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Twenty Years of Trials, Tribulations, and Research Progress in Bioethanol Technology

Selected Key Events Along the Way

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Abstract

The projected cost of ethanol production from cellulosic biomass has been reduced by almost a factor of four over the last 20 yr. Thus, it is now competitive for blending with gasoline, and several companies are working to build the first plants. However, technology development faced challenges at all levels. Because the benefits of bioethanol were not well understood, it was imperative to clarify and differentiate its attributes. Process engineering was invaluable in focusing on promising opportunities for improvements, particularly in light of budget reductions, and in tracking progress toward a competitive goal. Now it is vital for one or more commercial projects to be successful, and improving our understanding of process fundamentals will reduce the time and costs for commercialization. Additionally, the cost of bioethanol must be cut further to be competitive as a pure fuel in the open market, and aggressive technology advances are required to meet this target.

Index Entries: Biomass; biotechnology; ethanol; fuel; hydrolysis.

Introduction

Through sustained research, mostly funded by the Biofuels Program of the US Department of Energy (DOE), the cost of production of ethanol from low-cost cellulosic biomass has been made competitive for blending with gasoline, and several companies are working to commercialize this technology. However, the journey to reach this point has been challenging at all levels, and continuation was severely threatened many times. The intent of this article is to retrace some of this perilous path to present a perspective on key events, advancements, and remaining challenges for this powerful but historically underappreciated route to making a sustainable transportation fuel. More in-depth information on bioethanol technology, feedstock features, benefits, and other details can be found through a number of sources (e.g., *1–4*) as well as historic and more recent work funded by the US Department of Agriculture (e.g., *5,6*).

Benefits of Bioethanol Technology

Although more widely recognized now, the dramatic environmental, economic, strategic, and infrastructure advantages offered by the production of ethanol from abundant sources of lignocellulosic biomass were not appreciated in the past. Perhaps the most unique of these important attributes is the very low greenhouse gas emissions for the production and use of bioethanol, particularly when compared with other liquid transportation fuel options *(3,7,8)*. Because nonfermentable and unconverted materials left after making bioethanol can be burned or gasified to provide all the heat and power to run the process, and lignocellulosic crops require low levels of fertilizer and cultivation, fossil energy inputs are minimized if not eliminated for mature technology *(9–11)*, and net release of carbon dioxide is very low when evaluated in a cradle-to-grave (often called a full fuel cycle) analysis *(3,7,8)*. Bioethanol can also be important in helping meet the growing demand for energy in the developing world as these countries improve the living standards of more and more people *(12)*. An added benefit is that bioethanol could be made in many countries, including the United States, that have limited petroleum resources and rely heavily on imported oil, helping them to reduce their trade deficit and grow their economies. Furthermore, the substitution of bioethanol for fossil fuels will help reduce dependence on the imported oil that makes the United States and other countries susceptible to disruptions and price instabilities and could virtually cripple a transportation sector that almost totally relies on oil *(13)*. Bioethanol production can provide an attractive route to dispose of problematic wastes such as rice straw and wood wastes as mounting regulations limit their historic disposal method—burning *(14)*. In addition to augmenting the fuel supply, adding ethanol to gasoline increases octane and provides oxygen to promote more complete combustion, particularly in older vehicles *(1,3,15,16)*, but neat ethanol provides the greatest benefits with respect to both air and water pollution *(1,16)*. Most studies estimate that enough biomass could be available from wastes and dedicated energy crops to significantly decrease the huge amount of gasoline consumed in the United States *(3,15)*, and the cost of biomass itself is competitive with fossil resources. Because only biomass of the sustainable resources can be readily converted into liquid fuels such as ethanol and a wide range of organic chemicals in addition to food and animal feed (Lynd, L. R., personal communication), it is of paramount importance to develop this truly unique and powerful route to meeting the needs of society on an ongoing basis.

Changing Climate for Energy Technologies

The development of alternative sources of energy became a national priority in the early 1970s in response to the Libyan and later Arab oil embargoes *(17)*. Although this was really a petroleum crisis resulting from controlled production of oil by the Organization of Petroleum Exporters, it was labeled an "energy crisis," with efforts directed at developing any new source of energy. Included were government programs directed at converting abundant domestic resources such as coal into petroleum replacements, and big projects such as the Great Plains gasifier were funded through government grants and loan guarantees to accelerate technology applications.

The energy crisis of the 1970s also fed the development of technologies for utilizing renewable energy resources such as wind, solar, and biomass with the goal of immediate use, and the Office of Alcohol Fuels was created in the US DOE to accelerate scale up of ethanol and methanol production. Technical and economic evaluations of processes for making alcohols were completed, and loan guarantees and other forms of government assistance were awarded for construction of processes that were judged to be promising. Projects were funded to rapidly develop dilute acid, concentrated acid, cellulase enzyme, direct microbial conversion, and other techniques for converting cellulosic biomass into ethanol, and projects were also supported to produce methanol from biomass syngas and biodiesel from plant oils. However, of the biomass-related options, only ethanol production from corn was found to offer the near-term potential viewed critical at that time, and several plants were constructed to produce ethanol from corn starch through state and federal financial assistance, price subsidies, and other incentives. Consequently, ethanol and corn became synonymous.

Because some of these quick fix large projects for corn as well as other energy sources such as coal were poorly executed and not well conceived, costly failures resulted, leaving a bad taste for big government-funded projects. In addition, even though the protein in corn was concentrated in a valuable animal feed coproduct, many viewed conversion to ethanol as competing with food supplies, sparking controversy over food vs fuel. In the haste to build plants and because of large government subsidies, many of these plants used inefficient ethanol recovery equipment, feeding the perception that ethanol recovery is inefficient, even though modern distillation systems perform quite well. In addition, loan guarantees and subsidies were controversial. Some fuel problems were experienced when ethanol blends were used in older vehicles, which sparked more controversy; for example, the different solvent properties of ethanol would release built-up deposits, plugging fuel filters when first used.

In 1980, the climate for energy projects changed dramatically. While loan guarantees, subsidies, and other government incentives were common during the 1970s, the shift was to a free market approach in 1980, and the US federal government pushed to support only long-term, high-risk research that would be far too risky for industry to pursue. Funding for research on other than defense and a few other areas was reduced significantly, and attempts were made to dismantle the DOE. In this new climate, the development of bioethanol technology was threatened with elimination because it was confused with corn ethanol technology and judged to not have the long-term, high-risk profile favored for the new government philosophy. In addition, its promotion during the prior period as being ready for commercial use further jeopardized its continuation. Consequently, budgets were cut significantly almost yearly.

In the late 1980s, the philosophy shifted to a middle ground between immediate commercial use favored during the 1970s and long-term, high-risk research promoted in the early 1980s. Now technology development was motivated by market potential and the fit to economic and commercial needs. In this context, bioethanol was viewed as offering technology that could achieve very low costs. Just as important, the use of ethanol for transportation was recognized to have the potential to reduce the use of imported oil for transportation, the sector that consumed about two-thirds of all oil in the United States and that was almost totally dependent on this single energy source *(13)*. Bioethanol research budgets now increased significantly.

Unfortunately, the favorable position for bioethanol did not last long, and in the early 1990s the budgets dropped again. The shift was now to very immediate projects, particularly in the energy conservation area, and the time frames for bioethanol apparently were judged to be too long. However, this gradually changed over a 4-yr period, and funding began to swing more favorably in the latter part of the 1990s as interest mounted in commercial applications to address mounting waste problems in the agricultural and forestry sectors and heightened interest in oxygenates triggered by the Clean Air Act.

Bioethanol Process Identification

Against this background, process engineering evaluations of bioethanol technology were initially undertaken with the goal of identifying approaches for immediate applications in the 1970s. These culminated in several process designs by selected engineering and consulting firms using several enzymatic and dilute acid–based pathways *(18–21)*. However, none was judged to be competitive for immediate application, and the focus shifted to commercializing corn ethanol technologies to meet immediate energy needs.

Faced with the perception that bioethanol was not a high-risk, high-payback technology, bioethanol research was threatened with elimination in the early 1980s. At this point, John Wright at the then Solar Energy Research Institute, now National Renewable Energy Laboratory (NREL), extended the process-engineering evaluations to other systems such as the use of concentrated acids to hydrolyze biomass to sugars, seeking to identify options that have high potential for substantial cost reductions *(22,23)*. These studies were built on the engineering analyses conducted earlier *(18–21)* integrated with Icarus costing algorithms, vendor quotes, and other tools to upgrade the material and energy balances and costing. The result was the first consistent basis for costing of bioethanol technologies, allowing meaningful comparisons among the various options. This tool was particularly useful for benchmarking the current status of each option and defining opportunities to improve the technologies and their lower costs. These results were integrated into a comprehensive Fuel Alcohol Technology Evaluation (FATE) study in the mid-1980s, and based on these cost projections, tightening federal research budgets, and the emphasis on long-term, high-risk research in the 1980s, a decision was made to focus on enzymatically based bioethanol production technology *(24,25)*. Such technology was judged to be too risky for industry to pursue at that time and offered the promise for significant advances through application of the emerging field of biotechnology that could dramatically reduce costs and make bioethanol competitive.

The general process configuration for enzymatic hydrolysis begins with a material-handling operation that brings feedstock into the plant, where it is stored and prepared for processing. Next, biomass is milled and pretreated to open up its structure and overcome its natural resistance to biologic degradation. The resulting pretreated biomass liquid hydrolysate is neutralized and conditioned to remove or inactivate any compounds naturally released from the material (e.g., acetic acid, lignin) or formed by degradation of biomass (e.g., furfural) that are inhibitory to fermentation. Once technology was developed to convert the five-carbon sugars derived by hemicellulose hydrolysis, the liquid hydrolysate was sent to a fermentation step; otherwise, it had to be treated in waste disposal prior to discharge from the plant. A portion of the pretreated solids and possibly some of the liquid hydrolysate is sent to a separate enzyme production step in which a small portion of the total sugars is consumed by an organism such as the fungus *Trichoderma reesei* to make cellulase. The cellulase is then added back to the bulk of the pretreated solids to catalyze the breakdown of cellulose to release glucose, which many organisms, including common yeast, ferment to ethanol. Next, the fermentation broth is transferred to a series of distillation columns to recover ethanol. The lignin, water, enzymes, organisms, and other components leave with the column bottoms, and the solids are concentrated to feed the boiler that provides the heat and electricity for the entire process with any excess electricity sold. The liquid not retained with the solids is processed through a combined anaerobic and aerobic waste treatment process, with the clean water discharged from the plant or recycled to the process, the sludge disposed of, and the methane fed to the boiler. The ash from the boiler is landfilled *(9–11,24,25)*.

Technology Progress

In addition to identifying promising processes, the technoeconomic models allowed identification of research opportunities and tracking of research progress, keys to the reemergence of bioethanol development *(24,25)*. Initially, a sequential hydrolysis and fermentation route was employed for breakdown of cellulose to glucose and subsequent fermentation to ethanol, with a projected selling price of \$3.60/gallon for 1979 technology based on the use of a fungal strain known as QM9414 for cellulase production. Three years later, a strain known as Rut C30 could be used with a cost of about \$2.66/gallon, owing to a better balance in enzyme activity components and lower end product inhibition. A different cellulase known as 150L, developed by Genencor, improved hydrolysis results further, lowering the projected cost to \$2.25/gal for the year 1985. When this same cellulase enzyme was used in a simultaneous saccharification and fermentation (SSF) configuration, the estimated cost of bioethanol manufacture dropped to \$1.78/gal with the year taken as 1986. If the biomass feed rate is kept constant with more efficient cellulase rather than reducing the plant size to maintain a fixed ethanol capacity, the cost drops to about \$1.65/gal *(24,25)*.

Additional process advancements and simplifications were incorporated into the bioethanol process later, and the technology was reassessed through parallel studies by NREL and Chem Systems to determine the status and identify opportunities for further improvements *(9,10)*. The most significant change was the incorporation of a newly invented genetically engineered organism into the process that allowed fermentation of all sugars to ethanol for the first time. The projected cost of production including cash costs and capital recovery dropped to only \$1.22/gal. Note that there were also several additional differences in the basis for this more recent projection compared with the historic cost projections reported above with the use of a capital recovery factor of 0.20 instead of 0.13 to annualize capital costs being the most significant. Therefore, the projected costs from the historic studies would increase when adjusted to the same capital recovery factor and year dollars as for the NREL and Chem Systems studies. Recently, Wooley et al. (11) updated the cost projections based on further refinements in the cost methodology and more detailed engineering designs.

It is important to recognize the many caveats that apply to these cost estimates for bioethanol technology and that such cost projections should only be used to gage relative progress and identify opportunities to reduce costs further. Bioethanol costs are site specific and will change with many local factors. In addition, costs depend strongly on what type of organization (e.g., small company vs major operating company) does the project, how it is financed (e.g., debt vs equity), the technology used (e.g., risk and costs), and other factors. Also, these projections assume that the technology is for an *n*th plant that benefits from a substantial learning curve and has well-defined risk. Furthermore, such assessments are not likely to have access to important advanced technologies and the know-how that are proprietary or involve trade secrets. Thus, no one should expect to build a plant, particularly a first plant, based on such projections.

Although not obvious in the above economic summary, a key element underlying bioethanol cost reductions was improvements in pretreatment technology. Without pretreatment, sugar yields are low because cellulose is not readily accessible to the large cellulase enzyme protein structures. Over the years, various biologic, chemical, and physical pretreatment approaches have been studied in an attempt to increase the susceptibility of cellulose to attack by enzymes *(26,27)*, and several appear promising. However, building off early work on plug-flow systems by Grethlein and Converse *(28,29)*, researchers chose dilute sulfuric acid because of its relatively low cost and high hemicellulose sugar yields *(9,10,30)*. Steady progress has been made over the years in refining the technology further to remove hemicellulose with high yields and achieve good digestibility of cellulose, and the process has been demonstrated to be effective on a variety of biomass feedstocks *(31,32)*. High yields of about 85–90% or more of the sugars can be recovered from the hemicellulose fraction with temperatures around 160°C, reaction times of about 10 min, and acid levels of about 0.7%, and about 85 to >90% of the remaining solid cellulose can be enzymatically digested to produce glucose. However, dilute acid pretreatment is still a major cost element that introduces technically significant challenges to the process *(33)*.

Without a profitable use of the five-carbon sugars xylose and arabinose, bioethanol is too expensive, at $1.65/gal, to compete in commercial markets *(23,24)*. Natural organisms do not achieve high enough ethanol yields to be economically viable and typically require careful control of dissolved oxygen levels, which is difficult to accomplish in gigantic commercial fermentors. In addition, alternative products could not be identified that had a sufficient market to be compatible with large-scale ethanol production from cellulose *(34)*. The critical achievement in reducing the costs of ethanol production to the lower value projected by NREL was the genetic engineering of several bacteria to allow these organisms to ferment all five sugars (arabinose, galactose, glucose, mannose, and xylose) found in biomass to ethanol *(6,35,36)*. These organisms achieved excellent ethanol yields from all five of these sugars, a requirement critical to commercial success.

Because cellulose is the largest single fraction of biomass, one of the major challenges in the development of bioethanol technology is to improve the technology for hydrolysis of recalcitrant cellulose. In fact, most of the historic cost reductions reported from 1979 to 1986 resulted from improvements in dilute acid pretreatment and enzymatic hydrolysis of cellulose based on the cellulase-producing organism *T. reesei*, discovered during World War II *(24,25,37)*. In particular, the fungus evolved through classic mutations and strain selection from the earlier strains such as QM9414 to improved varieties such as Rut C30 developed at Rutgers University *(38)*. Later a cellulase known as 150L, produced by Genencor, was quite effective at cellulose hydrolysis because of enhanced levels of β-glucosidase that converted cellobiose into glucose *(39–41)*. Furthermore, even though the fermentation temperature must be reduced below that considered optimum for cellulase action to accommodate temperature limitations of known fermentative organisms, accumulation of glucose and cellobiose was minimized when 150L was employed in an SSF configuration, further reducing end product inhibition of the enzyme and improving the rates, yields, and concentrations of ethanol while also reducing the possibility of invasion by unwanted microorganisms *(42,43)*. Nonetheless, cellulase action is still slow, with SSF reaction times of about 5–7 d reported to achieve modest ethanol concentrations *(42,43)*, although others claim shorter times of 2 to 3 d *(44,45)*.

Following the identification of the SSF configuration for cellulose conversion by Takagi et al. *(46)* and Gauss et al. *(47)* in the mid-1970s, it became important to identify fermentative organisms that could tolerate the greater stress associated with the combined effects of high temperatures desired to increase rates of enzymatic hydrolysis, low glucose levels owing to rapid sugar metabolism by the fermenting organism, and high ethanol concentrations. A number of investigations followed to find the best organism-enzyme combinations with particular emphasis on thermotolerant yeast. Several organisms were identified that improved the rates, yields, and concentrations of ethanol formation *(39–43)*. However, it was found that rapid conversion of cellobiose to glucose was more important than the fermentation temperature. Thus, the best results were with a cellulase, such as Genencor 150L, that is higher than many in β-glucosidase *(39,43)*. An organism, such as *Brettanomyces custerii*, that can ferment cellobiose into ethanol either directly or in coculture with a more ethanol-tolerant yeast also enhances performance *(39,41)*. Some of the bacteria genetically engineered to ferment xylose to ethanol also have the ability to ferment cellobiose to ethanol, and genes have been inserted in others to impart this trait *(36)*.

Cellulase is produced commercially, but existing preparations are directed at low-volume, high-value specialty markets such as stone-washed jeans with the primary interest in providing carefully balanced properties that command high prices. Furthermore, research on cellulase production has been very limited for applications to production of low-cost sugars from cellulose for conversion to fuels and commodity chemicals *(48)*. Recent investigations project higher costs of about \$0.30–0.50/gal of ethanol produced if cellulase is manufactured on site or \$3.00/gal if it is purchased *(49,50)*. Such costs are higher than those estimated in the studies reported, pointing out the significant uncertainty in cellulase production technology and costs.

Features that differentiate cellulase production for bioethanol applications from current markets include the substrate used and the direct addition of whole broth to the SSF process. Production of cellulase on mixed liquid/solid hydrolysate from pretreatment instead of lactose and other more costly and limited carbon sources typically used commercially shows promise to reduce the cost of cellulase production and simplify the integrated production system *(51,52)*. In contrast to enzyme production for specialty markets in which cellulase is typically removed from the fungal source and then concentrated prior to shipment to the user, adding the entire cellulase production broth to SSF vessels improves performance because fungal bodies retain some cellulase and particularly β-glucosidase activity *(46,53)*. This approach also saves on capital investment by eliminating costly equipment and reduces the opportunity for microbial invasion by simplifying the process. Furthermore, any substrate not used for enzyme production passes to the SSF process and is converted to ethanol, increasing yields. The team who originally developed the SSF process termed whole-broth cellulase addition as a koji technique *(46)*.

Product recovery in all these studies is based on conventional distillation technology *(9–11,24,25)*. As pointed out earlier, there has been controversy about high-energy use for ethanol purification, but such concerns were based on inefficient, outdated technology employed by some companies during the emergence of the corn ethanol industry. The cost of and energy use by new distillation equipment is not significant in the production of bioethanol, and given the tremendous experience curve for distillation, the prospect for advances that will have a significant impact on bioethanol production costs is not high *(15)*.

These advancements can be viewed as falling into two major categories. The first can be summarized as progress in overcoming the recalcitrance of biomass and includes advances in pretreatment, cellulase properties, and integrated fermentations (SSF). The second can be described as overcoming the diversity of biomass sugars and centers on achieving fermentation of all five biomass sugars to ethanol with high yields. Gradual progress has been realized in the former while genetic engineering led to a major step forward for the latter.

Competitive Cost Goal

The other key to the reemergence of bioethanol research was the definition of a cost target that would make bioethanol technology competitive as a pure fuel in an open market. In fact, there is little hope that research on bioethanol would be of interest if the technology cannot offer a competitive position and would require continued subsidies. A goal of $0.60/gal of ethanol was set by the DOE in the mid-1980s and increased to $0.67/gal in about 1990, to be consistent with the National Energy Strategy being drafted at that time. At such a price, biomass ethanol could compete with gasoline derived from petroleum costing $25/barrel.

Although it is critical to have a competitive cost goal to justify research on bioethanol technology, it is just as important to verify that competitive costs can be achieved. Four approaches were applied to evaluate the ability to improve the technology to meet the cost goals. In one, sensitivity studies were used to determine the impact of key performance parameters on process economics. Combining all the possibilities identified with a slightly lower feedstock cost of \$34/dry ton resulted in a 40% cost reduction to about \$0.74/gal of ethanol, a value competitive with gasoline selling for about \$0.92/gal at the plant gate assuming bioethanol is used in a properly optimized spark ignition, internal combustion engine *(9,10)*.

Detailed process designs and economic evaluations such as those described provide useful estimates of the cost of production of bioethanol and identify targets for continued cost reductions, but they are confined by the process configuration selected initially. In addition, such studies are complex, making them time-consuming to apply and understand, and different studies can show quite different results, with poor economics possibly reflecting design rather than technology limitations. An alternative measure of the economic viability of bioethanol technology can be gained by a macroscopic evaluation, with one approach estimating an allowable capital cost based on estimates of revenues and all process costs and benchmarking the result against capital costs typical for corn ethanol plants *(54)*. The result was a capital cost allowance similar to that expected for a modern corn ethanol plant, supporting the notion that bioethanol technology could achieve a low enough cost to compete with gasoline through continued research.

Process studies were taken further to define specific technical opportunities to lower bioethanol production costs and estimate the resulting cost of production *(33)*. For this analysis, an advanced process configuration was chosen that focused on improved pretreatment technology fashioned after many features of hot-water pretreatment in conjunction with consolidated bioprocessing that combined the cellulase production, cellulose hydrolysis, cellulose sugar fermentation, and hemicellulose sugar fermentation steps in a single fermentor *(33,55)*. No other improvements relative to the NREL base case were included. Two levels of performance parameters were integrated into the system: one for the best performance conceivable and the other representative of advanced technology that is believed to be the most likely achievable by analogy with similar systems. Higher yields of hemicellulose sugars were also forecast for this approach, and lower-cost materials of construction and other cost reductions were applied. The consolidated biologic processing operations were projected to increase cellulose hydrolysis yields to 92% with subsequent fermentation to ethanol at a 90% yield. The ethanol concentration was set at 5% by weight, and the fermentation time was taken as 36 h. Continuous fermentation was employed, and as a result, costly seed fermentors were eliminated. Material and energy balances were calculated just as for the other studies and used in the estimation of capital and operating costs. Combining these advances resulted in a projected total bioethanol cost including return on investment of about \$0.50/gal in the advanced technology scenario for a plant using about 2.74 million dry tons/yr of feedstock costing \$38.60/delivered dry ton. More aggressive performance taken for the best possible technology reduced the projected total cost to about \$0.34/gal.

The latter study and the sensitivity studies for the base case process clearly indicate that significant advances in biologic processing and pretreatment are vital to low-cost bioethanol and that these areas even outweigh substantial scale-up in plant capacity. Enhancement of technical performance also reduces the cost but would not be sufficient to realize low-cost bioethanol without developing advanced process configurations. These results also reveal that even though advances in pretreatment can have one of the most significant effects on bioethanol economics of all the technology options considered, pretreatment remains by far the most costly step of the advanced process, suggesting that even lower cost options should be pursued.

Differentiation of Bioethanol

The quantification of research progress, definition of a competitive goal, and justification of that goal were quite similar to the approach followed by the Wind and highly successful Photovoltaics programs within the US DOE and were all vital to establishing that bioethanol offered economic promise. However, many still confused bioethanol with ethanol for corn. For example, corn ethanol was the subject of considerable controversy for many years because the amount of fossil fuels used, particularly for early corn fuel ethanol technology, resulted in few energy or greenhouse gas benefits. In addition, because production of bioethanol releases carbon dioxide during manufacture and use, many assumed it would have few greenhouse gas benefits. Several early studies showed this to be irrelevant because very little fossil fuel would be needed in the overall production cycle, with the result that the manufacture of bioethanol is one of the lowest greenhouse gas impact options available for the transportation sector *(7,8)*. Note that modern corn ethanol production based on state-of-the-art technology does reduce greenhouse gas emissions significantly relative to gasoline although not to the degree bioethanol production would.

Another point of confusion was the amount of feedstock available for bioethanol production and the cost of the raw material. Although the ultimate supply can always be debated in much the same fashion that the availability of petroleum has been debated for years, several studies show that cellulosic biomass is sufficiently abundant to make a sizeable impact in the transportation fuel market. Furthermore, if the efficiency of vehicles is improved to levels such as targeted by programs such as the Partnership for New Generation Vehicles, enough ethanol could be made from biomass to meet the total light-duty vehicle market demand in the United States *(15)*.

The cost of biomass is also competitive on a weight or energy content basis. As shown in Fig. 1, biomass costing \$42/t would compete with petroleum at about \$6/barrel on a weight basis or at about \$12.70/barrel on an energy content basis *(56)*. Thus, the primary challenge for bioethanol competitiveness is to reduce the cost of biomass processing to convert this low-cost raw material into a competitive product.

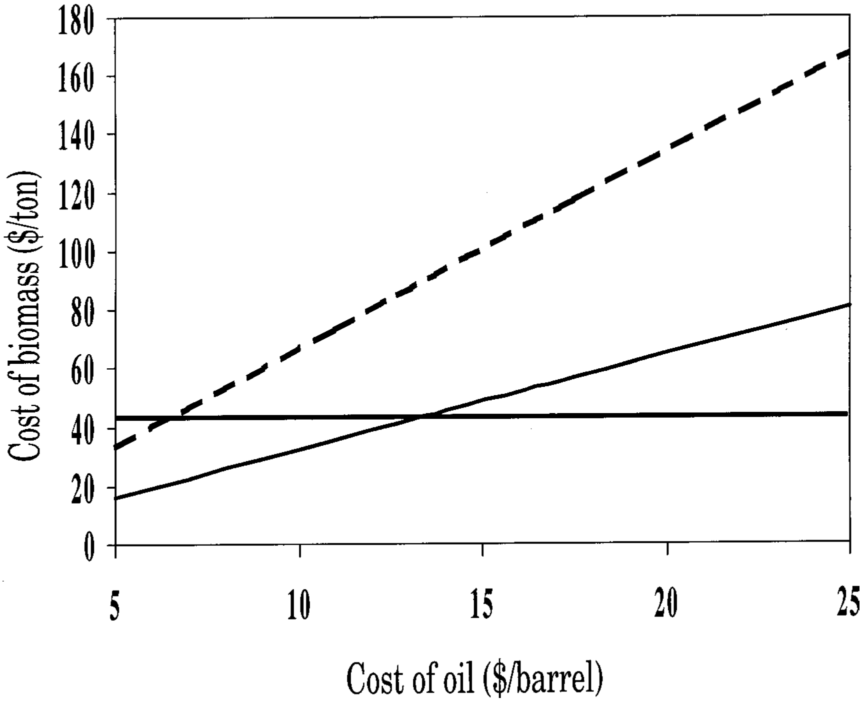

Fig. 1. Cost of biomass compared with the price of petroleum on an equivalent weight (dashed line) and energy content (diagonal line) basis (based on ref. *56*). The horizontal line represents the cost of biomass at $42/t.

The term *bioethanol* was adapted to ensure that the unique attributes owing to the use of cellulosic biomass could be appreciated *(1)*; some also apply the term *cellulosic ethanol* to differentiate the product. However, it is important to recognize the importance of corn ethanol to the development of bioethanol for use as a renewable transportation fuel. Corn growers and processors have done an outstanding job of developing a market for ethanol starting from virtually no ethanol use in the late 1970s, and there would be no established market for bioethanol without the corn ethanol industry, making it almost impossible to enter the market. Furthermore, all major automakers now warranty their vehicles to be compatible with ethanol, and flexible-fueled vehicles that can use any mixture of ethanol and gasoline below 85% ethanol are marketed because of the efforts of corn ethanol producers. In addition, corn ethanol producers have made major improvements in the energy efficiency of ethanol production and established the viability of large-scale fermentations. Both of these improvements facilitate the introduction of technology and improvements for bioethanol that would otherwise face a major hurdle. Thus, corn ethanol and bioethanol are complementary in both product and process evolution and together lead to a sustainable energy future.

Broadening the Product Slate

Historically, the US DOE Biofuels Program has focused almost exclusively on fuels for high-volume product markets and was not chartered to integrate technology for the production of chemicals from biomass in a biorefinery concept that could take advantage of synergies between the production of both bioethanol and chemicals. The program could only include the production of heat and electricity from residuals because they were needed to run the process. This was somewhat a manifestation of the fact that different congressional committees fund the fuels and chemicals programs. However, this has recently changed with the initiation of a new Bioenergy Initiative within the DOE that is hoped will lead to a comprehensive biorefinery process such as that depicted in Fig. 2 (p. 18) *(57)*. The recent introduction of the Sustainable Fuels and Chemicals Act championed by Senator Richard Lugar of Indiana and the Executive Order issued by President Clinton could accelerate progress toward this end and address the critical applied fundamental research needed to attain competitive technologies *(4)*.

Conclusion

Several companies are now striving to commercialize bioethanol technology *(58)*, and it is vital that one or more be successful if we are to enjoy the benefits at a scale that will make a significant difference. In addition, there is substantial promise that the technology can be improved to a point that the cost of bioethanol production will be competitive with fossil sources *(33)*. The great potential of bioethanol is finally being recognized at levels influential to technology funding as evidenced by the recent Foreign Affairs article on bioethanol published by Senator Richard Lugar from Indiana and former CIA director James Woolsey *(59)*. The Sustainable Fuels and Chemicals Act and the Executive Order are further indications of the recent recognition of the potential of biomass processing to a wide range of products in addition to bioethanol. In recent years, two National Research Council studies also illustrate the new importance finally being placed on biomass conversion *(60,61)*. The result is growing budgets for biomass conversion research and development that can catalyze a transition to a new platform for meeting our needs for organic fuels and chemicals on a sustainable basis.

This change also presents new challenges. Enhanced funding for biomass conversion means enhanced expectations for progress and realization of real benefits. Thus, the key now is to focus on critical needs: successfully commercializing technologies now and developing next-generation technologies that can substantially reduce the cost of biomass processing. In the end, what we really need most is the benefits biofuels offer, and such benefits can only come through large-scale commercial use. However, it is also important to realize that commercialization of new technology presents difficulties even greater than overcome in the past for the

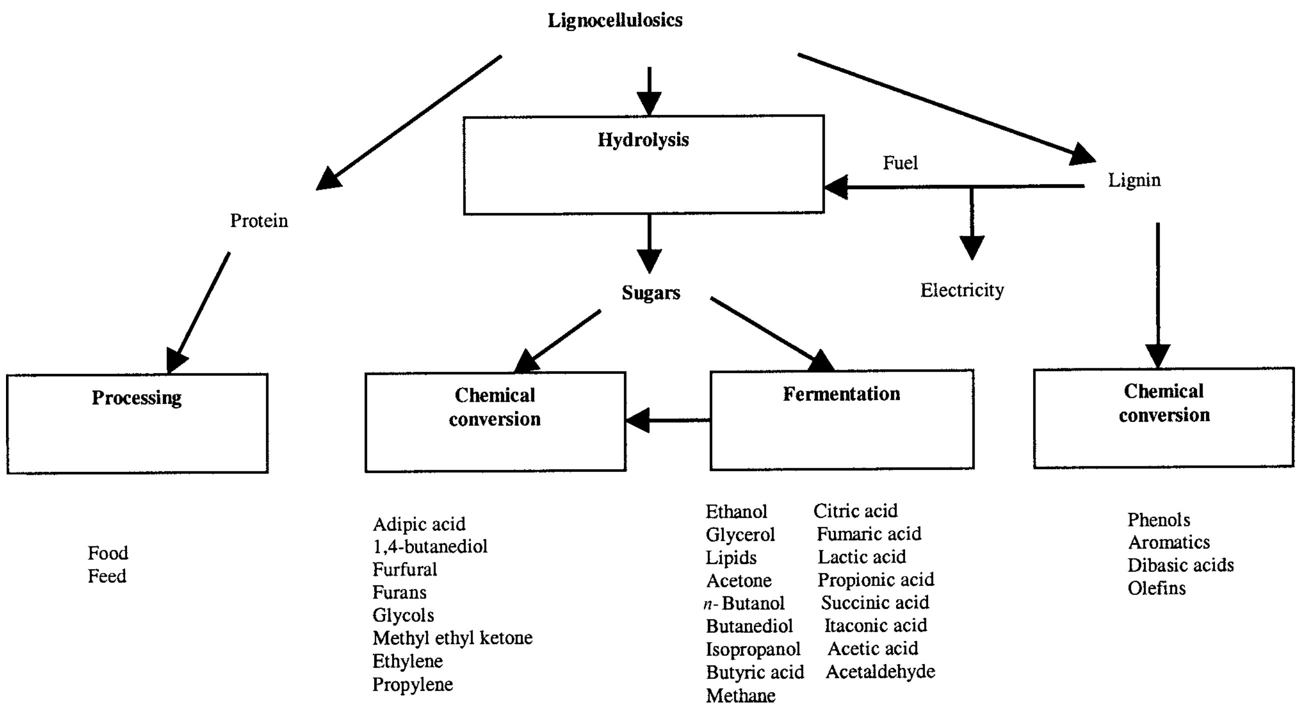

Fig. 2. Biorefinery for utilization of all the major fractions of biomass to make a wide range of products by fermentation and chemical conversion technologies *(57)*.

development of bioethanol technology, and tremendous dedication, persistence, and financial strength are required to clear this last remaining hurdle *(4)*.

In closing, this brief overview can only touch on some of the important challenges faced and progress made in developing bioethanol technology. It shows that although many envy the US position on bioethanol, considerable persistence was required to overcome countless obstacles, and the opportunity now afforded certainly did not emerge overnight or without considerable dedication and effort.

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