Cellulosic Ethanol: R&D Status and Carbon Emission Benefits

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1. Introduction

It is now generally agreed among forecasters that global demand for oil, mainly from developing nations, will grow by nearly 50 percent over the next 20 years. According to the Energy Information Administration (EIA)[1], the world will need another 35 million barrels of oil a day by the year 2015, up from 69 million barrels of oil a day in 1995. Increasing quantities of petroleum used in the United States are imported as domestic production declines even as demand rises. This lends special significance to the Biomass Ethanol Project of the Department of Energy (DOE) as a means of diversifying the fuel base in our transportation sector with a domestic renewable fuel. An important corollary to the notion of increasing energy security is the concept of energy diversity. Today, in the United States, natural gas, propane, methanol and biodiesel are establishing a place in the transportation fuel market. Bioethanol from cellulosic biomass is yet another option in the fuel mix that we seek to provide.

2. DOE's Bioethanol Research, Development and Demonstration Activities

In the beginning, enterprising companies will start up bioethanol plants in niche markets, i.e., areas with optimal feedstock supplies and prices and markets for ethanol. Eventually, the cellulosic ethanol industry will likely develop in the Midwest in view of favorable state incentives, consumers' attitude, and the relative ease with which the existing corn ethanol industry can gradually expand its feedstock base to encompass residues from the harvesting of corn and other crops. The new industry will likely develop as an evolutionary add-on to the current industry.

At this very early stage of the bioethanol industry, DOE is working with industry partners to demonstrate technologies using low cost feedstocks in niche markets involving agricultural wastes (bagasse, rice straw) and municipal solid wastes. Among the most interesting near term feedstocks identified for the year 2000-2005 are softwoods, which may come from forest thinning operations and the forest products industries. Forest residues represent a pressing environmental issue in many parts of the United States, (e.g., Northern California). Many of our forests have unprecedented levels of "fuel" which, when exposed to the summer dry conditions, are producing devastating forest fires.

Rice straw is another example of an environmental problem that is also an opportunity for bioethanol. California's rice growers are investigating alternatives to burning rice straw in the field. We have identified partners who are developing technology for bioethanol from rice straw.

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1. EIA, International Energy Outlook 1997, dated April 1997, Report No. DOE/EIA-0484(97), page 118, Table A3.

Bioenergy Feedstocks R&D

Low-cost agricultural harvesting residues and forestry wastes will be available for the pioneering plants of our cellulosic ethanol industry. However, as demand for such feedstocks grows, prices will rise. In the longer term, dedicated crops will be necessary to support a significant ethanol industry. Accordingly, DOE is developing low cost bioenergy feedstocks that will be deployed in the mid to long term. R&D efforts managed by DOE's Oak Ridge National Laboratory (ORNL) are currently centered on two model perennial crops, switchgrass and hybrid poplar.

Switchgrass is a prairie grass whose native range includes most of the land east of the Rocky Mountains. Hybrid poplars, which are produced by crossing cottonwood species, can be produced in most of the eastern half of the United States and the Pacific Northwest. DOE and others are also investigating willows as a potential tree crop. Willow production can occur in the Northeastern and Lake State Regions of the U.S. The use of perennials allow environmentally benign or beneficial use of low cost, marginal land by building up soil carbon, reducing erosion, and increasing water quality and other environmental benefits.

DOE has established feedstock development centers in the Midwest/Lake States and in the Southeast. These centers are patterned after successes in the Pacific Northwest, where clones developed at universities with DOE funding have been transferred to industry and used in commercial plantings. R&D activities at the centers range from biotechnology and breeding to field testing of improved varieties and clones suitable for the region. In many of these activities, DOE is collaborating with the Department of Agriculture (USDA). Table 1 indicates the types of bioenergy crops that can be produced in each region of the country.

Table 1. Likely Bioenergy Crops Produced by Region

Region	Likely Bioenergy Crops
Lake States (MI,MN,WI)	Switchgrass, hybrid poplar, willow
Corn Belt (IA,IL,IN,MO,OH)	Switchgrass, hybrid poplar
Appalachia (KY,NC,TN,VA,WV)	Switchgrass, hybrid poplar
Southeast (AL,GA,SC,MS,LA,AR)	Switchgrass, hybrid poplar
North Plains (eastern half of KS,NE,ND,SD)	Switchgrass, hybrid poplar
South Plains (eastern half of OK,TX)	Switchgrass, hybrid poplar
Northeast (PA,NY)	Switchgrass, hybrid poplar, willow
Pacific Northwest (OR,WA)	Hybrid poplar

It is further anticipated that bioenergy crops can be produced in additional areas, such as the Delta States region, but yield data are not yet available.

Ethanol Production R&D

DOE is also sponsoring R&D in biomass ethanol production technologies. For the mid- to long-term, two major technology areas have been identified that could provide significant cost reductions: pretreatment and hydrolysis. In the area of pretreatment technology, current technologies involve dilute acid treatment of the biomass which result in the release of the hemicellulose in the form of sugars. This allows the cellulose to be more easily converted during hydrolysis. Pretreatment technology that could offer significant cost reduction is based on a countercurrent process that uses a more efficient design of the dilute acid pretreatment. This method would also minimize the need for cellulase enzymes (described below).

Current hydrolysis technologies under development at DOE's National Renewable Energy Laboratory (NREL) are dependent upon the action of enzymes that are capable of hydrolyzing biomass to sugars which can then be fermented to ethanol. These enzymes, called cellulases, are currently available because of their use in the textile industry, but costs are high. Four colloquies were held in 1997, bringing major enzyme producers, ethanol producers, and research scientists at NREL and USDA together to determine the appropriate strategies needed to lower the cost of these enzymes. These stakeholder meetings are enabling the program to direct research efforts toward improvement of the enzymes, production protocols, and fruitful collaboration with the industrial elements needed to meet cellulase cost goals.

R&D needs to be proven in commercial demonstration projects and, for this purpose, the list of partners involved in the program is growing:

Arkenol – developers of acid hydrolysis technology for conversion of waste biomass to ethanol and chemicals

BC International – a company currently converting an existing ethanol facility to commercially demonstrate cellulosic ethanol technology using bagasse

SWAN Biomass – developers of enzymatic hydrolysis technology for ethanol production

Bioengineering Resources Inc. - developer of ethanol technology based on biomass gasification and subsequent conversion of the gases to ethanol

Masada Resources, Inc. - a company commercializing acid hydrolysis technology for ethanol production from cellulosic components in municipal solid waste

Morris Ag. Energy - a 7-million gallons per year corn ethanol producer who is participating in ORNL's novel fermentation reactor work.

Potential National Benefits

To estimate the benefits of a successful bioethanol industry, DOE analyzes the demand for ethanol as a function of ethanol prices, and potential ethanol supply and costs.

Approach

The demand analysis was performed using the ORNL Refinery Yield Model (ORNL-RYM),[2] a linear program that has extensive representations of refinery processes and investment options, crude oils and other raw materials, and refined products. The model's gasoline specifications include octane, Reid vapor pressure (RVP), oxygen content, sulfur, benzene, aromatics, total olefins, and distillation points. The model blends gasolines to satisfy formula and emissions standards mandated by the Clean Air Act Amendments and described by the U.S. Environmental Protection Agency Complex Model, which predicts pollutant emissions in terms of gasoline properties.[3]

For the ethanol demand study, it is assumed that the modeled refineries can produce subgrade gasolines for shipment to blenders who add optimal volumes of ethanol to produce the finished gasoline. Data for the ethanol demand study are based on information published by DOE, DOE's EIA, DOE contractors, the General Accounting Office, the National Petroleum Refiners Association, and industry journals.[2] The study cases investigate regional and seasonal refiner/blender demand for ethanol with variations in reformulated gasoline (RFG) production share, world oil price, cost of competing oxygenate, and ethanol cost.

Key findings from the demand analysis are:

- Annual ethanol demand is higher with lower production of RFG. The RFG share effect on ethanol demand depends on season. A higher RFG share in the summer substantially reduces ethanol demand. Because of limits on emissions of volatile organic compounds (VOCs), for which the major determinant is RVP, summer RFG is more costly to produce with high-RVP oxygenates like ethanol. Ethanol's attractiveness in summer conventional gasoline (CG) is enhanced by the 1 pound per square inch RVP waiver for 10 percent ethanol blends. While the ethanol-based oxygenate ETBE has a low RVP blending value, ETBE is more costly to produce or purchase over part of the demand curve, compared to the hydrocarbon-based oxygenate MTBE. Furthermore, the opportunity to use ethanol through production of ETBE is somewhat restricted by the premised maximum allowable oxygen content of 2.7 wt percent for ether-containing gasolines, compared to 3.5 wt percent for ethanol-containing gasolines. In the winter, allowable RVP is much higher, and there are no limits for VOC emissions.

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2. Hadder, G.R. 1997. *Estimation of Ethanol Demand in Gasoline*, ORNL-6926 draft report, Oak Ridge National Laboratory, Oak Ridge, TN, July.

3. U.S. Environmental Protection Agency. 1994. "Regulation of Fuel and Fuel Additives: Standards for Reformulated Gasoline: Final Rulemaking," *Federal Register*, 7716-7878, February 16.

RVP-related advantages disappear for winter CG. Winter RFG becomes more attractive for ethanol blending for a combination of reasons, including the higher refiner's revenue for RFG. The use of ethanol is promoted by higher production of winter RFG and oxygenated gasoline for carbon monoxide nonattainment areas. Nevertheless, ethanol blending in summer CG is greater than ethanol blending in winter gasolines for nonattainment areas, and the annualized ethanol demand is greater with a program that has a higher use of summer CG (a lower RFG share). RFG opt-in programs cannot be varied seasonally. States cannot make the illogical ozone policy decision to opt-in for winter RFG and opt-out for summer. Therefore, higher ethanol demand is favored by a lower RFG production share.

- With higher ethanol demand, gasoline production (excluding ethanol) falls. With the addition of ethanol to gasoline, the requirements for high quality gasoline blendstocks fall, and utilization falls for process units which produce these blendstocks.

- As refinery demand for cellulosic ethanol increases, greenhouse gas emissions decrease for gasoline and for refinery operations. The study assumes that cellulosic ethanol is used in gasoline blending and ether production. Greenhouse gas (GHG) emissions of cellulosic ethanol are low because much carbon dioxide released during biomass conversion to ethanol and ethanol combustion is absorbed during the growth of new biomass materials to replace those used during conversions. Other factors that contribute to lower emissions of cellulosic ethanol include reduced use of fertilizers, pesticides, tillage, and labor. Increased use of cellulosic ethanol has GHG reduction benefits due to reduction of refinery power and fuel use and reduction of GHG emissions in gasoline. As ethanol demand is increased in the study cases, GHG emissions of gasoline decrease by 2 to 5 percent, and GHG emissions associated with refinery fuel and power fall by as much as 6 percent.

- It is assumed that the maximum allowable oxygen content for ethanol blends is 3.5 weight (wt) percent. At lower refiner values for ethanol, ethanol demand could be greater if the maximum allowable oxygen content were increased. Modern vehicles can generally perform adequately at 6 wt percent oxygen, which corresponds to about 17 volume percent of ethanol.[4]

About 1.3 billion gallons of ethanol were actually used in U.S. transportation fuels in 1997.[5] For year 2010, ORNL-RYM estimates that ethanol demand for gasoline production and blending in the U.S. could be 10-11 billion gallons per year at a refiner/blender value of $0.36 per gallon (in 1995 dollars). The refinery model's ethanol demand curve of year 2010 is extrapolated to demand curves for five-year intervals between years 2000 and 2025, using extrapolation factors for

4. Energy and Environmental Analysis, Inc., "Specifications for Low Petroleum Gasoline," 1655 North Fort Meyer Drive, Arlington, VA.

5. U.S. Department of Energy, Energy Information Administration. 1997. *Monthly Oxygenate Report*, ftp://ftp.eia.doe.gov/pub/petroleum/data/monthly/oxydata.txt, Washington, DC, December.

petroleum prices and gasoline demand from the *Annual Energy Outlook 1997*.[6] A most important factor in the ethanol demand forecast is the assumed increase in future gasoline value, which makes the refiner willing to pay more for a given volume of ethanol. The plausibility of future-year ethanol demand estimates is supported by the fact that ORNL-RYM results agree well with recently observed demand for ethanol - when ethanol demand is expressed as a function of the difference in value between ethanol and gasoline.

ORNL developed supply curves for major biomass feedstocks--agricultural residues (corn stover and wheat straw), forest hardwoods and softwoods residues, corn, and bio-energy crops (hybrid poplars, switchgrass, willows)--for the years 2000, 2005, 2010, and 2015. Estimated agricultural residues prices include the cost of collecting the residues and a premium paid to farmers to compensate for nutrient losses, etc. Available quantities are adjusted for the quantities that must remain on the field to maintain soil carbon levels and limit erosion potential[7]. Softwood and hardwood forest residue supply curves are estimated by updating a model originally developed by Alan McQuillan, and include sound dead wood, live cull wood, and logging residues[8]. Estimated prices include the collection cost, processing, transporting, and a return for risk. Dedicated energy crop supply curves are based on the principle that farmers need to earn at least the same profit from energy crop production as could be earned using the land to produce other crops. A distribution of agricultural cash rental rates is used as a measure of the profitibility of the land when used to produce conventional agricultural crops. Energy crop yields are based on field trial results and expert opinion[9]. Energy crop production costs are estimated using the BIOCOST model, a model that estimates production costs for seven major crop regions using methodology consistent with that used by USDA to estimate the cost of producing conventional crops[10].

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6. U.S. Department of Energy, Energy Information Administration. 1996. *Annual Energy Outlook 1997*, DOE/EIA-0383(97), Washington, DC, December

7. D.T. Lightle, A Soil Conditioning Index for Cropland Managment Systems (Draft), U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, April 1997.

8. A. McQuillan, K. Skog, T. Nagle, and R. Loveless, Marginal Cost Supply Curves for Utilizing Forest Waste Wood in the United States, Unpublished Manuscript, University of Montana, Missourla, February 1984.

9. R.L. Graham, L.J. Allison, and D.A. Becker, ORECCL-Oak Ridge Energy Crop County Level Database, Proceedings of BIOENERGY '96 - The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, September 15-20, 1996, Nashville, TN, pp. 522-529.

10. M.E. Walsh and D.A. Becker, BIOCOST: A Software Program to Estimate the Cost of Producing Bioenergy Crops, Proceedings of BIOENERGY '96 - The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, September 15-20, 1996, Nashville, TN, pp. 480-486.

A technical and economic model of the conversion of lignocellulosic biomass to ethanol has been developed at NREL. The model uses the ASPEN Plus process simulation software from ASPEN Technology, Inc. to describe the material and energy balance of the conversion process. This process model uses experimental results developed in the laboratories of NREL and other reputable laboratories funded by the DOE, information from published literature sources and standard engineering practices to rigorously describe the thermodynamics of conversion to ethanol.

The material and energy balance is then used with best design practices of leading engineering firms to determine the capital equipment requirements. The costs of building the plant are obtained from equipment manufacturer quotes, where possible, or obtained from the cost estimation software of Icarus based on this design. The capital and operating costs are used to determine the cost of producing ethanol using a discounted cash flow analysis.

In general the model considers a large (50 million gallons of ethanol per year), completely integrated, green site plant including utilities, waste treatment and steam and electricity generation from residual lignin. By including all aspects of the plant a more accurate production cost will be determined.

The model can be used not only to analyze the current state of the research, but also to assess the potential cost savings of futuristic processing scenarios that are likely to result from further research and development. This model is used to analyze proposed R&D alternatives to quantify the expected cost saving in the production of ethanol and help determine if the proposed activities should be initiated.

Building on previous work by NREL and DynCorp, Technology and Management Services, Inc. (TMS) developed a system of linked spreadsheet models, the Systems Analysis Spreadsheet (SAS), to integrate the ORNL feedstock curves, the NREL conversion costs, and the ORNL refinery/blender demand, for program-level policy analysis. The SAS and its inputs include all necessary integrating costs to define a complete industry system (e.g. transportation and handling costs for both feedstocks and ethanol product) and looks forward from today through the year 2025. Ethanol supply and demand in a given year are determined by the intersection of their respective price vs. quantity curves to reflect a market-based economic outcome. Feedstock selection is determined by economic optimization to generate the lowest cost and price for ethanol at each level of demand. The SAS thus shows how, for each assumption set, the cellulosic ethanol industry might evolve from its present state into a competitive commercial industry with a significant share of the transportation fuel market.

Alternative incentive schedules for ethanol production over time may be introduced by the analyst to examine their impact on the rate of industry evolution. Other economic inputs to the SAS, which are readily varied for sensitivity studies, include financial parameters such as capital recovery factors, electricity byproduct credits, the degree of alternative uses of biomass feedstocks (e.g., for biopower production), and limitations on the availability of each potential feedstock in each time period to

reflect issues of physical availability, production lead-times and production expansion patterns compatible with experience with other agricultural crops. Outputs are in 5-year increments and include market shares for cellulosic ethanol, greenhouse gas benefits, other costs and benefits (externalities) and quantities of each feedstock used per year of the study period. The SAS then looks at benefit/cost ratios (national externality benefits/ethanol incentive costs), sensitivity studies for R&D prioritization, business and financial risk, and market penetration over time. New analytic capabilities with the present SAS include automated supply/demand solution, calculation of externality values (e.g., carbon emission avoidance), and risk analysis.

A primary goal for the SAS is to help build program credibility and understanding by:

- Using, as inputs, well-documented and peer reviewed analysis results from industry and the National Laboratories; and
- Integrating these inputs in a relatively simple set of spreadsheets that are freely available for external review, including all cell formulas and documentation.

Results

To illustrate the range of results obtained with the latest models and data, we use estimates of ethanol demand consistent with the oil market projections by the Energy Information Administration. We obtain results for both the Reference and High Oil Market cases of that publication, with world oil prices climbing from a 1996 level of $20.48 per barrel alternatively to $22.32 (Reference) or $28.71 (High) by 2020. For each of these two cases, we extrapolated the oil prices to 2025 and tested three three declining incentive schedules to stimulate the production of cellulosic ethanol and the growth of the industry simultaneously, with assumed continuous cost reduction achieved through ongoing research and development. These three incentive schedules (spotlighted at 5-year intervals) are tabulated below.

Production Incentive—$/gallon Ethanol In Indicated Year

Incentive Label	2000	2005	2010	2015	2020	2025
Extensive	0.35	0.35	0.35	0.16	0.08	—
Intermediate	0.28	0.24	0.20	0.06	—	—
Moderate	0.28	0.24	0.04	—	—	—

In all cases, incentive schedules have phased out by 2025 (if not earlier) and a fully market-based, economic and competitive cellulosic ethanol industry is in place. The unsubsidized level of production is alternatively 11.0 billion gallons per year (BGY) in the High Oil Market Case and 7.7

BGY in the Reference Case. These figures include corn-based production of ethanol at 1.4 BGY, with the remainder produced from cellulosic waste and energy crops.

We credit non-corn-based production with reduction in greenhouse gas emissions through use of ethanol in crude oil refineries and as a blendstock in gasoline. We calculate a cost of carbon avoidance by dividing the incentive expenditures (through whatever limited time period they are incurred) by the carbon emissions avoided through the case analysis period (2000 through 2025). This ethanol use simultaneously contributes to increased energy security and domestic jobs by displacing crude oil. Illustrative case results for the three Incentive Schedules are presented below (with the range of results reflecting the range of oil market conditions described by the alternative sets of oil price cases).

Ethanol Industry Evolution—Case Outputs

Case Output	Incentive Schedule Adopted		
	Extensive	**Intermediate**	**Moderate**
Illustrative Ethanol Production in 2010 (BGY)	8.0 to 10.4	5.9 to 9.0	3.8 to 6.7
Cumulative Ethanol Production through 2025 (Billions of Gallons)	120 to 190	100 to 160	75 to 140
Cumulative Emissions Avoided through 2025 (Millions of tonnes of Carbon)	210 to 320	170 to 270	130 to 240
Cost of Carbon Avoidance ($/Tonne of Carbon)	~ 85	~ 40	~ 15
Crude Oil Use Avoided through 2025 (Billions of barrels)	1.9 to 2.9	1.5 to 2.4	1.2 to 2.2

These case results suggest that an expanding domestic ethanol industry, based on cellulosic biomass as well as corn feedstocks, could provide very substantial, and possibly unique, national benefits, well repaying the costs of technology development, and be a major contributor to the successful future management and abatement of greenhouse gas emissions.