Near Term Application of Biotechnology to Fuel Ethanol Production from Lignocellulosic Biomass

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Opportunities for Innovation: Biotechnology

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PREFACE

This monograph in the "Opportunities for Innovation" series deals with biotechnology, a mature but explosive technology finding a rebirth in the discoveries of the structure of DNA and RNA that led to the development of advanced techniques for selectively altering the genetic makeup of cells though genetic engineering, development of monoclonal antibodies and hybridomas, and somaclonal variation of plant cells.

Biotechnology is being viewed by many as one of the major technological opportunities of this century ranking with the explosive growth of telecommunications, computers, and space exploration. Certainly the rush to participate by conservative established companies, new startup companies, investors, university scientists, governments, international organizations, and the media support this view. Expectations for the new biotechnology are very high. Whether such expectations will be completely realized is another matter. However, the flow of resources—money and trained scientific personnel—over the past decade into this new research area suggests that such prophecies may become self-fulfilling.

In general, biotechnology can be expected to have a major impact on fundamental human needs engendered in the market segments of: health care, agriculture, forestry, food ingredients, industrial chemicals, plastics, energy, mining, pollution control, and bioelectronics. At present, innovations in health care aimed at very high value-in-use therapeutic proteins are in the forefront with crop agriculture a far second. Innovations in pollution control are coming up strong as a result of increased public and regulatory pressure. However the interest in biological approaches to commodity chemicals based on renewable raw materials has waned as a result of the continued softness in crude oil prices.

Certainly the commercial stakes are high. Biopharmaceuticals, that reached U.S. sales levels of $2.4 billion in 1992, are forecast to reach $9.3 billion by 2002 among the market segments: cancer— $2.9 billion, cardiovascular—$2.1 billion, vaccines—$1.9 billion and hormones and growth factors—$1.8 billion. In addition, sales of diagnostics are expected to reach $2.5 billion from a current level of $1.0 billion.

Agricultural biotechnology, which has lagged health care in delivering new products, is expectantly poised for a growth rate of 35% per year with sales rising from $70 million in 1992 to over $1 billion by 2000.

About 97% of the current market for synthetic organic chemicals is technically, if not economically, vulnerable to replacement by bio-derived counterparts. This potential conversion amounts to 5 billion pounds of specialty chemicals valued at an average price of $1 per pound and 311 billion pounds of commodity chemicals valued at $108 billion. Thermoplastic polymers have an additional market potential for biopolymers of 51 billion pounds.

Opportunities for bioproducts as food ingredients amount to $1.76 billion in functional additives, $1.1 billion in non-nutritive sweeteners, and $300 million on fat replacers.

The EPA estimates that the cost of federally mandated pollution control and cleanup reached $115 billion in 1990. Continued public and regulatory pressure will promote the expansion of bioremediation. The use of indigenous bacteria and imported microbes to clean up contaminated soil and ground water is expected to grow at a rate of 20-30% in the 1990's—virtually regardless of prevailing economic conditions.

Likewise, the strict requirements of the Clean Air Act will create a market for the microbial desulfurization of coal by as much as $50 billion by 2000. The Act is also expected to expand the market for bioethanol as an octane enhancer in gasoline.

Similarly, chemically-treated bacteria, chitin, carrageenan, modified cellulosic wastes, and starch xanthate are all serious contenders in the market for the biological recovery of metals, expected to top $500 million in the United States by 2000.

The basic purpose of this project is to help small businesses get on the fast track in biotechnology research and development leading to the spin off of viable commercial businesses, probably with the help of larger companies having the resources for commercialization that are lacking in a small enterprise. Such resources could include financing, and positions in marketing, manufacturing, regulatory affairs, and raw material supply, to name a few.

This does not mean, however, that the objective of the monograph is restricted to providing the businessman with an immediate opportunity to apply biotechnology profitably. Indeed, commercialization may be many years away and the business catalyst might be the merger of organizational resources at a critical time in the research program. Almost all of the much heralded coalitions in human health care have occurred in this way.

A multifaceted approach has been taken in designing the monograph so as to include:

- Research on new products, even at the bench scale, based on a scientific discovery that if translatable to commercial scale would be assured of market acceptance. Pharmaceuticals for human or animal health care and plant growth regulators for agriculture would be examples of this category.
- Research on new or improved processes for producing existing products having commercially relevant objectives for scale up to viable businesses providing a competitive cost advantage over the incumbent processes. Certain speciality chemicals such as lactic acid and citric acid and commodity chemicals as ethanol and acetone/butanol are examples of this.
- Research on products or services mandated by legislation to alleviate the adverse effects of pollution in its various forms. Examples include: bioremediation, bioprocessing of minerals, biodegradable plastic packaging materials, algae systems for removing carbon dioxide from flue gas, etc.
- Research on products based on coal or renewable natural resources which, although at a current competitive cost disadvantage compared with products from petroleum feedstocks, have a strategic importance to the United States in the event of disruptions of international trade. Examples include ethanol, biogas, polymers for enhanced oil recovery, conversion of coal to liquid or gaseous fuels, etc.

In spite of the positive side of new bioproducts, the businessman must also be aware and prepared to deal with some cases in which a biotechnology solution to a particular problem creates additional problems, be they of technical, commercial, or societal nature. As a result, new products require exhaustive testing over long periods of time before they can be brought to the market.

Clearly, biotechnology can be a high risk, high reward business area.

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Substantial improvements over the last 10 years in enzyme-based conversion technologies for production of ethanol from lignocellulosic biomass now make commercial entry potentially attractive. In particular, opportunities are emerging to produce ethanol from low-cost sources of lignocellulosic biomass such as agricultural and forestry residues, municipal solid waste, and industrial wastes at costs less than the current price of ethanol from corn. A dilute acid pretreatment step results in high yields of fermentable sugars from the hemicellulose fractions of biomass as well as opening up the biomass structure to facilitate conversion of the cellulose into glucose. The simultaneous saccharification and fermentation (SSF) process breaks down the major cellulose fraction to glucose sugar and rapidly ferments glucose to ethanol. Through application of modern genetic engineering and other approaches, several technologies have emerged that provide high yields of ethanol from the previously difficult to utilize hemicellulosic sugars. Developments in these and other areas have reduced the projected selling price of ethanol from about $0.98/liter ($3.70/gallon) 10 years ago to only about $0.32/liter ($1.23/gallon) now for feedstocks costing $46/dry tonne ($42/ton). When niche opportunities such as use of inexpensive sources of lignocellulosic biomass or inexpensive debt financing are available, the projected costs can drop sufficiently below the approximate $0.35/liter ($1.32/gallon) selling price of ethanol made from corn to provide promising venture opportunities. The implementation of the Clean Air Act Amendments of 1990 provides ethanol with an immediate market as an oxygenate for blending with gasoline to reduce emissions of carbon monoxide and unburned hydrocarbons from vehicle exhaust. Addition of ethanol to gasoline also increases octane while reducing gasoline consumption. Some uncertainty has developed about the market for ethanol for direct blending with gasoline because of concern about increased evaporative losses of hydrocarbons and the potential impact of these components on ozone formation. Commercial processes are being introduced to react ethanol with isobutylene to form ethyl tertiary butyl ether (ETBE) that enjoys the same benefits as direct ethanol blends while reducing evaporative emissions from the gasoline blend. In the longer term, opportunities have been identified to reduce the price of ethanol to be competitive with gasoline without tax incentives. Large-scale substitution of ethanol derived from lignocellulosic biomass offers improved urban air quality, no net contribution of carbon dioxide to the atmosphere, improved international competitiveness, new markets for agricultural products, and substantial reductions in petroleum imports from unreliable sources.

Key words: biomass; economics; enzymatic conversion; ethanol; lignocellulosic.

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1. Introduction

Ethanol, a liquid fuel produced by fermenting sugars from biomass or by the catalytic hydration of ethylene, is an excellent transportation fuel. In recent years, interest in ethanol as an octane enhancer and fuel extender has increased dramatically in response to concerns associated with conventional transportation fuels. The implementation of the Clean Air Act Amendments of 1990 presents a potentially large and expanding market for ethanol as an oxygenate to improve air quality.

With OPEC controlling 75% of the world's oil reserves and approximately 50% of all petroleum used in the United States being imported, our nation is extremely vulnerable to oil supply interruptions. The Office of Technology Assessment projects that the United States will import about 61% of its petroleum by 2010 (U.S. Congress 1990). Petroleum imports can account for about 40% of the U.S. balance-of-payments deficit (Lynd et al. 1991a). Air quality problems such as ozone formation and carbon monoxide pollution result from use of gasoline in automobiles in many cities (U.S. EPA 1989). In addition, some predict that global climate change will result from carbon dioxide accumulation caused by burning petroleum and other fossil fuels (Intergovernment Panel on Climate Changes 1990). More and more agricultural land is being idled as crop productivity increases, resulting in a loss of agricultural income and employment (U.S. Department of Agriculture 1987). Eventual large-scale substitution of ethanol produced from renewable resources can improve energy security, reduce the balance-of-payments deficit, decrease urban air pollution, reduce accumulation of carbon dioxide in the atmosphere, and revitalize the farm economy (Lynd et al. 1991a).

Production of ethanol from sugar and starch has been practiced commercially for a number of years; however, large scale production of ethanol from these resources could increase its cost considerably. Although ethanol is made from ethylene for chemical applications, this technology has been displaced by fermentation ethanol for fuel use. Ethanol can also be made from lignocellulosic biomass, an inexpensive feedstock potentially available in large quantities. Acids or enzymes can break down the cellulose and hemicellulose chains that comprise the major fraction of the lignocellulose into their component sugar molecules for fermentation into ethanol. The challenge is to develop low-cost methods to convert the naturally resistant cellulose and hemicellulose economically. Through research advances achieved over the last few years, this technology has reached the point of commercial promise for use as a gasoline additive, and production of ethanol from low-cost renewable sources of lignocellulosic biomass such as agricultural and forestry residues and a significant fraction of municipal solid waste (MSW) provides immediate opportunities for profitable business ventures.

This chapter will focus on the production of ethanol from lignocellulosic biomass by fermentation and the comparison with existing technology for ethanol production from starch. First, an overview is provided of the use of ethanol as a blending agent and a neat fuel. Then a discussion is provided of the technology and economics for ethanol production from corn and lignocellulosic biomass. Energy balance considerations and implications for carbon dioxide accumulation are covered as well for ethanol from lignocellulosic biomass. The remaining sections of the chapter are organized in business plan format. In this vein, the strengths, weaknesses/barriers, opportunities, and threats/competition are discussed for ethanol production from biomass. Then the economic basis for development of a new business based on ethanol production from biomass is summarized. The intent is to facilitate adaptation of this information to the development of new profitable businesses based on immediate opportunities for commercialization of ethanol-from-biomass conversion technology.

2. Ethanol Fuel Properties and Value

Ethanol is currently added to gasoline in the United States to form a blend of 10% ethanol with 90% gasoline (called gasohol in the past). In Brazil, ethanol is also used as a hydrous ("neat") fuel; i.e., a fuel of about 95% ethanol and 5% water, as well as blended with gasoline. Table 74 summarizes the properties of ethanol compared to selected other fuel additives, gasoline, and methanol (Wyman and Hinman 1990).

2.1 Direct Ethanol Blends

When blended with gasoline, ethanol provides several benefits. First, it can be viewed as a fuel extender that replaces a portion of the gasoline with ethanol. In this case, the ethanol value is equal to the cost of the gasoline mixture that it displaces. Because ethanol has a lower heating

Table 74. Fuel properties for ethanol, methanol, ETBE, MTBE, isooctane, and gasoline

Property	Ethanol	Methanol	ETBE	MTBE	Isooctane	Unleaded Regular Gasoline
Formula	C_2H_5OH	CH_3OH	$(CH_3)_3COC_2H_5$	$(CH_3)_3COCH_3$	C_8H_{18}	C_4 TO C_{12}
Molecular Weight	46.07	32.04	102.18	88.15	114	NA[3]
Density, kg/m^3 @ 298 K	790	790	750	740	690	720-780
Air/Fuel Stoichiometric Ratio						
Mole Basis	14.29	7.14	42.86	35.71	59.5	57.28
Mass Basis	9.02	6.48	12.10	11.69	15.1	14.6
Higher Heating Value, kJ/kg	26.780	19.919	36.031	35.270	44.420	41.800-44.000
Lower Heating Value, kJ/L	21.156	15.736	27.023	26.100	30.650	31.350-33.000
Research Octane Number (RON)	106	106	118	106	100	91-93
Motor Octane Number (MON)	89	92	102	99	100	82-84
(RON + MON)/2	98	99	110	103	100	88
Blending RON	114-141[1]	135	117-120[2]	118	NA[3]	NA[3]
Blending MON	86-97[1]	105	101-104[2]	101	NA[3]	NA[3]
(BLENDING RON+MON)/2	115	120	111	110	NA[3]	NA[3]
Atmospheric Boiling Pt., K	351.6	337.8	344.8	328.6	398	300-498
Heat of Vaporization, kJ/kg	839	1104	308	329	406	377-502
Flash Pt., K	285	280	253	245	261	<233
Ignition Pt., K	697	737	583	733	683	553-702
Reid Vapor Pressure, kPa						
Pure Component	15.85		30.3	53.8		48.3 + 96.5
Blending	82.7-186	214+	27.7-34.5	55.1		55.1-103.4
Water Solubility, weight %						
Fuel in water	100	100	2	4.3	negligible	negligible
Water in fuel	100	100	0.6	1.4	negligible	negligible
Water Azeotrope, (atm b.p.), K	351.4	NA[3]	338.2	325.4	NA[3]	NA[3]
Water in Azeotrope, wt %	4.4	NA[3]	4.0	3.2	NA[3]	NA[3]

[1] 10% blends
[2] Assumed 12.7% blend
[3] Not Applicable
Source: Piel 1992; Ing. 1976; Exxon 1988; Bailey and Russell 1980; Pearson 1993.

value of about 21 megajoules/liter (76,000 Btu/gallon), while gasoline has a lower heating value of about 32 megajoules/liter (115,000 Btu/gallons), the value of ethanol as a fuel extender, V_e, is equal to the ratio of the lower heating value of ethanol, LHV_e, divided by the lower heating value of gasoline, LHV_g, times the price of gasoline, P_g:

$$V_e = (LHV_e/LHV_g)\ P_g.$$

Accordingly, ethanol would be worth about 66% as much as gasoline. As shown in figure 55, if gasoline sells for about $0.16 to $0.17/liter ($0.60 to $0.64/gallon) at the refinery gate, ethanol would only be worth about $0.11/liter ($0.42/gallon), well below the current wholesale price of ethanol.

Studies by Southwest Research Institute (Tosh et al. 1985) as well as others have shown that there is no statistically significant difference in mileage traveled on a given volume of fuel for vehicles operated on ethanol blends compared to those operated on straight gasoline. This result implies that ethanol, when blended with gasoline, provides the same range and therefore, effective energy content, as gasoline. Thus, the value of ethanol would be equal to the price of the gasoline it replaces or about $0.16 to $0.17/liter ($0.60 to $0.64/gallon). This is still far lower than the current selling price of ethanol. However, the U.S. government currently provides a tax incentive equal to $0.14/liter ($0.54/gallon) of ethanol from renewable resources (e.g., corn or lignocellulosic biomass), thereby increasing its value accordingly, and a blender is willing to pay about $0.30/liter ($1.15/gallon) for ethanol just as a replacement for gasoline (fig. 55). This tax incentive is scheduled to expire in the year 2000.

Ethanol has a blending octane of 115, and when ethanol is blended with gasoline, it increases the octane of the fuel mixture compared to the gasoline from which it is made. As a result, ethanol increases the value of the mixed fuel compared to the blending stock to which it is added, and the price that a blending company is willing to pay for ethanol as a octane booster is given by the following relationship:

$$(P+\Delta p)f + P(1-f) = P + V$$

in which P is the price of the base gasoline in which ethanol is added, Δp is the additional price that the blender is willing to pay for ethanol, V is the increase in value of the blended fuel, and f is the fraction of ethanol added to gasoline. This relationship is on a volumetric basis and neglects the small changes in volume when gasoline and ethanol

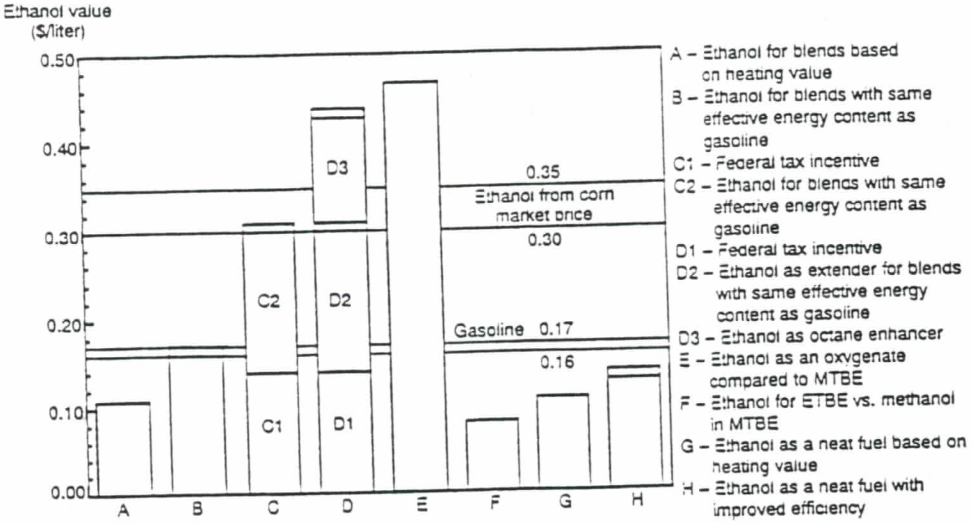


Fig. 55. The value of ethanol as a direct blending agent, for production of ETBE, and for use as a neat fuel.

are blended together. From this equation, an expression can be derived for the additional price Δp that the blender is willing to pay for ethanol:

$$\Delta p = \frac{V}{f}.$$

When ethanol is blended with gasoline to form a 10% mixture, the octane level of the gasoline is increased from regular to above that of mid-grade. If mid-grade is worth 1.3 cents/liter (5.0 cents/gallon) more than regular gasoline, ethanol will be worth $0.13/liter ($0.49/gallon) more than the gasoline to which it is added. Thus, if we assume our base gasoline price is $0.16 to $0.17 liter ($0.60 to $0.64/gallon), the total price that the blender would be willing to pay for ethanol now becomes on the order of $0.30/liter ($1.15/gallon). When the federal tax incentive of about $0.14/liter ($0.54/gallon) is added, the blender can afford to pay $0.44/liter ($1.66/gallon) for ethanol as shown in figure 55. This is well above the current market price of about $.30 to $0.35/liter ($1.15 to $1.35/gallon). An additional advantage is the ability to displace aromatics.

In addition to increasing the octane of the fuel to which it is blended, ethanol provides oxygen in the blended gasoline. The addition of oxygen to gasoline is now mandated during the winter months for carbon monoxide non-attainment areas under the Clean Air Act Amendments of 1990. Addition of oxygen will also be required for reformulated gasoline in ozone non-attainment areas beginning in 1995. Thus, it is necessary for blenders to find inexpensive sources of oxygen to use in gasoline. At the current time, the primary oxygenates used are ethanol and methyl tertiary butyl ether (MTBE). Ignoring other factors impacting what a blender is willing to pay for ethanol, the value of ethanol, V_e, as an oxygenate is given by the following relationship in terms of the price of competing products on a volumetric basis:

$$V_e = \frac{n_e\, \rho_e\, M_o}{n_o\, \rho_o\, M_e} C_o$$

in which V_e is the price that someone would be willing to pay for ethanol based on equal cost for the oxygen provided, n is the number of oxygen atoms in a formula weight of an oxygenate, ρ is the density of an oxygenate, M is its molecular weight, the subscript e refers to ethanol, the subscript o refers to the competing oxygenate, and C_o is the cost of the competing oxygenate. Since all the leading oxygenates have one oxygen atom in their formulae and the densities are quite similar, the primary factor affecting the value of ethanol is the ratio of the molecular weight of the competing oxygenate to that of ethanol. Only methanol has a lower molecular weight than ethanol of the oxygenates listed in table 74, but it is not used as an additive in the United States because of its high blending vapor pressure. The lowest molecular weight of the other competing oxygenates is that of MTBE, but its molecular weight of 88 is almost twice that of ethanol at 46. When the other terms in the above relationship are included, ethanol is found to be worth 2.04 times the price of MTBE on a volumetric basis. For MTBE selling for about \$0.23/liter (\$0.87/gallon), ethanol is worth \$0.47/liter (\$1.80/gallon), far above its retail price (fig. 55). Thus, use as an oxygenate considerably enhances the value of ethanol as a blending agent.

A number of other factors must be included in determining the value and suitability of fuel additives. These include energy content, miscibility with gasoline and water, impact on the vapor pressure of the blend, impact on other components that must be removed or added and their cost, tendency to phase separate in the presence of water, and other additive attributes or problems. Evaluation of the impact of these factors on the price a blender is willing to pay for an additive is complex, often requiring incorporation of a refinery model. However, it is important to consider their effects in the final determination of the value of ethanol and other additives, in addition to the considerations discussed above.

2.2 Ethyl Tertiary Butyl Ether (ETBE)

Ethanol can be reacted with isobutylene to form ETBE. Although the Environmental Protection Agency (EPA) currently allows 12.7% ETBE blends, if ETBE were blended at 22%, each gallon of fuel would use the same amount of ethanol as a 10% direct ethanol blend. Many of the properties of ETBE are close to those of gasoline. For example, the air-fuel stoichiometric ratio, heating value, latent heat of vaporization, and solubility characteristics are similar to gasoline. The blending octane number of ETBE is about the same as for pure ethanol, and engine performance is enhanced for ETBE blends. As shown in table 74, ETBE is quite similar to MTBE except that it lowers the vapor pressure of the gasoline to which it is added.

Although similar considerations would seem to apply to ETBE as for ethanol in assessing the value of ETBE as a gasoline extender, octane enhancer, and oxygenate, ETBE has additional value as a fuel additive because of increased regulations to reduce evaporative emissions of gasoline by lowering vapor pressure and depressing ozone formation. Consideration of the expression for assessing the value of ETBE as an oxygenate compared to MTBE suggests that ETBE is worth approximately 87% of the price of MTBE. From this, we could deduce that the ethanol used to produce ETBE is worth about 70% of the price of methanol used to manufacture MTBE. With methanol selling for about \$0.12/liter (\$0.45/gallon), ethanol would have to sell for about \$0.084/liter (\$0.32/gallon) to be competitive for ETBE production, far below the current ethanol selling price (fig. 55). Yet, many major oil companies are now beginning to manufacture large trial batches of ETBE, because its reduction of vapor pressure allows them to leave more volatile and inexpensive compounds such as n-butane in the gasoline while still meeting vapor pressure requirements. In addition, it is fully miscible with gasoline, does not suffer phase separation problems, and allows reduction of aromatics content. This suggests ETBE is worth substantially more than a simple evaluation as a source of fuel oxygen would suggest.

2.3 Neat Ethanol

Ethanol is used widely as a neat fuel (nearly pure) in Brazil. In that country, hydrous ethanol containing about 95% ethanol and 5% water is used directly as the fuel for dedicated-ethanol vehicles. As a neat fuel, the price that customers are willing to pay for ethanol, A, is given by the relationship:

$$A = \eta e p$$

in which η is the relative efficiency for ethanol use compared to gasoline, e is the ratio of volumetric energy content of ethanol compared to gasoline, and p is the price of gasoline. Based on lower heating values, we can see that the energy ratio e is about 0.66 for ethanol compared to gasoline. Thus, if we assume no increase in efficiency for use of ethanol relative to gasoline, ethanol would have to sell for about two-thirds of the price of gasoline to be competitive (fig. 55). However, experience with ethanol in dedicated, optimized engines suggests that ethanol use can achieve about a 20% increase in engine efficiency relative to gasoline use because of the higher octane of ethanol, its higher heat of vaporization, and other favorable engine properties (Lynd et al. 1991a). If a value of 1.2 is utilized for η in our previous equation, the customer would be willing to pay about 83% of the price of gasoline for ethanol or about \$0.13 to \$0.14/liter (\$0.49 to \$0.53/gallon) at the plant gate (fig. 55). This price range is well below the current price of ethanol derived from corn. Thus, use of ethanol as a neat fuel requires advances in technology for ethanol production from lignocellulosic biomass or corn to bring the price to levels competitive with gasoline on the open market unless environmental concerns dictate other than simple economic criteria be applied. As a result, blending of ethanol with gasoline is more promising in the near term.

3. Technology Status

In this section, the technology for production of ethanol from corn and other starch crops as well as lignocellulosic biomass will be described. The availability of these materials and the corresponding ethanol potential will be estimated. Production of ethanol from sugar crops is not discussed because the price of sugar is too high to make it a viable feedstock for ethanol production in the United States (Commodity Research Bureau 1991).

3.1 Ethanol from Corn and Other Starch Crops

Ethanol can be produced by the breakdown of starch from corn and other grains to form sugars for fermentation to ethanol. Currently, corn is the predominant starch crop used for this purpose in the United States. Therefore, this discussion will focus on corn, although the technology could be directly applied to other starch crops such as milo or wheat.

3.1.1 Corn Composition and Availability. As shown in figure 56, corn is composed of about 70% to 75% starch, with the remaining fractions consisting of about 10% protein, 4.5% oil, and 10%–15% other materials such as fiber, ash, and sugar (Watson et al. 1987). The starch can be broken down or hydrolyzed to produce glucose sugar which can be fermented into ethanol. The non-starch fraction of corn can be converted into a variety of feed and food co-products.

Essentially all fuel ethanol produced in the United States today is made from corn by one of two processes: dry or wet milling. Ethanol production from corn has grown considerably from only about 0.1% of the gasoline sold in the country in 1981 to about 3.8 gigaliters (1 billion gallons) of ethanol or close to 1% of the gasoline market in 1992. About 8.6 dry megatonnes (400 million bushels) of corn and other starch crops are now converted into ethanol annually at about 50 fuel ethanol production facilities in the United States (U.S. Department of Agriculture 1987). It has been estimated that about 15 to 19 gigaliters (4 to 5 billion gallons) of ethanol per year could be produced from corn and other starch crops in this country utilizing about 34 to 43 megatonnes (1.6 to 2.0 billion bushels) of corn. However, the U.S. Department of Agriculture predicts that further expansion in corn production will place strong downward pressure on co-product prices while straining the ability of the agricultural community to produce such large amounts of corn, resulting in higher corn prices (USDA 1989). Thus, corn ethanol provides a significant potential for ethanol production in this country in the near term, but substantial expansion to a major share of the transportation fuel market requires consideration of other resources.

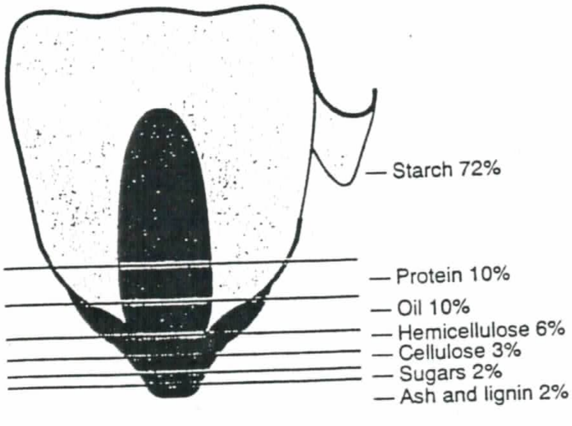


Fig. 56. Corn kernels are composed predominantly of starch with the remaining material being made up of protein, oil, fiber, ash, and sugar.

3.1.2 Ethanol Production Processes. Corn can be converted into ethanol in a dry-milling process in which the corn is first milled to a fine particle size. The wet milled corn is heated, and enzymes are added to the corn to break down the starch into the sugar glucose, which yeasts ferment into ethanol. About 440 to 458 liters of ethanol are produced per tonne (2.5 to 2.6 gallons/bushel) of corn processed in a dry-milling operation. An approximately equal weight of 340 to 360 kilograms per tonne of corn (16 to 17 pounds/bushel) of carbon dioxide evolve during fermentation for the dry-milling process. In addition, 360 to 380 kilograms per tonne of corn (17 to 18 pounds/bushel) of an animal feed co-product called distillers dried grains with solubles (DDGS) are produced. DDGS contains about 27% protein (Watson et al. 1989, Lewis and Grimes 1988). Figure 57 depicts the dry-milling process, which is geared primarily for ethanol production; about one-third of the ethanol produced in the United States is produced in dry-milling operations.

In the wet-milling process, the components of corn (oil, protein, fiber, solubles, and starch) are first separated from each other. The oil is refined to a high quality, yielding about 37 kilograms of corn oil per tonne (1.75 pounds per bushel). The protein is dried and sold as high-protein animal feed known as corn gluten meal. About 72 kilo-

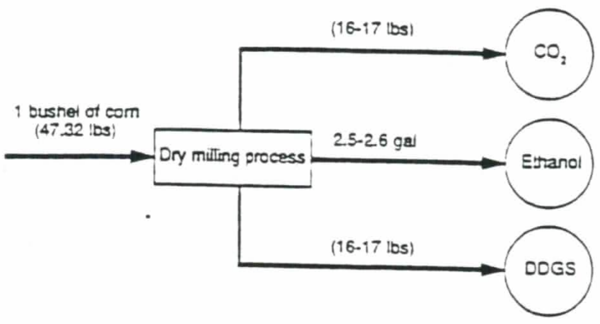


Fig. 57. Block flow diagram for dry milling of corn to ethanol with production of the animal feed co-product DDGS.

grams of this 60% protein product are produced per tonne of corn processed (3.4 pounds per bushel). The fiber and solubles are combined and sold as a low-protein animal feed, termed corn gluten feed, that contains about 21% protein; 275 kilograms of corn gluten feed result from one tonne of dry corn (13 pounds per bushel). Enzymes can convert starch to glucose to make products including high-fructose corn syrup and sweeteners such as dextrose. The glucose can also be fermented to produce about 440 liters of ethanol per dry tonne of corn (2.5 gallons per bushel) (Lewis and Grimes 1988). Figure 58 illustrates the wet-milling process as applied to ethanol production. Wet milling produces about two-thirds of the approximately 3.8 gigaliters (GL) (1.0 billion gallons) of ethanol now sold annually in the United States. However, it is important to note that not all wet-milling plants produce ethanol, and of those that do, ethanol production is often seasonal to utilize plant capacity that has been idled by lulls in demand for other starch-based products, particularly high-fructose corn syrup.

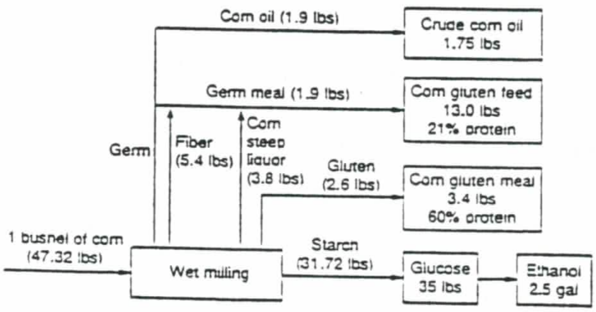


Fig. 58. Simplified schematic of the wet-milling process for production of ethanol from corn along with food-grade corn oil and the animal feed co-products corn gluten feed and corn gluten meal.

One company, Archer-Daniels Midland (ADM), produces the majority of fuel ethanol from corn in the United States and accounts for more than 55% of total U.S. capacity (Wheeler et al. 1991). Table 75 summarizes the major ethanol producers from corn and other starch crops.

3.2 Lignocellulosic Biomass Composition and Availability

Lignocellulosic biomass includes agricultural residues such as corn cobs and wheat straw, forestry wastes, industrial processing residues such as waste streams in the pulp and paper industry, a significant fraction of MSW, and woody and herbaceous plants grown as feedstocks for production of ethanol or other fuels. Although the external appearance of these many forms of biomass is quite different, the composition is very similar, as shown in figure 59. The largest fraction, typically 35% to 50%, is cellulose, a polymer of glucose that can be broken down or hydrolyzed to yield individual glucose molecules. yield individual glucose molecules. Because most of cellulose is crystalline, it is difficult to break down, but once glucose is produced, this six-carbon sugar can be readily fermented into ethanol. The second largest constituent of biomass is generally hemicellulose, comprising 20% to 30% of the material. Hemicellulose is also a polymer of sugars, but the types and distribution of sugar molecules in the polymer varies with the source of biomass. With the exception of softwoods, a five-carbon sugar known as xylose is typically the predominant component, and while hemicellulose is readily broken down to form sugars for most sources of biomass, many of the five-carbon sugars cannot be converted into ethanol with conventional fermentative organisms. The bulk of the remaining fraction of biomass (about 15% to 25%) is lignin, a phenyl-propene polymer of complex composition that cannot be fermented to ethanol. Various plant oils, proteins, and other compounds classified as extractives, plus ash, make up the rest of the biomass structure.

Table 76 summarizes the potential availability of lignocellulosic biomass within the United States. Information is presented on agricultural, forestry, and municipal wastes. Estimates are also given on the quantities of lignocellulosic biomass that could be grown as energy crops on idle, excess, and potential cropland as well as forest land. This table includes targets for biomass productivities along with the projected availability of land. From this

Table 75

U.S. producers of ethanol from corn (Wheeler et al 1991)

COMPANY	PLANT LOCATION	CAPACITY (MMgal/yr)	START-UP DATE	FEEDSTOCK	BY-PRODUCTS	MARKETS
American Diversified Corporation	Hastings, NE	13	1984	Corn, milo	DDGS	Fuel only
Archer-Daniels Midland Company	Cedar Rapids, IA	700 (for all ADM facilities)		Corn	CO_2, corn oil, gluten feed and meal	Fuel & Industrial
	Clinton, IA					Fuel & Industrial
	Decatur, IL					Fuel & Industrial
	Peoria, IL			Corn	DDGS	Fuel only
Biocom USA Ltd.	Jennings, LA	40				ETBE only
CENEX Agrifuels Co.	Walhalla, ND	11	1985	Barley, corn	DDGS, CO_2	Fuel only
Grain Processing Corporation	Muscatine, IA	60	1942	Corn	DDGS, CO_2	Industrial & Beverage
H.J. Heinz Company (Roquette)	Keokuk, IA	11	1988	Corn	Corn, gluten feed, corn gluten meal, & CO_2	Fuel only
High Plains Corporation	Colwich, KS	10	1985	Milo, corn	DDGS, livestock feed, CO_2	Fuel only
Kentucky Agricultural Energy Corporation [a]	Franklin, KY	(21)	1982	Corn	DDGS, CO_2	Fuel only
Midwest Grain Products, Incorporated	Atchison, KY	22	1942	Corn, milo, wheat	CO_2, DDGS	Beverage, fuel & industrial
	Pekin, IL	19	1980	Corn, milo, wheat	CO_2, DDGS	Beverage, fuel & industrial
New Energy Company of Indiana	South Bend, IN	63	1984	Corn	CO_2, DDGS	Fuel only
Pekin Energy	Pekin, IL	80		Corn		Primarily fuel
Portales Energy Company, Inc.	Portales, NM	10	1985	Corn, sorghum	CO_2	Fuel only
South Point Ethanol	South Point, OH	60	1982	Corn	DDGS, CO_2	Fuel only
A.E. Staley Manufacturing Company	Loudon, TN	60	1982	Corn	Cornstarch, corn oil, corn gluten feed	Primarily fuel; small amounts of industrial & beverage
Tennol Energy Company	Jasper, TN	(25)	1986	Corn	DDGS, CO_2	Fuel only

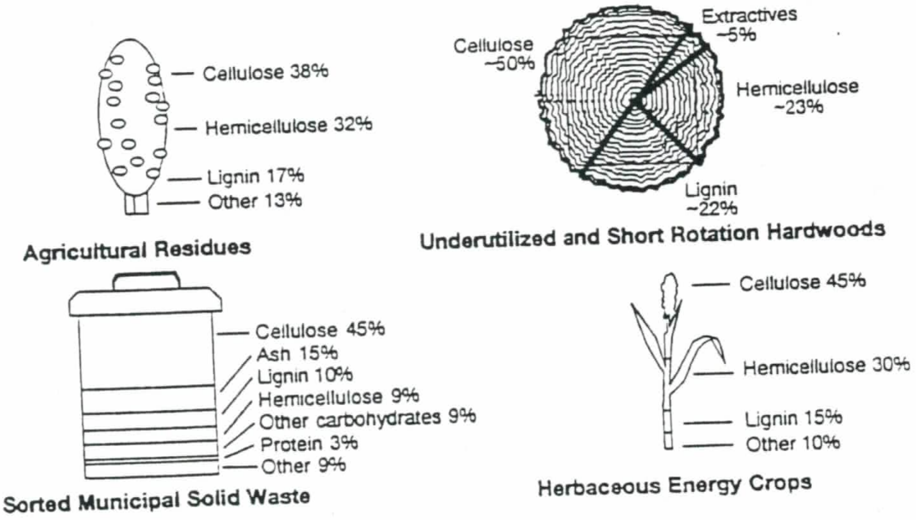


Fig. 59. The major fraction of the various forms of lignocellulosic biomass is cellulose, with hemicellulose being the second largest component for most biomass sources. Lignin, extractives, and ash comprise the remainder of these materials.

Table 76. Potential availability of lignocellulosic biomass and the corresponding ethanol production (Lynd et al. 1991a)

	Productivity		Land Available		Biomass Availability		Ethanol Potential		Energy Potential	
	Tonnes/ Hectare/Yr	Tons/ Acre/Yr	10^6 Hectares	10^6 Acres	Megatonnes	10^6 Tons	GL	Billions of Gallons	GJ[b]	Quads[b]
Waste Materials										
· Agricultural					203	224	84.8	22.4	1.8×10^9	1.7
· Forestry					167	184	69.6	18.4	1.5×10^9	1.4
· MSW					111	122	34.8	9.2	7.4×10^8	0.7
Lignocellulosic Biomass										
· Cropland										
Idled (1988)[a]	11/22	5/10	32	78	354-707	390-780	149.5-293.7	39.5-77.6	3.2×10^9-6.2×10^9	3.0-5.9
Excess (2012)[a]	11/22	5/10	61	150	680-1361	750-1500	283.9-567.8	75.0-150.0	6.0×10^9-1.2×10^{10}	5.7-11.4
Potential	7/18	3/8	61	150	408-1088	450-1200	169.2-453.4	44.7-119.8	3.6×10^9-9.6×10^9	3.4-9.1
· Forest Land	7	3	39	96	263	290	109.4	28.9	2.3×10^9	2.2
Total			132-161	324-396	1506-3193	1660-3520	617.3-1319.8	163.1-348.7	1.3×10^{10}-2.8×10^{10}	12.4-26.5

[a] Values are for biomass production potential in 1988 and 2012 based on expected availability of land and current and future biomass production (Lynd et al. 1991a).

[b] Ethanol rated at its lower heating value without consideration for possible efficiency improvements that would result in displacement of greater quantities of gasoline.

information, the potential supply of biomass is derived. For waste streams, these values are estimated from the potentially collectable fraction of such materials based on other studies. The potential amount of ethanol that could be produced and its energy impact are calculated from the biomass estimates based on the information described in the paper by Lynd et al. (1991a).

It is evident from this table that on the order of 190 gigaliters (50 billion gallons) of ethanol could be produced annually from waste materials alone. Production of about 510 gigaliters (140 billion gallons) per year of ethanol would be required to replace the current annual gasoline market of approximately 410 gigaliters (110 billion gallons) because of the slightly lower volumetric energy content of ethanol fuels. Therefore, the amount of ethanol that could be produced from waste materials would not be adequate to replace all gasoline use in the country. However, when we include the amount of ethanol that could be derived from energy crops, the total amount of ethanol potentially available could be far more than required to displace all gasoline use. Thus, ethanol from lignocellulosic biomass presents a substantial potential for major displacement of fossil fuels in this country.

3.3 Acid Hydrolysis of Lignocellulosic Biomass

Over the years, a number of processes have been studied for converting lignocellulosic biomass into ethanol catalyzed by dilute or concentrated acid. As illustrated in figure 60, the biomass is reduced in size to facilitate acid diffusion into the biomass in a pretreatment step. The cellulose fraction is hydrolyzed by the acids to produce glucose, which can be fermented into ethanol. The soluble xylose and most of the other sugars derived from hemicellulose by the acid-catalyzed hydrolysis reaction can also be fermented to ethanol, and the lignin can be burned as fuel to power the rest of the process, converted to octane boosters, or used as feedstocks for the production of chemicals.

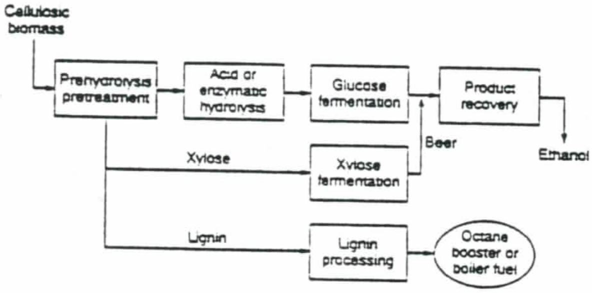


Fig. 60. Generalized process flow diagram for conversion of lignocellulosic biomass to ethanol by acid- or enzyme-catalyzed hydrolysis of cellulose.

At dilute acid concentrations, high temperatures of about 200 to 240 °C (390 to 460 °F) are required to hydrolyze the cellulose to sugars (Wright 1983 and 1988). Unfortunately, these conditions are also severe enough to degrade glucose into substantial quantities of hydroxymethyl furfural (HMF), which can in turn form tars. Similarly, xylose degrades to furfural and tars. Substantial formation of degradation products can not be avoided at the harsh conditions required for dilute acid hydrolysis, so the degradation products must be sold as coproducts to achieve favorable economics. However, markets for these products are not sufficient to complement large-scale ethanol production (Gaines and Karpuk 1987). Acid-catalyzed processes provide a near-term technology for production of fuel-grade ethanol from lignocellulosic biomass, but the low ethanol yields (50%–70%) and limited co-product markets typical of dilute acid systems make these processes unable to compete with existing fuel options in the long term (Wright 1983 and 1988).

Several dilute acid hydrolysis pilot plants were constructed in the United States during World War II as part of an effort to produce ethanol for fuel use, but the economics were unfavorable to continue operation in a free market economy. Dilute acid-catalyzed processes are currently operated in the Soviet Union for converting lignocellulosic biomass into ethanol and single cell protein (Wenzl 1970). In this country, the Tennessee Valley Authority (TVA) has a pilot plant for converting MSW to ethanol using dilute acid hydrolysis (Bulls et al. 1992).

Halogen or concentrated sulfuric acid processes can be carried out at near ambient temperatures, and little if any sugar degradation results (Goldstein and Easter 1992, Goldstein et al. 1983). Therefore, they achieve the high yields essential to economic viability. However, because low-cost acids (e.g., sulfuric) must be used in large amounts while more potent halogen acids are relatively expensive, recycle of acids by efficient low-cost recovery operations is vital to achieve economic operation. Unfortunately, the acids must also be recovered at a cost substantially lower than that of producing these inexpensive materials in the first place (Wright et al. 1985). Concentrated acid technology is being offered for conversion of low-cost materials such as MSW into ethanol (Goldstein and Easter 1992), but the prospects for further cost reductions appear limited.

3.4 Enzymatic Hydrolysis of Lignocellulosic Biomass

Instead of acids, cellulase enzymes catalyze the breakdown of cellulose into glucose for subsequent fermentation to ethanol, as shown in figure 60. Enzyme-catalyzed processes achieve high yields under mild conditions with relatively low amounts of catalyst. Because enzymes are highly selective in the reactions they catalyze, by-products such as those accompanying dilute acid hydrolysis are not formed, and treatment of wastes is reduced. Enzymes are also biodegradable and environmentally benign. Over the years, several enzyme-catalyzed processes have been studied in the laboratory, but only a few investigations have been taken to a larger scale. Recent advances in enzymatic technology have reduced the costs of ethanol production to the point that large-scale operation appears economically viable, and larger scale operation is warranted to prove process performance. For more details on technology for both enzymatic and dilute acid catalyzed processes for conversion of lignocellulosic biomass into ethanol than can be offered here, the reader is referred to a chapter by Schell et al. (1992).

3.4.1 Pretreatment. Lignocellulosic biomass is naturally resistant to enzymatic attack, and a pretreatment step is required to open up the structure and overcome this resistance if the enzyme-catalyzed hydrolysis process is to proceed at acceptable rates and yields. Several options have been considered for biomass pretreatment including steam explosion (Brownell and Saddler 1984, Brownell et al. 1986), acid-catalyzed steam explosion (Clark and Mackie 1987), ammonia fiber explosion (Holtzapple et al. 1990, Dale and Moreira 1982, Dale et al. 1985), organosolv (Chum et al. 1985), supercritical extraction (Chou 1986, Reyes et al. 1989), and dilute acid. At this time, the dilute sulfuric acid process appears to be an attractive near-term option with economic potential (Schell et al. 1991, Knappert et al. 1980 and 1981). In this process, about 0.5% sulfuric acid is added to the feedstock, and the mixture is heated to around 140 to 160 °C for 5 to 20 minutes (Grohmann et al. 1985 and 1986; Torget et al. 1990). Under these conditions, most of the hemicellulose is broken down to form xylose and other sugars, leaving a porous structure of primarily cellulose and lignin that is more accessible to enzymatic attack. Evaluation of the dilute acid process with various agricultural residues, short-rotation hardwoods, and herbaceous energy crops has consistently shown that the conversion yields correlate well with the degree of hemicellulose removal (Grohmann et al. 1986; Torget et al. 1988, 1990 and 1991). Although this process has good near-term potential, significant benefits would result if a low-cost scheme could be devised that would also remove lignin, because the solid lignin associated with the cellulose creates some processing difficulties in the fermentation step. In addition, it would be useful to employ a catalyst that does not require neutralization with formation of salts.

3.4.2 Enzyme Production. Several organisms, including bacteria and fungi, produce cellulase enzymes that can be used to hydrolyze cellulose into glucose sugar. Currently, genetically altered strains of the fungus Trichoderma reesei are generally favored for cellulase production because relatively high yields, productivities, and specific activities of cellulase are realized. The best performance is usually achieved in the fed-batch mode of operation in which lignocellulosic biomass is metered into the fermenter during the growth of the fungus and the production of cellulase (Watson et al. 1984). Simple batch production of cellulase with the addition of all ingredients at the beginning of the enzyme production cycle may also be used. Continuous enzyme production has typically suffered from lower cellulase productivities (Hendy et al. 1984).

3.4.3 Cellulose Hydrolysis and Glucose Fermentation. Three approaches have received the most attention for conversion of the cellulose fraction into ethanol: separate hydrolysis and fermentation, simultaneous saccharification and fermentation, and direct microbial conversion.

- Separate Hydrolysis and Fermentation (SHF)

In the SHF process, the lignocellulosic biomass is first pretreated to open up the biomass structure and facilitate subsequent processing. A small portion of the pretreated biomass is added to an enzyme production vessel to support growth of a fungus or other microorganism that releases cellulase enzyme. The cellulase is then added to the bulk of the pretreated substrate in a hydrolysis reactor, catalyzing the breakdown of the cellulose to glucose. The resulting sugar stream passes to a fermenter, where yeast or other microorganisms convert the glucose into ethanol (Mandels et al. 1974, Wilke et al. 1976).

- Simultaneous Saccharification and Fermentation (SSF)

The production of cellulase is virtually the same for the SSF process as for SHF. However, for the SSF approach, hydrolysis and fermentation are combined in one vessel. The presence of yeast with the cellulase minimizes the accumulation of glucose in the vessel. Because glucose slows down the action of current cellulase enzymes, higher ethanol production rates, yields, and concentrations are possible for SSF than SHF (Gauss et al. 1976, Takagi et al. 1977, Ghosh et al. 1982).

Over the last several years, a number of studies have identified combinations of cellulase enzymes and yeast to speed the rate of conversion of lignocellulosic biomass to ethanol (Spindler et al. 1988, 1989, 1990 and 1991; Wyman et al. 1986; Lastick et al. 1989). Figure 61 illustrates the results of conversion of lignocellulosic biomass into ethanol for selected feedstocks with the SSF process and the SHF process. As shown for each of the feedstocks, the SSF approach achieves much higher yields of ethanol at the same enzyme loading than the SHF approach. As illustrated in figure 62, cellulase is a mixture of enzyme components designated as endoglucanase, exoglucanase, and β-glucosidase. Endoglucanase breaks the cellulase chain somewhere along its length while exoglucanase breaks off sugar dimers called cellobiose from the end of the chain. β-glucosidase then converts the cellobiose into glucose molecules for fermentation to ethanol. Cellobiose is a powerful inhibitor of cellulase enzyme, particularly the exoglucanase component of figure 62, and it appears that adding β-glucosidase minimizes the accumulation of cellobiose in the fermentation broth. Therefore, higher yields are achieved when the β-glucosidase is added to the fermentation broth than when it is not. Similar benefits have been found by employing cellobiose-fermenting yeast or cellulase enzyme with greater β-glucosidase activity typical of many modern formulations.

Seven or eight years ago, it required on the order of 2 weeks to convert the cellulose into ethanol in an SSF process at yields of approximately 70% (Lastick et al. 1984). By selection of cellulase with enhanced characteristics, such as higher levels of β-glucosidase, as well as selection of yeasts that perform well under SSF conditions, on the order of 90% to 95% of the cellulose entering the SSF process can be converted into ethanol in about 3–7 days for a variety of feedstocks (Spindler et al. 1990 and 1991).

- Direct Microbial Conversion (DMC)

The DMC process combines the enzyme production, cellulose hydrolysis, and sugar fermentation steps in one vessel (Veldhuis et al. 1936; Ng et al. 1977; Garvey et al. 1978; Lynd et al. 1989). In the most tested configuration, two bacteria are employed, one that produces cellulase enzymes and ferments glucose formed by the breakdown of cellulose while the other ferments the five-carbon sugars from hemicellulose into ethanol. Unfortunately, the bacteria also produce a number of

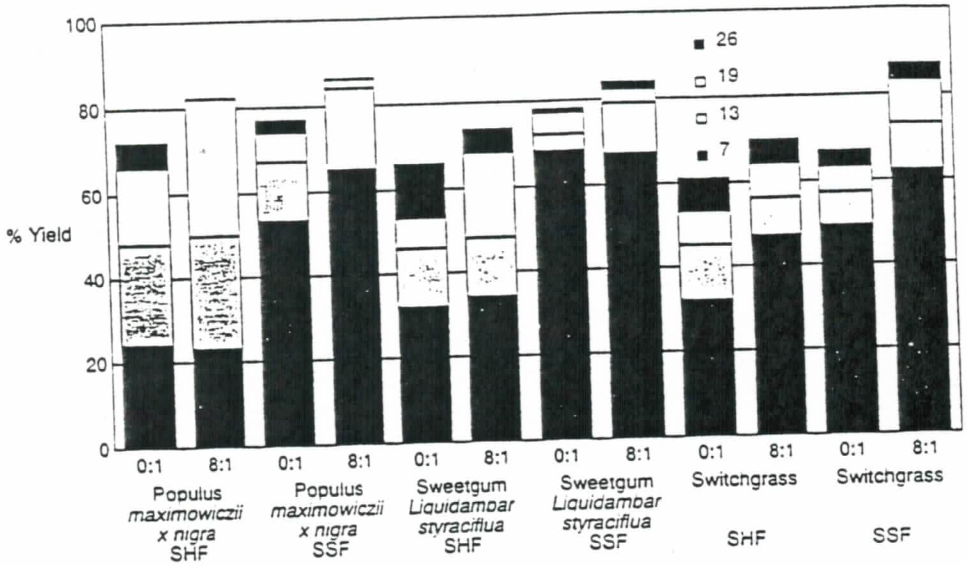


Fig. 61. Comparison of theoretical ethanol yields of cellulose to ethanol from the SSF and SHF processes with different substrates, cellulase concentrations (7, 13, 19, and 26 International Units/gram of substrate), and with (8:1) and without (0:1) β-glucosidase supplementation.

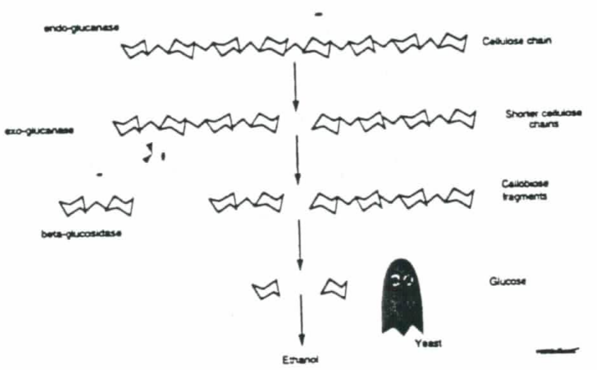


Fig. 62. Cellulase is a mixture of enzymes known as endoglucanase, exoglucanase, and β-glucosidase that act synergistically to break down cellulose into glucose that yeast can ferment into ethanol.

products in addition to ethanol, and yields are currently lower than for SHF or SSF processes. There is evidence that yields could be increased by process modifications (Lynd et al. 1991b). The bacteria are also not very tolerant to ethanol, and a dilute ethanol product results. If efforts to enhance ethanol yields are successful, the DMC approach could be the most attractive due to several advantageous features such as reduced capital cost for fermenters and lower power requirements.

At this time, the SSF approach is generally favored for ethanol production because it achieves higher rates, yields, and concentrations of ethanol than the SHF or DMC options (Wright 1988, Wright et al. 1988). High yields increase revenue while reducing waste treatment costs, and higher rates and concentrations lower capital and operating costs. In addition, about half as many fermenters are needed as for the SHF approach, further reducing capital and operating costs. The presence of ethanol in the fermentation broth reduces the possibility of contamination by unwanted microbes. Other approaches may be developed in the future to achieve similar or better performance than SSF.

3.4.4 Hemicellulose Conversion. The hemicellulose polymers in lignocellulosic biomass such as hardwoods, agricultural residues, and herbaceous plants can be readily broken down to form xylose and other sugars during the dilute acid pretreatment step (Grohmann et al. 1985). However, until recently, five-carbon sugars such as xylose could not be effectively utilized, and it was necessary to send these materials to waste disposal or find a suitable coproduct application, such as furfural. From an economic perspective, this costs the process twice: first, we are throwing away the xylose we paid for as part of the feedstock and second, the cost of waste disposal for such a major fraction of the feedstock inflicts a large economic penalty on the process. Several options, outlined below, have been examined for xylose utilization.

- Conversion of Xylose into Furfural

For dilute acid-catalyzed breakdown of cellulose to fermentation sugars, a significant fraction of the xylose degrades into furfural (Brennan et al. 1986; Kwarteng 1983; Wright 1988c). Similarly, the xylose left after pretreatment can also be reacted to furfural by heating with acid. This product is currently manufactured for use in foundry and other applications, so it could be sold as a co-product, generating additional revenues. However, the furfural market would be quickly saturated by the volume of furfural that would accompany large-scale fuel ethanol production (Gaines and Karpuk 1987). Thus, although furfural sales could prove valuable for initial introduction of a few ethanol plants, it would not support the commercialization of a large ethanol industry.

- Yeast for Ethanol Production from Xylose

Another avenue is to use certain strains of yeast that are known to ferment xylose into ethanol, such as Candida shehatae, Pichia stipitis, and Pachysolen tannophilus (Skoog and Hahn-Hager 1988; Prior et al. 1989; Jeffries 1990). These strains require small amounts of oxygen (microaerophilic operation) in the fermentation broth to ferment xylose (Grootjen et al. 1990; Ligthelm et al. 1988). Large-scale production of ethanol fuels will probably require the use of huge fermenters with volumes approaching a million gallons each, and proper control of oxygen in such large vessels could be difficult. These yeast strains typically cannot yet achieve as high ethanol yields, rates, or tolerance as conventional strains that ferment glucose. Improvements in such strains could result in economic application for xylose conversion to ethanol.

- Other Microorganisms for Ethanol Production

Other microorganisms, such as thermophilic bacteria and fungi, can anaerobically ferment xylose into ethanol (Carreira et al. 1983; Christakopoulos 1991; Lacis and Lawford 1988 and 1989; Lynd 1989, Buchert et al. 1989; Antonopoulos and Wene 1987; Asther and Khan 1984; Slapack et al. 1987). Ethanol tolerance has not been satisfactorily demonstrated for bacteria, although some new evidence suggests previous conclusions may have been premature (Lynd et al. 1991b). Historic data suggest that ethanol yields are low, but new information indicates that the yields could be improved in continuous culture. The fungi evaluated currently suffer from similar limitations in both ethanol tolerance and yield.

- Simultaneous Isomerization and Fermentation of Xylose to Ethanol

Several groups have studied the use of xylose isomerase enzyme to convert xylose into an isomer called xylulose that many yeast can ferment into ethanol under anaerobic conditions (Jeffries 1981; Chaing et al. 1981; Tewari et al. 1985). Researchers have genetically engineered the common bacteria Escherichia coli to produce large quantities of xylose isomerase for such a process, and ethanol yields of 70% of theoretical have been achieved in the simultaneous isomerization and fermentation of xylose process (Lastick et al. 1990). In this configuration, the enzyme and yeast are employed together to drive the equilibrium-limited fermentation to near completion, with the primary yield loss resulting from xylitol formation. This process has the advantage of employing anaerobic yeast that are easier to use at a large scale, but the need to provide xylose isomerase enzyme and adjust for differences in pH optima between the yeast and enzyme complicate the technology.

- Genetically Altered Bacteria

Researchers at the University of Florida have successfully introduced the genes from the glucose fermenting bacterium Zymomonas mobilis into the common bacterium E. coli so that the latter can now ferment xylose directly into ethanol (Ingram and Conway 1988; Ingram et al. 1987). This group has also successfully applied this approach to other bacteria including Klebsiella oxytoca (Wood and Ingram 1992; Ohta et al. 1991; Burchhardt and Ingram 1992). As a result, a single organism can ferment xylose as well as other sugars, and data suggest high yields are possible. However, these bacteria require operation at near neutral pH while production of by-product acids could drive the pH down, requiring addition of bases to control the pH. These genetically engineered bacteria are a very promising approach to five-carbon sugar utilization.

Full integration of these technologies into the overall conversion process is required to evaluate and improve their performance. Advantages could also result by genetic modifications or other approaches.

3.4.5 Lignin Utilization. Lignin generally represents the third largest fraction of lignocellulosic biomass and is often present in similar quantities to the hemicellulose fraction. Thus, it is important to derive value from lignin if economic ethanol production is to be achieved. Three options, discussed below, lead the possibilities for lignin use.

- Use as a Boiler Fuel

  Lignin has a high energy content and can be used as a boiler fuel (Wright 1988c; Hinman et al. 1992; Domalski et al. 1987). The amount of lignin in most feedstocks is more than enough to supply all the heat required for the entire ethanol conversion process, plus generate enough electricity to meet its electrical demands. In fact, excess electricity beyond all of these needs is generated, and additional revenue can be generated from electricity exports from the plant (Hinman et al. 1992; Chem Systems 1990). The electricity sold for current plant designs is equivalent to about 8% of the fuel value of the ethanol product, and greater revenues are likely as the technology is improved to require less process heat and electricity.

- Production of Octane Boosters

  Lignin is a complex phenolic polymer that can be broken down to form a mixture of monomeric phenolic compounds and hydrocarbons (Johnson et al. 1990). The phenolic fraction can be reacted with alcohols to form methyl or ethyl aryl ethers, which are good oxygenated octane boosters. Because octane boosters are more valuable than boiler fuel, this option for lignin use would generate more revenue. However, the technology must be improved to provide high product yields, and the conversion costs must be low enough to provide a net income gain for the ethanol plant.

- Production of Chemicals from Lignin

  A number of chemicals could be produced from lignin including phenolic compounds, aromatics, dibasic acids, and olefins (Busche 1985). Such materials could have a high value that would augment the total revenue for the ethanol plant. However, just as for the conversion of lignin into octane boosters, the cost of the conversion process must be low enough to ensure a net income gain. In addition, high yields of target products will likely be necessary to achieve economic viability. The spectrum of products that could be derived from lignin must have sufficient market volume to match the expected output for large-scale use of ethanol technology or lignin use will only support a few ethanol plants (Gaines and Karpuk 1989).

3.4.6 Ethanol Recovery. About a 3% to 12% solution of ethanol in water is produced in the fermentation process, with the exact concentration determined by the substrate, fermentative microorganism, enzyme, and process configuration. In addition, yeast, inerts such as lignin, enzymes, unreacted carbohydrates, and various salts remain in the broth. In most commercial applications, the entire mixture is fed to a distillation (beer) column that concentrates the ethanol in the overhead product while allowing the solids and water to exit from the bottom. The enriched ethanol stream passes to a second distillation (rectification) column for concentration to the ethanol-water azeotrope of about 95% by weight ethanol. To use ethanol as a hydrous fuel, this azeotropic mixture is suitable without further processing (Hinman et al. 1992; Chem Systems 1990), provided the appropriate distribution infrastructure is available.

Water has a low miscibility in gasoline, and almost all the water must be removed from ethanol that will be blended with gasoline. To break the ethanol-water azeotrope, a third component such as benzene or cyclohexane can be added to allow purification of ethanol by tertiary distillation. Alternatively, molecular sieves such as corn grits can be used to preferentially adsorb the ethanol or water. Membranes can also be used that are permeable to one of the components, typically water, while retaining the other by a technology called pervaporation. At this time, distillation with a third component and molecular sieves are favored commercially.

4. Energy Balance and Impact on Carbon Dioxide Accumulation

Energy costs can be an important element in the economics of a process. In addition, the impact of ethanol technology on displacement of imported oil depends on the amounts and types of energy used by the process. Considerable controversy and confusion exists about how to interpret this information for energy efficiency and the impact on the potential for global climate change. Energy inputs must be accounted for and the performance of ethanol must be properly compared to that for fossil fuels if comparisons are to be made among fuels.

4.1 Energy Use

Figure 63 summarizes energy flows for the production of ethanol from lignocellulosic biomass (Lynd et al. 1991a). Modest energy inputs are required to grow lignocellulosic biomass because cultivation and fertilizer needs are not large. In addition, no process energy input is shown because the lignin contained in the feedstock can be used as a boiler fuel, and the amount of energy contained in the lignin is sufficient to produce process heat and electricity for the overall process. The equivalent of about 8% of the ethanol fuel value can be sold as electricity based on current technology (Chem Systems 1990; Hinman et al. 1992), thereby displacing about three times that amount of fossil energy inputs for electricity production by power companies.

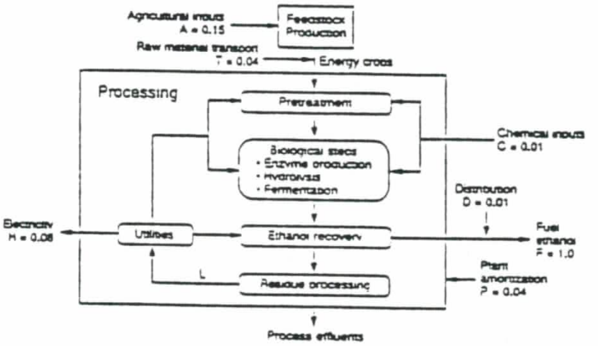


Fig. 63. Energy requirements and outputs for production of ethanol from lignocellulosic biomass based on one unit of ethanol energy output.

If the amount of fossil energy inputs are totaled for current technology (Chem Systems 1990), about 5.3 megajoules/liter (19,000 Btu/gallon) of ethanol are required for ethanol production from lignocellulosic biomass, as shown in table 77. Alternatively, three times the electricity produced could be subtracted from the fossil fuel requirements to account for the fossil fuel that would be used in any event for producing that quantity of electricity (Ho 1989). In this case, the net amount of fossil fuel use, as shown in table 77, is only about 0.2 megajoules/liter (700 Btu/gallon) of ethanol. For comparison, fossil sources account for about 3.9 megajoules/liter (11,000 Btu/gallon) of gasoline produced. Gasoline has a lower heating value of about 32 megajoules/liter (115,000 Btu/gallon), compared to ethanol at 21 megajoules/liter (76,000 Btu/gallon).

One measure of the efficiency of ethanol production is to calculate the ratio R defined as the amount of energy produced by the process compared to the amount of fossil fuel used (Lynd et al. 1991a):

$$R = \text{Energy Outputs/Fossil Energy Inputs.}$$

In this case, the fuel value of the ethanol is added to three times the amount of excess electricity sold (to account for the thermal energy displaced), and the quantity is divided by the total fossil fuel inputs. Based on the information in table 77, ethanol fuel and thermal energy outputs are about five times greater than the total fossil fuel inputs for current lignocellulosic biomass conversion technology. Of course, if fuels and fertilizers derived from renewable resources were used in place of the fossil sources assumed in this analysis, R would become virtually infinite.

An alternative approach to measuring energy efficiency is to calculate the ratio ER of the energy in the products less external energy inputs to the energy content of the feedstock (Wyman et al. 1992);

$$ER = \frac{\text{Energy in Products} - \text{External Energy Inputs}}{\text{Energy in Feedstocks}}.$$

For current technology for ethanol production from lignocellulosic biomass with exported electricity weighted by a factor of three to account for the

Table 77. Energy inputs and carbon dioxide released in ethanol production from lignocellulosic biomass

Process	Feedstock Production	Raw Material Transport	Chemical Inputs	Process Energy	Plant Amortization	Fuel Distribution	Total Fossil Use	Coproduct Displacement of Fossil Fuel[1]	Net Fossil Fuel
Assumed Fossil Fuel	Natural Gas	Petroleum	Natural Gas	None	Natural Gas	Petroleum	–	–	–
MJ/L Ethanol	3.2	0.84	0.22	–	0.84	0.22	5.3	5.1	0.22
Carbon Dioxide Released g/L	180	60	12	–	48	12	310	550	-240

[1] Calculated on the basis of the exported electricity displacing coal-generated electricity, at 33% efficiency.

amount of thermal energy displaced and accounting for the energy required to grow biomass, this ratio is equal to about 0.43. For improvements in the technology, the ratio ER becomes about 0.56 (Wyman et al. 1992).

It is important to note that although fermentation of sugars to ethanol results in the release of almost as much carbon dioxide as ethanol produced by weight, nearly all of the energy from the cellulose and hemicellulose fractions remains in the ethanol product formed (Wyman and Hinman 1990). Thus, the conversion process concentrates the energy from the solid biomass into a liquid form more compatible with our transportation infrastructure, and since the value of both the feedstock and the product should be assessed on an energy content basis, the weight loss is actually beneficial. The main loss of feedstock energy as measured by eq (7) is the thermal energy of the lignin needed to drive the conversion process and secondarily the fraction of cellulose and hemicellulose that is not converted into products. Reductions in the need for process energy will therefore greatly improve this measure of efficiency.

4.2 Carbon Dioxide Released

The contribution of ethanol production to carbon dioxide accumulation in the atmosphere can be estimated by weighing the quantities of fossil fuels used according to the amount of carbon dioxide released by each. For the purposes of this discussion and with reference to figure 63, natural gas is assumed to be the fuel source for agricultural (A), chemical (C), and plant amortization (P) inputs; petroleum is assumed for transportation (T) and distribution (D). Coal is assumed to be the fuel used for conventional electricity generation. Combining carbon dioxide release data for these sources with the energy requirements presented in figure 63 gives the results presented in table 77 for ethanol derived from lignocellulosic biomass. Only carbon dioxide produced by combustion of fossil fuels is included because carbon dioxide generated during fermentation of biomass cellulose and hemicellulose and combustion of lignin, ethanol, and other biomass fractions would be recycled to grow new biomass to replace that harvested for energy production.

It is interesting to note that if the equivalent carbon dioxide release for production of electricity by coal is subtracted from the fossil fuel sources for ethanol production from lignocellulosic biomass, a negative carbon dioxide contribution results (table 77). This outcome is due to the low usage of fossil fuels for conversion of lignocellulosic biomass to ethanol and the displacement of fossil-generated electricity in the grid. To produce an equivalent amount of electricity from coal would actually produce more carbon dioxide than the total net released during ethanol production, and subtracting the amount of carbon dioxide that would have resulted anyway for generation of that quantity of electricity by coal gives a net credit of 0.24 kilograms of CO_2/liter of ethanol produced (2.0 pounds/gallon).

From the data in table 77, it appears that production of ethanol from lignocellulosic biomass would be a minor contributor of carbon dioxide to the atmosphere, because all of the process heat is produced by combustion of lignin, a renewable feedstock. In addition, limited fossil fuel inputs are needed to grow lignocellulosic biomass. Furthermore, biomass sources of fuels and fertilizers could be substituted for the fossil fuels assumed in this analysis, resulting in no carbon dioxide release from fossil sources for ethanol from lignocellulosic biomass. By way of comparison, gasoline use releases a total of 82 kilograms of CO_2/gigajoule (190 pounds CO_2/million Btu) or 2.61 kilograms/liter (22 pounds/gallon).

4.3 Ethanol Utilization

To compare carbon dioxide release between ethanol and fossil fuels, it is important to establish the relative amounts of fuel required to travel equivalent distances with each fuel. In the United States, ethanol is typically blended with gasoline at 10% concentrations. As mentioned earlier, the energy content of ethanol is 21 megajoules/liter (76,000 Btu/gallon); gasoline contains about 50% more energy at 32 megajoules/liter (115,000 Btu/gallon). By accounting for each of these factors, the energy content of the blend is about 31 megajoules/liter (110,000 Btu/gallon). If the range of a vehicle is assumed to be proportional to the energy density of the fuel, 1.036 volumes of blend would be required to travel the same distance as one volume of gasoline. On the other hand, data from Southwest Research Institute (Tosh et at. 1985) as well as others have shown that there is no statistically significant difference in the mileage for a 10% blend versus that of regular gasoline. In effect, this evidence suggests that the ethanol blended with gasoline has an energy density equivalent to 32 megajoules/liter (115,000 Btu/gallons).

Use of neat ethanol can be considered in at least two different ways. First, the amount of one fuel needed to travel the same distance as for another fuel can be determined by the ratio of the lower heating values of the two fuels. Thus, about 50% more ethanol would be required than for gasoline to give the same service. For an engine designed for gasoline use with only modifications in timing and air-to-fuel ratio to allow combustion of ethanol, ethanol fuel would give such a range. However, because ethanol has more favorable fuel properties such as a higher octane and heat of vaporization than gasoline, an engine optimized for ethanol can be 20% to 30% more efficient than a gasoline engine (Lynd et al. 1991a, Wyman and Hinman 1990). Assuming the latter results in a ethanol driving range of about 80% of that of gasoline on a volumetric basis.

4.4 Comparisons of Fossil Fuel Use and Carbon Dioxide Release

Table 78 presents a comparison of the fossil fuel requirements for ethanol from lignocellulosic biomass and gasoline. Consideration is given to blends and neat fuel use and to comparison of the amount of ethanol required based on lower heating value and probable distance traveled on an equal volume. The lower end of the range shown is with credit given for fossil fuel displacement for electricity production, while the higher end does not account for excess electricity production. Blends of ethanol from lignocellulosic biomass with gasoline always yield lower fossil fuel use than gasoline alone. Furthermore, for neat fuel markets, ethanol production from lignocellulosic biomass requires one-fifth or less fossil fuel inputs than gasoline, depending on the accounting given for electricity production and the assumed efficiency of ethanol utilization.

Table 78. Fossil fuel use and carbon dioxide released for ethanol from lignocellulosic biomass

Form of Fuel Use	Fossil Fuel Used (MJ/L of Gasoline Equivalent)	CO_2 Released[a] (kg CO_2/L of Gasoline Equivalent)
10% Blends Based on Lower Heating Value	33.6 - 34.1	2.40/2.47
10% Blends at Same Range as Gasoline	32.4 - 32.9	2.33/2.39
Neat Ethanol Fuel Based on Lower Heating Value	0.33 - 8.0	-0.36/0.47
Neat Ethanol Fuel Based on Improved Efficiency	0.28 - 6.6	-0.30/0.38
Gasoline	36.0	2.61

[a] First value is dervied by subtracting equivalent carbon dioxide released by coal fired electric plant, second value is for all carbon dioxide assigned to ethanol production.

Also presented in table 78 is the amount of carbon dioxide released when a vehicle is propelled the same distance by ethanol as gasoline. Again, based on the low use of fossil fuels in production of ethanol from lignocellulosic biomass, this fuel scores very well in minimizing carbon dioxide emissions that could contribute to global climate change. If we subtract the carbon dioxide emissions that would have resulted from coal to generate the amount of electrical energy exported from the ethanol plant, the net effect is that ethanol reduces carbon dioxide accumulation. It may be more appropriate to assign the carbon dioxide released to both electricity and ethanol based on the relative energy contributions and compare each to the alternative, but the benefits would still be substantial.

5. Ethanol Economics

Economics for ethanol production from starch crops and lignocellulosic biomass will both be summarized. Three important elements influence the overall economics: feedstock price, operating costs, and annualized capital charges. Each of these elements are discussed in the following sections.

5.1 Corn Ethanol

The cost of ethanol production from corn is influenced substantially by the price of corn and the price at which co-products can be sold. Therefore, these factors are considered first. Then, the capital and operating costs for a corn ethanol plant are combined with corn prices and revenues from co-products to predict the selling price of ethanol that is required to achieve a target rate of return on capital invested.

5.1.1 Corn and Co-Product Prices. Table 79 presents the historical variation in prices of corn and co-products derived from dry- and wet-milling processes, during the period from 1981 to 1988 (Lewis and Grimes 1988). From this table, it is apparent that the selling price of corn varies considerably. For instance, the highest price for corn was in 1984 at a price of $164/dry tonne ($3.52/bushel). The lowest price was only 2 years later at a price of $56.80/dry tonne ($1.22/bushel). Co-product prices also varied considerably over this time frame. The highest co-product price for dry milling occurred in 1984 at a price of $76.90/dry tonne ($1.65/bushel) of corn processed. The low co-product price for dry milling was only a year later

Table 79. Extremes in corn and coproduct prices for dry- and wet-milling processes[1]

		$/dry tonne of corn[2] ($/liter ethanol produced)		
	Year	Corn Cost	Coproduct Price[3]	Net Cost[4]
High corn cost				
Dry milling	1984	164.00 (0.358)	69.40 (0.151)	94.60 (0.207)
Wet milling	1984	164.00 (0.372)	80.10 (0.182)	83.90 (0.190)
Low corn cost				
Dry milling	1986	56.80 (0.124)	48.90 (0.107)	7.90 (0.017)
Wet milling	1986	56.80 (0.129)	58.20 (0.132)	-1.40 (-0.003)
High co-product price				
Dry milling	1984	154.00 (0.336)	76.90 (0.168)	77.10 (0.168)
Wet milling	1983	158.00 (0.357)	86.70 (0.197)	71.30 (0.160)
Low co-product price				
Dry milling	1985	130.00 (0.284)	35.90 (0.078)	94.10 (0.206)
Wet milling	1985	116.00 (0.264)	57.80 (0.131)	58.20 (0.133)
High net cost				
Dry milling	1985	130.00 (0.284)	35.90 (0.078)	94.10 (0.206)
Wet milling	1984	149.00 (0.337)	62.00 (0.141)	87.00 (0.196)
Low net cost				
Dry milling	1986	56.80 (0.124)	48.90 (0.107)	7.90 (0.017)
Wet milling	1986	56.80 (0.129)	58.20 (0.132)	-1.40 (-0.003)

[1] Data from Lewis and Grimes (1988) without credit for sale of carbon dioxide for 1981 to 1988.
[2] Multiply values shown by 0.02151 to obtain price in $/bushel.
[3] Co-product price is revenue generated by co-product sales/tonne of corn processed.
[4] Net cost is defined as the cost of the corn less the revenue generated from the sales of co-products produced/dry tonne of corn.

at $35.90/dry tonne ($0.77/bushel). In the wet-milling operation, the highest price for co-products was in 1983 at $86.70/dry tonne ($1.86/bushel) of corn processed, while the lowest co-product price for wet milling was in 1985 at $57.80/tonne ($1.24/bushel). All of the values presented in table 6 do not include co-product revenue from carbon dioxide sales.

Perhaps a more telling indicator of the cost of corn to the ethanol producer, termed the net cost of corn is presented in table 79. The net cost of corn is defined as the cost of the corn purchased minus the selling price of the co-products. For dry milling, the highest net cost of corn was in 1985 at $94.10/tonne ($2.03/bushel) of dry corn, while the lowest net cost of corn was only one year later at $7.90/tonne ($0.17/bushel) of dry corn. In the wet milling, the highest net cost of corn was in 1984 at $87.00/tonne ($1.86/bushel) processed. Because of the number of co-products generated in wet milling and their fairly high value, the low net price of corn was actually a negative $1.40/tonne ($0.03/bushel) of dry corn in 1986—in effect, the processor was being "paid" to convert the corn into ethanol because of high co-product revenues.

Also shown in table 79 is the corn cost in terms of the volume of ethanol produced. The first column indicates the cost of corn only, while the second column, labeled co-product prices, provides the value of the co-products in terms of the volume of ethanol produced. The difference between these two entries is provided in the third column, net cost, in terms of the volume of ethanol produced. The highest net cost of corn corresponds to about $0.20/liter ($0.80/gallon) of ethanol. By comparison, ethanol is only worth about $0.30 to $0.35/liter ($1.15 to $1.35/gallon) of ethanol. On the other hand, the low net price of the corn feedstock is practically zero.

5.1.2 Corn Ethanol Economics. Table 80 presents the operating and capital costs associated with the production of ethanol from corn based on the USDA Cost Effectiveness Study (USDA 1987). These prices are all for a grass roots facility (a facility built on previously unutilized ground) and are translated into 1990 dollars using Nelson-Farrar cost indices (Oil and Gas Journal 1990). The values shown indicate lower capital costs for larger scale plants because of economies of scale. One would typically expect the capital costs associated with wet-milling operations to be at the high end of the values shown, while dry-milling operations would be at the lower end of the range. Also included in the table are the range of fuel and electricity costs expected, depending on the efficiency of the operation and to some extent the scale. Chemicals, enzymes, and yeast costs are greatly influenced by whether or not these ingredients are produced on site or are purchased. Maintenance and personnel costs along with insurance rates are included in the table as well.

It is important to note that lower capital costs are possible than those shown in table 80 for plants that are integrated into existing facilities. Such op-

Table 80. Variable, fixed, and capital costs for production of ethanol from corn[1]

	Plant size, ML/year (M gal/year)	
	<150 (40)	150–950 (40–250)
Capital investment $/annual liter ($/annual gallon)	0.87 (3.28)	$0.58–0.72 (2.19–2.73)
Fuel, $/liter produced ($/gallon) Coal	0.029–0.040 (0.11–0.15)	0.029–0.040 (0.11–0.15)
Electricity, $/liter produced ($/gallon)	0.011–0.016 (0.04–0.06)	0.011–0.016 (0.04–0.06)
Chemicals, enzymes, yeasts, $/liter produced ($/gallon)	0.010-0.032 (0.04-0.12)	0.010–0.032 (0.04–0.12)
Maintenance, $/liter produced ($/gallon)	0.029–0.043 (0.11–0.16)	0.029–0.043 (0.11–0.16)
Personnel $/liter produced ($/gallon)	0.048 (0.18)	0.017 (0.06)
Taxes & insurance, % of capital	2.0%	2.0%

[1] From USDA reference (1987) for a modern plant built on an undeveloped site (grass roots plant); transformed to 1990 dollars.

Table 81. Predicted selling price of ethanol from corn based on the economic parameters in Table 82[1]

Process	Plant Size ML/yr EtOH[2]	Capital	Feed	O&M	Coproducts	Ethanol
		(1990$/L EtOH)				
Wet Mill with Low Net Corn Cost	378	0.158	0.129	0.145	0.133	0.299
Wet Mill with High Net Corn Cost	378	0.163	0.338	0.144	0.141	0.504
Dry Mill with Low Net Corn Cost	189	0.129	0.125	0.141	0.107	0.288
Dry Mill with High Net Corn Cost	189	0.133	0.286	0.142	0.079	0.482

[1] Ethanol yields are 440 liters/tonne of corn for a wet-mill process and 458 liters/tonne of corn for a dry-mill process.

[2] Pure 100% ethanol.

erations can cut the capital costs approximately in half. On the other hand, poorly engineered plants can be twice as costly as the values given. Of course, such facilities would be unlikely to be economical.

Table 81 presents the estimated costs of production of ethanol from corn based on the data given in tables 79 and 80. Estimates are provided for large, efficient wet- and dry-milling operations in this table. Scenarios are given for high net costs of corn for each type of facility as well as for low net costs of corn. All values are 1990 dollars. From these cost estimates, it can be seen that co-product revenue has a substantial impact on corn ethanol economic viability. All costs are estimated based on the economic parameters provided in table 82 (Chem Systems 1990).

5.2 Biomass Ethanol

Ethanol is not yet produced commercially from lignocellulosic biomass in the United States. Therefore, the economics of the technology must be estimated from available information on feedstock costs and conceptual process engineering studies.

5.2.1 Feedstock Costs. Several forms of wastes such as agricultural residues, MSW, and forestry residues could be used to produce ethanol. Large tipping fees of $100/tonne ($90/ton) and more are paid for disposal of MSW in some regions of the country. Therefore, it is possible that such feedstocks might be obtained at no cost or the processor may be actually paid to accept such materials, although costs will no doubt be incurred in feedstock preparation and handling. Forestry residues have been estimated to cost from $20 to $36/dry tonne ($18 to $33/ton). Agricultural residues could cost in the range of $24 to $49/dry tonne ($22 to $44/ton) (Wyman and Hinman, 1990, Lynd 1989).

Energy crops can also be used for production of ethanol from biomass. However, such technology has not been demonstrated, and estimation of the

Table 82. Economic parameters for estimating ethanol selling price for corn and lignocellulosic biomass[1]

U.S. dollars, fourth quarter 1990.

Operating rate of 91%, equal to 8,000 hours/year.

General plant overhead at 65% of operating costs.

Direct overhead at 45% of labor and supervision.

Maintenance at 3% of inside battery limits costs.

Insurance and property taxes at 1.5% of total fixed investment.

No sales expenses.

No inflation.

Working capital is paid out at plant startup and recovered at the end of the life of the project. It is calculated as the sum of the following:

Feedstock inventory - 1 month's supply of raw materials valued at delivered prices.

Finished product inventory - Half a month's supply of principal product and coproducts (if any) valued at the gross cost of production based on liquid or solid product storage and excluding items not normally stored.

Accounts receivable - 1 month's gross cost of production.

Cash - 1 week's out-of-pocket expenses estimated at the gross cost of production less depreciation.

Less a fifth item:

Accounts payable - 1 month's supply of raw materials at delivered prices.

Capital charges[2] are calculated for a 10% discounted cash flow rate of return with the following parameters:

Three years of construction with expenditures of 30% in the first year, 50% in the second year, and 20% in the third year.

Fifteen years of operation.

Income tax rate of 37%.

Capacity buildup to 60% of nameplate capacity in the first year of operation, 80% in the second year, and 100% from the third year onward.

Straight line depreciation over 5 years for inside battery limits and 15 years for outside battery limits investment.

[1] Based on Chem Systems 1990

[2] Addition of an annual capital charge calculated as 20% of the total capital investment to the cost of production will give approximately the same predicted selling price.

cost of these materials is somewhat more difficult. It is thought that woody crops could be produced at a cost of \$34 to \$68/dry tonne (\$31 to \$62/ton). Herbaceous crops are estimated to cost from \$27 to \$45/dry tonne (\$24 to \$41/ton) (Wyman and Hinman, 1990).

5.2.2 Biomass Ethanol Economics. The economics of ethanol production from lignocellulosic biomass have been the subject of a number of investigations over the past 10 years (Chem Systems 1984; Arthur D. Little 1984; Badger Engineers 1984; Stone and Webster 1985a and 1985b). Processes have been studied for both acid- and enzyme-catalyzed breakdown of cellulose to form glucose sugar followed by fermentation of the glucose to ethanol. These studies have also included conversion of hemicellulosic sugars into products such as furfural and other chemicals as well as ethanol. Through these studies, enzymatic conversion based on SSF technology is favored to be competitive in the near term while offering substantial opportunities for improvement. Recently, Chem Systems performed a study for the National Renewable Energy Laboratory (NREL) through the support of the U.S. Department of Energy, to estimate the cost of ethanol from lignocellulosic biomass (Chem Systems 1990). The Chem Systems analysis was based on dilute acid pretreatment of biomass to break down the hemicellulose fraction to release xylose and other sugars into solution. A small fraction of the wet solids from pretreatment, containing primarily cellulose and lignin, was sent

Table 83. Capital and operating cost estimates for ethanol production from lignocellulosic biomass

	Reference Case[1]	Larger Scale[1]	Modified Case[2]
Plant Size			
Feed Rate, dry tonnes/day	1742	8078	1742
Product Rate, ML/year (denatured, hydrous)	219	1096	221
Feed Price, 1990 US $/dry tonne	46	46	46
Capital Cost, MM US $ (1990)			
Feed Handling	7.13	28.27	7.16
Prehydrolysis	23.23	91.84	23.68
Xylose Fermentation	6.21	24.66	6.16
Cellulase Production	2.68	10.64	2.76
SSF Fermentation	22.26	88.41	20.93
Ethanol Purification	3.88	10.98	3.99
Offsite Tankage	3.14	7.58	4.09
Environmental Systems	4.10	11.71	3.96
Utilities/Auxiliaries	59.36	169.46	55.66
Erected Plant Cost	131.98	443.55	128.39
Start-up	6.56	22.16	6.42
Total Capital Investment	138.53	465.71	134.81
Working Capital	6.63	29.94	6.31
Operating Costs, MM US $/Year (1990)			
Variable Costs			
Feedstock	26.88	134.39	26.88
Catalyst and Chemicals	9.38	46.88	8.14
Solids Disposal	0.40	2.00	0.40
Water	0.12	0.58	0.14
Utilities	(3.22)	(16.10)	(4.15)
Fixed Costs			
Labor	1.68	3.34	1.57
Maintenance	4.16	13.86	3.85
General Overhead	3.79	11.18	3.52
Direct Overhead	0.75	1.50	0.71
Insurance, Property Tax	2.08	6.99	2.02
Total Operating Cost	46.01	204.61	43.08

[1] Chem Systems 1990
[2] Hinman et al. 1992

to an enzyme production step where cellulase enzymes were produced by the fungus T. reesei. The enzymes were then added to the bulk of the pretreated solid material along with yeast for conversion into ethanol by the SSF process. In this economic study, the xylose and other sugars released during pretreatment were converted into ethanol based on data for the genetically engineered E.coli strain developed at the University of Florida. Continuous fermentation was assumed for all fermentation steps other than enzyme production, which was a batch operation. The ethanol produced during the fermentation operations was recovered by a conventional distillation system. Gasoline was added to denature the ethanol for sale as a neat fuel. The resulting fuel contained about 90.3% ethanol, 4.7% water, and 5% gasoline by weight. The lignin recovered from the bottom of the distillation column was burned as a boiler fuel to provide all the heat and electricity for the process as well as excess electricity that was sold for additional revenue. Chem Systems estimated the capital and operating costs for the process and from that, estimated the selling price of ethanol.

Table 83 provides the capital and operating costs for ethanol production from lignocellulosic biomass, as estimated by Chem Systems. The price estimates were translated from the 1987 dollars used in the Chem System study to 1990 dollars in table 83 based on the Nelson-Farrar Cost Index (Oil and Gas Journal 1990). Costs were derived at biomass feed rates of 1,742 and 8,708 dry tonnes/day (1,920 and 9,600 tons/day). Feedstock was assumed to cost $46/dry tonne ($42/ton). At the

Table 84. Discounted cash flow for ethanol production from lignocellulosic biomass for the Chem Systems Reference Case (all dollars in millions)

Capital Cost	$131.98
Start-up Costs	$6.56
Total Plant Cost	$138.53
Ethanol Selling Price	$0.345/Liter
Production Rate	219 Million Liters/Year

Items	Years																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Percent of Capital Paid	30.0%	50.0%	20.0%															
Capital Investment	$39.59	$65.99	$26.40															
Start-up Costs				$6.56														
Working Capital				$6.63														$(6.63)
Total Annual Capital Outlay	$39.59	$65.99	$26.40	$13.19	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$(6.63)
Total Capital Investment	$39.59	$105.58	$131.98	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$145.16	$138.53
Percent of Nameplate	0%	0%	0%	60%	80%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Production Rate, MM Liters/Year				131.5	175.4	219.2	219.2	219.2	219.2	219.2	219.2	219.2	219.2	219.2	219.2	219.2	219.2	219.2
Ethanol Revenue				$45.40	$60.53	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66	$75.66
Electricity Revenue				1.93	2.58	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22
Feedstock Cost				16.13	21.50	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88
Chemicals, Solids Disposal, Water				5.94	7.92	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90
Fixed Operating Costs				12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45
Total Costs				$34.52	$41.88	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23	$49.23
Income Before Depreciation, Taxes				$12.81	$21.23	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65	$29.65
Depreciation				17.52	17.52	17.52	17.52	17.52	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44
Income After Depreciation				$(4.71)	$3.72	$12.14	$12.14	$12.14	$25.21	$25.21	$25.21	$25.21	$25.21	$25.21	$25.21	$25.21	$25.21	$25.21
Income Tax				0.00	1.37	4.49	4.49	4.49	9.33	9.33	9.33	9.33	9.33	9.33	9.33	9.33	9.33	9.33
Income After Tax				$(4.71)	$2.34	$7.65	$7.65	$7.65	$15.88	$15.88	$15.88	$15.88	$15.88	$15.88	$15.88	$15.88	$15.88	$15.88
Total Cash (Depreciation plus Income After Tax)				$12.81	$19.86	$25.16	$25.16	$25.16	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32
Annual Cash Flow	$(39.59)	$(65.99)	$(26.40)	$(0.38)	$19.86	$25.16	$25.16	$25.16	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$20.32	$26.95
Discounted Cash Flow	$(39.59)	$(59.99)	$(21.81)	$(0.28)	$13.56	$15.62	$14.20	$12.91	$9.48	$8.62	$7.84	$7.12	$6.48	$5.89	$5.35	$4.87	$4.42	$5.33
Cumulative Discounted Cash Flow	$(39.59)	$(99.58)	$(121.40)	$(121.68)	$(108.12)	$(92.49)	$(78.29)	$(65.38)	$(55.90)	$(47.28)	$(39.44)	$(32.32)	$(25.84)	$(19.96)	$(14.60)	$(9.74)	$(5.31)	$0.02

lower feed rate, 219 million liters/year (58 million gallons/year) of denatured ethanol could be produced, while at the higher feed rate 1,096 million liters/year (290 million gallons/year) of denatured ethanol could be derived. The total capital investment required, including start-up costs, are about $139 million for the smaller plant size and $466 million for the larger scale operation. Total operating costs for the smaller scale plant are estimated to be about $46 million, while those for the larger scale plant are estimated to be about $205 million.

Table 84 presents a discounted cash flow analysis for the smaller scale case studied by Chem Systems. This analysis takes into account start-up costs as well as working capital requirements for the plant and is based on financial parameters provided in table 82. Based on this discounted cash flow analysis, an ethanol selling price of $0.345/liter ($1.31/gallon) of denatured fuel is projected for this Chem Systems reference case when converted to 1990 dollars. This selling price covers all costs of production plus provides a 10% real rate of return on the investment as outlined previously. A similar analysis, as summarized in table 85, predicts an ethanol selling price of about $0.278/liter ($1.05/gallon) for the larger scale Chem Systems process. The later price is somewhat below the current market price of ethanol of about $0.30 to $0.35/liter ($1.15 to $1.35/gallon).

Based on the Chem Systems study, NREL investigated several options to further reduce the price of ethanol from lignocellulosic biomass (Hinman et al. 1992), and a process design was developed with costs summarized in table 83. A lignocellulosic biomass feed rate of 1,742 dry tonnes/day (1,920 tons/day) was assumed with a denatured hydrous ethanol production rate of 221 million liters/year (58 million gallons/year). Once again, the feedstock price was taken as $46/dry tonne ($42/ton) in 1990 dollars. Capital and operating costs were estimated as shown for this process and the results used in a cash flow analysis to predict the selling price of ethanol. In this case, an ethanol selling price of about $0.324/liter ($1.23/gallon) was predicted for the smaller scale plant, as shown in table 85. Even though this price is somewhat higher than that predicted by Chem Systems for a larger scale operation, it shows that ethanol could be produced from lignocellulosic biomass at the smaller scale at prices competitive with ethanol from corn. Furthermore, immediate opportunities have been identified to reduce the costs of ethanol somewhat further by optimizing enzyme loading in combination with SSF performance.

Table 85. Cost projections for production of ethanol from lignocellulosic biomass

Process	Plant Size[1] ML/yr EtOH	Capital	Feed	O&M	Electricity	Ethanol
		(1990$/L EtOH)				
Reference	219	0.135	0.123	0.102	0.015	0.345
Larger Scale	1,096	0.091	0.123	0.079	0.015	0.278
Modified	221	0.130	0.121	0.092	0.019	0.324

[1] Denatured, hydrous ethanol

5.2.3 Opportunities for Advancement. Based on the cash flow analysis presented, enzymatic conversion of lignocellulosic biomass using technology available in 1982 would have resulted in an ethanol selling price of about $0.98 (1990 dollars) per liter ($3.70/gallon) (Wright 1988a and 1988b). Through advancements in this technology, the price has been reduced to about $0.32 per liter ($1.23/gallon) now (Hinman et al. 1992). Furthermore, a substantial number of opportunities have been identified to reduce the price to $0.17 to $0.18 per liter ($0.67/gallon). These include improving the yields of ethanol through the development of better enzymes that can be produced at lower costs. Enzymes that can provide faster breakdown of cellulose could reduce conversion time from about 5 to 7 days to only 2 to 3 days and result in significant reduction in capital and operating costs. More efficient pretreatment systems can result in enhanced yields of ethanol during the enzymatic hydrolysis step, through greater accessibility of the cellulose, as well as less degradation of cellulose, xylose, and other carbohydrates during the pretreatment step. Improvements in pretreatment technology could also result in lower capital and operating costs. Improved organisms to enhance yields of ethanol from the hemicellulose sugars could be developed, along with lower costs media, for each of the fermentation operations. The economics would benefit from increased ethanol concentrations of around 6% to 8%, although advanced distillation systems may make recovery of lower ethanol concentrations cost effective. Production of co-products from the lignin fraction, other than electricity, could also improve the economics of ethanol production. Because feedstock costs are a significant fraction of the final product selling price, improvements in feedstock related technology could improve the economics of ethanol production through greater economies of scale, decreased feedstocks costs, and less feedstock that cannot be fermented into ethanol. The number of mutually exclusive paths for reducing the cost of ethanol production from lignocellulosic biomass is so substantial that the probability of achieving the target price of about $0.17 to $0.18/liter ($0.67/gallon) is quite high.

6. Strengths

Ethanol has immediate application for blending with gasoline. Through the implementation of the Clean Air Act Amendments of 1990, the need for oxygenates such as ethanol and ETBE is expanding dramatically. In addition, as the technology for production of ethanol from lignocellulosic biomass is improved, the cost of ethanol can be reduced, and the market could grow further. Low cost feedstocks are immediately available that will allow early introduction of this technology into the oxygenate market. As the opportunities to lower the cost of ethanol are realized, the price could drop enough to make neat fuel use viable.

6.1 Ethanol's Flexibility as a Fuel

Ethanol can be directly blended with gasoline. In this application, ethanol is valued as a fuel extender, octane booster, and an oxygenate. Combining the merits of each of these attributes with the existing tax incentive to promote the use of ethanol produced from biomass results in an immediate competitive position at projected selling prices for lignocellulosic biomass.

Ethanol can also be converted into ETBE for blending with gasoline. ETBE is valued as a fuel extender, octane booster, and oxygenate. At slightly below existing corn ethanol process, ethanol would see wide use for ETBE production because of the ability of ETBE to reduce the vapor pressure of gasoline.

Finally, ethanol can be used as a virtually pure or neat fuel. Because ethanol has a low vapor pressure and high octane along with other favorable fuel properties, it is one of the front running options for replacement of gasoline to address air pollution issues. Its price has been historically too high to compete with other options such as methanol, but if opportunities can be realized to reduce the price to be competitive with gasoline, ethanol could see widespread use as a neat fuel.

6.2 Opportunities for Technology Improvement

Technology for production of ethanol from lignocellulosic biomass is rapidly evolving, and the power of modern biotechnology and bioprocessing can be called on to radically alter the economics. Because so many options are available for advancing the technology, the probability of success is quite high. Although some time will be required before the advances are realized and are shown to be commercially viable, the opportunity is promising to produce ethanol at a far lower cost in the future. Thus, those that enter the marketplace for ethanol production from lignocellulosic biomass now can look forward to technology that could result in lower costs and expanded markets in the future. Furthermore, pilot plants are being constructed at the National Renewable Energy Laboratory (NREL) and other sites to demonstrate the technology for ethanol production from lignocellulosic biomass. These pilot plants will demonstrate the viability of technology that is available now as well as provide a facility to develop and test improvements in the technology in the future. Such facilities could provide significant support to those that commercialize lignocellulosic conversion technology in the near term.

6.3 Near-Term Availability of Feedstocks

A diverse range of existing lignocellulosic materials can be converted into ethanol, including waste materials such as MSW, agricultural residues, and forestry wastes. Many of these wastes may be available at low costs, which makes them attractive for early introduction into the marketplace. Another potential source of low-cost feedstocks in the near term is cellulose fines from the paper and pulp industry. Additionally, the low-value fiber in corn that is now blended with corn gluten feed in the wet-milling industry is high in cellulose and hemicellulose content. In the dry milling of corn, the fiber is left behind in the DDGS co-product that is sold as animal feed. Conversion of the fiber from either one of these animal feed co-products into ethanol could enhance overall ethanol yields from the plant by about 14% to 16% and result in a higher protein content in the animal feed co-products that may have a higher market value. The latter could be true because animal feed co-products are generally sold on the basis of their protein content, and conversion of the fiber into ethanol would leave a higher fraction of protein.

Many other lignocellulosic materials are also now available that could serve as very low-cost feedstocks for early introduction of this technology in the marketplace. Although the quantity of low-cost materials is limited as far as substantial impact of ethanol on the transportation fuel market, such feedstocks are still sufficient to provide an opportunity for early introduction of ethanol technology at a significant scale, as evident by table 76. Then, as advances are made in the technology for ethanol production from lignocellulosic biomass, higher cost energy crops could be employed as feedstocks for ethanol production at prices competitive with conventional fuels.

7. Weaknesses/Barriers

If entering the ethanol business, it is important to ensure the issues impacting the markets, the technology, and the source of raw material are considered. Some controversies surround the use of ethanol as a fuel, and the entrepreneur must be aware of these before embarking in this field. In addition, it is important to establish a sound technology position and recognize opportunities to reduce the risk in the future. Finally, a sufficient source of feedstock must be available.

7.1 Fuel Issues

Although ethanol increases octane and provides oxygen when blended with gasoline, it is not as widely used as one might expect based on the value calculated for the product. This contradiction may be partly due to some perceived difficulties with ethanol blends. First, ethanol is not fungible with gasoline; that is, it is not completely compatible, and problems such as separation in water can result with the storage and transport of ethanol in pipelines. Of particular concern is the tendency of ethanol to phase separate with any water present in pipelines or storage tanks (Ludlow 1989). In addition, the vaporization characteristics of ethanol blends are different than those of regular gasoline. For instance, blending ethanol with gasoline increases the Reid vapor pressure (RVP) by about 3.4 to 6.9 kilopascals (05. to 1.0 psi). As a result, ethanol blends are more subject to vapor lock in engine fuel lines. Although the characteristics of the base gasoline could be changed to accommodate ethanol, ethanol is primarily blended with regular gasoline by small blenders who are not equipped to change the base-blending stock to compensate for ethanol addition. As a result, some of the public perceive ethanol unfavorably and are reluctant to purchase fuels that contain ethanol. Thus, it may be necessary to sell ethanol at a somewhat lower price than one might expect based on its fuel properties to compensate for the poor public perception. The fact that most major gasoline producers do not manufacture ethanol may lead to lower use as well.

One of the critical issues currently facing ethanol use in blends is the impact of the increase in RVP on air quality. Greater evaporative emissions result with increased RVP, and more of the fuel mixture is released into the atmosphere during vehicle refueling and as running losses when the fuel moves through the fuel system. Thus, even though use of ethanol has been shown to reduce the emissions of unburned hydrocarbons and carbon monoxide from the tailpipe of vehicles, many argue that the higher evaporative and running loss emissions more than compensate for this benefit (Anderson 1992a and 1992b). Release of unburned hydrocarbons from fueling and running losses, as well as carbon monoxide and other tailpipe emissions, contributes to the formation of ozone in cities such as Los Angeles. As a result there is still considerable debate about whether or not direct ethanol blends should be allowed during summer months under the Clean Air Act Amendments to improve urban air quality. The decision on the viability of ethanol in this market will have a substantial impact on its future sales. On the other hand, because ETBE lowers the RVP of gasoline mixtures, these factors are not an issue. Pure ethanol also has a very low vapor pressure and would have advantages in addressing these emissions.

7.2 Intellectual Property

An important aspect of commercializing ethanol technology could be development of protected technical positions through patents and trade secrets. As one brings this technology into the marketplace successfully, other companies may wish to follow with similar processes. If the technology is not properly protected, these companies will be free to utilize the success of the first risk-takers to their advantage. However, if these first companies into the market have proper protection for their technology, they can prevent others from capitalizing on their success without proper remuneration.

Another aspect to intellectual property considerations is that some of the key technologies for ethanol production are already owned by companies in this business. For instance, strains of E.coli, Kliebsella oxytoca, and other microorganisms have been genetically engineered to ferment xylose and other five-carbon sugars to ethanol, with apparently high yields. Because these technologies are protected, others cannot apply them without proper licensing arrangements with the owners of the inventions. Similar considerations apply to other technologies in the production of ethanol from biomass. Thus, if companies wish to produce ethanol from lignocellulosic biomass, they should be thoroughly familiar with the technologies available and ownership positions in these technologies before embarking on this venture.

7.3 Technology Maturity

The technology for production of ethanol from lignocellulosic biomass has emerged rapidly over the last few years. However, despite the favorable cost projections for ethanol production and the opportunity for significant further advancements, the technology has mainly been tested at the bench scale. A critical need is to establish the performance of the technology in fully integrated systems. Furthermore, integrations of this type must be carried to a large enough scale so that meaningful mechanical, biological, and chemical performance data can be gathered. It is necessary to establish how the various chemicals that result from each process step and accumulate through recycling of water affect process performance, particularly for biologically catalyzed steps. Furthermore, good data are needed on energy requirements for mixing and other mechanical operations in the process. Pilot plants are being constructed at NREL and other locations to gather such data, which will enhance the prospects for technology commercialization. However, until those data are available, considerable uncertainty exists about how well the processes will perform versus the projections made in process economics studies.

7.4 Feedstock Supply

One of the critical issues facing ethanol production from lignocellulosic biomass is ensuring an adequate supply of feedstock for a very large-scale plant. Before building a large plant, a guaranteed supply of feedstock is needed at an established price. However, no one is willing to plant a large land area with feedstock without having a guaranteed user of that material. Because woody forms of biomass can require five to ten years to establish growth, it may be difficult to get large-scale biomass systems in place that will feed a commercial plant when it is ready to operate. Furthermore, the establishment of such a large biomass supply entails substantial investment in addition to that associated with building the plant for ethanol production. The result is that the combined capital requirements for construction of a plant plus developing a reliable source of biomass may be too great for many start up companies to undertake. Use of waste materials such as municipal solid wastes or agricultural and forestry wastes which could be contracted for on a long-term basis could alleviate this difficulty for initial plants until the technology is established. Herbaceous crops can also be established in only a year to provide a source of energy crops more quickly for ethanol production.

8. Opportunities

Demand for alternative fuels and oxygenates such as ethanol in the United States has grown steadily over the last few years and is expected to skyrocket in the next two decades and beyond. Several factors including energy security, economic prosperity, and environmental concerns are responsible for this increased demand.

8.1 Regulatory Requirements for Oxygenates

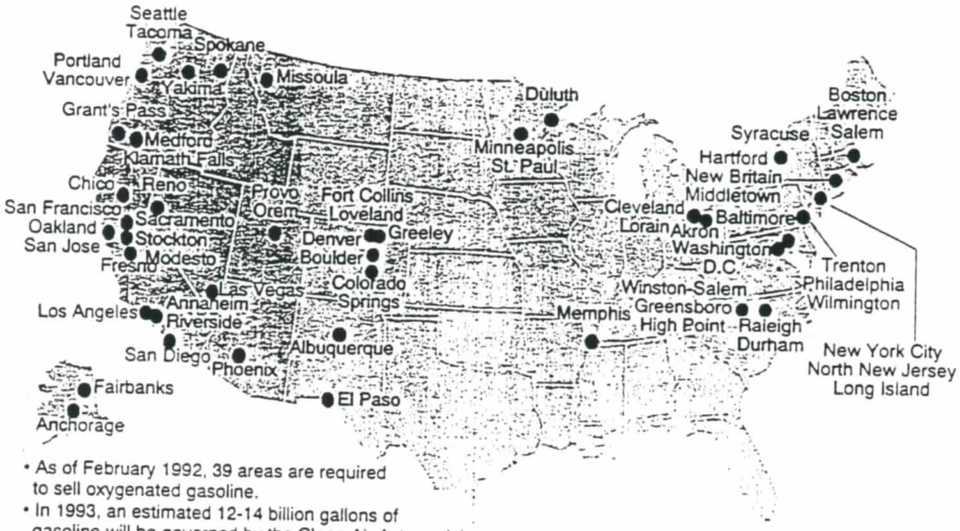
Conventional transportation fuels have significant adverse impacts on land, air, and water resources. Air pollution, global climate change, oil spills, and toxic waste generation can result from the use and production of petroleum-based transportation fuels. Air pollution from transportation fuels occurs during transfer and storage as well as end use. Reactive hydrocarbons and toxic compounds such as 1,3 butadiene and benzene are the principal air emissions resulting from fuel storage and transfer. Combustion products include carbon dioxide, carbon monoxide, nitrogen oxides (NO_x), reactive hydrocarbons, and small amounts of particulate matter and sulfur dioxide.

Much of the air pollution in the United States is caused by petroleum-based transportation fuels. Sulfur dioxide, particulate matter, carbon monoxide, nitrogen oxides, and ozone formed from reactive hydrocarbons and nitrogen oxide in the presence of sunlight are pollutants, and their emissions are regulated. Each of these pollutants has serious adverse impacts on human health and the environment, and the Clean Air Act and its Amendments of 1990 are directed at regulating releases that contribute to their accumulation. Ozone causes respiratory damage in humans and may also adversely affect crops (U.S. Congress 1990). Oxides of nitrogen and sulfur combine with water vapor in the atmosphere to form acid rain. In addition, nitrogen oxide (NO_2) can cause fatal lung damage and nitric oxide (NO) is an asphyxiant (Danielson 1973). Carbon monoxide also results in health risks at concentrations exceeding 9 parts per million (ppm). Sulfur dioxide and particulate matter reduce visibility and have a synergistic effect as lung and eye irritants. The California Air Resources Board (CARB) estimates that 43% of reactive organic gases, 57% of the nitrogen oxides, and 82% of carbon monoxide in the major California urban areas resulted from automobile emissions (Sperling 1990). Air pollution has enormous economic, social, and environmental impacts including human sickness and death, agricultural productivity decreases, building corrosion, visibility reduction, and wildlife habitation (De Luchi et al. 1987). For example, use of gasoline and diesel fuel increases deaths by 30,000 in the United States annually. The external non-market cost of air pollution in the United States is estimated to range from $11 billion to $187 billion annually (Sperling 1990). If these costs were factored into the price of gasoline, alternative fuels might have been introduced into the U.S. market much sooner.

Thirty-nine areas in the United States exceed the National Ambient Air Quality Standards (NAAQS) for carbon monoxide (Federal Register

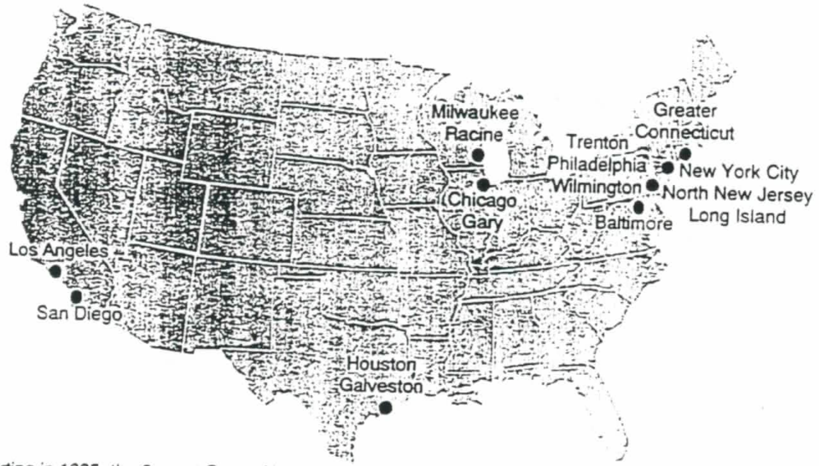
1992). Through the Clean Air Act Amendments of 1990, these areas must use fuels with a minimum oxygen content of 2.7% for at least 4 winter months beginning on November 1, 1992. For those areas that still do not attain the standards by December 2000, the minimum oxygen content for fuels will be raised to 3.1% (Scherr et al. 1991). These oxygenated gasoline requirements will affect 32.1% of the gasoline pool. In 1989, this would affect a gasoline demand of almost 140 gigaliters (37 billion gallons). Figures 64 and 65 show the areas of the United States currently subject to these provisions of the Clean Air Act Amendments of 1990 for carbon monoxide and ozone, respectively.

Some states and air quality regions may have different requirements from those listed above. CARB has petitioned the EPA to lower the oxygen content of its winter time blends from the minimum 2.7% required to a range of 1.8%–2.2% (Octane Week 1991). Although emissions of carbon monoxide increase with lower fuel oxygen content, emissions of NO_x decrease. Because of California's severe ozone non-attainment status, CARB believes that NO_x is a bigger problem than carbon monoxide and that this trade-off is warranted. Several other sources support this position and have indicated that the EPA has been remiss in aggressively reducing emissions of volatile organic com-



- As of February 1992, 39 areas are required to sell oxygenated gasoline.
- In 1993, an estimated 12-14 billion gallons of gasoline will be governed by the Clean Air Act provisions.

Fig. 64. 1990 Clean Air Act Amendments – Carbon Monoxide Nonattainment Areas.



- Starting in 1995, the 9 worst Ozone Nonattainment Areas in the country must sell only reformulated gasoline.
- Collectively, these areas account for approximately 25% of the motor fuel sold in the country.

Fig. 65. 1990 Clean Air Act Amendments – Ozone Nonattainment Areas.

pounds (VOC's) as a precursor to ozone and ignoring NO_x, another precursor to ozone (Octane Week 1991a). Some studies have shown that NO_x has a much bigger role to play in ozone formation than VOC's, depending on the relative amounts of these two components in the air.

In other regions, the carbon monoxide control season may be longer than the 4-month minimum required by the Clean Air Act Amendments because of the severity and the duration of the elevated levels of carbon monoxide in these areas. The EPA has proposed increasing carbon monoxide seasons in 6 areas: New York City, Northern New Jersey, Las Vegas, Phoenix, Los Angeles, and Spokane (Federal Register 1992). However, New York City has made a counter proposal of a 2.7% oxygen content for 5 months and a 2.0% oxygen content for the remaining 7 months.

Beginning in 1995, nine areas with ozone concentrations of greater than 0.16 ppm and a population of greater than 250,000 will be required to use reformulated gasoline (RFG). RFG must contain at least 2% oxygen by weight, no more than 25% by volume aromatics, less than 1% by volume benzene, and no lead or other heavy metals. RFG must also contain detergents to prevent the accumulations of deposits in engines or fuel supply systems.

Vehicles using RFG must meet several other performance-based emissions standards. Aggregate emissions of ozone-forming VOC's and toxics (e.g., benzene, 1,3 butadiene, polycyclic organic matter, acetaldehyde, and formaldehyde) must be 15% below (on a mass basis) the same emissions from vehicles using "baseline gasoline." In addition, emissions of NO_x from baseline vehicles using RFG must not be greater than the NO_x emissions from baseline vehicles using "baseline gasoline." In 2000, the required reduction in both VOCs and toxics increases to 25%. If the EPA decides this level is technologically or economically infeasible, however, the required decrease can be reduced to 20%.

Reformulated gasoline standards have not yet been finalized, but EPA has issued its proposed rule based on the accord developed by the Clean Fuels Advisory Committee during its regulatory negotiations (Reg-Neg) in August 1991. Twenty-eight representatives signed the accord from a diverse group of industries such as alternative fuels, petroleum refining, auto manufacturing, and agriculture. State regulatory agencies and the EPA also signed the accord. This process, outlined in the Clean Air Act Amendments of 1990, is designed to avoid the lengthy court battles that usually follow a ruling.

The nine affected areas represent 22% of the U.S. gasoline demand (Jones and Lareau 1991). If all potential ozone non-attainment areas opt into the program, almost 54% of the U.S. gasoline supply would require reformulation. Some overlap with the oxygenate program exists. About 26% of all U.S. gasoline is supplied to areas that are affected by the oxygenate and reformulated gasoline requirements (Jones and Lareau 1991).

In addition to the federal regulations, aggressive air pollution policies are being implemented in the state of California as well as individual air quality control regions comprised of large metropolitan areas such as Los Angeles. These regulations will also affect the markets for both oxygenates and alternative fuels and are likely a good indication of the direction of future regulations.

The potential for ethanol as a direct blending agent or use of ETBE is substantial in the United States. Currently, about 3.8 billion liters/year (1.0 billion gallons/year) of ethanol produced from corn is blended with gasoline. This level is somewhat less than 1% of the gasoline market. With mandates under the Clean Air Act Amendments of 1990 for enhanced oxygen levels in gasoline in cities occupied by more than half the U.S. population, the growth in the oxygenate market in the near future will be substantial. When ethanol is produced at prices competitive with MTBE, it would gather a substantial fraction of that market. Blending oxygenates in half of the gasoline in the United States could evolve into an annual market on the order of 19 billion liters (5.0 billion gallons) of ethanol. Even if ethanol shared this market equally with MTBE, on the order of 9 to 10 billion liters (2.4 to 2.6 billion gallons) of ethanol could be required annually within the next several years.

8.2 Neat Fuel Needs

Domestic transportation fuels are almost exclusively (about 97%) derived from petroleum and account for about 64% of the total petroleum used in the United States. Greater than one-fourth of the total U.S. energy use is consumed directly by the transportation sector, and when indirect energy uses (e.g., road building and repair, petroleum refining) are included, energy consumption in this sector rises to 40% (Gordon 1991).

Few substitutes are currently available for petroleum-based transportation fuels, and the mobility of the United States is extremely vulnerable both strategically and economically to supply disruptions. Iraq's invasion of Kuwait as well as the energy crisis of the 1970s underscore this vulnerability. For example, the estimated cumulative economic impact of the 1973–74 embargo and the 1979 petroleum cutoff was a gross national product (GNP) loss of at least 10% (100 billion dollars) in 1985. Petroleum imports also have a major impact on the trade deficit; in 1989 oil imports contributed about 40% ($44.7 billion of $111 billion) of the trade deficit.

The federal Alternative Motor Fuels Act (AMFA) of 1988 affects the neat ethanol market. It promotes the use of alternative fuels, including ethanol, in government fleet vehicles as the first step in their large-scale commercialization. The federal government and many state governments are providing incentives for the production of ethanol from renewable resources. The market for ethanol could eventually expand to up to 530 billion liters (140 billion gallons) as a neat fuel, provided it could be sold at prices competitive with gasoline and other substitute fuels that could enter the market.

In October of 1992, the 102nd Congress passed, and the President signed the first comprehensive energy policy act for this nation in 20 years. The Energy Policy Act, or EPACT, has many provisions which address multiple forms of energy production and use. Section 1202 characterizes the general goals of the Alcohol from Biomass Program which "shall be to advance the research and development to a point where alcohol from biomass technology is cost-competitive with conventional hydrocarbon transportation fuels, and to promote the integration of this technology into the transportation fuel section of the economy." It sets some specific goals for ethanol from biomass including: reduction of the cost of alcohol to 70 cents per gallon, improvement of the overall biomass carbohydrate conversion efficiency to 91 percent, reduction of the capital cost component of the cost of alcohol to 23 cents per gallon, and reduction of the operating and maintenance component of the cost of alcohol to 47 cents per gallon.

8.3 Niche Markets

Although substantial reductions in the price of ethanol from lignocellulosic biomass are possible through advances in the technology, ethanol from lignocellulosic materials can be produced at prices competitive with corn ethanol in the near term. Furthermore, examination of the costs summarized in table 85 reveals several areas for cost reduction. First, we see that feedstock costs comprise about $0.12/liter ($0.45/gallon) of the total projected ethanol price of $0.32/liter ($1.23/gallon). Therefore, if low-cost wastes such as MSW, agricultural or forestry residues, or other materials with little to no cost were utilized, a substantial reduction in price would be possible.

The return on capital comprises an element in the predicted selling price about equal to that of feedstock costs, on the order of $0.13/liter ($0.49/gallon) of ethanol produced. If low-cost debt that is tax deductible, such as municipal bonds, were used to finance the plant, these funds would leverage the investment and reduce the required ethanol selling price. Thus, arrangements with municipalities or utilities could provide valuable sources of financing for initial ethanol plants. Although leveraging is beneficial during good economic times, it must be remembered that it becomes detrimental if prices are squeezed.

The cost projections shown for ethanol production from lignocellulosic biomass are all based on construction of a grass roots plant. However, if an ethanol production facility were built at an existing chemical or fuel production site, many of these costs could be substantially reduced. It can be seen in the capital cost summaries in table 83 that utilities, environmental systems, and off-site tankage represent close to half the estimated total erected plant cost for an ethanol production facility. Therefore, if these costs could be reduced by using such systems in an existing plant, the price of ethanol could be reduced substantially.

In addition to these various steps to reduce costs, it may be possible to enhance co-product revenues from the ethanol process. For example, sale of electricity at a higher price than that assumed here could enhance revenues substantially. Alternatively, it may be possible to use better heat integration to increase the amount of electricity available for sale. If it were desirable to burn coal or other fuels in initial plants to provide steam and electricity, the lignin fraction of the biomass could be converted into higher value products, such as adhesives or other chemicals. Obviously, the revenue derived from the sale of more electricity or lignin co-products must be sufficient to cover the additional cost associated with generation of such products and provide greater net income.

8.4 Long-Term Benefits

Conventional transportation fuels contribute to the buildup of carbon dioxide and other gases in the atmosphere, which may trap heat and affect global climate change. The increase of greenhouse gases in the atmosphere is significant; for example, the level of carbon dioxide has risen by 25% since the mid 1800s and the concentration of methane is increasing at a rate 400 times the natural variability. Although the severity of the "greenhouse effect" is under debate, its possible consequences include the transformation of large areas of the world from heavily forested woodlands to deserts, loss of much of the corn belt in the Midwest, and flooding of coastal cities.

Carbon monoxide, although not a greenhouse gas itself, does increase atmospheric concentrations of methane and ozone and promotes reaction of NO to NO_2, the first step in ozone formation. It also reacts with the hydroxyl radical (OH), a scavenger of methane. Thus, carbon monoxide indirectly contributes to the buildup of greenhouse gases. In fact, the depletion of hydroxyl radicals is estimated to have an effect equivalent to the emissions of a few million tons of methane per year. The primary source of carbon monoxide emissions is transportation; about two-thirds of the U.S. carbon monoxide emissions result from transportation activities.

Production and use of petroleum-based transportation fuels also impart significant adverse effects to land and water resources as a result of oil spills and toxic waste generation. On the other hand, many alternative fuels could be made from the waste products of industries such as agriculture, pulp and paper, and food processing. Production of alternative fuels from these resources would have several benefits: it would lessen the environmental impact of these industries on land and water resources and would reduce their associated direct and indirect costs. In addition, another source of revenue for these industries would be created.

Use of surplus agricultural products and the development of the domestic energy crop industry are two other potential benefits for the production of alternative fuels, such as ethanol from biomass. Conversion of surplus agricultural products into alternative fuels utilizes products that would otherwise be allowed to decay, often releasing methane, a powerful greenhouse gas. It also generates additional revenue for farmers. Significant quantities of ethanol could be produced from this source. Substantial potential also exists for the creation of an energy crop industry.

9. Threats/Competition

Several octane boosters and oxygenates are commercially available for blending with gasoline other than ethanol. In addition, methanol is a strong candidate as a neat fuel to replace gasoline. In order to be successful, ethanol must not only compete with these alternates based on price, but environmental regulations can also influence the selection of oxygenates or neat fuels in the future.

9.1 Market Competition

The demand for oxygenates will increase significantly in the coming years. Most of these increases will occur before 1999 as the oxygenate and RFG standards are implemented. Initially, the market for ethanol will be as an oxygenate additive to gasoline in areas that do not meet air quality standards. A number of other oxygenates, including methyl tertiary butyl ether, tertiary amyl methyl ether, methanol, tertiary butyl alcohol, and isopropanol, will be competing for a share of this market. The demand for neat alternative fuels will also increase; however, it is not anticipated that this demand will be as rapid in the near-term as for oxygenates.

9.1.1 Methyl Tertiary Butyl Ether (MTBE). Alcohols are not fungible with gasoline—they do not ship and handle like other gasoline components. Therefore, they cannot be handled like conventional gasoline in common pipelines and tanks and are not swapped like normal gasoline. This drawback can be overcome if alcohols are converted to fungible ether blend stocks. Methanol can be reacted with isobutylene to form MTBE, which is currently the most popular oxygenate and is traded globally. Worldwide capacity today is approximately 257,700 barrels/day (132,000 barrels/day ethanol equivalent), and most of this is in the United States (Haigwood 1991). Use of MTBE outside of the United States is expected to rise as an oxygenate and with the global phaseout of lead compounds from gasoline. Currently, Europe is the only significant MTBE market outside the United States; however, the market in the Far East is expected to grow in the 1990s. This demand could be quite significant since Japan recently lifted its ban on MTBE use in gasoline. In 1995, worldwide demand for MTBE is projected to be between

470,000 and 615,000 barrels/day (241,000–315,000 barrels/day ethanol equivalent). Future capacity is expected to come from the United States, Saudi Arabia, Malaupia, Canada, Venezuela, and Mexico (Stodolsky and Singh 1991).

9.1.2 Tertiary Amyl Methyl Ether (TAME). TAME is not expected to capture a significant portion of the oxygenate market (i.e., approximately 10%) because of the relatively small quantity of C_5 streams (required to produce TAME) that is available in domestic refineries (Wood 1991). However, because TAME is produced from small facilities using in-house feedstocks and not from stand-alone capital-intensive units, it should be cost competitive (API 1988).

9.1.3 Methanol. Methanol, primarily manufactured by thermal processes at rapid rates, can be produced from fossil fuels such as natural gas, petroleum naphthas, and coal, and from biomass resources such as woody and herbaceous plants. Because methanol increases the RVP significantly, methanol is not widely accepted for blending with gasoline in the United States. However, methanol is routinely used on a co-solvent basis in Europe at levels up to 3% in gasoline. In 1988, the worldwide use of methanol as a gasoline additive was 180 megaliters (47 million gallons).

Methanol can be employed directly as a neat (close to 100%) fuel, with many fuel properties that are desirable. Neat alcohols provide superior efficiency and performance to gasoline in properly optimized engines because they require lower stoichiometric air/fuel ratios, have higher latent heats of vaporization, provide higher octane values, and have a lower flame temperature. Thus, methanol is often preferred to gasoline for high performance in automobile races such as the Indianapolis 500.

Currently, mixtures of 85% methanol and 15% gasoline (known as M85) are often preferred over pure methanol for automotive use. The addition of gasoline increases the vapor pressure of the fuel enough to facilitate cold starting. Further engine development is needed to cold start engines with pure methanol, particularly during winter months in colder climates.

9.1.4 Tertiary Butyl Alcohol (TBA). Currently, there is no market for TBA as a gasoline blending agent, and all TBA available for fuel use is converted to isobutylene for MTBE production (API 1988). n-Butanol produced with conventional technology is estimated to cost from $0.69 to $0.82/liter ($2.60/gallon to $3.10/gallon) (1990 $) via synthetic methods (Leeper et al. 1991). Fermentation methods project a cost of butanol of $1.05/liter ($4.00/gallon) (1990 $). Neither of these oxygenates is expected to capture a significant portion of the market because they are not economically attractive compared to other options.

9.1.5 Isopropanol (IPA). Currently, most IPA and TBA is made synthetically; however, both can be produced from biomass using both biochemical and thermochemical techniques. IPA is too expensive to be used as a gasoline blending agent but has been used in gasoline at a concentration of less than 2% to prevent carburetor icing (API 1988). Costs for IPA may decrease, however, as refiners use captive C_4 streams to make MTBE; currently these streams are reacted with propylene (Wood 1991). IPA produced by conventional methods is projected to cost from $0.41 to $0.59/liter ($1.56/gallon to $2.23/gallon) (1990 $) (Leeper et al. 1991). Fermentation derived propanol is estimated to cost from $0.82 to $1.00/liter ($3.10/gallon to $3.78/gallon) (Leeper et al. 1991). Thus, propanols are not cost competitive in the oxygenate market, at this time.

Table 86 presents a comparison of properties for seven oxygenates. As shown, each has potential advantages and disadvantages with no individual option being the best in all categories. Therefore, the transportation and oxygenate markets of the future will likely be met by a mix of fuel choices to meet specific applications.

9.2 Emissions Regulations

Some proponents of ethanol contend that the EPA ruling on reformulated gasoline unfairly discriminates against ethanol because this agreement has no RVP waiver for ethanol blends. Furthermore, they feel the oxygen content of RFG during months with ozone violations may be limited to less than 3.5 wt%. When ethanol is blended with gasoline, the RVP of the mixture increases by about 6.9 kiloPascal (1.0 psi), even though ethanol has a much lower vapor pressure than gasoline. This increase is due to the polar structure of ethanol while gasoline is nonpolar. The incompatibility of the two results in increased evaporation of the components of gasoline such as butanes and benzene. Thus, although ethanol blends reduce tailpipe emissions, evaporative emissions during refueling and running losses are expected to be greater. For ethanol to be blended into RFG, either the unblended gasoline must have an RVP that is about 6.9 kiloPascal (1.0 psi) lower than that required for the final product or else a waiver is required. Because refiners will not likely provide blending feedstock gasoline at a

Table 86. Oxygenate comparison (Piel 1991, Federal Register 1992)

Oxygenate	Economics	Environmental Fuel Properties	Impacts End-Use Emissions	Vehicle Octane Rating	Performance Heating Value	Engine Components Compatibility	Supply	Health & Safety	Government Policies
MTBE	(+) Low - Moderate Cost	(0) Moderate Blend RVP	(0) Inc. NO_x; Dec. CO	(+) 3rd Highest Blend Octane	(0) 3rd Highest LHV	(+) Fungible in wet system	(-) Now all from non-renewables	(-) Effects similar to gasoline	(0) No specific policies
ETBE	DNA (1)	(+) 2nd Lowest Blend RVP	(0) Inc. NO_x; Dec. CO	(+) 2nd Highest Blend Octane	(0) 2nd Highest LHV	(+) Fungible in wet system	(0) Domestic, renewable ethanol feed	(-) Effects similar to gasoline	(0) No specific policies
TAME	DNA (2)	(++) Lowest Blend RVP	(0) Inc. NO_x; Dec. CO	(+) Increased Blend Octane	(+) Highest LHV	(+) Fungible in wet system	(-) Now all from non-renewables	(-) Effects similar to gasoline	(0) No specific policies
Ethanol	(-) Somewhat High Cost	(-) High Blend RVP	(0) Inc. NO_x; Dec. CO	(++) Highest Blend	(-) 2nd Lowest LHV	(-) Not fungible; corrosive	(+) Domestic, renewable feedstock	(+) Biodegradable	(+) Tax incentives
Methanol	(++) Low	(--) Very high Blend RVP	(0) Inc. NO_x; Dec. CO	(+) Increased Blend Octane	(-) Lowest LHV	(-) Not fungible; corrosive	(-) Now all from non-renewables	(-) Toxic; transparent flame	(+) Tax incentives for renewable
TBA	(-) Very High Cost	(0) Moderate Blend RVP	(0) Inc. NO_x; Dec. CO	(0) Lowest Octane Increase	(0) 3rd Highest LHV	(0) Fungible but soluble	(-) Now all from non-renewables	DNA	(0) No specific policies
IPA	(-) Very High Cost	(-) High Blend RVP	(0) Inc. NO_x; Dec. CO	(+) Increased Blend Octane	(0) 2nd Lowest LHV	(0) Fungible, but soluble	(-) Now all from non-renewables	DNA	(0) No specific policies

Notes:
(1) Likely high: depends on ethanol feedstock costs.
(2) Likely low to moderate because of in-house use of C_5 streams.
NOTE: DNA implies data not available.

lower RVP, the ethanol industry supports an RVP waiver to ensure competitiveness. The EPA, however, does not think that it could legally provide a waiver for ethanol blends because the RFG standard requires a 15% reduction in VOC emissions and provides no RVP waiver.

In the first 2 years of the reformulated gasoline program, the EPA will use an air model known as the Simple Model that uses a mass-based emissions standard to regulate ozone precursors such reactive hydrocarbons. Because ethanol increases the vapor pressure of gasoline, greater quantities of reactive hydrocarbons (on a mass basis) are emitted from RFG with ethanol. Therefore, the 15% reduction in hydrocarbon emissions cannot be met. In later years, EPA may use the Complex Model which uses a reactivity standard to project the impact of emissions of reactive hydrocarbons on air quality. Using this model, ethanol may show improvements in air quality because the lower reactivity of the hydrocarbons released by ethanol blends could more than compensate for the greater quantity that are released. EPA acknowledges that the limited participation of ethanol in early years of the RFG program would likely decrease its use in the future even though the Complex Model may reverse the findings of the Simple Model.

In October 1992, the Bush administration announced that the 6.9 kiloPascal (1.0 psi) waiver will apply to all ethanol-RFG blends for up to 30% of the market in northern cities (Anderson 1992a and 1992b). To compensate for any increase in ozone-forming emissions, the RVP of gasoline will be lowered by 2.0 kiloPascal (0.3 psi) to a RVP of 54 kiloPascal (7.8 psig). Gasoline with this vapor pressure specification is now sold in southern cities in the summer. States may also choose to apply the waiver to more than 30% of the market if they compensate by additional RVP reductions on gasoline. Southern cities can either employ the RFG program as it was originally planned with a 50 kiloPascal (7.2 psig) gasoline or they can apply the waiver to 20% of the market if they reduce the RVP by 1.4 kiloPascal (0.2 psi) to 48 kiloPascal (7.0 psig).

Some of the other features of this announcement include a call for tax legislation to support conversion of ethanol to ETBE. It also ensures that 39 carbon monoxide non-attainment cities will participate in the oxygenated fuels program in the fall of 1992 and discourages states from reducing ethanol use by imposing caps on oxygenate levels.

Another factor working against ethanol is the proposed oxygen limit in RFG of 2.1 wt% during months of ozone exceedances. This oxygen concentration corresponds to an ethanol content of 6% by volume. Ethanol gasoline blends of less than 9.8% ethanol by volume are ineligible for the federal excise tax exemption and thus are less economically attractive. Both of these factors (RVP and oxygen content limitations) may restrict the use of ethanol blends in ozone non-attainment areas. Although

Table 87. Advantages and disadvantages of ethanol from lignocellulosic biomass as a transportation fuel

ADVANTAGES	DISADVANTAGES
Familiar, organic liquid	Raises the RVP when blended with gasoline
Produced from renewable resource	Lower energy content than gasoline; more frequent refueling
Domestic resource base	Initial distribution may be difficult
Few engine modifications required	High flashpoint and wide flammability limits could form flammable mixtures in fuel tank
High-octane fuel	Degrades some elastomers, plastics, and metals
Greater engine efficiency	Cold temperature starts may be difficult as neat fuel
Flexible fuel and dual fuel vehicles available	Corrosive with water
Low toxicity	Separates from gasoline in mixtures when exposed to water
Few driver behavior modifications required	
Lower emissions of reactive hydrocarbons and air toxics	
Emissions are less photochemically reactive for neat fuel	
Potential solution to oxygenate requirements of the Clean Air Act Amendments of 1990	
Reduces carbon monoxide emissions when blended with gasoline	
Contributes little, if any, net CO_2 to atmosphere	
Creates jobs in farm economy	
Re-uses waste products	

the RFG provisions are currently required in only 9 areas nationwide, the other 87 ozone non-attainment areas may choose to adopt these standards or "opt in" regardless of their population. Table 87 summarizes some advantages and disadvantages of using ethanol as a transportation fuel, assuming it can be made at a low cost from lignocellulosic biomass.

10. The Business Venture

The current projected selling price of ethanol from lignocellulosic biomass is competitive with the price of ethanol from corn. In addition, for certain niche opportunities, the projected price of ethanol would be substantially lower and would compensate for the uncertainty in the price estimates and provide a higher rate of return for first-of-a-kind technology.

10.1 Projected Ethanol Selling Price

The technology described earlier represents an enzyme-based process currently thought to be technically viable for production of ethanol from lignocellulosic biomass. It is based on the best available data from bench-scale experiments on each of the process steps as well as information gathered from operating corn ethanol plants. Tradeoffs have been made among operations of each process step to at least partially optimize the economics of the overall process.

Table 88 presents the discounted cash flow analysis for the modified case according to the economic parameters provided in table 82. As summarized earlier in table 85, the projected price of ethanol for this case is about $0.32/liter ($1.23/gallon). This is well within the range of the current market price of ethanol from corn of from $0.30 to $0.35/liter ($1.15 to $1.35/gallon). Thus, at the price projection shown, ethanol could be produced from lignocellulosic biomass at prices competitive with ethanol from corn.

Table 88. Discounted cash flow for ethanol production from lignocellulosic biomass for modified case (all dollars in millions)

Capital Cost	$128.39 MM
Start-up Costs	$6.42
Total Plant Cost	$134.81
Ethanol Selling Price	$0.324/Liter
Production Rate	221 Million Liters/Year

Items	Years																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Percent of Capital Paid	30.0%	50.0%	20.0%															
Capital Invested	$38.52	$64.20	$25.68															
Start-up Cost				$6.42														
Working Capital				$6.31														$(6.31)
Total Annual Capital Outlay	$38.52	$64.20	$25.68	$12.73	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$(6.31)
Total Capital Investment	$38.52	$102.71	$128.39	$141.12	$141.12	$141.12	$141.12	$141.12	$141.12	$141.12	$141.122	$141.12	$141.12	$141.12	$141.12	$141.12	$141.12	$134.81
Percent of Nameplate	0%	0%	0%	60%	80%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Production Rate, MM Liters/Year				132.9	177.1	221.4	221.4	221.4	221.4	221.4	221.4	221.4	221.4	221.4	221.4	221.4	221.4	221.4
Ethanol Revenue				$43.11	$57.48	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85	$71.85
Electricity Revenue				2.49	3.32	4.15	4.15	4.15	4.15	4.15	4.15	4.15	4.15	4.15	4.15	4.15	4.15	4.15
Feedstock Cost				16.13	21.50	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88	26.88
Chemicals, Solids Disposal, Water				5.21	6.94	8.68	8.68	8.68	8.68	8.68	8.68	8.68	8.68	8.68	8.68	8.68	8.68	8.68
Fixed Operating Costs				11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67	11.67
Total Costs				$33.01	$40.12	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23	$47.23
Income Before Depreciation, Taxes				$12.59	$20.68	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77	$28.77
Depreciation				17.18	17.18	17.18	17.18	17.18	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25
Income After Depreciation				$(4.59)	$3.50	$11.59	$11.59	$11.59	$24.52	$24.52	$24.52	$24.52	$24.52	$24.52	$24.52	$24.52	$24.52	$24.52
Income Tax				0.00	1.29	4.29	4.29	4.29	9.07	9.07	9.07	9.07	9.07	9.07	9.07	9.07	9.07	9.07
Income After Tax				$(4.59)	$2.20	$7.30	$7.30	$7.30	$15.45	$15.45	$15.45	$15.45	$15.45	$15.45	$15.45	$15.45	$15.45	$15.45
Total Cash (Depreciation plus Income After Tax)				$12.59	$19.39	$24.48	$24.48	$24.48	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70
Annual Cash Flow	$(38.52)	$(64.20)	$(25.68)	$0.14	$19.39	$24.48	$24.48	$24.48	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$19.70	$26.01
Discounted Cash Flow	$(38.52)	$(58.36)	$(21.22)	$0.10	$13.24	$15.20	$13.82	$12.56	$9.19	$8.35	$7.59	$6.90	$6.28	$5.71	$5.19	$4.72	$4.29	$5.14
Cumulative Discounted Cash Flow	$(38.52)	$(96.88)	$(118.10)	$(118.20)	$(104.96)	$(89.76)	$(75.94)	$(63.37)	$(54.18)	$(45.83)	$(38.24)	$(31.33)	$(25.06)	$(19.35)	$(14.17)	$(9.45)	$(5.17)	$(0.02)

It is important to note that the economic parameters used in this chapter to estimate ethanol selling prices are probably most appropriate for a mature process. However, the technology for ethanol production from lignocellulosic biomass has not yet been fully integrated from front to back of the process at either the bench or pilot scale. Therefore, although the evidence gathered to date is strong that the process flowsheet used to project engineering economics will be verified, uncertainty still exists in the actual process details and interactions. Consequently, the costs could be greater than those used in these projections and/or the performance may not fully meet expectations. In addition, the cost of funds would almost certainly be higher for a first-of-a-kind plant than used in the analyses presented here for an Nth plant to compensate for the additional risk associated with such an investment.

Typically, cost estimates of the type used here have an uncertainty range of about 30% to 40%. Table 89 summarizes the consequences of the cost of capital equipment exceeding the engineering estimates by 40%. Also shown in table 89 is the projected price of ethanol for a 20% real rate of return to the investor. The projected selling price for either scenario exceeds the current market price of corn. As a result, investors may not be willing to invest in a first-of-a-kind process with the projected price so close to the market value of the product.

Table 89. Cost projections for production of ethanol from lignocellulosic biomass for improved technology, additional costs, and niche markets

Process	Plant Size[1] ML/yr EtOH	Capital	Feed	O&M	Electricity	Ethanol
		(1990$/L EtOH)				
Improved	221	0.130	0.121	0.092	0.019	0.324
40% Increase in Capital Costs	221	0.186	0.121	0.095	0.019	0.383
20% Real Rate of Return	221	0.250	0.121	0.092	0.019	0.444
No Cost Feedstock	221	0.128	0.000	0.092	0.019	0.201
Plant Add-on	221	0.072	0.121	0.088	0.019	0.262
Extra Co-product Revenue	221	0.130	0.121	0.092	0.038	0.305
Debt Financing	221	0.081	0.121	0.092	0.019	0.275

[1] Denatured, hydrous ethanol

10.2 Near-Term Market Niches

Several opportunities could be pursued to reduce the cost of ethanol production and provide a buffer for the investor against the uncertainty in the price estimates. The first option is to use a low-cost lignocellulosic waste material that is available in sufficient quantity to support the operation of an ethanol plant. A number of examples of such materials were provided earlier. As shown in table 89, use of a free feedstock would drop the projected price of ethanol by about $0.12/liter ($0.45/gallon) to a cost well below the market price for ethanol from corn.

Another option to lower the cost of ethanol is to reduce the capital investment by building the process as an add-on to an existing plant or by employing used equipment such as from a closed corn ethanol process. To illustrate the impact of this alternative, off site equipment was assumed to be provided by an existing plant, and the discounted cash flow analysis of table 89 was performed with no off site equipment costs. For such a process add-on, the projected selling price drops to about $0.26/liter ($0.98/gallon) even without a low cost feedstock, a price that is once again well below the current selling price range for ethanol from corn.

Increasing the net revenue from co-products will also lower the required selling price of ethanol to achieve a required return on investment. The economics presented are all based on generation of heat and electricity for the process with the solid residue after fermentation and the sale of the extra electricity left after meeting process requirements. It may be possible to obtain higher electricity prices than those assumed in these analyses. It may also be desirable to convert some fraction of the lignin into other products such as adhesives with coal or other fuels used to make up heat and electricity requirements if necessary, depending on the fraction of lignin used. To illustrate such options, the impact of doubling the revenue from electricity sales while maintaining other costs the same is summarized in table 89. In such a situation, the revenue required from ethanol sales can be reduced in direct proportion to the increase in co-product revenue.

An alternative scenario that could provide an attractive approach to reducing the cost of ethanol production is through the use of debt financing for some portion of the ethanol plant. The cost of debt financing is generally lower than for equity funds because debt investors have first priority on the company assets in the event of a business failure. In addition, interest payments on debt are deductible from income before taxes while the net profit of the operation is taxed before return is provided to the equity holders. To illustrate the impact of debt financing on the cost of ethanol production, it was assumed that 80% of the capital equipment costs of the plant were paid from debt with a real rate of return to the debt holders of 5%.

Furthermore, the entire loan was repaid at the end of the plant life. In this case, the cost of ethanol dropped about $0.05/liter ($0.19/gallon) from total equity financing, as shown in table 89.

11. Conclusions

Substantial progress has been made on enzyme based technology for converting lignocellulosic biomass into ethanol. The projected selling price of ethanol has dropped from almost $1.00/liter ($3.70/gallon) 10 years ago to about $0.32/liter ($1.23/gallon) now (all in 1990 dollars), a price competitive with the market range now realized for ethanol from corn. Yet, because the technology has not been proven at a large scale, the price projections are subject to uncertainty, and it may be difficult to finance pioneer plants at prices so close to the market value. However, a number of market niches such as use of low-cost feedstocks, debt financing, higher co-product values, and incorporation into an existing plant could reduce the costs of ethanol substantially and facilitate immediate profitable entry of the technology into commercial markets. The potential to further improve the technology for ethanol production to reduce the price to levels competitive with gasoline without tax incentives promises long-term growth in ethanol markets, particularly to those establishing a technical position early.

In the near term, ethanol will continue to be used as a blending additive with gasoline to boost octane and provide fuel oxygen. Ethanol blends have been shown to reduce emissions of carbon monoxide and unburned hydrocarbons from vehicle exhaust. However, considerable controversy has developed over the impact of ethanol blends on evaporative losses and ozone formation, and the resolution of this issue could have substantial impact on the growth of ethanol markets for blends. Ethanol is beginning to be used to produce the gasoline additive ETBE, which provides similar benefits to direct ethanol blending while meeting gasoline fungibility requirements and reducing smog-forming evaporative emissions as well as those from vehicle exhaust. ETBE could provide a near-term growth market, although ethanol prices will likely have to be lower than for direct blends.

In the longer term, the potential domestic supply of biomass for ethanol production could be more than sufficient to allow displacement of all gasoline used in the United States by neat ethanol. Large-scale substitution of neat ethanol for gasoline would reduce imports of vulnerable supplies of petroleum and decrease the trade deficit. Use of neat ethanol would improve urban air quality by decreasing ozone. Because carbon dioxide is perpetually recycled between biomass, fuel, and carbon dioxide for ethanol production from lignocellulosic biomass, little if any net carbon dioxide is contributed to the atmosphere, thereby decreasing the possibility of global climate change.

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