TOPICAL PAPER

Potential Synergies and Challenges in Refining Cellulosic Biomass to Fuels, Chemicals, and Power

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Lignocellulosic biomass such as agricultural and forestry residues and dedicated crops provides a low-cost and uniquely sustainable resource for production of many organic fuels and chemicals that can reduce greenhouse gas emissions, enhance energy security, improve the economy, dispose of problematic solid wastes, and improve air quality. A technoeconomic analysis of biologically processing lignocellulosics to ethanol is adapted to project the cost of making sugar intermediates for producing a range of such products, and sugar costs are predicted to drop with plant size as a result of economies of scale that outweigh increased biomass transport costs for facilities processing less than about 10,000 dry tons per day. Criteria are then reviewed for identifying promising chemicals in addition to fuel ethanol to make from these low cost cellulosic sugars. It is found that the large market for ethanol makes it possible to achieve economies of scale that reduce sugar costs, and coproducing chemicals promises greater profit margins or lower production costs for a given return on investment. Additionally, power can be sold at low prices without a significant impact on the selling price of sugars. However, manufacture of multiple products introduces additional technical, marketing, risk, scale-up, and other challenges that must be considered in refining of lignocellulosics.

Introduction

Plant matter (biomass) provides the only known sustainable resource for manufacture of organic fuels and chemicals that are so important to our current standard of living. Furthermore, the cost and availability of many forms of lignocellulosic (also termed just cellulosic) biomass such as municipal solid waste, agricultural and forestry residues, and herbaceous and woody crops grown for energy production offer the possibility of making these invaluable products at prices competitive with those now derived from fossil resources (*1*−*3*). In fact, cellulosics at $42/dry ton have about the same cost as petroleum costing $7/barrel based on equivalent mass and petroleum costing about $12−13/barrel based on equivalent energy content (*4*). Although the latter values are somewhat sensitive to feedstock composition, the basic conclusion is that cellulosic-based products can be competitive with products now derived from depletable fossil resources provided processing costs are reduced.

Over the past 2 decades, the cost of biologically converting cellulosic biomass to ethanol has been reduced from almost $5.00/gal to only about $1.20/gal through improvements in two primary areas: overcoming the recalcitrance of biomass and overcoming the diversity of composition of the material (*5*, *6*). A portion of the former advances have been realized incrementally through reducing energy and chemical costs and improving yields for pretreatment operations that prepare cellulosics for downstream biological operations. In addition, better cellulase enzymes and development of process configurations that streamline operations and enhance performance have contributed to reducing the cost of converting recalcitrant cellulosics into sugars and fermenting the sugars to ethanol. However, although such improvements were vital, an essential development to reach current costs was the genetic engineering of microorganisms so the five sugars in cellulosics (arabinose, galactose, glucose, mannose, and xylose) could all be fermented to ethanol with high yields (*5*, *6*). As a result of these advances, several companies now seek to commercialize the first cellulosic ethanol plants.

Cellulosic ethanol technology is generally based on hydrolysis of the hemicellulose and cellulose fractions (representing about 70% of the material) to release fermentable sugars (*6*). Although most of the emphasis has been on fermenting the sugars to ethanol, the same operations are applicable to producing sugars that could be fermented to many chemicals, and a few studies have developed criteria for selection of products and examined the economics of some promising options (*2*, *3*). However, the consequences of making both ethanol and chemicals in the same facility has not been examined, and this study was undertaken to estimate whether coproduction of both types of products in a single cellulosic refinery offered important synergies that improve economics. On this basis, the cost of producing sugars from cellulosics as an intermediate for making multiple products was estimated using published cellulosic ethanol costing information (*7*, *8*). Past process engineering studies have also shown that lignin and other solids left after sugar

10.1021/bp025654l CCC: $25.00
Published on Web 11/20/2002

release can be burned to generate all the heat and electricity needed for the process with excess available to export to generate added revenue for the operation (*7*–*9*). In fact, the use of lignin as a boiler fuel is a key to achieving little if any net release of carbon dioxide that can lead to global climate change in a life cycle analysis for biomass ethanol production (*10*). Furthermore, export of excess electricity into the power grid has significant implications in terms of displacing fossil-derived electricity with additional greenhouse gas benefits (*11*), and exported electricity provides a valuable source of sustainable baseload power that can complement intermittent sources such as wind and photovoltaic power. Thus, the relationship between export of excess electricity and overall lignocellulosics refinery economics was also investigated.

Approach

The baseline for this study was developed from the process design and engineering analysis reported by the National Renewable Energy Laboratory for an enzyme-based process for converting lignocellulosics into ethanol (*7*, *8*). NREL and its consultants devoted considerable effort to developing detailed performance data and cost information that provides a useful basis for this process analysis. The NREL report also provides considerable detail on baseline sizes, costs, cost scaling factors, and other attributes for each item of equipment in the nine process areas defined in their design (*8*); using this information affords the reader easy access to the background needed to perform the same or similar analysis, if desired. In addition, using this publicly available information avoids possibly jeopardizing proprietary information. However, it is important to note that the values reported here have not been verified by NREL, performance and costs better than applied by NREL have been achieved for some unit operations, and some operations included in the NREL design could be eliminated or changed.

The same feedstock was employed for this study as used by NREL, wood chips with a composition of 42.67% cellulose, 19.05% xylan, 3.93% mannan, 0.79% arabinan, 0.24% galactan, 4.64% acetate, 27.68% lignin, 1.00% ash, and 47.90% moisture. Just as in the NREL base case design, the chips are received at the plant, conveyed to the process, and pretreated at 22% solids at a temperature of about 190 °C and a pressure of 12.2 atm for 10 min with 0.5% sulfuric acid. The latter pretreatment step hydrolyzes most of the hemicellulose fraction, releasing its constituent sugars arabinose, galactose, glucose, mannose, and xylose into solution, and also makes the cellulose fraction accessible to hydrolysis by enzymes with high yields. The product from pretreatment is flash cooled to quench the reaction and remove much of the furfural and hydroxymethyl furfural and a portion of the acetic acid released during hemicellulose hydrolysis. Next, the liquid hydrolyzate containing fermentable sugars is separated from the remaining solids in a washing system, and most of the remaining acetic acid is taken from the liquid portion by continuous ion exchange. An overliming approach is then applied to remove remaining inhibitors in the liquid, and the pH is brought back down to the range needed for fermentation. Gypsum solids formed during these steps are filtered out. The conditioned liquid hydrolyzate is combined with the washed solids from pretreatment, and a small portion of this slurry, e.g., about 5%, is diverted to a batch enzyme production step to be used as a substrate and inducer for manufacture of cellulase. Consistent with the NREL basis, we assumed that cellulase yields are about 200 FPU per gram of xylose plus cellulose fed and that the productivity was 75 FPU per liter hour. These enzymes are then added back to the much larger fraction of pretreated slurry to breakdown cellulose into glucose.

At this point, an important departure was made from the NREL process design and methodology: the hemicellulose and cellulose fractions were just converted to sugars that could be used as an intermediate for conversion to any one of a number of chemicals in addition to ethanol. Thus, the ethanol fermentation and recovery operations were not included at this point, although waste disposal, power generation, and other costs were maintained as in the NREL study. On this basis, an overall sugar cost was calculated to indicate the price that all downstream products could be charged for use of the sugars. This cost serves as a platform for estimating the cost of supplying sugars for manufacture of ethanol and chemicals as coproducts and provides a useful indication of the effects of the scale of operation, sale of electricity from burning lignin and other residuals, and changes in other key parameters affecting the overall process.

Material and energy balances, yields, rates, and operating and equipment costs for all of the steps from feedstock handling and storage to manufacture of sugars as summarized above were applied on the same basis as reported by NREL. In addition, the power law scale factors reported by NREL were used to estimate the change in cost of each equipment item with varying cellulosic feed rates, and the same installation factors were applied as reported by NREL. This information was all incorporated into an Excel spreadsheet to allow us to easily estimate the operating and capital costs as the lignocellulosic biomass feed rate was changed. The same capital recovery approach and factors were also applied as reported by NREL to estimate the cost of capital per unit output that would achieve the target return on capital for equity financing. Combining cash costs and unit capital recovery charges provides a measure of the minimum selling price of the sugars produced that would meet return on investment criteria, and this combined quantity is termed the total cost of sugars.

Tradeoffs of Economies of Scale versus Feedstock Costs

Because the cost of equipment increases with capacity to a power less than 1 for almost all items of equipment and labor requirements do not increase linearly with overall plant capacity, one would expect significant economies of scale for a process that manufactures lignocellulosic sugars. Application of the analysis above showed that operating costs (neglecting feedstock), capital recovery costs, and the sum of these two are projected to drop from about 1.45, 4.44, and 5.89 cents/pound, respectively, at a feedrate of 2,205 dry tons per day to about 0.95, 1.91, and 2.87 cents per pound, respectively, when the feedrate is increased to 22,050 dry tons per day. This trend is consistent with observations made by others and suggests that the economics could be better if more feedstock could be obtained than for the NREL base case rate of 2,205 dry tons per day (*8*, *12*, *13*).

Although the drop in processing costs with scale of operation is inviting, biomass must be moved over greater distances with greater transportation costs as the plant size increases, and the age-old question remains whether increasing feedstock costs outweigh the projected economies of scale. In reality, the answer is site-specific, as in many economic issues with biomass utilization, and the

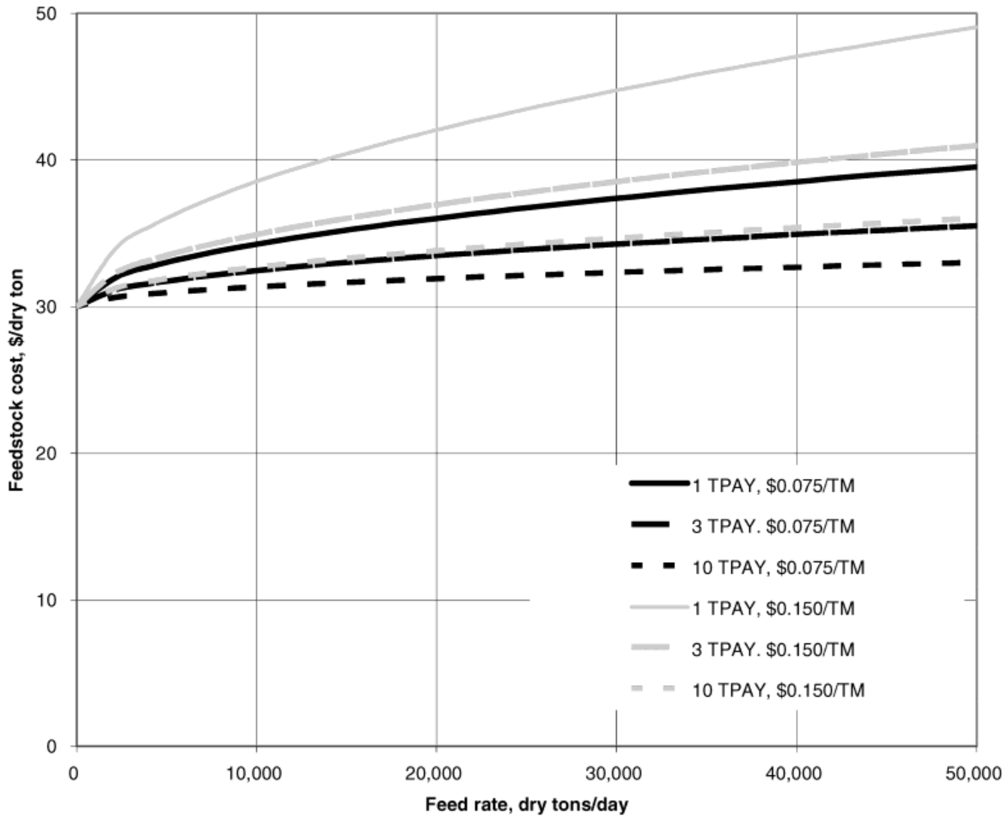

Figure 1. Cost of biomass in dollars per dry ton versus amount collected for productivities of 1, 3, and 10 dry tons/acre-year and transportation costs of $0.075 and $0.150/wet ton mile with a field cost of $30/dry ton.

overall cellulosic cost is influenced by such factors as biomass productivity, land use and availability, and mode of transport (e.g., truck, barge, rail). However, several assumptions were made to at least estimate how this issue might play out. First, it was assumed that the lignocellulosic feedstock is uniformly positioned around the plant site with transportation distance increasing as the square root of the amount needed. In addition, a fixed cost of biomass in the field of $30/dry ton was assumed, and the impacts of biomass productivities of 1 and 10 dry tons per acre-year and transportation costs of from $0.075 to $0.150 per wet-ton mile on the cost of the feedstock were estimated, the latter being based on reported values (*12*, *13*). It was further assumed that the feedstock contained 50% moisture by weight. As summarized for some of these parameters in Figure 1, biomass productivity and the cost of transportation both have important effects on feedstock costs and must be included in an analysis of the impact of project capacity on overall costs.

The cost of feedstock was next integrated with the processing costs to include the effect of scale of operation. A base case process was first defined for a 1 dry ton/acre/year biomass production rate (which might represent use of agricultural residues or limitations in the area available to grow energy crops), a $30/dry ton field cost of biomass, a $0.125/wet ton transportation cost, and no electricity sales. The costs for feedstock, other operating expenses, and capital recovery are shown in Figure 2 for this case along with the total cost of sugars, and the overall cost of production drops until a feedrate of somewhat greater than 10,000 dry tons per day is reached. Beyond that, even though the feedstock costs continue to increase with scale of operation, the economies of scale tend to offset this trend, and the overall costs remain generally flat. This result suggests that there are no particular advantages to building a larger facility but that the optimum size is still quite large. These trends are consistent with several studies by Larson et al. (*12*, *13*) as well as the investigation included by NREL in their lead-in analysis to selecting a lower feed rate of only 2,205 dry tons per day (*8*). It is important to note, however, that feed rates of over 10,000 tons/day will present major logistical challenges that could make this level almost impossible to realize practically.

The 1 dry ton/acre/year value was felt to provide a possible indicator for use of agricultural residues. This lower productivity case may also be reasonable for the average productivity of some energy crops over a large area of land allowing for roads, buildings, inaccessible land, land devoted to other agricultural products, and other land uses that would limit production of cellulosic biomass for the process. However, higher availability is likely possible in many locations that would reduce costs, and a separate 10 dry tons/acre/year case was chosen to provide a sense of how much greater biomass availability could influence sugar costs. As shown in Figure 2, feedstock costs are now somewhat less than for the base case of 1 dry ton/acre/year but only have a substantial effect when the feed rate increases beyond the 10,000 dry ton/day quantity projected to be desirable at lower productivity. The total costs of sugars for the higher productivity case continue to drop beyond the 10,000 tons and only start to increase at about 50,000 dry tons/year feed rate. Thus, even larger facilities would appear desirable for high biomass productivities, but the logistical challenges mentioned above are likely to make such large facilities impractical.

Although these studies show that economies of scale for the production facility tend to be quite important and that large plants could be more cost-effective than smaller ones, other factors are likely to limit the scale practical. First, as already indicated, very large projects

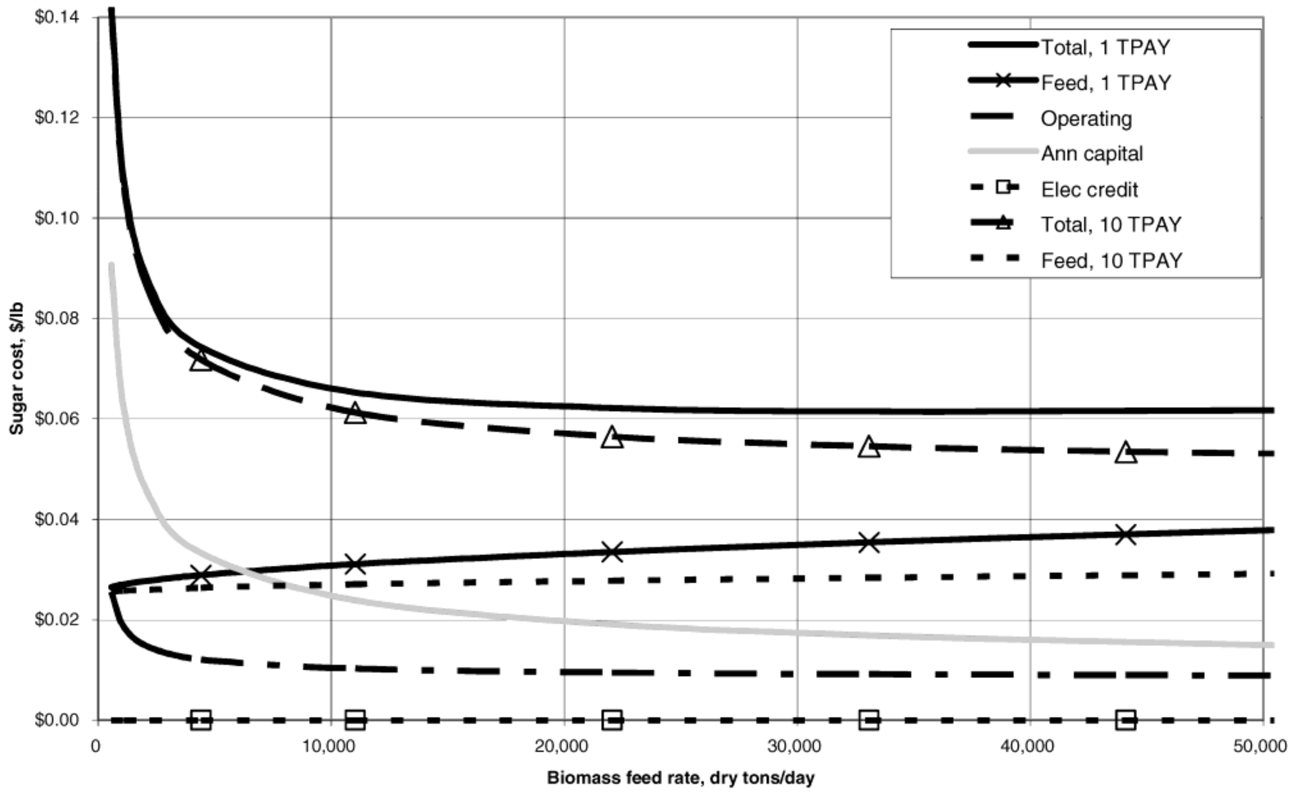

Figure 2. Cellulosic sugar costs for 1 and 10 dry ton/acre-year cellulosic biomass productivities for a field cost of $30/dry ton, a $0.125/wet-ton-mile transportation cost, and no electricity sales.

of more than 10,000 tons/day would suffer from significant logistical and other problems associated with acquiring and delivering so much feedstock. Furthermore, even though unit capital costs drop with scale, the total investment grows quickly. For example, while this study projects that a 2,205 dry ton/day facility producing about 460,000 tons per year of sugar would require about $200 million in capital investment, the projected cost of a 22,050 dry ton per day plant making about 4,600,000 tons per year of mixed sugars would be about $900 million. Gaining the capital backing for such a large plant would present a major challenge.

The effect of selling power produced by burning lignin and other residuals in excess of that needed to run the process was also investigated. As shown in Figure 3 for an electricity selling price of $0.05/kwh, sugar costs drop only slightly from our base case results because only a portion of the power made is available for sale. Thus, a variation in electricity selling price from zero, the base case, to $0.05/kwh has a relatively small effect on overall sugar costs, allowing such a facility to sell baseload power into a highly competitive electricity market.

Selection of Chemicals from Cellulosic Sugars

The next question is what to make from low cost sugars from a cellulosic biomass refinery. Although a broad range of possibilities have been identified (*14*), not all of these are promising, and more thorough scrutiny is appropriate. In particular, the net income after variable and fixed costs must be compared to the total capital outlay required to bring the project into operation, and the ratio of income before interest, taxes, and depreciation (IBITD) to total capital cost can be used as a simple indicator of return. To maximize IBITD, revenues should be maximized while variable and fixed costs are minimized. Factors that enhance revenue include high yields, high product selling price ("high value products"), high coproduct yields, and high coproduct selling prices. Periodically, some advocate seeking high value products with the justification that they will be more profitable, but a high selling price does not necessarily translate into an acceptable return that would attract investors to finance the capital costs of the project. It is also important to ensure reasonable variable and fixed costs by using low cost feedstocks, keeping labor use low, applying low cost and low amounts of other ingredients, minimizing electricity and fuel use, and keeping overhead costs low. Low capital expenditures are also essential to adequate returns, and considerations such as avoiding high temperatures and pressures, maintaining an environment that is compatible with low cost materials of construction, keeping the operations simple, having high conversion rates, avoiding expensive unit operations, and achieving economies of scale can be effective in improving return on investment.

Another important consideration in the selection of a product slate to make from cellulosic sugars is the size of the market. First, there tends to be an inverse relationship between market size and selling price (*15*). Thus, even if a "high value product" provides an attractive return on capital, its market may not be sufficient to use all the sugars from a plant of sufficient scale to be profitable. In this case, multiple products would have to be manufactured and sold. In fact, studies have shown that many of the chemicals that could be made by fermentation of cellulosic sugars do not have a large enough market to utilize all the sugars from one 2,205 dry ton per day facility of the type described by NREL (*2*, *3*, *16*). In one of these studies, only the following products were reported to be capable of using this much sugar: ethanol for 10% blends with gasoline (30), acetone (20), 2-propanol (11), acetic acid (7), butyraldehyde (6), butanol (4), ascorbic acid (3), adipic acid (3), propylene glycol (2), acrylic acid (2), acetaldehyde (1), and sorbitol

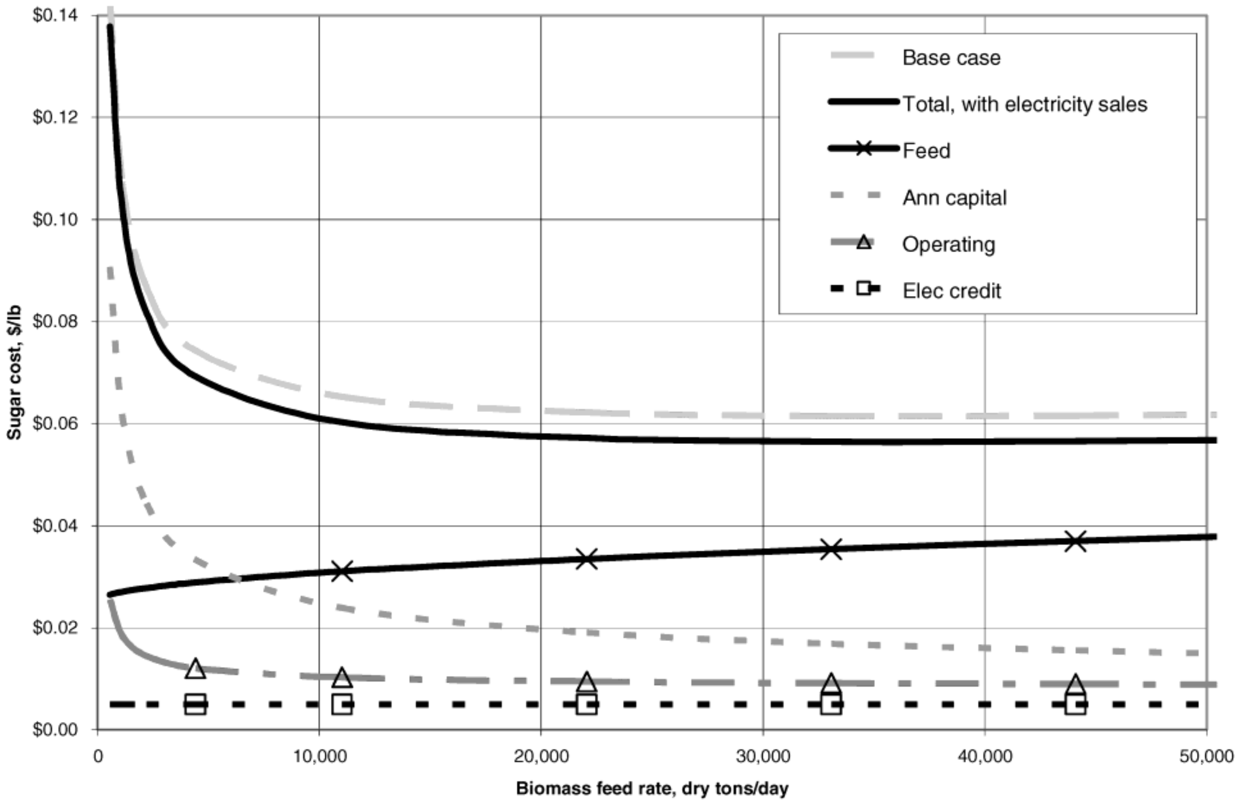

Figure 3. Cellulosic sugar costs for the base case process but with electricity sold at $0.05/kwh.

(1), where values in parentheses indicate the approximate number of facilities required to meet total market demand for each product based on current product yields (*2*). It is important to note that these volumes are estimates that are subject to some uncertainty and can change with selling price and the market response, but the point remains that only a few products have sufficient volume to be able to achieve economies of scale in a dedicated facility. Thus, coproduction of a number of such products would be required to realize low cost sugar intermediates that would provide a competitive advantage.

In addition to selecting a product or combination of products that can use enough sugar to support operation of a large enough facility to achieve economies of scale, it is important to ensure that the product yields and selling prices are sufficiently high to cover cash costs of production. Of course, this would require a full process design and costing to fully consider all the costs. However, because sufficient revenue must be gained to cover feedstock costs alone or there is no point of developing more detailed analyses, a comparison of the cost of the feedstock to the value of the products provides a simple basis on which to narrow the number of possibilities. To provide such a simple screening tool, a parameter termed the fraction of revenue for feedstock (FRF) was defined as the ratio of the cost of feedstock compared to the value of any product taking into account the yield of the product (*2*, *3*). Obviously, FRF must be less than 1.0 to just cover feedstock costs alone and would be expected to be less than 0.70 to allow some margin for other cash costs and a return on investment. Generally, we would also expect FRF to be nearer 0.70 for a commodity product in which feedstock costs are more dominant than for a specialty product for which FRF would be lower because conversion costs and profit margins become more important. Landucci et al. applied this test to evaluate the economic viability of a wide range of products based on their yields with current technology and also assuming the maximum possible carbon yields could be obtained. Many of those products considered passed this test, with succinic acid, glycerol, malic acid, acetic acid, and 2,3-butanediol being among the most promising (*2*, *3*).

Another consideration is the cost of making a product from sugars versus that for making the same product from conventional raw materials. Again, an accurate comparison of this type would require detailed analyses of both processes for each product possibility, a costly and protracted undertaking. However, simple screening tools can again be defined to narrow the possibilities, with Landucci et al. calculating the ratio of the cost of raw material for the existing process to 1.3 times the cost of sugars required to make the same product. The additional 0.30 factor was included to approximately allow for the cost of capital for a new process compared to an older existing facility that would likely have paid off much of the capital, as well as to provide an indication of how inflation would increase the cost of implementing technology with time. This ratio was termed the raw material cost ratio (RMCR), with a value greater than 1.0 required for a favorable position relative to the existing process. When this test was applied to the same slate of products as for the FRF criteria, succinic acid was found to be closest to meeting the requirement on the basis of yields with existing fermentative organisms. However, malic acid, glycerol, and 2,3-butanediol all became competitive if theoretical yields were applied (*2*, *3*).

Overall, these studies show that selection of products to make from fermentation sugars is more complex than just identifying "high value" products. First, a product or combination of products is needed that would have a large enough market to achieve economies of scale projected for production of cellulosic sugars. Such high volumes are also desirable if a significant impact on petroleum use is desired. High yields and high selling

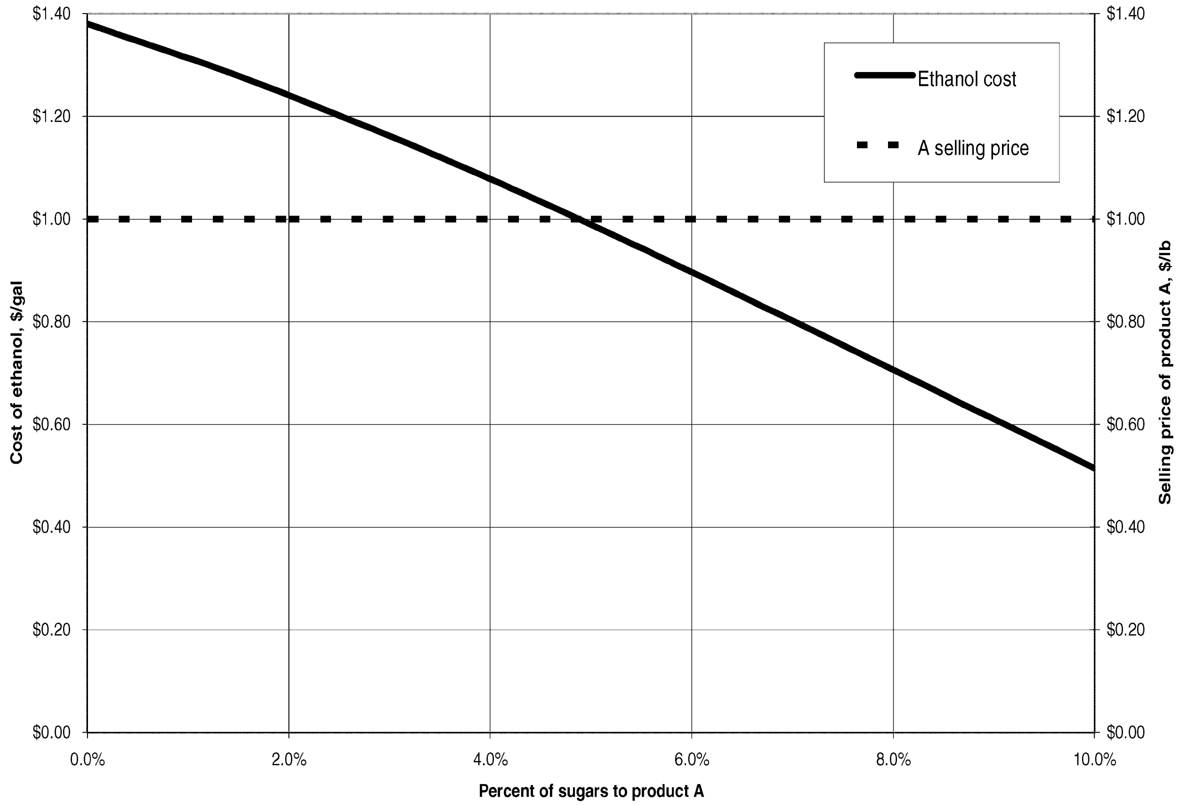

Figure 4. Cost of ethanol for a base case cellulosic refinery with a constant selling price of $1.00/lb for chemical A and electricity sold at $0.05/kwh.

prices of products are vital to maximize revenues, while low cash costs are needed to achieve acceptable net income. The return on investment also improves as capital costs decrease for a given net income. The product must have an advantage compared to the competition if it is to be a commercial success.

Economics of Coproduction of Chemicals and Ethanol from Cellulosic Sugars

An important goal of this study was to determine how coproduction of fuels and chemicals would impact the economics of a cellulosic refinery. Although sugar intermediates can be fermented into any one of a number of products, only conversion to ethanol and one other product was considered to keep the analysis tractable for this study. The chemical product was also assumed to meet all of the selection criteria just discussed. Although succinic acid was defined as being a leader among those considered based on the referenced analysis, substantial developments have been made in succinic acid and other technologies since the time of that study. In addition, the information on the change in the cost of succinic acid technology with scale of operation was limited. Thus, a hypothetical chemical “A” with cost characteristics similar to those defined by Landucci et al. for succinic acid was chosen to illustrate how coproduction of fuels and chemicals could impact costs. Chemical A was also assumed to have similar market features as those suggested by Landucci et al. for succinic acid, namely, that it is now sold at high prices into a limited market but that the market would grow substantially for use as a chemical intermediate if the selling price were to drop significantly (*2*, *3*).

For this analysis, a given fraction of the sugar was transferred to appropriate operations for ethanol fermentation and recovery and the rest to a process designed to make and recover the target chemical A. Material balances, energy flows, equipment sizes, and operating and capital costs were estimated on the basis of the specified sugar flowrates and processing yields and rates using published design and cost information for ethanol (*8*) and succinic acid (*2*, *3*). However, while sufficient information was available for ethanol to project the change in capital cost of each item of equipment in each operation with the amount of sugar sent to ethanol production, this detail was not available for succinic acid. Therefore, it was assumed that the overall capital cost for chemical A would vary according to two-thirds power of the ratio of sugar rate diverted to A to that for the base case cost defined by Landucci et al. The two-thirds power represents a reasonable rule of thumb for the overall effect of scale of operation on capital costs, but the capital cost of a particular process may not scale as favorably as this. Thus, this scale factor should only be taken as an initial indicator of how plant size impacts capital costs.

In one set of estimates, the selling price of ethanol was specified, and coproduct selling price was determined that would ensure the entire project met the target rate of return based on the same financial parameters as applied by NREL. This procedure was repeated but for a fixed selling price for chemical A to estimate the ethanol selling price required to achieve the same overall return on capital. The analysis was applied over a range of sugar splits for a given cellulosic feed rate to determine how the cost of either A or ethanol varied with allocation of sugar use.

Figure 4 illustrates a scenario based on a fixed selling price of chemical A of $1.00/lb but with the cost of ethanol calculated to ensure all cash costs were covered and that the return requirements as defined by NREL were met. In this case, the facility is assumed to process 2,205 tons per day of cellulosics with a field cost of $30/dry ton,

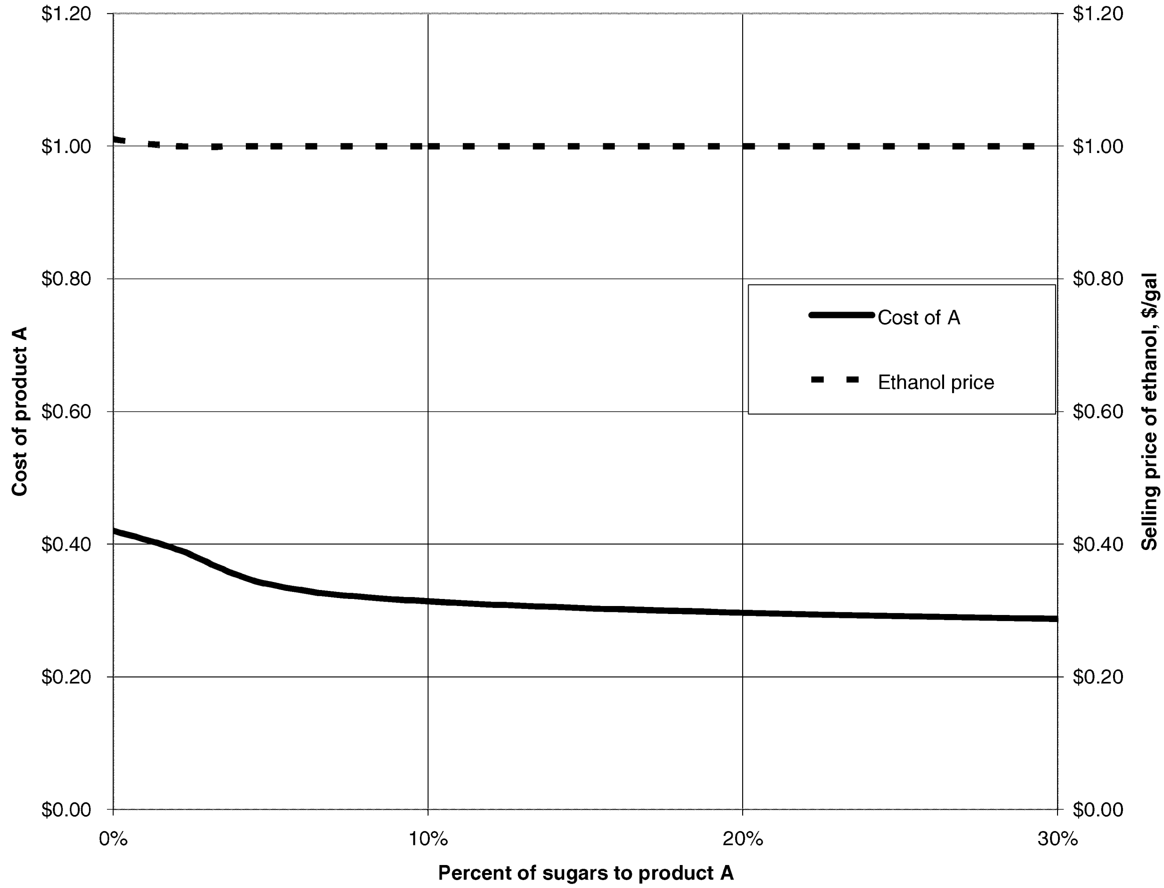

Figure 5. Cost of chemical product A in a cellulosic refinery processing 11,025 dry tons/day of cellulosics with a constant ethanol selling price of $1.00/gal, electricity sold at $0.05/kwh, and all other parameters as for the base case.

transportation cost of $0.125/wet ton, and sales of electricity at $0.05/kwh. As shown, the cost of ethanol drops from almost $1.40/gal if no chemical A is made to about $0.50/gal if 10% of the sugars are diverted to product A. This result suggests that A can be made at a cost of less than the $1.00/lb selling price, providing a margin to help cover the overall processing costs and putting less pressure on the required selling price of ethanol.

Of course, the critical assumption is that this much A can still be sold at $1.00/lb, and the alternative situation was considered with the selling price of ethanol fixed at $1.00/gal but for a larger feed rate of 11,025 dry tons/day of dry cellulosic feedrate. The cost of A needed to cover all cash costs and achieve the target return dropped from about $0.40/lb if little A is made to about $0.30/lb when 30% is diverted from ethanol to A, as shown in Figure 5. Even when only 5% of the sugars are fermented to A, the selling price of A would only have to be about $0.35/lb to cover all costs and realize the targeted return on capital. Thus, making ethanol supports construction of a larger facility that achieves most of the economies of scale estimated before, and the lower cost sugars that result make it possible to produce A at a much lower cost that would more likely be competitive in an expanded market.

Another scenario was evaluated in which ethanol was fixed at a selling price of $0.75/gal and the cost of A was estimated for the overall project to meet the target return on capital, again for the larger 11,025 ton/day facility. As shown in Figure 6, the cost of A started at very high values of over $2.00/lb when little A was made because the selling price of ethanol is less than its total cost including capital recovery for the particular plant design employed. However, the cost of A drops rapidly as sugars are diverted to this product, reaching about $0.30/lb if only A were made, again a cost that would appear to be attractive for reasonably large markets. Thus, these results suggest that coproduction of a chemical could make it possible to sell ethanol at a lower price profitably than for a dedicated ethanol process.

Other Considerations

Many other scenarios could be run to demonstrate the features of coproduction of a large volume product such as ethanol that can be sold into large markets and a chemical that may have higher margins but at lower volumes. However, this study was only directed at providing a sense of the possible trends and synergies that making multiple products could achieve, and more extensive considerations would go well beyond that goal. In addition, it is important to realize that such studies are only ballpark estimates and that cellulosic biomass processing designs and costs tend to be site-specific. Furthermore, the actual costs depend strongly on such factors as who builds the plant, how it is financed, when it is built, where it is built, and the technology used. Ultimately, no estimate, no matter how detailed, is meaningful until an actual commercial process is running profitably.

Beyond the cost of the process, many other factors must be addressed before an actual project can be commercialized. Costs, location, seasonal availability, transportation arrangements, and long terms contracts must be accurately developed for feedstocks, and long term contracts may be required for the off take from the plant before financing can be completed, making it more challenging if more than one product must be marketed. The com-

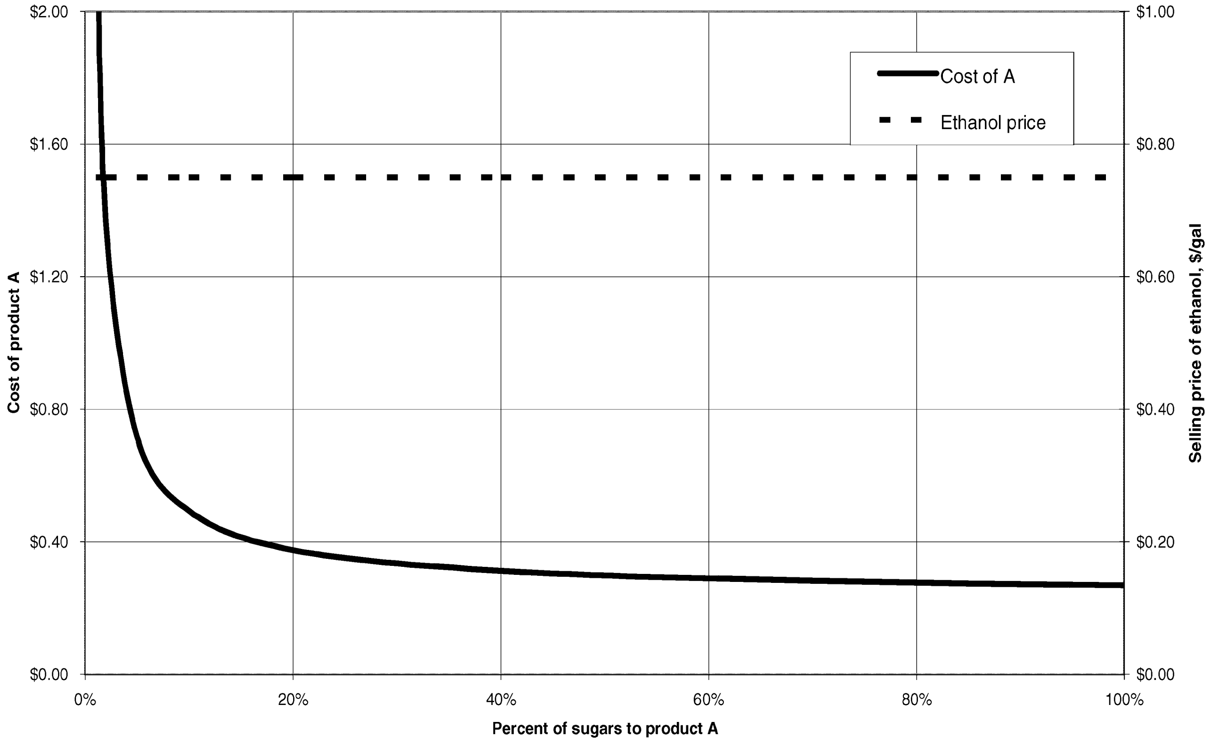

Figure 6. Cost of chemical product A in a cellulosic refinery processing 11,025 dry tons/day of cellulosics with a constant ethanol selling price of $0.75/gal, electricity sold at $0.05/kwh, and all other parameters as for the base case.

petitiveness of the technology and whether it can be protected from use by others also influence the ability to finance the project. Implementation of multiple new technologies to make several products is likely to significantly impede financing as the risk of using unproven technologies could be judged to be too high. Other factors that must be considered for successful introduction of products from cellulosic biomass are the location of the site relative to feedstock and markets; permitting requirements; the management, research, engineering, construction, and operating teams; the engineering, design, and construction contract; scrutiny by independent engineers; and others. These aspects could make commercialization of new technology for refining cellulosics to multiple products more challenging to achieve than for only one product. In fact, such considerations would likely make it more desirable to begin by commercializing one product initially and only expanding to others once the first is demonstrated.

It cannot be overemphasized that the costs and tradeoffs reported here are based on a series of cost and performance assumptions and should be considered as approximate indicators of the trends in the cost of producing sugar intermediates as well as ethanol and coproducts derived from these sugars. Although the process design and costing on which these estimates were based were developed through experimental research and careful analysis with support from engineering firms and vendors, data was not always available to fully validate the performance parameters applied. The results are also tied to a particular process configuration, set of technologies, and data that is available in the public domain. For example, the author is aware of different proprietary approaches that have been demonstrated on a large enough scale to convince investors of their merits and result in better costs and/or performance. In addition, capital recovery costs are very sensitive to the financial structure of the project, and biomass processing costs are expected to be site specific. Projection of the variation in capital costs with scale of operation requires that assumptions be made about maximum equipment sizes before additional units are added, and separating the cost of making sugars from those of converting the sugars into ethanol and a chemical coproduct required assumptions about cost and performance of the sugar production step. Overall, costs only become real when the process guarantees have been issued, the project is financed, and better yet, the processing facility is operational. For these reasons, cost estimates should be regarded as just that – estimates – and should not be used as absolute measures. Rather, technoeconomic studies should be viewed as valuable tools for identifying promising paths and strategies. In this role, analyses such as those used to develop these scenarios and the extensions applied here suggest important trends and synergies as well as challenges that should be carefully considered during the selection, design, and financing of cellulosic conversion technology.

Conclusions

Several important conclusions can be drawn from this analysis. First, projections based on current technologies suggest economies of scale that favor large processes and biomass feed rates before collection costs become great enough to slow this trend. Furthermore, the difference in sugar costs between higher and lower cellulosic biomass productivity scenarios does not appear to be very significant until the project size and associated capital costs and feedstock logistic issues become so great as to present significant challenges that would likely thwart construction of such large facilities. However, enhancing cellulosic biomass productivity would still have important benefits through reducing the total amount of land needed.

The projected economies of scale have important implications on the selection of products to make from cellulosic sugars because not all markets are sufficient to utilize all the sugars that could result for such large projects. Consequently, a combination of products may be needed to fully utilize this output, and fuel ethanol in particular has such a large market as to easily support large facilities. Other coproducts can then capitalize on the inexpensive sugars from a large operation to realize greater overall returns than if these coproducts were made in a smaller dedicated facility. Alternatively, production of chemicals in the same facility as a product with a large market such as ethanol can support lower ethanol selling prices than could be achieved in a dedicated ethanol plant and could also allow introduction of ethanol in initial plants that do not fully achieve economies of scale. However, it is important to not make so much of any one of these coproduct chemicals that their market value drops below the total cost of production in the overall facility. We also project that power can be sold at lower prices in such a facility with less impact on profitability than would likely be possible in a dedicated biomass power plant. Overall, these findings support the idea that a cellulosic refinery can produce a combination of fuels, chemicals, and power at lower costs than if just one of these products is made, and the benefits may well extend to recovery of protein, oils, minerals, and other biomass components. However, these results are preliminary, and site and technology-specific studies are needed for an actual application to define the exact tradeoffs, benefits, scale of operation, and other details for a financially successful project.

Although a cellulosic refinery promises important synergies, challenges must also be anticipated if one follows this path. First, it must be recognized that biomass contains five different sugars, and all of these must be fermented to saleable products to realize the high yields likely to be essential to economic success. We also must be willing to deal with marketing multiple products and fully understand the implications on financing the project. And, as mentioned before, we must be aware that the selling price of the coproducts will drop as the volume increases, limiting our ability to penetrate the market without cutting selling price. Beyond that, the risk profile of integrating additional technologies into a project must be addressed in the context of risk-reward requirements of the financing institution. We must also ensure that the feedstock supply is available and can be handled logistically for a large facility and that contracts can be developed to ensure its availability to the satisfaction of the financing entity. Cumulatively, these factors may present major challenges. On the other hand, continued research will likely result in lower cost hydrolysis technologies that would further improve sugar costs and reduce these barriers.

Acknowledgment

This work was made possible through the support of the Thayer School of Engineering at Dartmouth College, and the author is grateful for this support. The author thanks Dr. Raphael Katzen for confirming the general process design and costing in the NREL model and providing valuable suggestions and comments on this paper. Also, Michael Brennan, an undergraduate student at the Thayer School of Engineering at the time, did an excellent job of transferring capital cost information into spreadsheets that were used in this study. Finally, this study was possible because of the valuable contribution of the National Renewable Energy Laboratory in extensively documenting the information they developed for estimating the cost of ethanol from cellulosics through the support of the U.S. Department of Energy Biofuels Program.

References and Notes

(1) Lynd, L. R.; Cushman, J. H.; Nichols, R. J.; Wyman, C. E. Fuel Ethanol from Cellulosic Biomass. *Science* **1991**, *251*, 1318−1323.

(2) Bozell, J. J.; Landucci, R. *Alternative Feedstocks Program Technical and Economic Assessment: Thermal/Chemical and Bioprocessing Components*; National Renewable Energy Laboratory: Golden, CO, July 1993.

(3) Landucci, R.; Goodman, B. J.; Wyman, C. E. Methodology for Evaluating the Economics of Biologically Producing Chemicals and Materials from Alternative Feedstocks. *Appl. Biochem. Biotechnol.* **1994**, *45/46*, 677−696.

(4) Lynd, L. R.; Wyman, C. E.; Gerngross, T. U. Biocommodity Engineering. *Biotechnol. Prog.* **1999**, *15*, 777−793.

(5) Wyman, C. E. 20 Years of Trials, Tribulations, and Research Progress on Bioethanol Technology: Selected Key Events Along the Way. *Appl. Biochem. Biotechnol.* **2001**, *91−93*, 5−21.

(6) Wyman, C. E. Biomass Ethanol: Technical Progress, Opportunities, and Commercial Challenges. *Annu. Rev. Energy Environ.* **1999**, *24*, 189−226.

(7) Wooley, R.; Ruth, M.; Glassner, D.; Sheehan, J. Process Design and Costing of Bioethanol Technology: A Tool for Determining the Status and Direction of Research and Development. *Biotechnol. Prog.* **1999**, *15*, 794−803.

(8) Wooley, R.; Ruth, M,; Sheehan, J.; Ibsen, K.; Majdeski, H.; Galvez, A. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis: Current and Futuristic Scenarios*, Report NREL/TP-580-26157; National Renewable Energy Laboratory: Golden, CO, July, 1999.

(9) Hinman, N. D.; Schell, D. J.; Riley, C. J.; Bergeron, P. W.; Walter, P. J. Preliminary Estimate of the Cost of Ethanol Production for SSF Technology. *Appl. Biochem. Biotechnol.* **1992**, *34/35*, 639−649.

(10) Tyson, K. S. *Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline*, Volume I, Report NREL/TP-463-4950, DE94000227; National Renewable Energy Laboratory: Golden, CO, November, 1993.

(11) Wyman, C. E. Alternative Fuels from Biomass and Their Impact on Carbon Dioxide Accumulation. *Appl. Biochem. Biotechnol.* **1994**, *45/46*, 897−915.

(12) Marrison, C. I.; Larson, E. D. Cost Versus Scale for Advanced Plantation Based Biomass Energy Systems in the U. S. *The 1995 Symposium on Greenhouse Gas Emissions and Mitigation Research*, Report EPA/600/R-96/072; U.S. Environmental Protection Agency: Washington, DC, June 1996, pp 4-26 to 4-49.

(13) Larson, E. D. Technology for Electricity and Fuels from Biomass. *Ann. Rev. Energy Environ.* **1993**, *18*, 567−630.

(14) Wyman, C. E.; Goodman, B. J. Biotechnology for Production of Fuels, Chemicals, and Materials. *Appl. Biochem. Biotechnol.* **1993**, *39/40*, 41−59.

(15) Busche, R. M. The Business of Biomass. *Biotechnol. Prog.* **1985**, *1*(3), 165−180.

(16) Ruth, M. F.; Wooley, R. J. The Potential Cost of Lignocellulosic Sugar for Commodity Chemical Production. *4th Annual Green Chemistry and Engineering Conference*; Washington, DC, June 27−29, 2000.

Accepted for publication October 4, 2002.

BP025654L