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Factors Affecting the Market Penetration of Biomass-Derived Liquid Transportation Fuels

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ABSTRACT

The market for liquid transportation fuels in the United States is about 610×10^9 L (160×10^9 gal) annually, with gasoline accounting for about 420×10^9 L (110×10^9 gal). Presently, about 3.4×10^9 L (0.9×10^9 gal) of ethanol are utilized in ethanol-gasoline blends. The barriers to greater use of ethanol in the transportation sector are economic as well as structural and institutional. Areas to consider are feedstock production, feedstock conversion to ethanol, fueling infrastructure, vehicle stocks, consumer acceptance, and regulations. Of these areas, regulation is probably the most important.

Index Entries: Biomass; ethanol; regulations; market penetration; fuel; corn; energy crops.

INTRODUCTION

Liquid transportation fuels are the single largest market for petroleum products in the United States, accounting for about two-thirds of the petroleum product market. Ethanol supplies only about 0.4% of this market (calculated on an energy basis). Nearly all the ethanol supplied uses corn as its feedstock. This market is supported by a \$0.143/L (\$0.54/gal) federal subsidy, as well as additional state subsidies in some

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states, for ethanol derived from agricultural products used in 10% blends with gasoline. Without these subsidies, it is unlikely that ethanol would be used as a transportation fuel.

The Clean Air Act (CAA) as amended in 1990 requires the use of oxygenated fuels in regions not meeting ozone and carbon monoxide standards. As an oxygenated fuel, ethanol could be used to meet these requirements. Other fuels that can be used to meet oxygen requirements are methanol, methyl tertiary butyl ether (MTBE), ethyl tertiary butyl ether (ETBE), and tertiary amyl methyl ether (TAME). MTBE is derived from methanol and isobutylene, and methanol is derived from natural gas, although it could be derived from other sources, such as biomass. ETBE is derived from ethanol and isobutylene, and TAME is derived from 2-methyl-2-butene, 2-methyl-1-butene, and methanol. In addition to being oxygenated fuels, ethanol, ETBE, methanol, MTBE, and TAME are also sources of high octane. At present, MTBE is not only the preferred source of octane, but also the preferred source of oxygen.

Although the CAA gave rise to the hope that ethanol use would increase, this has not yet come to be. Soon after the CAA was amended, plans were announced to expand annual capacity by more than 1.3×10^9 L (350×10^6 gal) by the largest ethanol producer (Archer, Daniels, Midland [ADM]) and other ethanol producers. However, these plans have been put on hold pending more favorable regulatory rulings regarding pollution-abatement programs (*1*).

FEEDSTOCK PRODUCTION

In the year ended September 30, 1991, 9.0×10^6 Mg of corn were used to produce ethanol, which represents slightly <5% of the corn crop of the United States. The amount of corn that could be used as an ethanol feedstock is much higher than present consumption levels. Studies by the US General Accounting Office and by Abt Associates for the US Environmental Protection Agency show no significant barriers to increasing the amount of ethanol produced from corn by up to 20×10^9 L/yr (50×10^6 Mg/yr of corn) (*2,3*). Above these levels, significant increases in corn prices and, thus, ethanol costs are likely to occur. Thus, the amount of ethanol that can be produced from corn is self-limiting, because ethanol costs would be raised to uncompetitive levels unless subsidies were increased or use of ethanol were mandated either through law or regulation. In addition, greatly increased production of corn may be subject to environmental barriers within the agricultural sector, particularly in the areas of soil erosion and nitrate leaching into water.

Ethanol can also be produced from cellulosic feedstocks, such as wood and grasses. Cellulosic feedstocks from dedicated energy crops (short-rotation woody crops, and annual and perennial grasses) are presently the focus of the US Department of Energy feedstock program. Dedicated energy crops have advantages over corn and other grains in that these crops can give higher biomass and ethanol yields per unit land area, per unit nutrient input, and per unit of soil erosion, and also have lower per unit feedstock costs than corn. Disadvantages are that they are bulkier and are more difficult to process than corn.

Current corn prices are about $100/Mg (about $120/dry Mg) ($2.50/bu), and assuming that byproducts from corn processing to ethanol are worth about half of this cost, then the net feedstock cost is about $60/dry Mg. With higher levels of ethanol produced from corn, the corn cost would be higher, and the byproduct value less. About 80% of the corn byproducts are exported because European Community tariffs do not apply to the byproducts, but do apply to corn and other feed grains (barley, oats, and sorghum). The loss of the European market because of a change in European Community tariff policy could depress byproduct prices. Higher levels of byproduct availability might induce such a change in European Community policy. Estimated costs for dedicated energy crops range from about $35 to $70/dry Mg ($32 to $64/dry t) and are highly dependent on the yield achieved. Because energy crops give higher yields per unit land area than corn grain, their cost of production would not increase as quickly as that for corn in response to increases in ethanol production. Relative to corn, energy crops, such as perennial grasses and short-rotation woody crops, have the potential to reduce soil erosion and nitrate leaching substantially.

Perennial and annual grasses utilize conventional farm equipment to produce either hay or silage, and such equipment is present on many farms or easily obtainable. For short-rotation woody crops, planting and harvesting equipment is more specialized. Short-rotation woody crop harvesting equipment is more expensive than most farm equipment. Thus, either custom planting and harvesting operations must be established (common in the agricultural sector), or some cooperative must own the equipment. The added risk with short-rotation woody crops is that revenue from the operation comes only at harvest time, which may be 3–10 yr after planting. This may impede the acceptability of short-rotation woody crops by farmers.

CONVERSION

The corn-to-ethanol conversion process is a well-established technology. However, reductions in operating and capital costs are still being made. Gains are measured in the fractions of cents per liter. Conversion facilities are located near the source of raw materials, and thus, most capacity is in the Midwest.

Energy crop-to-ethanol processes are not yet commercial and are still undergoing laboratory research, although plans are being made to demonstrate these processes. In addition to energy crops, these processes can use other feedstocks, such as crop residues and wood wastes. It can be expected that most of these facilities would be located near sources of raw material, which would be where farmland is located, primarily the Midwest, Southeast, and Plains. Researchers at the National Renewable Energy Laboratory (NREL) project significant economies of scale with their conversion processes. Although a plant size of 1800 Mg/d (2000 t/d) of dry feedstock, which could produce between 190 and 285×10^6 L/yr (50 and 75×10^6 gal/yr), is small by chemical or oil-refining standards, it is large by agricultural or forestry standards. There are some agricultural and forestry processing facilities that are larger. The investment cost for such a facility is about $\$125 \times 10^6$. Although facilities larger than 1800 dry Mg/d (2000 dry t/d) are possible, the locations that can support such facilities may be limited to areas in which high crop yields and/or high crop land densities used for energy crop production could be obtained. In its developmental stage, though, the energy crop-to-ethanol industry will start with smaller facilities.

ETHANOL DISTRIBUTION AND FUELING INFRASTRUCTURE

One of the major disadvantages of ethanol (and also methanol) is that it does not use the same distribution system as presently exists for petroleum products. This is not to say that it cannot use this distribution system. Pipelines contain water and ethanol have an affinity for water. Water picked up by ethanol and then introduced into a gasoline engine can result in engine problems. Pipelines presently exist for crude oil, petroleum products, liquid petroleum gases, and natural gas. If the demand warrants, an additional pipeline system could certainly be built for ethanol. Until ethanol is shipped through pipelines, ethanol is at some cost disadvantage compared to gasoline or other fuels, such as MTBE, that can use the current pipeline distribution system.

Ethanol can be blended at up to 20% with gasoline and used in existing vehicles. To gain full advantage of ethanol's octane, it would have to be "splash" blended (i.e., blended at a gas station) with "suboctane" gasoline (i.e., gasoline with octane ratings below that which are sold at the pump). Pipelines generally do not ship suboctane gasoline, because it would require an additional set of storage tanks at the terminal or replacement of one of the existing grades presently shipped. This is especially true of "common" carriers (i.e., pipeline who will transport petroleum products for anyone), but not as much of a problem for a pipeline that ships for only one company. The US Environmental Protection Agency will work with oil refiners and pipelines to examine the feasibility of producing and shipping low-volatility, nonoxygenated gasoline (*4*). Perhaps similar efforts could take place with suboctane gasoline.

To gain the full environmental advantages of ethanol, it needs to be used as pure or almost pure fuel. To be used in its pure unblended state an additional pump at a gas station would be required, or one of the existing pumps would have to be dedicated to ethanol.

With ethanol, many of these disadvantages can be overcome if it is made into ETBE (*5*). ETBE is very similar to MTBE, but with some advantages over MTBE (a lower Reid Vapor Pressure [RVP], which is used as a measure for hydrocarbon emissions, and a higher octane number), and can use the present gasoline distribution system. Lack of compatibility with existing distribution systems is a major impediment to the greater use of alternative fuels, such as ethanol. Without a subsidy, ETBE is presently not competitively priced compared to MTBE. To be competitive, the price of ethanol must decrease relative to methanol.

ETHANOL-FUELED VEHICLES

Automobiles with conventional gasoline engines are presently using 10% ethanol–90% gasoline blends (by volume) (gasohol) and can use higher amounts of ethanol, up to about 20%. Blending within the current marketplace, however, does not take full advantage of ethanol characteristics. (As a neat fuel, ethanol has a low RVP. Ethanol's octane rating is 113, but to take advantage of that, it would need to be blended with suboctane gasoline, which is presently being done only by a few oil companies.)

Flexible-fueled vehicles are one way to overcome some of the marketplace obstacles facing ethanol. The vehicle would be able to operate on gasoline or ethanol (or other fuels), so a driver would not have to be concerned with the availability of ethanol. Of course, an operator of a flexible-fueled vehicle is most likely to operate the vehicle on the least costly fuel.

Ethanol-powered vehicles could run on pure ethanol, or perhaps blends of 85% ethanol and 15% unleaded gasoline. This requires availability of ethanol to operate the vehicle. This may be feasible for fleet vehicles that remain within the fueling radius of the fleet operator's base of operations. For widespread acceptance of ethanol vehicles by the public, ethanol fueling facilities would have to be readily accessible. The state of California, in cooperation with a number of oil companies, is in the process of installing methanol pumps across the state (*6*). A similar program would be necessary for neat ethanol pumps to be established. The major advantage of ethanol-powered vehicles over gasoline-powered vehicles is that they take full advantage of ethanol's characteristics, namely better fuel economy per unit energy combusted and better pollution characteristics. Flexible-fueled vehicles could be the bridge between gasoline-powered vehicles and ethanol-powered vehicles.

INSTITUTIONAL AND ENVIRONMENTAL CONSIDERATIONS

Pollutants regulated by the US Environmental Protection Agency (EPA) include sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (or volatile organic compounds [VOCs]). SO_2 and NO_x result in acid precipitation. In the presence of sunlight, NO_x and VOCs react to form ozone, which is a major ingredient of smog. The CAA Amendments of 1990 require: (1) that gasoline sold in ozone nonattainment areas (which account for 22% of gasoline sold in the United States) contain a minimum of 2% by weight oxygen (% wt O_2) by January 1, 1995 and (2) that gasoline sold in CO nonattainment areas (which account for 27% of gasoline sold in the United States) contain at least 2.7%wt O_2 during certain winter months by November 1, 1992.

Sources of oxygen for fuel include ethanol (34.7%wt O_2), methanol (49.9%wt O_2), ETBE (15.7%wt O_2), MTBE (18.2%wt O_2), and TAME (15.7%wt O_2). Which of these fuels and how much of these fuels will be sources of oxygen for gasoline are presently unknown. Ethanol has recently been selling for, excluding any subsidy, about \$0.30/L (\$1.15/gal) and MTBE about \$0.24/L (\$0.90/gal) (*7*). Therefore, on a percent oxygen added basis, even without any subsidy, ethanol is less expensive than MTBE, selling at about two-thirds of MTBE's cost. However, at the present time, MTBE is the source of oxygen of choice by the oil industry. Unlike ethanol, it is fungible with gasoline and can be shipped through existing product pipelines. The oil industry also controls its production. Also, MTBE can be added such that the blended fuel contains up to 2.7%wt O_2, whereas the other oxygenates, including ethanol, are limited to 2.1%wt O_2.

VOC emissions are affected by the RVP of gasoline and other fuels. Presently, gasoline in a 10% blend (by volume) with ethanol is allowed an RVP level that is 6.9×10^3 Pa (1.0 psi) higher than unblended gasoline. As a pure fuel, ethanol has an RVP of 1.6×10^4 Pa (2.3 psi), but in a 10% blend with gasoline, it increases the RVP of the blend. (Ethanol has a blending RVP of $1.2\text{-}1.5 \times 10^5$ Pa [17–22 psi] [*8*]). Unblended gasoline has an RVP of around 5.9×10^4 Pa [8.5 psi].) At higher blends with gasoline, the ethanol–gasoline blend may have a lower RVP. There is some evidence of this RVP phenomenon from experience in Brazil. Upcoming EPA testing will examine the RVP of blends containing $>10\%$ ethanol (*4*). Note that VOCs are generally a problem only during summer months. (This is because VOCs are a key to ozone [smog] formation, which is generally a summer problem.)

EPA has proposed that gasoline containing up to 3.5%wt O_2 will be allowed to be sold in months without ozone violations. States may request exemptions. During months of potential ozone violations, if a marketer of gasoline wishes to sell gasoline with 3.5%wt O_2, the marketer must show that such a fuel would not lead to increased emissions of NO_x (*7*).

The states of California and New York want to set a maximum oxygen content of gasoline during the winter months, because those states believe that the presence of oxygen in gasoline contributes to NO_x emissions. California wants to set a limit of 2.2 and New York 2.7%wt O_2 content gasoline (*7*). The data available on the relationship between fuel oxygen content and NO_x formation are not conclusive and need further investigation. The problem with these limits for ethanol producers is that in order to qualify for the $0.143/L ($0.54/gal) of ethanol exemption from the federal gasoline tax, ethanol must be in a 10% blend by volume with gasoline. A 10% ethanol–gasoline blend contains 3.5 to 3.7%wt O_2, depending on the specific gravity of the gasoline. Thus, if the oxygen content is limited to <3.5%wt O_2, an ethanol–gasoline blend will not qualify for the federal gasoline tax exemption and will not be competitively priced.

Oxygen in fuel suppresses the formation of CO. However, there is presently a dispute as to whether oxygen in fuel will make any contribution to reducing CO emissions in new vehicles because of sensors that control the amount of oxygen present during fuel combustion. In older vehicles, the presence of oxygen does contribute to a reduction of CO emissions.

Although not covered by the CAA, CO_2 emissions may be important, because as greenhouse gases, they account for about 50% of the potential greenhouse warming. However, at present, CO_2 emissions are neither controlled nor have any monetary cost attached to them. Emissions from gasoline combustion are 18.41 kg C/GJ (CO_2 Eq), and for upstream operations (exploration, production, refining, and so forth), 2.35 kg C/GJ, for a total release of 20.76 kg C/GJ (*9*).

Ethanol produced from corn has emissions of CO_2 that are typically lower than gasoline. Marland and Turhollow (*10*) estimate for their corn-to-ethanol base case a net emission rate of 16.45 kg C/GJ, with is 21% lower than the rate for gasoline. The range of emission rates estimated were from 3.98 to 19.38 kg C/GJ, depending on the assumptions made for fuel source and fuel energy requirements for the conversion of corn to ethanol, and how byproducts are treated.

CO_2 emissions are considerably lower for ethanol produced using dedicated energy crops (as compared to using corn) as the feedstock. The main reason for the rates being lower is that although the corn-to-ethanol process requires exogenous energy inputs (now primarily coal), all the energy requirements for the energy crop-to-ethanol process can be provided by the feedstock itself (lignin and unfermented carbohydrates).

Turhollow and Perlack (*11*) estimate net emissions of CO_2 from the production of dedicated energy crops using present production technology ranging from 1.30 to 1.93 kg C/GJ of energy contained in the biomass. For future production technology (the year 2010), emissions are estimated to range from 1.10 to 1.68 kg C/GJ of energy contained in the crop. Assuming 1.6 kg C/GJ of energy crop is representative of present crop production technology, the thermal efficiency of converting energy crops to ethanol is 40%, and no net addition of energy is required for the conversion profess, then CO_2 emissions are 4.0 kg C/GJ of ethanol. Assuming 1.4 kg C/GJ of energy crop is representative of future crop production technology, the thermal efficiency of converting energy crops to ethanol can be increased to 60%, and no net addition of energy is required for the conversion process, then CO_2 emissions are 2.3 kg C/GJ of ethanol.

These emission rates of 4.0 and 2.3 kg C/GJ of ethanol are far lower than the rate of 20.76 kg C/GJ of gasoline. Lynd et al. (*12*) state that in an ethanol engine, 1.0 L of ethanol can replace 0.8 L of gasoline. This is a gain in thermal efficiency of about 19% when using ethanol. Therefore, on a per unit distance traveled basis, the relative emissions of ethanol are even lower. For ethanol derived from energy crops, using both future production and conversion technologies and using the ethanol in an optimized ethanol engine, emissions are $<10\%$ of the CO_2 emissions from gasoline used in today's gasoline engines.

SUMMARY AND CONCLUSIONS

Ethanol presently accounts for about 0.4% (on an energy basis) of the liquid transportation fuel market in the United States. Most of this ethanol is derived from corn. Corn could provide at least five times as much ethanol without disrupting the corn markets. However, without the exemption from \$0.143/L (\$0.54/gal) of federal gasoline tax and some state gasoline taxes, it is unlikely that much ethanol would be used as a fuel. Ethanol, with a spot market price of about \$0.30/L (\$1.15/gal), is more costly as a fuel than gasoline, with a spot market price of \$0.16/L (\$0.60/gal). However, if "cleaner" gasoline fuels are produced as required by the CAA, the price of gasoline may be as much as \$0.04–\$0.05/L (\$0.16 to \$0.20/gal) higher than current prices (*13,14*).

Ethanol could also be produced from energy crops and other cellulosic feedstocks. The technology for converting cellulosic feedstocks to ethanol is presently being developed and should be demonstrated before the end of the century. Cellulosic feedstocks have the potential to produce more ethanol than corn and at a lower cost, and to reduce environmental impacts relative to those of corn.

The CAA amendments of 1990 could change the way ethanol is viewed. Originally, it was viewed as a gasoline extender and then as an octane enhancer. Now it may also be viewed as an oxygenate. The CAA will require minimum levels of oxygen in gasoline in CO and ozone nonattainment areas, in November 1992 and January 1995, respectively. Ethanol is a lower-cost source of oxygen than MTBE, which is presently the oxygenate of choice by the oil industry. Ethanol also appears to be a lower-cost octane enhancer than MTBE when the federal tax exemption is taken into account. MTBE is also one of the octane enhancers of choice by the oil industry.

So why is ethanol not being used more as both an octane enhancer and an oxygenate? Ethanol does have some logistical problems. It is not transported by petroleum product pipeline because of its affinity for water in the pipelines and storage considerations. The primary region of production of ethanol is in the Midwest, which is not convenient to the petroleum product distribution system. Ethanol is essentially limited to a 10% blend with gasoline by the way the federal gasoline tax exemption is written into law. To take full advantage of its octane rating, ethanol should be mixed with suboctane gasoline, but product pipelines generally do not ship suboctane gasoline because of logistical considerations.

A blend of 10% ethanol and 90% gasoline contains 3.5–3.7%wt O_2. To meet the minimum oxygen requirement for CO and ozone nonattainment areas, it would be needed to be blended at $<10\%$. Some states are seeking to set maximum a oxygen content on gasoline because of fears that NO_x emissions linearly increase with oxygen content. Until such issues as those relating to how the federal gasoline tax exemption works and oxygen requirements are resolved, the ethanol industry may not expand significantly.

Looking to the longer term, ethanol when produced from energy crops has net CO_2 emissions that are potentially $<10\%$ those of gasoline. If a tax is imposed on CO_2 emissions, each \$1/Mg CO_2 tax would increase the cost of gasoline by \$0.0024/L. (Each \$1/t CO_2 tax would increase the cost of gasoline by \$0.0081/gal.) Therefore, if greenhouse gas emissions become a major concern, this also represents a potential opportunity for increased ethanol use.

As gasoline is required to become "cleaner," its price will increase. This also increases the opportunity for ethanol to penetrate the transportation fuel market, either as ethanol or as ETBE. Researchers are working to reduce the cost of producing ethanol, to make ethanol a more attractive fuel. However, ethanol will probably not gain widespread acceptance as a motor fuel quickly. Flexible-fueled vehicles (and perhaps later ethanol-fueled vehicles) will be required to penetrate the vehicle market, and ethanol fueling pumps must be readily accessible. Perhaps the most important factor, though, will be how environmental quality laws and regulations are written and interpreted. The transportation sector will be required to meet increasingly strict environmental standards over time, both for vehicle and fuels. Whether ethanol will become a more important transportation fuel or component remains to be seen.

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