of the sugar plant). Once there, the cane is crushed through a series of rollers much like the rollers used of old to wring water from clothes after they had been washed. The juice extracted in this manner consists of a mixture of water and sucrose. The sucrose is concentrated by boiling off the water and is converted subsequently to ethanol by fermentation following the same procedures used to process corn to ethanol after the starch of the corn has been converted to sugar as discussed above. Burning bagasse left behind when the sucrose is separated from the cane provides the energy needed to boil off the water in the cane juice and to promote subsequent fermentation and concentration of the ethanol. Ethanol factories in Brazil are generally energy self-sufficient. Electricity requirements for the factories are met typically on site with turbines driven by steam produced by burning the bagasse, with a surplus available for sale to the national electricity grid. More than 1300 MW of electricity were generated in this manner in Brazil in 2001 with the excess of a little more than 10% (150 MW) sold to utilities (Wikipedia, 2006).

Ethanol as produced in Brazil today is clearly positive in terms of its implications for emission of greenhouse gases. The bulk of the CO_2 released either in the process of producing the ethanol or in its ultimate consumption represents CO_2 recycled by photosynthesis from the atmosphere. Fossil energy is consumed in producing the nitrogen fertilizer required to grow the sugar cane, in harvesting it (to the extent that harvesting is mechanized), in transporting the cane to the processing facility and in delivering the ethanol product to market. Emission of greenhouse gases (N_2O as well as CO_2) from the combination of these activities is more than offset, however, by the CO_2 saved by substituting ethanol for gasoline and the additional savings associated with the substitution of electricity produced by combustion of (photosynthetic) bagasse for electricity that would be produced otherwise by burning fossil fuels with associated emission of excess CO_2 to the atmosphere.

Today, approximately 50% of Brazil's sugar cane is used to make sugar with the balance devoted to production of ethanol. The decision on whether to make sugar or ethanol depends on prevailing prices for sugar and gasoline (ethanol's competition in the market). It is anticipated that in the future the balance will switch significantly in favor of ethanol (although that could change again as it did in the early 1990's depending on future trends in prices for sugar and oil). Current plans call for an investment in ethanol facilities of as much as $9 billion over the next six years with the aim of doubling the amount available for export by 2010 (Lynch, 2006). Annex 1 Parties to the Kyoto Climate Protocol (mainly countries of the European Union in addition to Canada and Japan - the United States and Australia declined to ratify the Protocol) are obligated to reduce emissions of greenhouse gases and clearly have an incentive to supply at least part of this capital. The Clean Development Mechanism (CDM) incorporated in the Protocol (Article 12) encourages investments by Annex 1 Parties in developing countries that can lead to net reductions in global emissions of greenhouse gases. Investing Parties are permitted under terms of the Protocol to assume credit for reductions certified under CDM. Credits so earned can be applied to offset obligations to which they are committed nationally under conditions of the Protocol.

An acre of land planted to sugar cane in Brazil today yields approximately 640 gallons of ethanol, an increase by more than a factor of 3 over yields achieved 25 years ago according to Luhnow and Samor (2006). This may be compared with the yield of ethanol obtained from corn in the U.S. in 2004, about 380 gallons per acre as discussed above. Production of 4 billion gallons of ethanol in Brazil in 2004 with a yield of 640 gallons per acre would have required processing sugar cane harvested from approximately 6.25 million acres, or 25,291 km^2 equal to about 0.3 % of the total land area of Brazil (9.37 billion km^2). In practice, the national average yield of ethanol was probably less than 640 gallons per acre (yields are appreciably lower in the northeast as compared to the south) and the estimate for the amount of land required to cultivate the necessary sugar cane should be increased accordingly. Wikipedia (2006) quotes a figure of 45,000 km^2 for land devoted to cultivation of sugar cane for purposes of ethanol production in 2000. This would correspond to a little more than 0.5% of the total land area of the country and represents probably a more reasonable estimate of the actual commitment. By way of comparison, the fraction of the land area of the lower 48 states of the U.S. used to cultivate corn for ethanol is equal to about 0.4 %, not very different from the fractional commitment of land to sugar cane ethanol in Brazil. The fraction of available solar energy converted to energy that can be employed as ethanol in the transportation sector is evaluated in Box 12.1.

A field planted to sugar cane can provide multiple crops. After the initial harvest, so long as the roots are not disturbed, the cane will regenerate. Up to ten harvests are possible as a result of a single planting. The yield of sugar cane from subsequent crops decreases with time, however, providing an incentive for early replanting. The high yield quoted by Luhnow and Samor (2006) may refer to experience relating to the early harvests following initial planting.

Box 12.1: Calculate the fraction of incident solar energy converted to ethanol by processing sugar cane under optimal conditions in Brazil. The average rate at which solar energy is absorbed by the Earth, as evaluated in Box 3.2, is equal to 241 W m^{-2}. Assume that solar energy available on average in the sugar cane growing regions of Brazil is approximately 25% higher than this, 300 W m^{-2}, reflecting the relatively low latitude of the cane growing region and the fact that the region is cloud free to a greater extent than the global average. Assume further that sugar cane grows for ten months a year (the harvest period lasts approximately two months). Assume a yield of ethanol of 640 gallons per acre as discussed above.

Solution:

As indicated earlier in this chapter, 1W is equivalent to an energy source of 9.48x10^{-4} BTU sec^{-1}. The total energy, E, available from the sun over a ten month period, assuming power input of 300 W m^{-2}, is given

$$\begin{aligned} E &= (3\text{x}10^2)(9.48x10^{-4})(2.62x10^7)\ \text{BTU m}^{-2} \\ &= 7.45\text{x}10^6\ \text{BTU m}^{-2} \end{aligned}$$

where 2.62x10^7 is the number of seconds corresponding to a time interval of 10 months. One acre corresponds to an area of 4.05x10^3 m^2. Hence the total solar energy available over a ten month period per acre, F, is given by

$$\begin{aligned} F &= (7.24\text{x}10^6)(4.05x10^3)\ \text{BTU} \\ &= 3.02\text{x}10^{10}\ \text{BTU} \end{aligned}$$

The energy content of a gallon of ethanol is equal to 7.6x10^4 BTU. The energy content of 650 gallons of ethanol, G, is given then by

$$\begin{aligned} G &= (7.6\text{x}10^4)(6.5x10^2)\ \text{BTU} \\ &= 4.94\text{x}10^7\ \text{BTU} \end{aligned}$$

It follows that the fraction, f, of the available solar energy converted to ethanol is given by

$$f = \frac{G}{F} = \frac{4.94x10^{7}}{3.02x10^{10}} = 1.6x10^{-3}$$

Conclusion: A little less than 0.2% of the available solar energy is converted to chemical energy in the form of ethanol, a reasonably impressive return given that sucrose accounts for only about 30% of the energy content of above-ground sugar cane biomass.

12.4 Ethanol from Cellulose

Cellulose, composed of long chains of glucose molecules, is the most abundant molecular component of the biosphere. Together with lignin, it is responsible for the structural integrity of plants - trees and grasses (trees are able to stand tall largely because of their cellulose and lignin). The primary cell walls of plants are composed mainly of cellulose with variable quantities of lignin included in the cell secondary walls. While cellulose is similar in elemental composition to starch, $(C_6H_{10}O_5)_n$, it is structurally quite distinct. Cellulose is an extended straight chain polymer: starch exhibits a characteristic coiled structure. Starch can be broken down more easily than cellulose to isolate its glucose components.

Cellulose cannot be digested directly by either humans or animals: ruminants (cattle sheep and goats) are able to live on cellulose but they do so through a symbiotic relationship with bacteria present in their stomachs (rumens). The grass the ruminant eats is processed and decomposed by the bacteria. The products of this decomposition provide the nutrient for the animal host providing at the same time nourishment for the bacteria (that is what we mean by a symbiotic relationship: profitable for both parties).

Several steps are required to produce the sugars from cellulose that can be fermented to make ethanol. First, the cellulose must be separated from the lignin. The preferred method in this case involves first breaking down the plant material into smaller units, elements no more than a few millimeters in size. The resulting pellets are treated subsequently by exposing them either to a dilute acid at high temperature (in excess of 230 C) or a more concentrated acid at lower temperature (100 C). The relatively large surface area relative to volume of the pellets as compared to the parent material promotes the efficiency with which the acid is able to access the plant material and isolate the cellulose. The advantage of the concentrated acid/low temperature treatment is that most of the sugar content of the cellulose is conserved, in contrast to the high temperature case where as much as 50% of the cellulose may be lost. The disadvantage is that the treatment takes a much longer time (hours) (Badger, 2002).

Further processing is required to release the fermentable sugars of the cellulose. The primary objective of current research is to find an economically efficient means to accomplish this task (Detchon, 2006). Genetic engineering of naturally occurring organisms offers a potential solution. Costs for production of the necessary enzymes have been reduced significantly (by a factor of 30) over the past five years as discussed by Detchon (2006). Ethanol is produced by subsequent fermentation following the methods discussed earlier for treating corn and sugar cane. A second possibility is to combine the two processes into a single procedure: to find (or more likely engineer) an organism that can both breakdown the cellulose and promote the fermentation required subsequently to produce the ethanol. This latter option is referred to as consolidated bioprocessing or CBP (NRDC, 2004).

There can be little doubt, in principle at least, that plant material can provide a viable source of ethanol. The challenge is to find the most efficient means to accomplish this objective, to assess its cost and future potential and to identify preferred sources of the necessary plant material, whether wood or grass or both. Current debate has focused on the potential of purposefully grown crops such as switchgrass or fast growing trees such as poplars and willows. It is clear that there is an opportunity also to use a variety of otherwise surplus or waste products including discarded paper, sawdust, and the stocks of crops such as corn and wheat (Detchon, 2006; Lave et al., 2001; NRDC, 2004).

Switchgrass is a perennial grass native to the American prairies (perennial means that after mowing, the grass will regrow: it does not need to be replanted). Since it is native, it is relatively pest resistant. Also, its demand for fertilizer, notably nitrogen, is significantly less than that for corn, by as much as a factor of 2 or 3 (NRDC, 2004; Pimentel and Patzek, 2005). It follows that the requirements for fossil energy inputs in growing switchgrass are significantly lower than those for corn (see the discussion in Section 12.2), particularly so if the energy stored in lignin is used to fuel the ethanol producing plant. Emission of greenhouse gases (allowing for the different climate-altering potential of the different gases) is reduced as a consequence, by close to 86% according to Farrell et al., 2006 (comparing their "Ethanol Today" and "Cellulosic" models).

The stated objective of the US Department of Energy is for ethanol production in the US to rise to the point where it can displace 60 billion gallons of gasoline annually by 2030 (US DOE, 2006). Given the lower energy content of ethanol relative to gasoline, this would require an annual production capacity for ethanol of 90 billion gallons. Is this realistic? How much land would it take?

The total land area of the US amounts to a little less than 2.3 billion acres, 1.9 billion acres in the lower 48 states. The United States Department of Agriculture (USDA) classifies agricultural land under four categories: cropland, grassland pasture and range, forest use land and land devoted to other special purposes (including highway, road and railroad rights-of way, national and state parks, wilderness areas, urban areas and land restricted for defense or industrial purposes). Cropland is further divided into land actively planted with crops, land that could be planted with crops but is currently idle (including land enrolled in the federal Conservation Program[*]), and cropland used only for pasture. The total land area devoted to agriculture in the US in 2002 amounted to 1.17 billion acres, almost all in the lower 48 states. Of this, cropland accounted for 442 million acres, grassland 584 acres with forested land used in part for grazing (generally forested areas occupied in part by grass) contributing an additional 134 million acres. Some 1.09 billion acres were classified as non-agricultural land, 723 million acres of this in the lower 48 states. A summary of US land use is presented for 2002 in Table 12.5. Trends over time are illustrated in Figure 12.2.

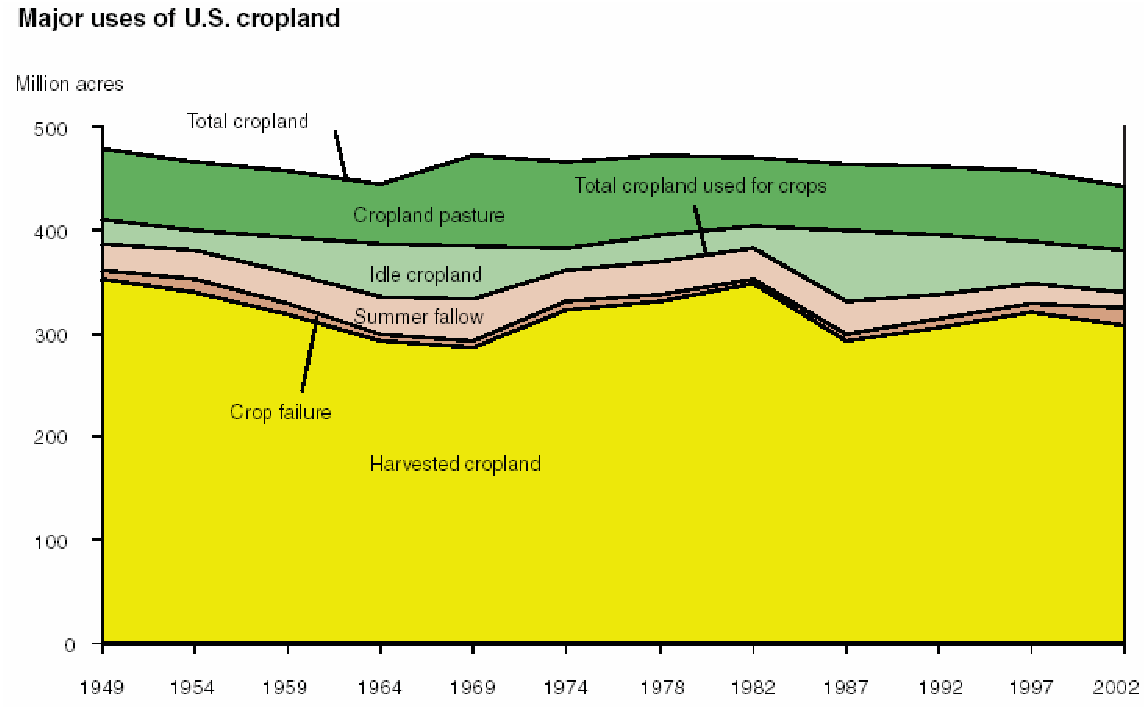
Major uses of U.S. cropland
Million acres
Total cropland
Total cropland used for crops
Cropland pasture
Idle cropland
Summer fallow
Crop failure
Harvested cropland
500
400
300
200
100
0
1949
1954
1959
1964
1969
1974
1978
1982
1987
1992
1997
2002

Figure 12.2

Table 12.5

Agricultural and nonagricultural uses of land, United States, 2002

Land use	Acreage 48 States	Acreage U.S.	Proportion of total 48 States	Proportion of total U.S.
	-----*Million acres*-----		-----*Percent*-----	
Agricultural				
Cropland:				
Cropland used for crops [1]	340	340	18.0	15.0
Idle cropland	40	40	2.1	1.8
Cropland used only for pasture	62	62	3.3	2.7
Grassland pasture and range	584	587	30.8	25.9
Forest-use land:				
Forest land grazed	134	134	7.1	5.9
Special uses:				
Farmsteads, farm roads	11	11	0.6	0.5
Total agricultural land [2]	1,171	1,174	61.8	51.8
Nonagricultural				
Forest-use land:				
Forest-use land not grazed [3]	425	517	22.4	22.8
Special uses:				
Transportation uses [4]	27	27	1.4	1.2
Recreation and wildlife areas [5]	100	242	5.3	10.7
National defense areas [6]	15	17	0.8	0.8
Urban land	59	60	3.1	2.6
Miscellaneous other land [7]	97	228	5.1	10.1
Total nonagricultural land [2]	723	1,091	38.2	48.2
Total land area [2]	1,894	2,264	100.0	100.0

[1] Cropland harvested, crop failure, and cultivated summer fallow.
[2] Breakdown of land uses may not add to totals due to rounding.
[3] Excludes 98 million acres of forest land in parks and other special uses.
[4] Rural highways, roads and railroad rights-of-way, and rural airports.
[5] National and State parks and related recreational areas, national and State wildlife refuges, and national wilderness and primitive areas.
[6] Federal land administered by the Department of Defense for military purposes and land administered by the Department of Energy.
[7] Includes miscellaneous uses not inventoried, and areas of little surface use such as marshes, open swamps, bare rock areas, desert, and tundra.
Sources: Estimates are based on reports and records of the Bureau of the Census (HUD/BOC, 1992, 2002, 2003) and Federal, State, and local land management and conservation agencies, including DOI/BLM, 2003; DOT/BTS, 2004; DOT/FAA, 2002; DOT/FHWA, 2002; DOT/FRA, 2004; USDA/FS 1989, 1998; DOI/FWS, 2001; GSA, 2001; GDT, 2000; USDA/NASS, 2004a, 2004b, 2005; DOI/NPS, 2002; USDA/NRCS, 2000, 2004a; and WI, 2002.

*The Conservation Reserve Program (CRP) was established in 1985 to compensate farmers who committed voluntarily to retire land considered environmentally sensitive.

Commitment periods under the program range from 10 to 15 years. Funds devoted to the program in 2002 amounted to $1.6 billion. Cropland retired under the program amounted to 34 million acres in 2002 (Lubowski et al., 2002).

As discussed earlier, 2.4 gallons of ethanol were produced from a bushel of corn kernels in 2004 (see Section 12.2). The mass of a bushel of corn is equal to 25.4 kg. It follows that approximately100 gallons of ethanol were produced from a ton of corn kernels in 2004. We shall assume as a point of departure that the yield of ethanol from biomass is similar to that for corn (1 ton biomass: 100 gallons of ethanol). Production of 90 billion gallons of ethanol would require therefore a source of 900 million tons of biomass. The yield of corn kernels from an acre of land in 2004 was equal to approximately 160 bushels, implying that the yield of biomass in the form of corn kernels from an acre of land in that year was equal to approximately 4 tons. If the biomass yield of cellulose per acre was comparable to that realized for corn kernels in 2004, it follows that we would require 225 million acres of land to replace 60 billion gallons of gasoline - more than six times the cropland acreage idled under the Federal Conservation Reserve Program (CRP), 60% of the land currently under active crop cultivation or 39% of all grassland and range. To displace 50% of current gasoline consumption we would need more than seven times the amount of cropland idled under CRP, 75% of all of the cropland currently in use or 49% of all grassland and range, a formidable commitment especially if the goal is at the same time to maintain current output from the agricultural sector. Details of these computations are summarized in Box 12.2.

A little more than half of the price of ethanol produced from corn in the US is represented by the cost of the corn feedstock (Pimentel and Patzek, 2005). The cost of cellulose is unlikely to exceed that of corn, but it could be comparable, especially so if marginal lands had to be developed (requiring extensive irrigation for example) to supply the necessary cellulose. The expense in producing ethanol from cellulose will be greater of necessity than the expense involved in producing it from corn. It is impossible, however, to assess the magnitude of these costs until the details of the manufacturing strategy are defined. It is clear though that for cellulosic ethanol to be viable it must be able to compete economically with ethanol from corn and both must be competitive with gasoline. The challenge here is that the price of gasoline is linked inextricably to the international price of oil and, as recent history has demonstrated, this can change rapidly, with price swings in both upward and downward directions. A prospective ethanol industry could be stillborn if oil prices were to drop markedly below $50 a barrel. Given the significant sources of capital required to develop a large-scale, national, ethanol manufacturing capacity, investors will need assurance for a reasonable return on their investments before committing their money.

This assurance could be provided by introducing a tax on gasoline linked to the production price for ethanol on an energy equivalent basis. The tax should increase in this case in response to a drop in the price of gasoline and would be unnecessary if the price of gasoline were to rise above some predetermined threshold. Given the political opposition to "new taxes", it would be important that such a tax should not be perceived as an additional source of government revenue. Revenue raised should be applied to reduce other government expenditures, ideally to compensate those most impacted by a gasoline surcharge – specifically the least advantaged members of our society. It could be applied for example to reduce the tax rate for lower income wage earners, or to decrease the taxes they pay for social security, or for a myriad of other, socially-desirable, revenue-neutral, purposes. It would fall on politicians to work out the details and convince citizens of the merits of any such gasoline/ethanol tax proposal.

Ethanol from cellulose has the potential to markedly reduce our dependence on imported oil, even though the goal to replace 50% of current domestic use of gasoline may be unrealistic (given the requirements for land and the competition with land required for agriculture). Replacing some portion of gasoline use with cellulose-produced ethanol can provide for an important reduction in emission of greenhouse gases. To realize the full environmental and fossil energy saving potential of cellulose produced ethanol, it will be important, however, to make use of the lignin associated with the cellulose in manufacturing the ethanol. Whether this happens in practice will depend inevitably on considerations of cost. In principle, corn stocks could be harvested in combination with corn kernels and the energy content of the stocks could be employed to provide the heat needed to fuel the boilers of the ethanol plants and to generate or at least supplement requirements for electricity (as with bagasse in Brazil). In practice, though, operators of corn based ethanol plants find it more economical in the US to use commercially available coal and electricity to supply their needs for energy.

Farrell et al (2005) estimate that the savings of oil in energy terms for cellulose produced ethanol used as a substitute for gasoline could amount to as much as 93% with reductions in greenhouse gas emissions (on a climate-altering equivalent basis) as large as 88 %, clearly a positive on both scores. Until the source of the cellulose, the means for its production and the details of its subsequent conversion to ethanol are clear, it will be difficult to assess definitively the accuracy of their conclusions.

12.5 Summary and concluding remarks

We provided a detailed discussion in Section 12.2 of the complex arguments relating to the use of corn-based ethanol as a substitute for gasoline in the US. The reader may have been understandably confused by the plethora of numbers quoted in this context. Hopefully, though, the Tables included in the Section provide a convenient summary of the facts.

We addressed a number of issues. The first concerned the energy balance of corn-based ethanol – inputs and outputs - associated with production of ethanol from corn. How does the fossil energy expended in producing ethanol compare with the energy recovered in the ethanol? Proponents, notably Shapouri and McAloon (2004), argue that the energy balance is distinctly positive (you invest much less than you gain by way of return). Opponents, Pimentel and Patzek (2005) for example, reach the opposite conclusion. We reviewed the arguments in Section 12.2 and reached the conclusion that the truth lies somewhere in the middle. As best we can tell with current data, the energy balance is mildly positive, by 20% or so, in agreement with conclusions reached earlier by Farrell et al (2005).

There is a net saving of gasoline and therefore imported oil associated with the use of ethanol produced from corn. The fossil fuel inputs employed in production of the ethanol under current practice in the US involve mainly coal and natural gas. We concluded that a gallon of ethanol could displace approximately 0.63 gallons of gasoline.

The savings in greenhouse gas emissions associated with corn derived ethanol are minimal when we consider the entire life cycle of the product, from the field used to grow the corn to the factory used to covert it to ethanol. The carbon transformed to CO_2 and released to the atmosphere when the ethanol is consumed may be considered simply as a return of carbon to the atmosphere, replacement of carbon taken up earlier by the corn plant when it grew using photosynthesis. But along the way, fossil energy was consumed - in planting, growing, harvesting and processing the corn - and extra CO_2 was added to the atmosphere - the carbon bound up for hundreds of millions of years in coal, oil and natural gas. In addition, microbial processing of nitrogen applied as fertilizer in the cornfield is responsible for emission of a greenhouse gas, N_2O, that is almost 300 times more efficient on a molecule per molecule basis than CO_2 as a climate-altering agent. The net result is a wash: the climate impact of using ethanol produced from corn is about the same as for gasoline when we take into account the detailed life cycles of the two products.

A recent General Motors advertisement, lauding the potential of corn-based ethanol, begins with the slogan: “Live green, go yellow”. The advertisement was taken to task by no less than the influential Consumer Reports magazine in its October 2006 issue. In an article titled “The ethanol myth”, the magazine reports on a test conducted using a 2007 Chevrolet Tahoe Flexible Fueled Vehicle (FFV) running on 85% ethanol, 15% gasoline (E85). The retail price of E85 at the pump in August 2006 averaged $2.91 a gallon. They found that the mileage of the car they tested running on E85 decreased from an already low 14 miles per gallon (mpg) on gasoline to 10 mpg on E85. To realize the same mileage with gasoline (accounting for the lower energy content of ethanol) they concluded that motorists would have had to pay $3.99 for a gallon of gasoline: clearly not a good deal. The price of ethanol may be artificially high at present reflecting a temporary mismatch between supply and demand. And it is possible that it could decrease significantly in the future with anticipated expansion of production capacity. In the long term, though, competition with the demand for corn as a feedstock for animals in the US and as a valuable commodity for export poses a dilemma. The advantages for the environment, specifically the contribution corn-based ethanol could make towards mitigating the problem of global climate change, are limited and would not appear to justify the cost of a major expansion of corn-based ethanol in the foreseeable future.

Prospects for ethanol as produced from sugar cane in Brazil are more promising. The yield of ethanol per acre planted with sugar cane is greater than for corn and there is potential for significant expansion of future production. Demand for ethanol in the US, in Europe, in Japan and elsewhere is likely to grow significantly over the next few years: Brazil may be best equipped to meet this demand. A potential problem could arise, however, if expansion of sugar cane production in Brazil were to increase pressure for conversion of land currently occupied by rain forest to purposes of agriculture, compensating for example for pasture lost in the subtropics, displaced as the result of an increased commitment to sugar cane. A large fraction of the world’s above ground carbon is stored in tropical rain forests. Current studies suggest that deforestation in the tropics is responsible for addition at present of as much as two billion tons of carbon every year to the atmosphere, 30% of the contribution from global consumption of fossil fuels

(McElroy, 2002). From an environmental point of view, it would be unfortunate if savings in greenhouse gas emissions associated with substitution of biomass produced ethanol for gasoline were to be offset by destruction of a critical global ecological resource, the tropical rain forests, site of so much of the world's irreplaceable biological diversity (Wilson, 1992).

In the long run, ethanol produced from cellulose may hold the greatest promise, as an environmentally constructive alternative to fossil fuel derived gasoline. Vast reservoirs of cellulose are stored in the boreal forests of Canada and Russia. And there is potential for significant production from switchgrass and other sources in the US and elsewhere (Argentina for example). Whether cellulose lives up to its promise as a source of fuel competitive with gasoline will depend, however, on results from the ongoing research program and on considerations of economics that are difficult to predict given uncertainties in what the future cost of ethanol produced from cellulose will be, in addition to uncertainties in the future price of oil. Creative public policy initiatives may be required to ensure a level playing field for ethanol and may be justified ultimately by considerations of the implications for global security and for the health of the global environment.

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