Promise and Cost of Cellulosic Ethanol for the U.S. Light-Duty Fleet

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ABSTRACT

Ethanol from biomass (trees and grasses) can provide a significant proportion of the fuel for the light duty fleet, alleviating concerns about volatile prices, energy dependence, and global warming. We examine the costs and quantity of ethanol that can be produced from corn and biomass, as well as infrastructure issues associated with transporting and retailing ethanol for blending in gasoline. Large, but feasible, amounts of land and investment are required. Large-scale production is unlikely to occur until biomass ethanol becomes cheaper than gasoline or is mandated by regulation of gasoline fuel economy or carbon dioxide emissions.

INTRODUCTION

Motorists desire inexpensive, safe, energy dense fuel. Gasoline and diesel have the desired attributes, aside from their steep price fluctuations. However, after adjusting for inflation, gasoline in the U.S. is much cheaper today than it was in the early 1980s, and is near its early 1970s level.

Almost all motorists are also voters. As citizens we have very different desires than we do when we stop to refuel our vehicles. While refueling costs are an issue, as citizens we are also concerned about environmental issues including air pollution, sustainability, and resource use. In particular, we are concerned about urban ozone, global climate change, and running out of inexpensive petroleum and other non-renewable resources. Vehicle tailpipe emissions are a major cause of urban ozone as well as a major source of carbon dioxide, the dominant greenhouse gas, causing global climate change. In addition to these environmental concerns, our massive imports of petroleum raise world prices and increase U.S. balance of payment deficits, both of which transfer economic and political power to the Persian Gulf nations. Our dependence on imported oil leads to higher defense expenditures, risks of war, and promotes

political instability in the Middle East. Finally, high petroleum prices make it more difficult, or even impossible, for poor nations to raise their standards of living.

Fuelling vehicles with ethanol from biomass (e.g., trees and/or grasses) can help to address each of these issues. Cellulosic ethanol is a sustainable, renewable, clean burning, uniform fuel with essentially no sulfur (which fouls emissions control systems on today's vehicles). Powering the light duty fleet with cellulosic ethanol has the potential to end net carbon dioxide emissions, since the growing plants would adsorb all the carbon dioxide emitted into the atmosphere. Trees and grasses to provide the biomass could be produced sustainably to enhance soil quality, reduce or eliminate soil erosion, and reduce flooding. Growing this biomass would enhance, not reduce, the ability of future generations to feed themselves or produce biomass ethanol. Ethanol would be produced within the USA and so there would be no balance of payments issues and no transfer of economic power to OPEC nations. World trade in ethanol, with nations such as Brazil and Argentina exporting billions of gallons of ethanol each year, would erode OPEC's power and reduce the danger of war in the Persian Gulf. Finally, growing biomass and transforming it into ethanol would produce many new jobs, particularly in rural areas.

Unfortunately, producing cellulosic ethanol to fuel a large part of the light duty fleet presents several difficulties. These include the following (to be addressed in more detail in the remaining sections of the paper):

- of primary importance, ethanol is currently more expensive than gasoline and is projected to remain so for the near and midterm [CEC 2001],
- growing biomass for the ethanol feedstock requires a great deal of land, which raises land use and ecosystem issues,
- the current fuel distribution system is not well adopted to distribute ethanol,

- although conventional gasoline light-duty vehicles sold in the US are designed and certified to run on "gasohol" (gasoline with up to 10% ethanol), these vehicles would have to be modified to run on gasoline blends with more ethanol,
- low level ethanol-gasoline blends, especially E10 to E20, are more volatile than either neat gasoline or neat ethanol (these hydrocarbon emissions promote ozone formation).

ETHANOL AS A MOTOR FUEL

Approximately 1% of the U.S. highway motor vehicle fuel market is ethanol blended with gasoline. The 1.4 to 1.8 billion gallons of ethanol are almost entirely produced from corn. The corn ethanol industry would disappear without federal and state tax incentives or requirements, as described in COST OF MOTOR FUELS. The federal and state incentive programs were designed to increase the price of corn to help farmers and to make a modest reduction in oil imports.

Knowledge of how to transform corn into ethanol is quite old. The potential amount of ethanol that can be produced from corn is limited. Much more ethanol could be obtained from cellulose, a process still undergoing rapid improvement. However, growing corn is more energy and labor intensive than growing trees and grasses. The net energy from growing corn to produce ethanol is not great, since petroleum is used for making fertilizer, running farm equipment, and harvesting and producing the ethanol. In contrast, trees and grasses are bred to maximize biomass output, not food output. Thus, the biomass yields are higher and farmer requires less pesticides, fertilizer, and irrigation. As the technology matures, producing ethanol from trees and grasses will give higher yields, greater total productivity, and lower cost.

COST OF PRODUCING ETHANOL

Gasoline currently sells for just over \$1 per gallon at the refinery gate (net of taxes, distribution and retailing costs); an equivalent amount of ethanol (accounting for ethanol's lower energy density) is expected to cost perhaps \$1.70. A recent study by the California Energy Commission [CEC 2001] reports a near term Target Ethanol Price for California from woody and agricultural feedstocks of \$1.69-1.73 per gallon ethanol and a midterm price of \$1.23-1.24/gallon ethanol – these Target Prices are defined as the required sales prices needed for profitable plant operation, or a sales price where an ethanol plant would be sufficiently profitable to achieve a rate of return expected by investors. The Target Price includes operating costs, debt service and return on investment. An assessment of the potential of biomass ethanol for the U.S. recently completed for the International Energy Agency [IEA 2000] estimates near term base case lignocellulosic ethanol production costs (cash costs only) of \$0.182/liter (\$0.69/gal) ethanol and

including capital recovery, \$0.359 per liter (\$1.36/gal) ethanol. These values are per gallon of ethanol, not to be confused with per gallon gasoline equivalent.

Ethanol currently enjoys federal and, in some places, state tax incentives for volumes of 10, 7.7 and 5.7 % in gasoline. The federal gasoline excise tax exemption on ethanol is currently \$0.053 per gallon and the full exemption applies to ethanol/gasoline blends at 10%, with proportionately smaller amounts applying to the lower blends. The exemption provides a \$0.53 per gallon exemption from excise taxes for each gallon of ethanol that is blended with gasoline. The state subsidy can be much higher. For example, Louisiana exempts gasohol from state sales tax if the ethanol is produced within the state.

The federal incentives are scheduled to expire in 2007. Dropping the \$0.53/gal subsidy likely would end production of ethanol from corn, unless the oxygenate requirement raises the price that gasoline retailers are willing to pay for ethanol. The tax subsidy for higher ethanol blends, such as E85, is smaller and so this fuel is more expensive than gasoline and is not produced (estimated to be \$0.35 per gallon ethanol to producers for E85 [CEC 2001]).

ETHANOL PRODUCTION ISSUES

Corn is the largest source of feedstock for ethanol production today in the US. In 1998, 10 billion bushels of corn were produced, of which 5% was used to make ethanol. Some small amounts of ethanol are produced from waste materials: beverage, whey, potato wastes and paper wastes. These waste materials account for about 5% of the 1.4 billion gallons of ethanol produced in 1999.

Corn derived ethanol, whether produced by wet milling or dry milling ultimately, converts corn starches and sugar to ethanol via fermentation. The main differences in the dry versus wet milling processes are related to the number of co-products produced from each process. Dry milling produces a single co-product (distiller's dried grains with solubles (DDGS) an animal feed supplement), while wet milling produces multiple products (starch sweeteners, gluten feed and meal, along with corn oil.

Ethanol from lignocellulosic feedstocks is a less proven process for producing ethanol. Cellulosic processing has been developing since the early 70's. The main differences between corn processing and cellulosic feedstocks revolve around the front-end processes used to convert the feedstock to fermentable sugars. Starch and cellulose are essentially long polymers of sugars. However, in cellulose the fermentable sugars are found in a complex of cellulose bound with lignin and hemicellulose. This combination requires more intense processing using steam and acid, much harsher conditions than needed to remove starch from the corn

kernel. Processing converts the hemicellulose to an array of C₅ sugars, which engineered microorganisms can convert to ethanol. Traditional ethanol fermenting microorganisms are used to convert the glucose (a C₆ sugar) obtained from cellulose to ethanol. Almost, all plant designs use the lignin for fuel within the plant and excess heat is converted to electricity for sale.

The US Department of Energy (DOE) has investigated various cellulosic processing options and believe that an enzyme based simultaneous saccharification fermentation (SSF) process is the most promising process for conversion of cellulose to ethanol [Wooley 1999]. Commercial processes are currently under development with Iogen Corporation and BCI at the most advanced stages.

The DOE process starts with reducing the size of the incoming feedstock; it is then treated using dilute acid at high temperature. The acid hydrolyzes the hemicellulose to constituent five carbon (C₅) sugars, mainly xylose and arabinose. The hemicellulose digestion makes the cellulose more available to enzyme treatment. Part of the cellulose/lignin complex is used to generate cellulases, the enzymes responsible for converting cellulose to glucose. The remaining cellulose/lignin, cellulase, and the C₅ sugars are combined and the appropriate microorganism is added to ferment the sugars to ethanol. Ethanol is separated from the solids, unreacted lignin. The lignin stream is burned to produce steam and electricity. Distillation and a molecular sieve are used to separate the ethanol.

Agricultural wastes and municipal solid wastes are likely to be the first sources of cellulosic feedstocks, due to availability, costs and the need to solve existing environmental problems related to the wastes. The most prominent among the waste cellulosic possibilities are corn stocks, sugarcane, bagasse, and various straws (wheat, rice, etc.). For larger amounts of biomass, dedicated energy crops such as switchgrass and poplars would be grown.

Growing woody and herbaceous biomass to make ethanol is land intensive. Replacing the 130 billion gallons of gasoline used in the U.S. light-duty fleet would require an estimated 300-500 million acres. While there is land in the US to grow this biomass, almost all the arable land not currently used for crops, pasture, housing and roads, national forests and parks would be required. If this much land were devoted to biomass production, care would have to be taken to ensure that land for recreational opportunities increased and that biodiversity was not harmed.

INTRODUCING ETHANOL: A SCENARIO

Consider a scenario in which ethanol production is increased aggressively. In particular, assume that the goal is to provide 10% of motor fuel in the form of

gasohol with 10% ethanol. If so, about 14 billion gallons of ethanol would be required. This is an ambitious scenario, projecting ethanol use beyond the levels normally considered. For example, IEA 2000 looks at two future biofuels scenarios. The first offers a modest increase (10%) in use over 5 years and the second, a dramatic increase over 10 years to 5% of total motor fuels use (43 billion liters would be used in the US per year).

Producing the level of ethanol for our scenario would require an investment in the associated infrastructure of the new fuel. Some of this infrastructure is already in place, supporting the current 1.4-1.8 billion gallons of ethanol use. However, the increased production of ethanol from corn and cellulose would require changes in feedstock production and transportation, ethanol production, and ethanol distribution and retailing.

ETHANOL FROM CORN

The corn milling industry could potentially produce up to 5 billion gallons of ethanol before co-product market saturation makes ethanol production uncompetitive. Unless other co-product alternatives develop, this could be viewed as a production ceiling for corn derived ethanol. The current milling industry capacity is around 2 billion gallons. The additional 3 billion gallons could be derived from process improvements (ethanol yield from starch or conversion from corn fiber), increased corn yields (bushels/acre) and/or additional planted acreage.

A National Research Council [NRC 1999] study estimates that 2 billion gallons of ethanol could be derived just from increased corn yield. The final billion gallons of ethanol would require an additional 3 million acres of corn, about a 4% increase in acreage dedicated to corn production. Some of this additional acreage could be offset by process improvements. Such improvements are expected to increase ethanol yield from starch by at least 10%. The DOE, the US Department of Agriculture, and the National Corn Growers Association are investigating the use of corn fiber (now sold with gluten feed) to increase ethanol yield further from a bushel of corn. If successful, this development could increase overall ethanol yield by 20%. If all wet mills adopted this strategy, an additional 400 to 700 million gallons of ethanol could be produced annually. Corn derived ethanol should be looked at as low risk ethanol production since it will be based on an expansion of proven technologies, use of conventional agriculture and feedstock and the ethanol product will be handled and shipped via an incremental use of the present infrastructure (rail, tanks, trucks etc). New plants would take 3 to 5 years to build and commission. On-site expansion of existing facilities could be done sooner. Thus, the industry could be expected to expand as demand dictates. However, corn production is unlikely to provide 14 billion gallons of ethanol; cellulosic ethanol would be needed.

Potential Ethanol Capacity of Corn Milling Industry	
Source of Ethanol	Amount of Ethanol (Billions of Gallons)
Current Capacity	2.3
Increased Corn Yields	2.0
Additional Acreage	1.0 ¹
Total	5.3

¹ - Possible Process Improvement 0.7 to 1.0 billion gallons could offset acreage needs

ETHANOL FROM BIOMASS

Among the waste cellulosic possibilities, corn stocks are available in the highest amounts, as much as 100 to 200 million metric tons per year. Bagasse could contribute 700,000 metric tons. Using the more conservative figures, and if all of the corn stocks and bagasse were collected, about 6.5 billion gallons of ethanol could be produced annually. However, only 30 to 60% of the total corn stocks and bagasse could be collected, reducing the potential ethanol to 2 to 4 billion gallons annually. In optimistic estimates, DOE has suggested that 14 billion gallons of ethanol could be produced from this source meeting the needs of E10 in the US.

The yield of corn waste per acre is about 1.6 tons. Energy crops have a 3 to 5 fold yield advantage (switchgrass yields about 5.5 tons/acre). The amount of ethanol produced from a ton of agricultural waste is essentially the same as that produced from a ton of energy crops. The overall ethanol production economics is extremely sensitive to feedstock associated cost of which transportation costs could be as high as \$5 per ton. Concentrating on switchgrass and using published conservative yields for both production of switchgrass and ethanol production from switchgrass, it would take 80 to just over 100 million metric tons of switchgrass to generate the remaining 6 to 8 billion gallons of ethanol needed for E10. 16-21 million acres of land would be required to produce this biomass, which could be drawn from idle or marginal farmland.

Sources of Ethanol for E10 production		
Feedstock Source	Potential Production (billion gallons)	Estimated Land Required (million acres)
Corn	5	3
Agricultural Residue	2 to 4	-
Energy Crops	6 to 8	16 to 21

ETHANOL CAPITAL REQUIRMENTS

The capital cost for corn ethanol facilities is estimated to be \$2 per annual gallon of ethanol capacity. If the corn-milling infrastructure expands to its estimated 5 billion gallons maximum capacity, the capital cost of this

expansion would be approximately \$6 billion. Even the most optimistic cellulosic ethanol capital costs are \$4 per annual gallon of capacity and are about the same for bagasse or switchgrass. To produce the 14 billion gallons of ethanol required to make all gasoline into E10 would require an investment of \$38 billion. A commercial scale cellulosic plant is estimated to produce 50 million gallons of ethanol per year. 160 new plants would be needed to produce the additional 8 billion gallons of cellulosic ethanol along with a 15 large corn process facilities producing 200 million gallons of ethanol per year per plant. To put this into perspective the oil industry has 244 refineries in the US and the corn milling industry currently has 58 wet mills.

CONCLUSION

Ethanol, particularly that produced from energy crops, could provide much or all of the motor fuel in the USA, replacing almost all gasoline. The principal advantages of doing so are:

1. A large step toward energy independence,
2. Lower pollutant emissions, and
3. No net carbon dioxide emissions.

The principal disadvantages are:

1. The cost is estimated to be 60-70 cents per gallon higher than gasoline, at least in the short run,
2. 300-500 million acres would be required to grow the trees and switchgrass, with associated concerns about recreation and biodiversity, and
3. A large investment in infrastructure would be required and there would be transition difficulties.

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