Outlook for Biomass Ethanol Production and Demand

by Joseph DiPardo

The production of ethanol from corn is a mature technology that is not likely to see significant reductions in production costs. The ability to produce ethanol from low-cost biomass will be key to making it competitive as a gasoline additive. If Department of Energy goals are met, the cost of producing ethanol could be reduced by as much as 60 cents per gallon by 2015 with cellulosic conversion technology. This paper presents a midterm forecast for biomass ethanol production under three different technology cases for the period 2000 to 2020, based on projections developed from the Energy Information Administration's National Energy Modeling System. An overview of cellulose conversion technology and various feedstock options and a brief history of ethanol usage in the United States are also presented.

Introduction

Ethanol has been used as fuel in the United States since at least 1908. Although early efforts to sustain a U.S. ethanol program failed, oil supply disruptions in the Middle East and environmental concerns over the use of lead as a gasoline octane booster renewed interest in ethanol in the late 1970s. Ethanol production in the United States grew from 175 million gallons in 1980 to 1.4 billion gallons in 1998, with support from Federal and State ethanol tax subsidies and the mandated use of high-oxygen gasolines.

Demand for ethanol could increase further if methyl tertiary butyl ether (MTBE) is eliminated from gasoline. In March 1999, Governor Gray Davis announced a phaseout of the use of MTBE in gasoline by 2002 in California, which uses 25 percent of the global production of MTBE.[1] It is unclear, however, whether the U.S. Congress will eliminate the minimum oxygen requirement in reformulated gasoline (RFG), an action that would reduce the need for ethanol. If the oxygen requirement is eliminated, ethanol will still be valuable as an octane booster and could make up some of the lost MTBE volume.

At present, extending the volume of conventional gasoline is a significant end use for ethanol, as is its use as an oxygenate. To succeed in these markets, the cost of ethanol must be close to the wholesale price of gasoline, currently made possible by the Federal ethanol subsidy; however, the subsidy is due to expire in 2007, and although the incentive has been extended in the past, in order for ethanol to compete on its own merits the cost of producing it must be reduced substantially.

The production of ethanol from corn is a mature technology that is not likely to see significant reductions in production costs. Substantial cost reductions may be possible, however, if cellulose-based feedstocks are used instead of corn. Producers are experimenting with units equipped to convert cellulose-based feedstocks, using sulfuric acid to break down cellulose and hemicellulose into fermentable sugar. Although the process is expensive at present, advances in biotechnology could decrease conversion costs substantially. If Department of Energy goals are met, the cost of producing ethanol could be reduced by as much as 60 cents per gallon by 2015.

The ability to produce ethanol from low-cost biomass will be key to making ethanol competitive with gasoline. This analysis presents a brief overview of cellulose conversion technology and various feedstock options, followed by an examination of projected ethanol costs and gasoline prices under various technological scenarios for cellulose ethanol conversion, as well as the uncertainty of oil prices. All prices quoted in this paper are in 1998 dollars unless otherwise noted. Projections are developed from the Energy Information Administration's National Energy Modeling System.[2]

Background

The use of ethanol as an automobile fuel in the United States dates as far back as 1908, to the Ford Model T. Henry

Ford was a supporter of home-grown renewable fuels, and his Model T could be modified to run on either gasoline or pure alcohol.[3] Ethanol was used to fuel cars well into the 1920s and 1930s as several efforts were made to sustain a U.S. ethanol program. Standard Oil marketed a 25-percent ethanol by volume gasoline in the 1920s in the Baltimore area.

Ford and others continued to promote the use of ethanol, and by 1938 an alcohol plant in Atchison, Kansas, was producing 18 million gallons of ethanol a year, supplying more than 2,000 service stations in the Midwest.[4] By the 1940s, however, efforts to sustain the U.S. ethanol program had failed. After World War II, there was little interest in the use of agricultural crops to produce liquid fuels. Fuels from petroleum and natural gas became available in large quantities at low cost, eliminating the economic incentives for production of liquid fuels from crops. Federal officials quickly lost interest in alcohol fuel production, and many of the wartime distilleries were dismantled. Others were converted to beverage alcohol plants.[5]

Interest in ethanol was renewed in the 1970s, when oil supply disruptions in the Middle East became a national security issue and America began to phase out lead (an octane booster) from gasoline. The American Oil Company and several other major oil companies began to market ethanol as a gasoline volume extender and as an octane booster.[6] Ethanol was blended directly into gasoline in a mix of 10 percent ethanol and 90 percent gasoline, called gasohol. In 1978, Congress approved the National Energy Act, which included a Federal tax exemption for gasoline containing 10 percent alcohol.[7] The Federal subsidy reduced the cost of ethanol to around the wholesale price of gasoline, making it economically viable as a gasoline blending component. The growth of ethanol was enhanced substantially by State tax incentives to ethanol producers. By 1980, 25 States had exempted ethanol from all or part of their gasoline excise taxes in order to promote consumption.[8] Ethanol production jumped from just over 10 million gallons in 1979 to 175 million gallons in 1980.[9] Federal and State tax incentives made ethanol economically attractive in the Midwest, but the difficulty and high cost of transporting ethanol precluded consumption in other markets.

Since 1980, ethanol has enjoyed considerable success. U.S. production has grown by about 12 percent per year, reaching 1.4 billion gallons in 1998 (Figure 1). U.S. gasoline consumption in 1998 was approximately 120 billion gallons. The ethanol program received a boost from Congress in 1990 with the passage of the Clean Air Act Amendments (CAAA90). Congress mandated the use of oxygenated fuels (with a minimum of 2.7 percent oxygen by volume) in specific regions of the United States during the winter months to reduce carbon monoxide. The two most common methods to increase the oxygen level of gasoline are blending with MTBE and blending with ethanol. Because ethanol has a higher oxygen content than MTBE, only about half the volume is required to produce the same oxygen level in gasoline. This allows ethanol, typically more expensive than MTBE, to compete favorably with MTBE for the wintertime oxygenate market. Unfortunately, ethanol's high volatility, measured by Reid vapor pressure (Rvp), limits its use in hot weather, where evaporative emissions can contribute to ozone formation. Nevertheless, ethanol's expanded role as a clean-air additive has allowed it to penetrate markets outside the Midwest (Figure 2).

Figure 1. U.S. Fuel Ethanol Production, 1980-1998

Figure 2. Regional Percentages of Total U.S. Ethanol Consumption, 1990 and 1996

Although most ethanol consumption is in conventional gasoline engines, which are limited to a 10-percent ethanol blend (E10), there is also some demand for ethanol blended in higher concentrations, such as E85 (85 percent ethanol, 15 percent gasoline). E85 vehicles are currently in use as government fleet vehicles, flexible-fuel passenger vehicles, and urban transit buses. Demand for ethanol in E85 has grown from 144,000 gallons in 1992 to 2 million gallons in 1998. Most E85 use falls under government mandates to use alternative fuels. Ethanol does not compete directly with gasoline, even at comparable costs, because its energy (Btu) content is lower than that of gasoline. It takes approximately 1.5 gallons of ethanol do deliver the same mileage as 1 gallon of gasoline.

Ethanol use is also being expanded to multi-component fuel systems. P-series fuels, created by Pure Energy Corp., are blends of ethanol, methyltetrahydrofuran (MTHF), natural gas liquids, and in some cases butane to meet cold-start requirements.[10] Pure Energy is also developing a new fuel called OxyDiesel, composed of 80 percent diesel fuel, 15 percent ethanol, and 5 percent blending agent to raise cetane levels.[11] The company has developed an additive system to prevent water absorption for a stable ethanol-diesel mixture that can be shipped through a pipeline.[12] Currently, fuels blended with ethanol cannot be shipped in multifuel pipelines, because the moisture in pipelines and storage tanks is absorbed by the ethanol, causing it to separate from gasoline. Rather, the petroleum-based gasoline components have to be shipped separately and then blended with ethanol at a terminal as the product is loaded into trucks.

The demand for ethanol could increase if MTBE were eliminated from gasoline. MTBE (in addition to its use in high oxygen fuels) is widely used as a year-round gasoline additive for RFG to meet the legislated requirement for 2.0

percent oxygen by weight. The use of MTBE has recently been questioned, however, because traces of the additive have been found in 5 to 10 percent of the drinking water supplies in areas using RFG. In 1999, concerns about water quality resulted in the announcement of a State-wide phaseout of MTBE by the Governor of California, as well as numerous legislative proposals at both the State and Federal levels aimed at reducing or eliminating the use of MTBE in gasoline. Ethanol would be the leading candidate to replace MTBE, although it is not without its drawbacks. Compared with MTBE, ethanol use results in higher evaporative emissions of smog-forming volatile organic compounds (VOCs), requiring refiners to remove other gasoline components such as pentanes or butanes to meet the Rvp limits set by the U.S. Environmental Protection Agency (EPA).

Logistics is also an issue for ethanol use. At present, ethanol supplies come primarily from the Midwest, where the majority of ethanol is produced from corn feedstocks. Downstream Alternatives, Inc., has analyzed the logistics of supplying ethanol to California, in a study for the Renewable Fuels Association.[13] The analysis found that, because of the distances involved, the only viable alternatives for transporting ethanol to California would be rail shipments or marine cargoes. Rail shipment would be required for ethanol plants that are landlocked. In addition, small plants (less than 80 millions gallons production capacity) would not be likely to ship by marine cargo, which requires large shipment volumes. Rail transit times from Midwest ethanol plants to California can range from 2 to 3 weeks, with typical costs of 14 to 17 cents per gallon, depending on the plant of origin and the market destination.

Larger ethanol plants located on the water would have the option to ship waterborne cargoes. Product would be shipped down the Mississippi via barge and then staged at a terminal in New Orleans until sufficient quantities of ethanol were accumulated for shipment. The ethanol would then be shipped south through the Panama Canal and north to California ports. The entire process would take a minimum of 34 days, and the costs would be nearly the same as the costs for rail shipments. In both cases, the ethanol would then have to be transported from a rail or marine terminal by truck to a final destination terminal before blending into gasoline. In addition, some terminals would need to make modifications to offer ethanol even if tankage were adequate to accommodate ethanol blending.

The cost of producing and transporting ethanol will continue to limit its use as a renewable fuel. Ethanol relies heavily on Federal and State subsidies to remain economically viable as a gasoline blending component. The current Federal subsidy, at 54 cents per gallon, makes it possible for ethanol to compete as a gasoline additive. Corn prices are the dominant cost factor in ethanol production, and ethanol supply is extremely sensitive to corn prices, as was seen in 1996. Ethanol production dropped sharply in mid-1996 (Figure 3), when late planting due to wet conditions resulted in short corn supplies and higher prices.[14]

Figure 3. Change in U.S. Corn Price and Ethanol Production From 1995 to1996

Substantial reductions in ethanol production costs may be made possible by replacing corn with less expensive cellulose-based feedstocks. Cellulosic feedstocks include agricultural wastes, grasses and woods, and other low-value biomass such as municipal waste. Although cellulosic materials are less expensive than corn, they are more costly to convert to ethanol because of the extensive processing required. Cellulase enzymes (used to convert cellulose to sugar) at $0.45 per gallon of ethanol are currently too expensive for commercial use. Current technology, however, could reduce the cost of enzymes to less than $0.10 per gallon of ethanol if a sufficient market develops.[15] Advances in biotechnology could lower costs further by allowing fermentation of the nonglucose sugars produced in the hydrolysis of cellulose using genetically engineered bacteria. If Department of Energy goals are met, the cost of producing ethanol could be reduced by as much as 60 cents per gallon by 2015.[16] Currently, the cost of producing ethanol from cellulose is estimated to be between $1.15 and $1.43 per gallon in 1998 dollars.[17]

Technology

Ethanol is produced from the fermentation of sugar by enzymes produced from specific varieties of yeast. The five major sugars are the five-carbon xylose and arabinose and the six-carbon glucose, galactose, and mannose.[18] Traditional fermentation processes rely on yeasts that convert six-carbon sugars to ethanol. Glucose, the preferred form of sugar for fermentation, is contained in both carbohydrates and cellulose. Because carbohydrates are easier than cellulose to convert to glucose, the majority of ethanol currently produced in the United States is made from corn, which produces large quantities of carbohydrates.[19] Also, the organisms and enzymes for carbohydrate conversion and glucose fermentation on a commercial scale are readily available.

The conversion of cellulosic biomass to ethanol parallels the corn conversion process. The cellulose must first be converted to sugars by hydrolysis and then fermented to produce ethanol (Figure 4). Cellulosic feedstocks (composed of cellulose and hemicellulose) are more difficult to convert to sugar than are carbohydrates. Two common methods for converting cellulose to sugar are dilute acid hydrolysis and concentrated acid hydrolysis, both of which use sulfuric acid. Dilute acid hydrolysis occurs in two stages to take advantage of the differences between hemicellulose and cellulose. The first stage is performed at low temperature to maximize the yield from the

hemicellulose, and the second, higher temperature stage is optimized for hydrolysis of the cellulose portion of the feedstock. Concentrated acid hydrolysis uses a dilute acid pretreatment to separate the hemicellulose and cellulose. The biomass is then dried before the addition of the concentrated sulfuric acid. Water is added to dilute the acid and then heated to release the sugars, producing a gel that can be separated from residual solids. Column chromatographic is used to separate the acid from the sugars.[20]

Figure 4. Ethanol Production From Corn and Cellulose

Both the dilute and concentrated acid processes have several drawbacks. Dilute acid hydrolysis of cellulose tends to yield a large amount of byproducts. Concentrated acid hydrolysis forms fewer byproducts, but for economic reasons the acid must be recycled. The separation and reconcentration of the sulfuric acid adds more complexity to the process. In addition, sulfuric acid is highly corrosive and difficult to handle. The concentrated and dilute sulfuric acid processes are performed at high temperatures (100 and 220oC) which can degrade the sugars, reducing the carbon source and ultimately lowering the ethanol yield.[21] Thus, the concentrated acid process has a smaller potential for cost reductions from process improvements. The National Renewable Energy Laboratory (NREL) estimates that the cumulative impact of improvements in acid recovery and sugar yield for the concentrated acid process could provide savings of 14 cents per gallon, whereas process improvements for the dilute acid technology could save around 19 cents per gallon.

A new approach under consideration is countercurrent hydrolysis. Countercurrent hydrolysis is a two stage process. In the first stage, cellulose feedstock is introduced to a horizontal co-current reactor with a conveyor. Steam is added to raise the temperature to 180oC (no acid is added at this point). After a residence time of about 8 minutes, during which some 60 percent of the hemicellulose is hydrolyzed, the feed exits the reactor. It then enters the second stage through a vertical reactor operated at 225oC. Very dilute sulfuric acid is added to the feed at this stage, where virtually all of the remaining hemicellulose and, depending on the residence time, anywhere from 60 percent to all of the cellulose is hydrolyzed. The countercurrent hydrolysis process offers more potential for cost reductions than the dilute sulfuric acid process. NREL estimates this process may allow an increase in glucose yields to 84 percent, an increase in fermentation temperature to 55oC, and an increase in fermentation yield of ethanol to 95 percent, with potential cumulative production cost savings of about 33 cents per gallon.[22]

The greatest potential for ethanol production from biomass, however, lies in enzymatic hydrolysis of cellulose. The enzyme cellulase, now used in the textile industry to stone wash denim and in detergents, simply replaces the sulfuric acid in the hydrolysis step. The cellulase can be used at lower temperatures, 30 to 50oC, which reduces the degradation of the sugars.[23] In addition, process improvements now allow simultaneous saccharification and fermentation (SSF). In the SSF process, cellulase and fermenting yeast are combined, so that as sugars are produced, the fermentative organisms convert them to ethanol in the same step. In the long term, enzyme technology is expected to have the biggest payoff. NREL estimates that future cost reductions could be four times greater for the enzyme process than for the concentrated acid process and three time greater than for the dilute acid process.[24] Achieving such cost reductions would require substantial reductions in the current cost of producing cellulase enzymes and increased yield in the conversion of nonglucose sugars to ethanol.

Once the hydrolysis of the cellulose is achieved, the resulting sugars must be fermented to produce ethanol. In addition to glucose, hydrolysis produces other six-carbon sugars from cellulose and five-carbon sugars from hemicellulose that are not readily fermented to ethanol by naturally occurring organisms. They can be converted to ethanol by genetically engineered yeasts that are currently available, but the ethanol yields are not sufficient to make the process economically attractive. It also remains to be seen whether the yeasts can be made hardy enough for production of ethanol on a commercial scale.[25]

The concentrated acid and dilute acid processes have been targeted for near-term deployment because of their maturity. BC International is building a facility in Louisiana that is designed to convert bagasse (sugarcane residue) into ethanol by the dilute sulfuric acid process, although its long-term plan is to convert the plant to an enzyme process. Masada Resource Group is planning to locate a municipal solid waste (MSW) to ethanol plant in New York using the concentrated acid hydrolysis process, which may be better suited than enzymes to heterogeneous cellulose sources (such as MSW). Arkenol is working to establish a commercial facility in Sacramento, California, to convert rice straw to ethanol, also using the concentrated acid hydrolysis process.[26]

Feedstock

A large variety of feedstocks are currently available for producing ethanol from cellulosic biomass. The materials being considered can be categorized as agricultural waste, forest residue, MSW, and energy crops. Agricultural waste available for ethanol conversion includes crop residues such as wheat straw, corn stover (leaves, stalks, and cobs), rice straw, and bagasse (sugar cane waste). Forestry waste includes underutilized wood and logging residues;

rough, rotten, and salvable dead wood; and excess saplings and small trees. MSW contains some cellulosic materials, such as paper. Energy crops, developed and grown specifically for fuel, include fast-growing trees, shrubs, and grasses such as hybrid poplars, willows, and switchgrass.[27]

Although the choice of feedstock for ethanol conversion is largely a cost issue, feedstock selection has also focused on environmental issues. Materials normally targeted for disposal include forest thinnings collected as part of an effort to improve forest health, MSW, and certain agricultural residues, such as rice straw. Although forest residues are not large in volume, they represent an opportunity to decrease the fire hazard associated with the dead wood present in many National Forests. Small quantities of forest thinnings can be collected at relatively low cost, but collection costs rise rapidly as quantities increase.

An issue of particular concern in California is the disposal of residue from rice crops. Traditionally, rice straw has been burned, but that practice is being phased out under California law. California's recent ban on MTBE, coupled with its forests and rice crop, provides an ideal opportunity for biomass ethanol production. BC International is developing two such projects: the Collins Pine Ethanol Project, a 23 million gallon per year plant using forest thinnings and wood wastes as feedstock, and the Gridley Ethanol Project, a 20 million gallon per year ethanol plant using rice straw as its primary feedstock.[28] In addition, as mentioned above, Arkenol is working on a commercial facility in Sacramento, using rice straw as a feedstock.

Agricultural residues, in particular corn stover, represent a tremendous resource base for biomass ethanol production. Agricultural residues, in the long term, would be the sources of biomass that could support substantial growth of the ethanol industry. At conversion yields of around 60 to 100 gallons per dry ton, the available corn stover inventory would be sufficient to support 7 to 12 billion gallons of ethanol production per year,[29] as compared with approximately 1.4 billion gallons of ethanol production from corn in 1998. However, the U.S. Department of Agriculture (USDA) and other appropriate entities must undertake rigorous research on the environmental effects of large-scale removal of crop residues.

The cost of agricultural residues is not nearly as sensitive to supply as is the cost of forest residues, although the availability of corn stover could be affected by a poor crop year. The relatively low rise in cost as a function of feedstock use is due to the relatively high density of material available that does not involve competition for farmland. In addition, the feedstock is located in the corn-processing belt, an area that has an established infrastructure for collecting and transporting agricultural materials. It is also located near existing grain ethanol plants, which could be expanded to produce ethanol from stover.[30] Initially, locally available labor and residue collection equipment might have to be supplemented with labor and equipment brought in from other locations for residue harvesting and storage operations, if the plants involved are of sufficient scale. Eventually, however, when the local collection infrastructure has been built up, costs would come down.

Dedicated energy crops such as switchgrass, hybrid willow, and hybrid poplar are another long-term feedstock option. Switchgrass is grown on a 10-year crop rotation basis, and harvest can begin in year 1 in some locations and year 2 in others. Willows require a 22-year rotation, with the first harvest in year 4 and subsequent harvests every 3 years thereafter. Hybrid poplar requires 6 years to reach harvest age in the Pacific Northwest, 8 years in the Southeast, Southern Plains, and South Central regions, and 10 years in the Corn Belt, Lake States, Northeast and Northern Plains regions. Thus, if it were planted in the spring of 2000, switchgrass could be harvested in 2000 or 2001, willow could be harvested in 2004, and poplars could be harvested in 2006, 2008, or 2010, depending on the region.

The use of cellulosic biomass in the production of ethanol also has environmental benefits. Converting cellulose to ethanol increases the net energy balance of ethanol compared to converting corn to ethanol. The net energy balance is calculated by subtracting the energy required to produce a gallon of ethanol from the energy contained in a gallon of ethanol (approximately 76,000 Btu). Corn-based ethanol has a net energy balance of 20,000 to 25,000 Btu per gallon, whereas cellulosic ethanol has a net energy balance of more than 60,000 Btu per gallon.[31] In addition, cellulosic ethanol use can reduce greenhouse gas emissions. Argonne National Laboratory estimates that a 2-percent reduction in greenhouse gas emissions per vehicle mile traveled is achieved when corn-based ethanol is used in gasohol (E10), and that a 24- to 26-percent reduction is achieved when it is used in E85. Cellulosic ethanol can produce an 8- to 10-percent reduction in greenhouse gas emissions when used in E10 and a 68- to 91-percent reduction when used in E85.[32]

Forecast

The National Energy Modeling System (NEMS) was used to analyze the potential for cellulose-based ethanol production under various technological scenarios, assuming either a continuation of the Federal ethanol subsidy through 2020 or expiration of the subsidy in 2008. NEMS is a computer-based modeling system of U.S. energy

markets for the midterm period of 1998 to 2020. NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics. The Petroleum Market Model (PMM), a submodule of NEMS, is a linear programming representation of refining. It represents the pricing of petroleum products and crude oil, product import activity, and domestic refinery operations, subject to the demand for petroleum products, the prices of raw material inputs and imported petroleum products, the costs of investment, and the domestic production of crude oil and natural gas liquids.

The PMM includes an ethanol supply function that provides the linear program with supply curves for corn- and cellulose-based ethanol, allowing the PMM to project transportation ethanol supply throughout the NEMS forecast period. The ethanol model provides prices in the form of annual price-quantity curves. The curves, derived from an ethanol production cost function, represent the prices of ethanol at which associated quantities of transportation ethanol are expected to be available for production of E85 and ethyl tertiary butyl ether (ETBE), and for blending with gasoline.

The three PMM petroleum product supply regions are derived from the Petroleum Administration for Defense Districts (PADDs) as follows: region 1 represents PADD I, region 2 is an aggregate of PADDs II, III, and IV, and region 3 represents PADD V (Figure 5). The PMM demand regions are the nine U.S. Census divisions (Figure 6). Ethanol supply regions are also aggregated by Census division. The majority of ethanol supply derived from corn[33] is located in Census divisions 3 and 4, with smaller amounts in divisions 6, 8, and 9, representing current supply. Cellulosic ethanol supplies become available in 2001 in Census divisions 2 and 7 at demonstration levels, and the majority of the projected growth (beginning in 2003) is in divisions 3, 4, and 9.

Figure 5. Petroleum Administration for Defense Districts (PADDs)

Figure 6. U.S. Census Divisions

The largest growth in cellulose ethanol production is projected for Census divisions 3 and 4, the corn belt, where a tremendous supply of corn stover exists, as well as an established infrastructure for collecting and transporting agricultural materials. Census division 9 (mainly California) is projected to be the next largest producer of cellulose ethanol. It is assumed that ethanol will replace MTBE as the oxygenate for reformulated gasoline in California when the ban on MTBE takes effect in 2003, significantly increasing demand in the region. California's vast agricultural resources could sustain a cellulose ethanol industry of about 3 billion gallons per year.[34]

The NEMS model was used to project potential biomass ethanol production in three different technological scenarios. The scenarios are based on the technologies described above and their associated cost savings potential. A reference case, similar to the *Annual Energy Outlook 2000* (*AEO2000*) reference case,[35] a high technology case, and a low technology case were examined. In addition, the effectiveness of the cost reductions projected by NREL was measured by the competitiveness of cellulose ethanol in the absence of the Federal subsidy.

The Federal Highway Bill of 1998 extended the current tax credit for ethanol through 2007 but stipulated reductions from the current 54 cents per gallon to 53 cents in 2001, 52 cents in 2003, and 51 cents in 2005. Although gasoline tax and tax credit provisions include "sunset" clauses that limit their duration, they have been extended historically. Therefore, a NEMS model assumption for *AEO2000* was that the Federal subsidy would be extended at 51 cents per gallon through 2020.

State subsidies were also modeled in NEMS. While some ethanol-producing States do not subsidize ethanol, others offer tax incentives for gasoline blended with ethanol and for ethanol production, which vary from $0.10 to $0.40 per gallon (in nominal dollars). For modeling purposes, a volume-weighted average of $0.10 per gallon was used for corn-based ethanol in Census divisions 3 and 4.

The three technological simulations were run under two conditions to determine whether and at what price cellulose ethanol could remain competitive without the benefit of the Federal subsidy. Condition one extends the Federal subsidy at 51 cents per gallon through 2020, and condition two discontinues the subsidy in 2008.

Assumptions

Feedstock

The ethanol model uses a process costing approach to model the impacts of net feedstock production costs plus capital and operating costs associated with converting feedstock to ethanol. Corn feedstock prices were derived from

USDA projections for the prices of corn and corn coproducts.[36] Feedstock costs were calculated by subtracting the price of corn coproducts of wet and dry milling from the price of corn. Coproducts of wet milling were limited to corn gluten feed, corn gluten meal, and corn oil. Coproducts of dry milling consisted of distillers dried grains. USDA data were also used to vary corn and co-product prices as a function of ethanol demand. A study by Price et al.[37] simulates the changes in production and consumption of major crops that would be caused by a change in corn ethanol production.

Cellulosic feedstock supply and prices are modeled in the NEMS Renewable Fuels Module.[38] Biomass supply for ethanol competes with captive and noncaptive biomass markets. Captive markets pertain to users with dedicated biomass supplies who burn byproducts resulting from the manufacturing process. The noncaptive market includes the commercial, electric utility, transportation, and industrial sectors. The model calculates a supply schedule for each Census division, which defines the quantity and cost relationships of biomass resources accessible to all noncaptive consumers.

Biomass resources in the Renewable Fuels Module are an aggregation of forest products, wood wastes, crop residues, and energy crops. The forest products data were developed from U.S. Forest Service data,[39] wood residue data were assembled from State and regional agency reports by Antares Group, Inc.,[40] and crop residue data were developed by Oak Ridge National Laboratory.[41] Separate data for energy crops were compiled from an Oak Ridge National Laboratory database[42] for each model year, 2010-2020, and added to the sum from the three other categories. The maximum share of cultivated cropland that would be used for energy crops was about 10 percent. A resource-related cost adjustment factor was also imposed to treat competing uses of the resource. For example, land could be used for other fiber or food crops, or the wood could be used for construction, at alternate prices. Figure 7 illustrates the composite U.S. total supply curve in 2010 for the first 50 million dry tons of biomass.

Figure 7. U.S. Composite Biomass Supply Curve, 2010

Technology/Costs

Conversion plant process costs (capital and operating) were assumed to be independent of production quantities. Plant size was considered in the overall cost of production, but it was assumed that savings from economies of scale would be offset by increased costs for feedstock collection.[43] The operating costs (exclusive of energy) and capital costs for corn feedstocks[44] were assumed to be constant over time. The amount of energy required to convert corn to ethanol, taken from Wang,[45] was assumed to decrease linearly over time. Prices for coal and natural gas consumed during the conversion process were provided from the NEMS Coal Market Module and Natural Gas Transmission and Distribution Module, respectively. Total corn ethanol cost in the model was computed to be approximately $1.10 per gallon in 2000. The conversion and capital cost data for cellulose, derived from Wooley et al.,[46] were assumed to decrease over time at rates that varied across the technological scenarios. Wooley estimates production costs for a plant with a capacity of 2,000 tons per day (approximately 50 million gallons of ethanol) at $0.77 to $1.04 per gallon. An average of $0.91 per gallon was assumed as the initial cost for year 2000, resulting in a total cost for cellulosic ethanol production of approximately $1.29 per gallon. All costs are given in 1998 dollars.

The methods of ethanol conversion assumed for this forecast varied across technological scenarios and were chosen according to their potential for cost reduction. Cumulative cost savings as a result of process improvements were based on NREL projections for each technology,[47] calculated from a base conversion cost of $0.91 per gallon. Currently, there are several projects underway to produce ethanol from cellulose using either concentrated or dilute sulfuric acid hydrolysis technology. The low technology case assumed that the technology would continue to be used throughout the forecast period, and that process improvements would provide cost savings of 16 cents per gallon of ethanol by 2015. The countercurrent hydrolysis approach was chosen for the reference case technology. The countercurrent process improves on the dilute acid process, providing potential production cost savings of 30 cents per gallon of ethanol by 2015. The most advanced conversion process, with the greatest potential for cost reduction, is the enzymatic hydrolysis process. This process was assumed for the high technology case, with production cost savings of 60 cents per gallon of ethanol by 2015. Figure 8 compares ethanol price projections in the three technology cases with motor gasoline prices in the reference, low, and high world oil price cases.

Figure 8. Ethanol and Motor Gasoline Prices at the Terminal, 2000-2020

Capacity

An important modeling consideration for the forecast of ethanol production from cellulose is the rate of capacity growth over the forecast period. Capacity expansion rates were projected using an algorithm derived from the Mansfield and Blackman statistical models of new technology market penetration. Mansfield[48] investigated the

factors that cause an innovation to spread through an industry. He examined the rate of substitution between time periods t and $t+1$ and hypothesized that the proportion of firms at time t that introduce the innovation by time $t+1$ is a function of: (1) the proportion of firms that have already introduced it at time t, (2) the profitability of the innovation relative to other investments, and (3) the size of the investment required to install the technology. He developed a deterministic model and fitted and tested it against data for 12 innovations in 4 industries.

Mansfield's assumptions in functional notation are given by:

$$[n(t+1) - n(t)]/[N - n(t)] = f(B, S, n(t)/N) \quad,$$

where

N = the total number of firms that may adopt the innovation,

$n(t)$ = the total number of firms that have adopted the innovation by time t,

B = profitability of the innovation relative to other investments, and

S = the size of the investment needed to install the technology.

Mansfield then takes the first nonconstant term of the Taylor's expansion for f to rewrite the hypothesis as a differential equation:

$$dn(t)/dt = 2 \, n(t)/N \, [N - n(t)] \quad,$$

where the constant, 2, consists of the terms

$$2 = Z + a_1 B + a_2 S.$$

Mansfield assumes, because of the limited number of innovations, that the coefficients of profitability and investment are constant over industries. The average payout period required by the firms to justify investments divided by the average payout period for the innovation is used as a measure of B. To measure S, he uses the average initial investment in the innovation as a percentage of the average total assets of the firms. Using these data, he obtains a least squares estimate of the parameters, resulting in the equation:

$2 = Z + 0.53 B - 0.027 S (r = 0.997) \quad,$
(0.015)   (0.014)

where the constants for the four industries (Z) are: -0.57 (coal mining), -0.52 (iron and steel), -0.59 (railroads), and -0.29 (brewing).

In his followup work, Blackman[49] revised the model so that the extent of substitution was defined in terms of market share captured by the new technology rather than in terms of the cumulative number of firms employing the innovation. He applied the model to describe innovations dynamics in the commercial jet engine market and in the electrical utility and automotive sectors.

Blackman's market share formulation is given by:

$$N(t) = 1 / [1 + \exp(-k - 2t)] \quad,$$

where

$N(t)$ = market share of new product, and

k = constant determined by initial conditions.

In the absence of historical data, Blackman suggested the use of an Innovation Index to estimate Z. The Innovation Index measures the relative propensity toward innovation in various industrial sectors of the U.S. economy. The index is derived from input variables that reflect the extent to which resources are allocated to achieve innovation in selected industrial sectors and output variables that measure the extent to which new product and process innovation is achieved. Blackman hypothesized that a relationship might exist between the value of Z for an industrial sector and the value of the Innovation Index for that sector. The hypothesis was tested using Z values from the steel, food and kindred products, aerospace, automotive, and electrical machinery sectors. The following

regression equation was obtained:

$$Z = 0.2221\ I - 0.3165\ (r = 0.92)\quad,$$
$$(0.0645)$$

where

I = the industry-specific Innovation Index.

Blackman computed the Innovation Index for 12 industrial sectors (Table 1). A positive Innovation Index indicates a strong tendency for an industry to innovate; a negative value indicates a weaker tendency for innovation.

Table 1. Innovation Index for Twelve Industrial Sectors

Blackman's market share equation was used in NEMS to predict the rate of capacity expansion of cellulosic ethanol production. The cellulosic ethanol production capacity in year t is equal to the share of the market achieved in that year, $N(t)$, times the total potential market for ethanol. The total ethanol market is defined as the sum of the potential gasohol market (10 percent blending of all traditional gasoline), the RFG oxygenate market, and the wintertime oxygenated gasoline market (approximately 12 billion gallons). The market penetration algorithm begins when the market share has reached 3 percent of the total market.

The constant k was determined from the initial condition; that is, at $t_0 = 0$, the market share $N(t_0) = 0.03$. An initial growth rate of 12 percent per year (the approximate growth rate of corn-based ethanol production) was used to reach the 3-percent market penetration threshold. The parameters I, B, and S were assumed to vary across technological scenarios. The range for I was selected around the petroleum industry index (-0.64). The profitability index B increased from the low technology to the high technology case, reflecting the reduced costs of ethanol production. Profitability also varied across Census division, being highest in Census division 9. Several factors led to this decision. It was assumed that ethanol would be the oxygenate to replace MTBE in California RFG, creating a large increase in demand (over 550 million gallons in 2003) in the high-value RFG market. Census divisions 3 and 4 supply the Midwestern gasohol market, a lower value product, and the East Coast market, where the cost of transporting ethanol would further reduce profitability. The size of investment, S, is the relative size of the investment as a fraction of the total value of the firm. The low technology case uses a 50-percent fraction, implying high risk. The reference case uses 25 percent of the firm's value, and the high technology case uses 10 percent. The parameter values assumed for the forecast are summarized in Table 2.

Table 2. Blackman-Mansfield Parameter Values

Results Federal Subsidy Extended to 2020

Benefitting from the assumed continuation of the Federal ethanol subsidy, gasoline blending of ethanol (in gasohol and RFG) is projected to increase by 1.4 percent per year from 2000 to 2020 in the reference case (Figure 9). Total U.S. cellulose ethanol production is projected to increase by 22 percent per year, reaching 850 million gallons by 2020 (Figure 10). Because cellulosic ethanol production capacity in Census division 9 does not grow sufficiently to meet California RFG demand, supplies of ethanol from the Midwest are needed to meet demand in Census division 9.

Figure 9. Projected Motor Gasoline Blending With Ethanol, 2000-2020

In the high technology case, more rapid market penetration of cellulosic ethanol is projected, resulting in 4.0-percent annual growth in gasoline blending. Cellulose ethanol production grows by 30 percent per year, reaching 2.8 billion gallons by 2020 (Figure 10). In the low technology case, production costs limit the growth of biomass ethanol production in the Midwest; however, biomass ethanol produced in Census division 9 competes favorably with corn-based supplies from the Midwest because of the cost of transportation. U.S. production of biomass ethanol grows to 347 million gallons by 2020 in the low technology case. Production in the reference and high technology cases is limited only by assumptions on capacity expansion, indicating that ethanol from biomass is economically competitive in both cases. In the low technology case, nearly all the projected production is a result of the model requirement for ethanol blending in E85 and California RFG.

Figure 10. Projected Biomass Ethanol Production, 2000-2020

Federal Subsidy Eliminated in 2008

When the Federal ethanol subsidy is assumed to be eliminated in 2008, gasohol and RFG blending with ethanol

ceases in all three technology cases. Biomass ethanol production still is projected to grow in the reference and high technology cases, however, replacing the more expensive corn ethanol to meet California RFG and E85 demand. (A NEMS model assumption for this study was that demand for E85 would remain fixed and that RFG oxygenate demand in California would be met with ethanol.) In the low technology case, the projected growth of biomass ethanol production is similar under the subsidy extension and subsidy elimination assumptions, occurring only in Census division 9 to meet the required California RFG demand. Conventional gasoline blending of ethanol is projected to resume in the high technology case by 2018, when capacity begins to exceed the required demand for ethanol in RFG and E85.

An alternative high technology case with capacity limited only by feedstock availability was also run, to determine the price at which blending of ethanol with conventional gasoline would occur without the benefit of a Federal subsidy. In this case, gasoline blending is projected to resume in 2010 in Census divisions 3 and 4 (Midwest), when the cost of cellulose ethanol drops to $0.82 per gallon. Ethanol begins to penetrate other markets in 2014, when costs fall to $0.68 per gallon.

Interestingly, the value of ethanol varies depending on how it is blended with gasoline. The marginal value of ethanol is higher in the projections when it is used as an oxygenate for RFG than when it is used as a volume extender. The projected marginal value of ethanol increases by $0.04 per gallon in Census division 3 and by $0.13 per gallon in Census division 9 when RFG blending begins in 2003 (Figure 11). Ethanol is also used as an oxygenate for wintertime fuels in areas that mandate the use of high oxygen (2.7 percent) fuels. Although ethanol is more expensive, it competes favorably with MTBE because it can provide the 2.7 percent oxygen requirement with only about 50 percent of the volume of MTBE. The NEMS model projects that ethanol will maintain its wintertime market share in high oxygen gasoline even in the absence of the Federal subsidy.

Figure 11. Marginal Value of Ethanol With and Without RFG Blending

Conclusion

Ethanol has enjoyed some success as a renewable fuel, primarily as a gasoline volume extender and also as an oxygenate for high-oxygen fuels, an oxygenate in RFG in some markets, and potentially as a fuel in flexible-fuel vehicles. A large part of its success has been the Federal ethanol subsidy. With the subsidy due to expire in 2008, however, it is not clear whether ethanol will continue to receive political support. Thus, the future of ethanol may depend on whether it can compete with crude oil on its own merits.

Ethanol costs could be reduced dramatically if efforts to produce ethanol from biomass are successful. Biomass feedstocks, including forest residue, agricultural residue, and energy crops, are abundant and relatively inexpensive, and they are expected to lower the cost of producing ethanol and provide stability to supply and price. In addition, the use of corn stover would lend continued support to the U.S. corn industry. Analysis of NREL technological goals for cellulose ethanol conversion suggests that ethanol could compete favorably with other gasoline additives without the benefit of a Federal subsidy if the goals were achieved. Enzymatic hydrolysis of cellulose appears to have the most potential for achieving the goals, but substantial reductions in the cost of producing cellulase enzymes and improvements in the fermentation of nonglucose sugars to ethanol still are needed.

The ban on MTBE in California could provide additional incentives for the development of cellulose-based ethanol. If ethanol were used to replace MTBE in Federal RFG, demand for ethanol in California would increase by more than 550 million gallons per year. California has vast biomass resources that could support the additional demand. In addition, the cost of transporting Midwest ethanol would allow cellulosic ethanol to compete favorably in the market. Ultimately, ethanol's future in RFG could depend on whether Congress eliminates the minimum oxygen requirement included in the CAAA90. Without the minimum oxygen requirement, refiners would have more flexibility to meet RFG specifications with blending alternatives, such as alkylates, depending on an individual refinery's configuration and market conditions. Ethanol would still be valuable as an octane booster, however, and could make up for some of the lost volume of MTBE.

Significant barriers to the success of cellulose-derived ethanol remain. For example, it may be difficult to create strains of genetically engineered yeast that are hardy enough to be used for ethanol production on a commercial scale. In addition, genetically modified organisms may have to be strictly contained. Other issues include the cost and mechanical difficulties associated with processing large amounts of wet solids. Proponents of biomass ethanol remain confident, however, that the process will succeed and low-cost ethanol will become a reality.