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Strategic Biorefinery Analysis: Analysis of Biorefineries

January 24, 2002 – July 1, 2002

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Subcontract Report
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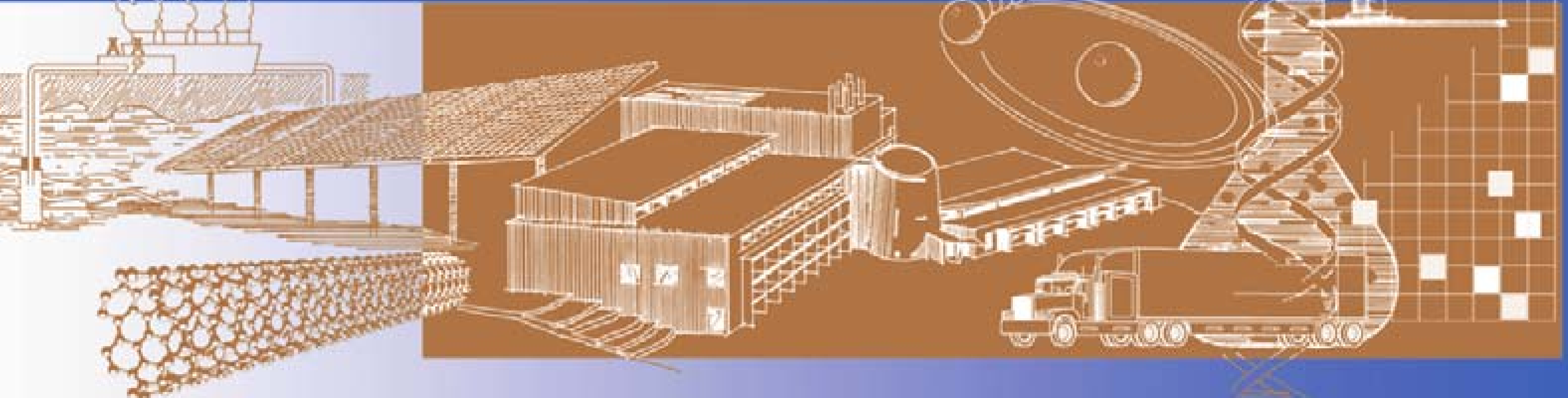

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NREL Technical Monitor: J. Jechura
Prepared under Subcontract No. ADZ-2-31086-01

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Contract No. DE-AC36-99-GO10337

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This publication received no editorial review at NREL

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

EXECUTIVE SUMMARY

Petroleum refineries producing multiple classes of products emerged during the 1940s and have been a hallmark of the chemical process industry ever since. At that time, refinery product slates were extended to include products such as high-octane aviation gasoline and petrochemical feedstock for explosives and synthetic rubber. Presently, about 85 percent by mass of the aggregated output of petroleum refining consists of fuels (gasoline, distillate fuel oil, jet fuel, residual fuel oil), with the remaining 15 percent consisting of over half a dozen product types that add considerably to the profitability of the overall operation while ensuring that all fractions of crude oil are used.

Multi-product corn wet mills appeared in their current form in the 1970s, prompted by the development of commercial technology for production of high fructose corn syrup (HFCS), which today has largely replaced sugar produced from cane in the U.S. Sweeteners—including HFCS, glucose, and dextrose—today account for about 37 percent of the output of the U.S. corn wet milling industry, with gluten feed and gluten meal accounting for about an additional 32 percent, and the balance consisting of starch, ethanol, carbon dioxide and corn oil.

The last decade has seen intense activity in the area of developing new biologically produced products. During this period, biotechnology has gone from being a peripheral consideration to a central element in the business strategies of many companies in the chemical process industry. Cargill Dow, for example, has made polylactic acid the centerpiece of its operations and DuPont is developing the capability to manufacture biologically derived 1,3-propanediol, which it expects to eventually replace nylon. For these and other new bioproducts at the commodity end of the spectrum—i.e. having relatively low price and high volume—near-term production is generally expected to be based on carbohydrate generated from corn wet mills. As such chemicals enter the market, they further diversify the already considerable slate of wet milling products, making the term “corn refining” more and more applicable.

Over the coming decade, many anticipate a new category of refining processes based on cellulosic biomass. From an economic perspective, such “biomass refining” is attractive because it may provide a means to access markets for products whose volume is too high and/or price too low to be accessed using corn as a raw material. From a societal perspective, biomass refining is attractive because of its potential contributions to sustainable resource supply, energy security, and rural economic development. Consistent with these interests, both the private and public sectors are active today in anticipating and enabling the emergence of a new biomass refining industry.

This study seeks to identify and understand the advantages of producing ethanol in a biomass refinery as compared to a single-product facility. In *Report 1: Review of Existing Refinery Examples*, we examined two existing industries that employ a multi-product refinery approach—

petroleum refining and corn wet milling—and identified several key features of the refinery approach:

- refineries typically become increasingly diversified over time;
- product slate selection depends on many factors such as market demand, feedstock composition, and available processing equipment and capacity;
- operating flexibility enables refineries to shift outputs over time;
- process improvement invariably makes the cost of raw material the dominant factor in overall refinery economics.

Fuels are the main product of mature petroleum refining processes, and this is likely to be the case for a mature biomass refining industry as well. There are few organic chemicals and polymers with markets large enough to serve as primary products for one full-sized biomass refinery, especially when no single facility can expect to command full market share. With this in mind, we centered our analysis around biomass refineries producing ethanol as a primary product, cogenerated power, and fermentation-derived coproducts. We used two previously published process designs—a near-term technology case and an advanced technology case—to quantify processing costs for ethanol production and power cogeneration. We quantified coproduct recovery costs using economic models developed by co-author Ron Landucci.

In our analysis, we demonstrate that per unit processing capital cost declines with increasing scale and that power cogeneration using the biomass feedstock's lignin fraction significantly lowers processing costs. The fact that process energy can be derived from residual material represents an important advantage that cellulosic ethanol biomass refineries have over corn ethanol mills, in which process energy must be purchased externally. It also points to a key motivating factor behind the biorefinery concept—to maximize the value generated from a heterogeneous feedstock, refineries make use of all component fractions, producing a variety of coproducts in the process.

Another benefit of biomass refineries is that the primary product selling price can be lowered significantly by coproducing higher value, lower volume products such as succinic acid, which we considered in this study. Coproducing small-market products in a biomass refinery also provides economies of scale that reduce the cost of making such products below levels that can be achieved through dedicated production. We note that the market size for most potential high-value coproducts is not large enough to support full-scale dedicated production. And, if the market were to increase to the extent that it could support dedicated production, the coproduct would cease to be high-value, having become a commodity itself.

Regarding biomass refinery product slate selection, we assert that assembling a diverse product slate is important, both because capturing modest market share of several coproducts can significantly reduce the primary product selling price, and because product diversity helps protect the biorefinery from seasonal demand cycles and market downturns. We also suggest that selecting coproducts having the potential to become platform intermediates makes strategic sense for the biomass refining industry—doing so will foster the commoditization of these chemicals by taking advantage of the economies of scale provided by producing small amounts of the coproduct in an ethanol biomass refinery. Thus, early generation ethanol biomass refineries can serve as incubators for chemicals that can then become high-volume products in their own right. Another product slate strategy worth considering is to produce two or more large volume products in addition to smaller-volume, higher margin coproducts. The ability to swing production from one major product to another depending on market conditions—especially if the major products are not closely related—would make the refinery more resilient to demand cycles and downturns.

We conclude by summarizing the advantages of the biorefinery concept as compared to dedicated production of a single product:

Revenues from high-value coproducts reduce the selling price of the primary product.

The economies of scale provided by a full-size biomass refinery lowers the processing costs of low-volume, high-value coproducts.

Less fractional market displacement is required for cost-effective production of high-value coproducts as a result of the economies of scale provided by the primary product.

Biomass refineries maximize value generated from heterogeneous feedstock, making use of component fractions.

Common process elements are involved in producing fermentable carbohydrate, regardless of whether one or more products are produced.

Coproduction can provide process integration benefits (e.g. meeting process energy requirements with electricity and steam cogenerated from process residues).

We also note that achieving the economic advantages of biomass refining—i.e. lower primary product price and lower production costs for low-volume/high margin coproducts—is fostered by coproduction of multiple products in the long term. The realization of potential societal benefits—i.e. establishing a sustainable resource supply, enhancing energy security, and boosting rural economic development—is largely dependent on producing biobased energy due to the vast size of energy markets relative to those for chemicals and materials. (The annual growth in U.S. fossil fuel consumption, for example, is comparable in size to domestic markets for both polymers and primary organic chemicals.) As a result, indirect long-term contribution of biobased chemicals and materials resulting from increasing the economic viability of energy production may well be larger than the direct contribution from fossil fuel displacement per se. Regarding the future development of the biomass refining industry, we note that though multi-product refineries are the likely long-term end point, commercial installations may well add one new product/process at a time in order to avoid compounding risk, much like petroleum refining and corn wet milling which began as single-product processes and developed into multi-product industries over time.

Finally, we remark that there are two key technical objectives to achieve for biomass refining to be commercially viable: 1) overcoming the recalcitrance of cellulosic such that the carbohydrate fraction can be easily preserved and converted into reactive intermediates and 2) developing a diverse array of value-added bioproducts from such reactive intermediates. There is currently strong economic incentive for industry to pursue the second objective, and many companies such as Cargill Dow and DuPont are already doing so using corn as a feedstock. Further technical progress in the area of product diversification, however, provides minimal benefit with respect to the first objective, an area for which there is minimal economic incentive at present: today, cellulosic feedstocks offer little if any price advantage. (In the long term, however, as biomass refining technology matures, the transfer cost of soluble sugars derived from cellulosics has the potential to be half that derived from corn.) In light of this limited economic incentive and the profound societal benefits that stand to result from biomass refining, we submit that the first objective represents an appropriate target for government-sponsored R&D, as technical progress in this area will benefit most potential biomass refineries and help to establish the industry.

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Introduction

As we detailed in *Report 1: Review of Existing Refinery Examples*, petroleum refineries producing multiple classes of products emerged during the 1940s and have been a hallmark of the chemical process industry ever since. At that time, refinery product slates were extended to include products such as high-octane aviation gasoline and petrochemical feedstock for explosives and synthetic rubber. Presently, about 85 percent by mass of the aggregated output of petroleum refining consists of fuels (gasoline, distillate fuel oil, jet fuel, residual fuel oil), with the remaining 15 percent consisting of over half a dozen product types that add considerably to the profitability of the overall operation while ensuring that all fractions of crude oil are used.

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This is not to say that the concept of biomass refining is new, as researchers have been discussing its potential and challenges for over 20 years. In light of this, it's worth citing a few examples of studies that have helped to shape the concept's development:

- Levy et al. (1), Bungay (2), and Dale (3) were among the first treatments of biomass refining to appear in the literature.
- Busche (4) has discussed biorefining in the context of enhancing the U.S. strategic supply of organic chemicals.

- Leeper and Andrews (5) have considered several issues—economics, feedstock availability, environmental impact, and energy requirements—as they pertain to biorefining.
- Wyman and Goodman (6) have provided a detailed account of several potential biorefinery configurations.
- Landucci et al. (7) have developed a methodology to evaluate the economics of biologically produced chemicals and materials.
- Most recently, Wyman (8) has completed a technoeconomic analysis that examines some of the synergies of producing ethanol, chemicals, and electricity in a biomass refinery.

In the present report, after examining the underlying motivations for biomass refining in more detail, we consider the fundamental factors that favor the production of multiple products from biomass as well as aspects affecting product slate selection. We close by identifying technical challenges that must be met and commenting on the roles of the private and public sectors in productively addressing these challenges.

Motivations for Biomass Refining

Table 1 summarizes the economic and societal motivations discussed below.

Table 1. Motivations for biomass refining.

I. Economic Motivations:
• *Feedstock cost:* May provide a means to access markets for bioproducts whose volume is too high and/or price too low to be accessed using corn as a raw material.
• *New markets:* Provides potential to create new markets such as polylactic acid and 1,3-propanediol.
• *Tax incentives:* Can benefit from tax incentives likely to be offered to promote such investment.
II. Societal Motivations:
• *Sustainable resource supply:* Biomass refining has the potential to significantly reduce both greenhouse gas emissions and the extent of non-renewable resource depletion.
• *Energy security:* By reducing U.S. dependence on foreign oil and the military investment associated with this dependence, large-scale biomass refining would enhance our nation's energy security.
• *Rural economic development:* By creating a large market for energy crops, could potentially balance demand for agricultural products with current production capacity.

In the long term, the transfer cost of soluble sugars derived from cellulosic biomass is expected to be half that of corn-derived sugars (9). (Note: the transfer cost represents the net price adjusted for coproduct revenues, operating costs, annualized capital costs, and carbohydrate conversion efficiency. In essence, it is the price of carbohydrate that a company would have to charge itself to recover its cost at a given return on investment.) As a result, biomass refining may provide a means to access markets for bioproducts whose volume is too high and/or price too low to be accessed using corn as a raw material. Biorefining also has the potential to create new markets for products such as polylactic acid and 1,3-propanediol. Furthermore, companies investing in biorefineries can expect to capitalize upon the tax incentives that will likely be offered to promote such investment and realize public relations benefits by investing in green technology.

At the same time, biorefining also has tremendous potential to benefit society. Cellulosic biomass—the only foreseeable, sustainable source of organic fuels, chemicals and materials (9)—can help facilitate a global transition to equitable economies and societies built upon sustainable resources. Biomass energy—especially biofuels—holds the most promise to bring about positive change in this direction, since energy production and consumption dwarfs that of either chemicals or materials.[1] Large-scale use of bioenergy would improve environmental health, both because it is a renewable resource and because its production and consumption results in low net greenhouse gas emissions—approaching zero in some cases(10). By reducing U.S. dependence on foreign oil, especially Middle Eastern oil, and the military investment associated with this dependence, bioenergy would also enhance national security—and global security, as oil-exporting countries would have less ability to influence world events. In addition, bioenergy would strengthen the macroeconomic condition of rural communities—demand for agricultural products (i.e. energy crops) could potentially rise to a level in balance with current productive capacity—and society as a whole.

Model Basis and Description

U.S. market sizes for categories of products which biorefineries might produce are shown in Figures 1 and 2. These figures convey the dominant market size of energy relative to materials, feed, and chemicals—so large, in fact, that annual growth in fossil fuel consumption is comparable in size (55 MM tons/year) to both the production of polymers (50 MM tons/year) and of primary organic chemicals (60 MM tons/year). (Note: In Figure 1, the bars representing energy markets are all subcategories of the Total Fossil Fuels category, both in terms of energy type—i.e. petroleum—and in terms of function—i.e. electricity and fuels.) Fuels are the main product of mature petroleum refining processes, and this is likely to be the case for a mature biorefining industry as well. Figure 2 further indicates that there are few organic chemicals and polymers with markets large enough to serve as primary products for one full-sized biorefinery especially when no single facility can expect to command full market share. With this in mind, we have chosen to center our analysis around biorefineries having ethanol as a primary product, cogenerated power, and fermentation-derived coproducts.

Note: In this analysis, the capacity of a full-scale biorefinery is assumed to be 10,000 dry tons/day, which corresponds to 300 MM gal ethanol/year for a conversion yield of 85 gal ethanol/dry ton. This scale is comparable in size to the largest U.S. corn wet mills—Archer Daniels Midland's Decatur, IL plant, for example, processes an estimated 15,500 dry tons of corn per day (11). The corresponding one-way transport radius to collect biomass at this scale is

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[1] Currently, U.S. demand for primary organic chemicals (~60 MM ton/yr) and polymers (~50 MM ton/yr) combined is only 4 percent of total demand for fossil fuels (2664 MM ton/yr; reference 13).

calculated to be 48 miles (assuming 2 dry ton/acre/year yield with 37.5 percent land used to grow biomass), on par with the 50-mile maximum commonly assumed. Please see Appendix A for more details on the calculation of biomass transportation cost used in this analysis.

A schematic diagram for a cellulosic biomass refinery having ethanol as a primary product is shown in Figure 3. This configuration involves producing one or more fermentation products—i.e. ethanol plus coproducts derived from carbohydrate fractions (cellulose and hemicellulose)—as well as steam and electricity from the lignin-rich fermentation residue using a conventional Rankine power cycle. Though such a biorefinery represents just one of many possible coproduction configurations—coproducing lipid-derived and pyrolysis-derived products are two other examples—the example fully illustrates the key advantages of the biorefinery concept.

A brief description of the process follows. For a thorough overview of cellulosic ethanol technology and process configurations, please refer to Wyman (12).

31. Feedstock is brought into the plant where it is stored and prepared for processing.

Biomass is pretreated, making it amenable to subsequent biological conversion. Protein for use as animal feed may also be recovered during this operation. Dale (3) has described the tremendous potential of protein recovery in this context.

The carbohydrate fraction of pretreated biomass is converted to ethanol and coproducts via enzymatic hydrolysis and fermentation.

Ethanol is recovered via distillation. Recovery methods vary for each fermentation coproduct according to its individual properties.

The residual byproduct stream—primarily lignin—undergoes processing: separated water is treated; the residual solids stream is used to feed a power cogeneration plant that provides all the steam and electricity for the process as well as excess electricity for export.

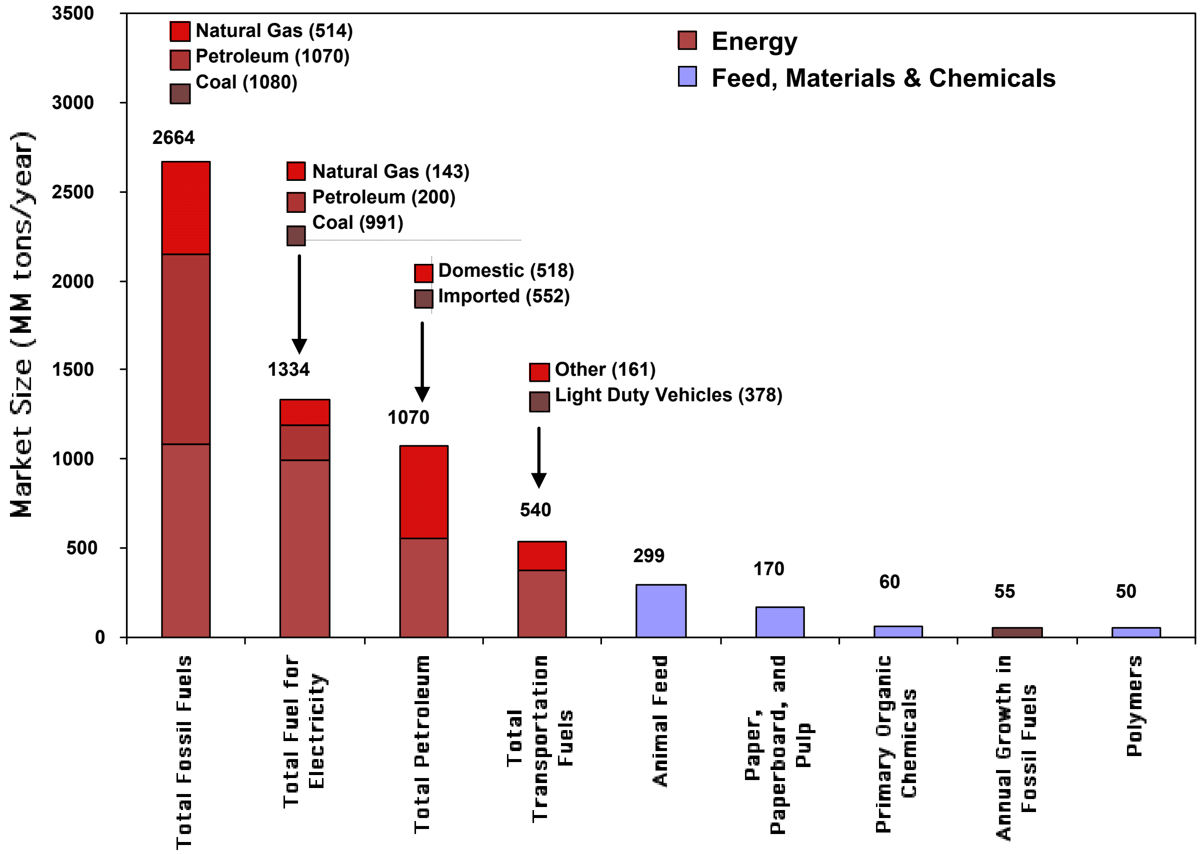

Figure 1. U.S. market sizes for major categories of potential biorefinery products. Sources: fossil fuels and petroleum (13), transportation fuels (14), animal feed (15), pulp and paper (16), organic chemicals (17, 18), and polymers (19).

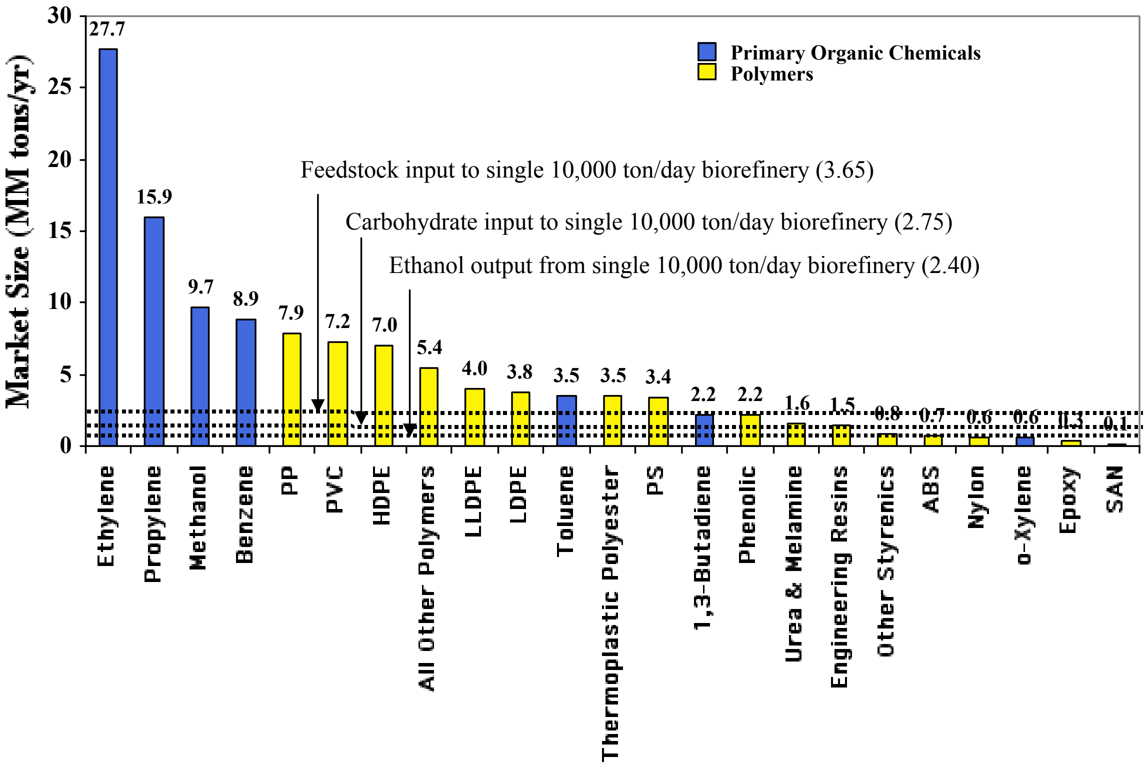

Figure 2. U.S. market sizes of polymers and primary organic chemicals. Sources: organic chemicals (17, 18), polymers (19). Polymer acronyms: PP—polypropylene; PVC—polyvinyl chloride; HDPE—high density polyethylene; LLDPE—linear low-density polyethylene; LDPE—low-density polyethylene; PS—polystyrene; ABS—acrylonitrile-butadiene-styrene; SAN—styrene-acrylonitrile.

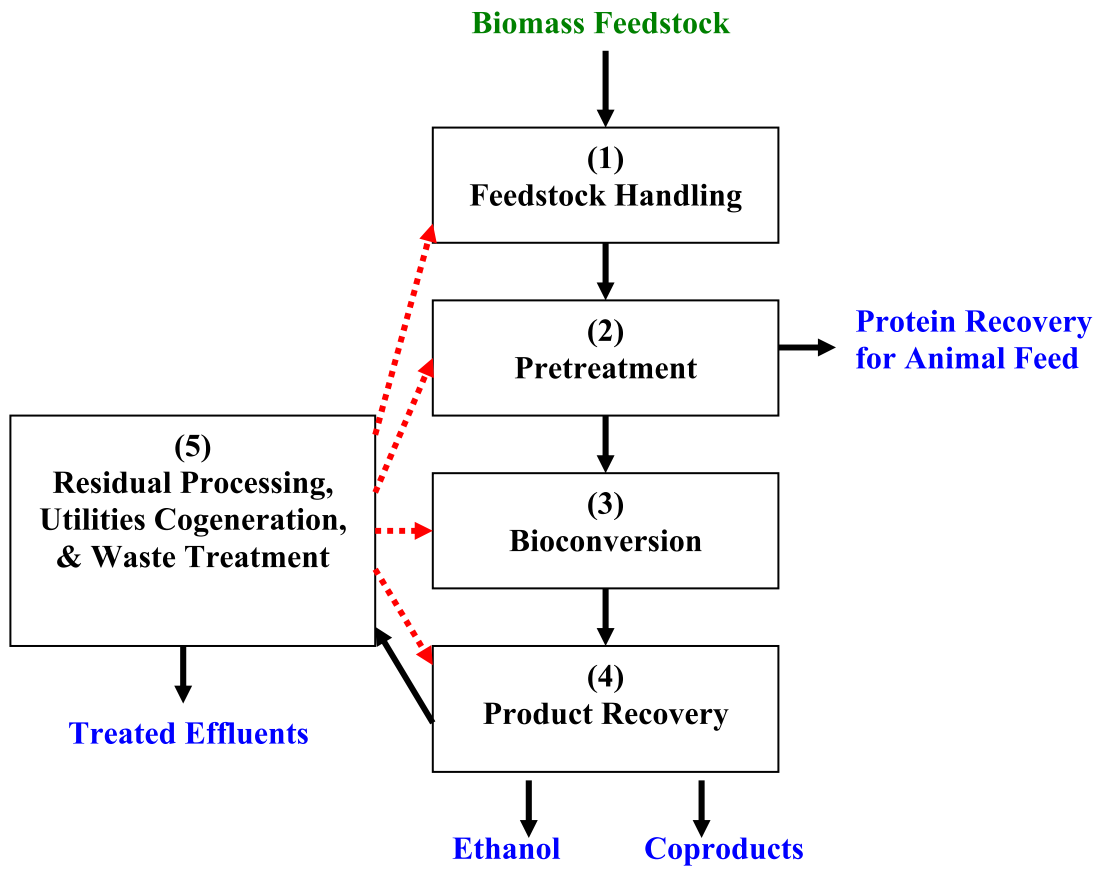

Figure 3. Schematic diagram for ethanol-based biorefinery. Solid lines represent material streams; dashed lines represent energy (electricity and/or steam) streams.

We used two previously published process designs—a near-term base case developed by the National Renewable Energy Laboratory (NREL) (20) and an advanced technology case developed by Lynd et al. (21)—to quantify processing costs for ethanol production and power cogeneration. For the near-term case, the conceptual design and costs are based on a 2010 plant start-up date. The process design also assumes the plant is "nth" generation, meaning that several plants using the same technology would already have been built and operating. The advanced case, meanwhile, assumes the plant has a level of maturity comparable to a petroleum refinery.

Key process parameters and economic values of the process designs are summarized in Table 2. Recovery costs for the coproducts considered in this analysis are based on unpublished models of Ron Landucci. Cost summaries of these models are presented in Appendix C. Feedstock transportation costs are calculated using methods from a study by Arthur D. Little, Inc. (reference 22; see Appendix A for details). Results are presented in 2001 dollars, updated to an overall CE (*Chemical Engineering*) cost index value of 394.3.

Table 2. Key process parameters and economic values of near-term and advanced technology cellulosic ethanol process designs.

Process Area	**Units**	**Near-Term**	**Advanced**
Scale	MM gal ethanol/year	69.3	283.8
Feedstock Type	-	Corn Stover	Poplar
Delivered Feedstock Cost	$/dry ton	30	38
Feedstock Rate	dry ton/year	772,266	2,738,000
Feedstock Composition	% cellulose	37.4	46.8
	% hemicellulose	27.6	24.4
	% lignin	18.0	24.0
	% other	17.0	4.8
Glucose Hydrolysis Yield	% theoretical	90.7	92
Pentosan Recovery	% theoretical	90	95
Glucan Fermentation Yield	% theoretical	95	90
Pentosan Fermentation Yield	% theoretical	85	90
Ethanol Yield	gal/dry ton feedstock	89.7	103.7
Installed Capital Cost	$	121,397,227	290,742,088
Operating Costs			
Feedstock	$/gallon ethanol	0.334	0.367
Other Raw Materials	$/gallon ethanol	0.184[a]	0.010
Waste Disposal	$/gallon ethanol	0.029	-
Electricity	$/gallon ethanol	-0.093	-0.122
Labor	$/gallon ethanol	0.031	0.026
Maintenance	$/gallon ethanol	0.033	0.020
Overhead	$/gallon ethanol	0.019	0.016
Taxes & Insurance	$/gallon ethanol	0.026	0.015
Capital Recovery	$/gallon ethanol	0.503	0.180
Total (equals ethanol price)	$/gallon ethanol	1.067	0.511

[a]Includes cellulase (0.101 $/gallon ethanol) and corn steep liquor (0.028 $/gallon ethanol). Capital recovery cost = 0.176*installed capital cost (20). Electricity valued at $0.041/kWh for near-term case, (20) and $0.040/kWh for advanced case (21). Capital installation factor = 2.75 (27). Equipment scaling exponent = 0.7 (20). Labor scaling exponent = 0.3, (21). Overhead = 0.6*labor cost, (20). Taxes and insurance = 0.015*installed capital cost, (20, 21). Maintenance = 0.02*installed capital cost (18).

It's worth noting a few key differences between the near-term and advanced technology models that account for the significant cost savings of the advanced technology process design. Pretreatment is one area where significant capital cost savings are anticipated by the advanced process design. The advanced case employs liquid hot water pretreatment; the near-term process design uses dilute acid pretreatment (1.1% wt. sulfuric acid), which requires more expensive reactor materials of construction and an extra unit operation to neutralize and condition the pretreated biomass and pretreatment hydrolyzate. Biological conversion is another area where capital cost savings are expected from mature technology. The near-term case uses two process steps: saccharification using purchased cellulase, followed by fermentation. The advance case, meanwhile, employs consolidated bioprocessing in which cellulase production, saccharification, and ethanol production occur in one unit operation by a single microbial community. Capital costs for such a configuration are lower relative to the near-term design's two-step scheme because fewer process vessels are required. A large cost reduction also occurs for other raw materials in the advanced case: no acid or lime is required for pretreatment and no externally purchased cellulase is required for biological conversion.

Using a scaling exponent of 0.7 for all purchased equipment costs and 0.3 for labor, and applying a capital installation factor of 2.75, we generated the processing cost—excluding separation costs—versus plant capacity curves shown in Figure 4. The equipment scaling exponent represents the average value used in the NREL study (20); the labor scaling exponent is the same as used in the advanced case study (21); the capital installation factor is from McAloon et al. (27). The figure presents the processing cost associated with production of unrecovered product. (Note: the values represented by the curves are equivalent to the variable U, which we introduce in Equation 4 below.) We've found it useful to treat separation costs separately for reasons we will elaborate upon below. The figure illustrates the well-known result that per unit processing cost declines with increasing scale. The plot also demonstrates that power cogeneration using the biomass feedstock's lignin fraction significantly lowers processing costs—by as much as 24 percent for the near-term technology case and 41 percent for the advanced technology case. (Note: Both ethanol-only scenarios were calculated by eliminating capital and operating costs associated with power cogeneration while adding process steam valued at \$4.50 per 1000 lbs as an operating expense.) In both cases, lignin-rich process residues provide all required process energy and extra electricity for export as well. This feature is also characteristic of the petroleum refining industry in which most, if not all, process energy requirements can be met using feedstock-derived residues. That process energy can be derived from residual material represents an important advantage that cellulosic ethanol biorefineries have over corn ethanol mills, in which process energy must be purchased externally.

This result points to a key motivating factor behind the biorefinery concept: feedstock heterogeneity. To maximize the value generated from a heterogeneous feedstock, refineries make use of all component fractions, producing a variety of coproducts in the process. For example, a corn wet mill's product slate—including sweeteners and ethanol derived from starch, gluten products, and corn oil—is largely a result of kernel composition. Petroleum refineries, meanwhile, produce certain products from heavy fractions of crude oil—residual fuel oil and asphalt, for example—and others such as LPG from light fractions. Similarly, a biorefinery's product slate will be shaped in part by the heterogeneous nature of its feedstock.

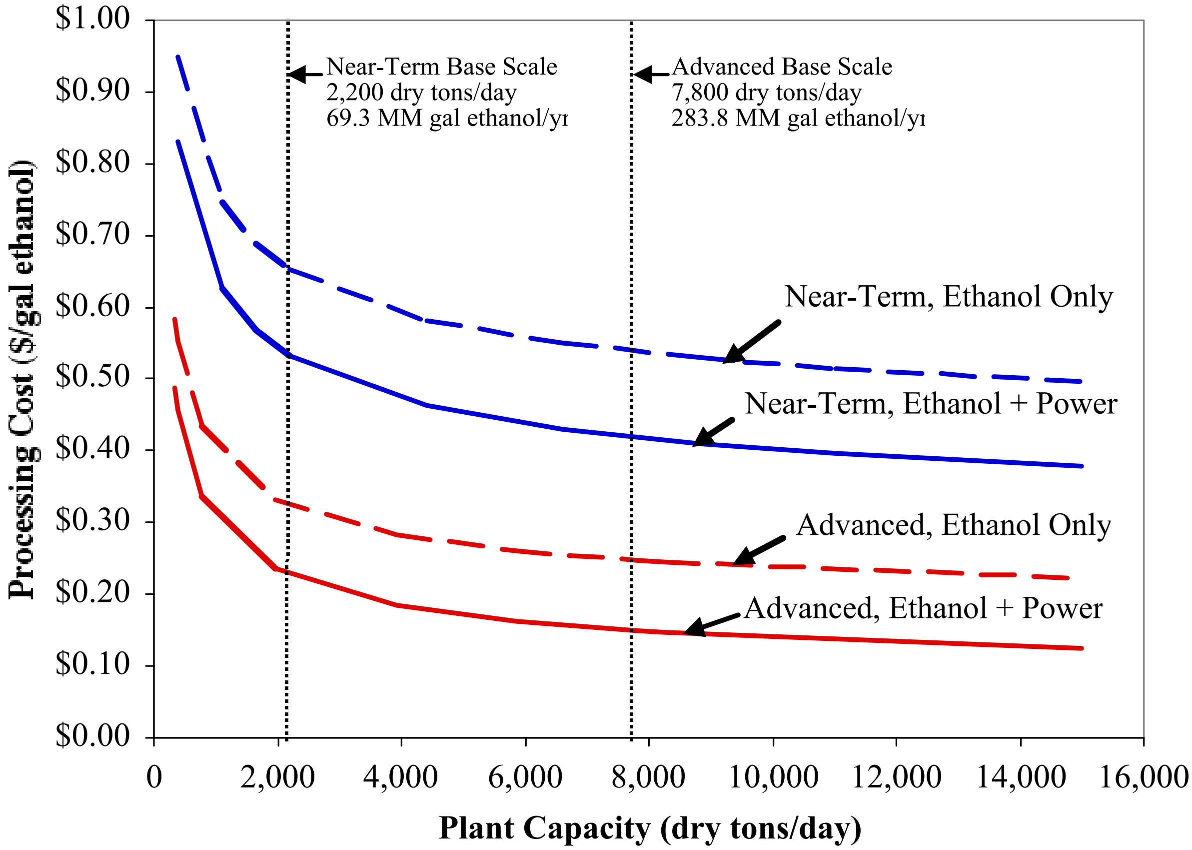

Figure 4. Processing cost—excluding product separation—versus plant capacity.

Benefit of Coproducts on Primary Product Price

The ability to capitalize upon feedstock heterogeneity is but one advantage offered by biorefineries. Another is that the allowable primary product selling price can be lowered significantly by coproducing higher value, lower volume products such as succinic acid which will be considered here. Annual sales of succinic acid in the U.S.—sold at $2.68 to $4.00 per pound—are currently in excess of 33 million pounds (23). At present, it is manufactured largely from maleic anhydride—produced petrochemically from butane—though some succinic acid produced via fermentation is sold as a food additive. Succinic acid is also used in the production of pharmaceuticals, surfactants, detergents, and ingredients to stimulate animal and plant growth. Because of its apparent cost-competitive economics (23, 24), fermentation-derived succinate has the potential to become a high volume commodity, serving as a platform intermediate for dozens of industrial chemicals currently produced petrochemically, including adipic acid, 1,4-butanediol, tetrahydrofuran, γ-butyrolactone, and n-methylpyrrolidone (23).

Figure 5 plots ethanol price as a function of the amount of succinic acid coproduced in a full-scale cellulosic ethanol biorefinery. In the figure, the near-term and advanced cases have been scaled to 9,500 and 8,300 dry tons feedstock/day, respectively—equivalent to an annual ethanol output of 300 MM gallons/year for both cases when all feedstock is allocated to ethanol production. (Note: Decreased ethanol output resulting from feedstock allocated to succinic acid coproduction has been accounted for in Figure 5, and in all other coproduction scenarios.) Process parameters and economic values for succinic acid recovery are listed in Table 3. Succinic acid recovery costs (Table 3) are based on a proprietary model of Ron Landucci which involves three steps:

1) addition of ammonia to fermentation broth to produce diammonium succinate;

2) addition of sulfuric acid to form ammonium sulfate and succinic acid;

3) polish succinic acid by performing a recrystallization using methanol.

The recovery process relies on two physical attributes of the system: First, the minimal solubility of succinic acid in water in the presence of sulfuric acid is used to separate succinic acid from the sulfates. Second, succinic acid is soluble in methanol, while sulfates are not. The succinic acid recovery model used has a scale of 100 MM lb/year. An exponent of 0.7 has been used to scale all product recovery equipment costs.

The figure assumes a selling price of $2.68 per pound for succinic acid and an upper coproduction limit equal to the current total market size—an amount that would require less than 2 percent of the total feedstock to be allocated toward its production. It should be noted that it is not realistic to expect that a single biorefinery could capture the entire succinic acid market, and as will be discussed below, the selling price of succinic acid would inevitably drop were the market to expand to support coproduction of 33 million pounds. (It is conceivable, however, that a biorefinery could create and dominate an entirely new high-value product market—Cargill Dow, for example, is the only manufacturer of polylactic acid.) Nonetheless, Figure 5 indicates that even a modest coproduction level of 10 million pounds—an amount requiring only 0.5 percent of the total feedstock—would significantly lower the selling price of ethanol by about $0.08/gallon for both the near-term and advanced technology scenarios. This illustrates that even niche markets can have a profound effect on refinery economics. For this reason, many petroleum refineries integrate downstream processing of high-value petrochemicals into their operations.

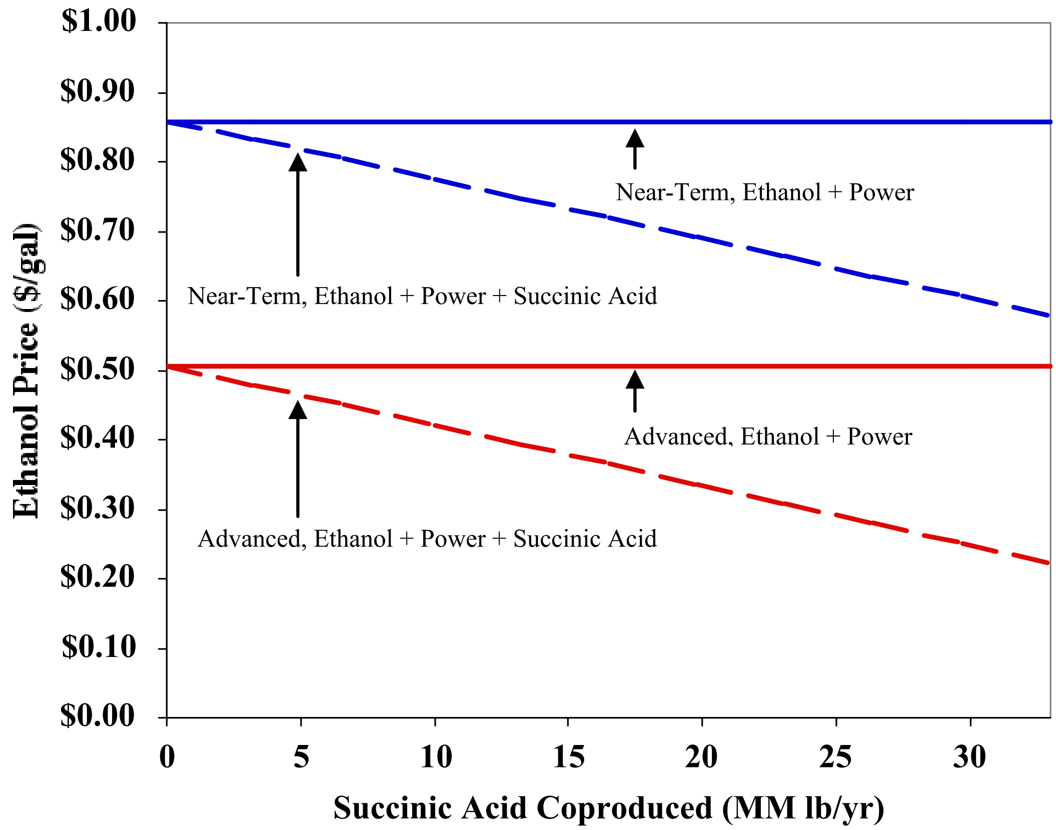

Figure 5. Ethanol price as a function of succinic acid coproduction level in a full-scale cellulosic ethanol biorefinery. “Full-scale” refers to 9,500 dry tons feedstock/day, near-term case, and 8,300 dry tons feedstock/day, advanced case, which is equivalent to an annual ethanol output of 300 MM gallons/year for both cases when all feedstock is allocated to ethanol production.

Table 3. Key process parameters and economic values of succinic acid recovery model.

Process Area	**Units**	***Values***	
Scale	MM lb succinic acid/year	100	10
Succinc Acid Yield	lb/lb glucose	0.88[a]	0.88[a]
(Near-term)	lb/lb dry feedstock	0.33	0.33
(Advanced)		0.42	0.42
Installed Capital Cost	$	14,535,377	2,900,189
Operating Costs			
Raw Materials	$/lb succinc acid	0.0026	0.0026
Microfilter	$/lb succinc acid	0.0021	0.0021
Electricity	$/lb succinc acid	0.0107	0.0107
Steam	$/lb succinc acid	0.0205	0.0205
Maintenance	$/lb succinc acid	0.0029	0.0058
Taxes & Insurance	$/lb succinc acid	0.0022	0.0044
Capital Recovery	$/lb succinc acid	0.0256	0.0510
Total	$/lb succinc acid	0.0666	0.0971

[a] From (25).

Capital recovery = 0.176*installed capital cost, (20). Electricity valued at $0.04/kWh. Steam valued at $2.00/1000 lb. Capital installation factor = 2.75 (27). Equipment scaling exponent = 0.7. Taxes and insurance = 0.015*installed capital cost, (20). Maintenance = 0.02*installed capital cost, (20).

Benefit of Primary Product on Coproduct Price

Coproducing small-market products in a biorefinery also takes advantage of economies of scale that reduce the cost of making such products below levels that can be achieved through dedicated production. To illustrate this point, we expand upon the process margin framework we proposed in *Report 1: Review of Existing Biorefinery Examples,* in which we quantified the contribution of the primary feedstock and externally produced process energy to the total value of a biorefinery:

$$M_A = V - (F + E) \qquad [1]$$

$$M_R = \frac{M_A}{(F + E)} \qquad [2]$$

where

V = value of all products (\$/ton feedstock)

M_A = absolute process margin (\$/ton feedstock)

F = cost of primary feedstock (\$/ton)

E = cost of purchased, externally produced process energy (\$/ton feedstock)

The absolute margin includes all components of value exclusive of the cost of primary feedstock and purchased process energy (i.e. steam and electricity that is not derived from primary feedstock)—operating costs, capital recovery, profit, labor, maintenance, taxes, insurance, and depreciation, for example. Total product value, V, is defined as:

$$V = SY_{P/F}\left\{1 - \sum_i f_i\right\} + \sum_i S_i f_i Y_{i/F} \qquad [3]$$

where

S = selling price of the primary product (\$/unit product)

f_i= fraction of feedstock devoted to production of ith coproduct

$Y_{P/F}$ = yield of primary product (unit/ton feedstock)

S_i = selling price of the i^{th-} coproduct (\$/unit product)

$Y_{i/F}$ = yield of the ith coproduct (unit/ton feedstock)

Low values of M_R correspond to processes where raw material costs are dominant. Therefore, as commodity refining processes mature, the relative margin can be expected to decrease, approaching an asymptotic value.

We've found it useful to separate the absolute margin (Equation 1) into two components: 1) the cost for all processing steps except product recovery, U; and 2) the cost of product recovery, R:

$$M_A = U + \sum_j R_j Y_{j/F} \qquad [4]$$

where

M_A = absolute process margin, as defined as in Equation 1 ($/ton feedstock)

U = processing cost for steps prior to product recovery ($/ton feedstock)

R_j = cost of product recovery for jth product ($/unit product)

j = any product (primary product or coproduct)

$Y_{j/F}$ = yield of the jth product (unit/ton feedstock)

In the case of cellulosic feedstocks, for example, steps other than separation include feedstock receiving, pretreatment, cellulase production—if simultaneous saccharification and fermentation is used—hydrolysis/fermentation, utilities, and waste treatment. These steps can be thought of as comprising the component of the overall processing cost, *U,* associated with production of unrecovered products.

We justify this treatment by noting that the cost of feedstock handling, pretreatment, cellulase production—if included—utilities and waste treatment is largely independent of the fermentation product being produced and whether one or many such products are produced. The cost of fermentation on a per unit feedstock basis is also largely independent of the product produced and the number of products produced. This statement is supported by observing that the rate of hydrolysis, and hence fermenter productivity, is primarily a function of cellulase loading and only secondarily a function of the product made. In addition, the number of fermenters in even a moderately-sized biorefinery is so large—greater than 25 for many designs—that the cost of fermentation capacity does not depend on whether this capacity is devoted to one product or to several products. The above observations underscore the inherent flexibility of biomass refineries configured to produce fermentation products—a variety of such products can potentially be produced using common process elements upstream of product recovery.

The allowable selling price of any product, A_i, must cover the absolute process margin, excluding recovery costs of all other products—these costs are accounted for in the selling prices of the other products—and the costs of primary feedstock and external process energy.

$$A_i = \frac{M_A - \sum_{j \neq i} R_j Y_{j/F} + (F+E)}{Y_{i/F}} = \frac{U}{Y_{i/F}} + R_i + \frac{(F+E)}{Y_{i/F}} \qquad [5]$$

The allowable selling price of succinic acid as a function of biorefinery plant capacity for the advanced case is shown in Figure 6. The x-axis represents a continuum from a dedicated 10 MM lb/year succinic acid plant at the lower limit, to a full-scale ethanol biorefinery with power cogeneration coproducing the same amount of succinic acid at the upper limit. The figure was constructed using values from the advanced ethanol process design to calculate, *U,* the processing cost for steps prior to product recovery, and values from an unpublished economic model by co-author Landucci to calculate succinic acid recovery cost, *R.* Feedstock cost, *F,* as a function of scale was calculated according to methods presented in Appendix A.

The figure shows that the allowable selling price of succinic acid decreases from \$0.40/lb in a dedicated configuration to \$0.16/lb when coproduced in large biorefinery. The near-term case (data not shown) predicts a price of \$0.49/lb for dedicated production at 10 MM lb/year succinic acid with power cogeneration and \$0.21/lb for a full-scale biorefinery with power. At a scale of 100 MM lb/year succinic acid without power cogeneration, the near-term case without power cogeneration (data not shown) predicts a price of \$0.26/lb for dedicated production—comparable to cost estimates at that scale by Landucci (\$0.33/lb) and Zeikus et al. (\$0.25/lb, reference 23) for processing configurations without power cogeneration.

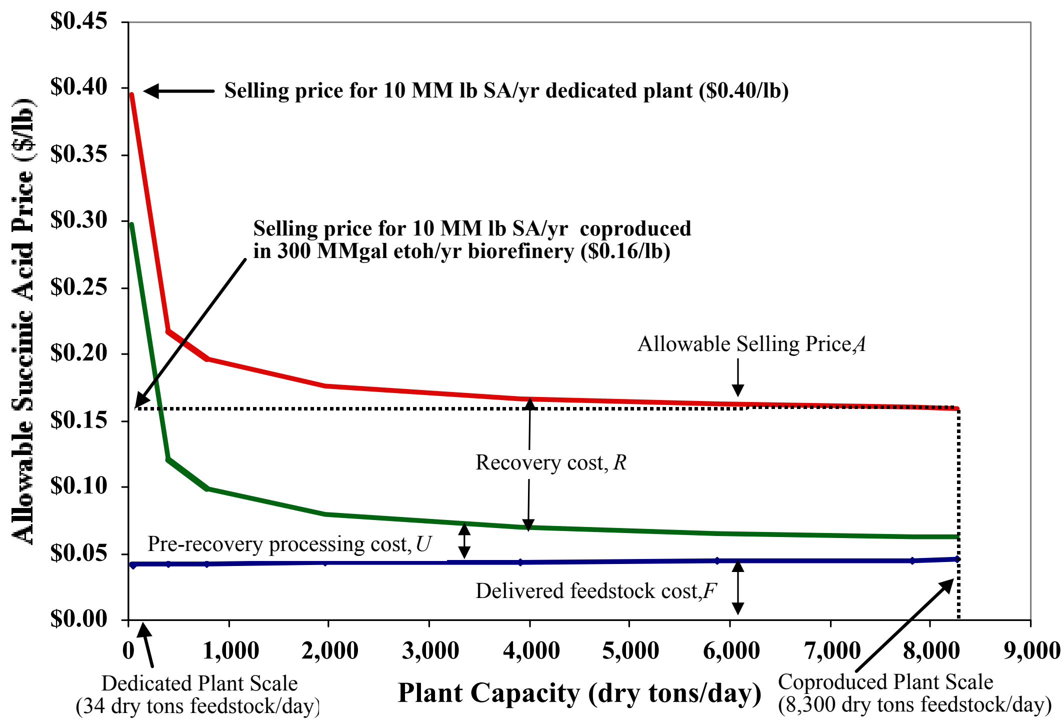

Figure 6. Allowable succinic acid selling price versus plant capacity for advanced technology case.

In Figure 6, one can also see that the value of processing cost exclusive of product recovery, *U,* is a strong function of scale—it contributes \$0.26/lb to the price at 34 dry tons/day, and \$0.02/lb at 8,000 dry tons/day. Meanwhile, feedstock cost, *F*, increases moderately with increased plant capacity—contributing \$0.04/lb at 400 dry tons/day versus \$0.05/lb at 8,000 dry tons/day—due to longer transport distances. Since the production level of succinic acid remains constant in this example—10 MM lb/year—cost of product recovery, *R*—contributing \$0.10/lb to the price—is independent of scale.

Anticipating Technological Maturity

Combining Equations 1, 2, and 3, the primary product selling price can be expressed as a linear function of the relative margin:

$$S = \left[\frac{(F+E)}{Y_{P/F}(1-\sum_i f_i)} \right] M_R + \left[\frac{(F+E) - \sum_i S_i f_i Y_{i/F}}{Y_{P/F}(1-\sum_i f_i)} \right] \qquad [6]$$

Equation 6 is an operating line that can be used to represent the impact of both technological maturity and of coproduction on the selling price of a primary product. The intercept corresponds to the price of the primary product if the process margin were. One can also see from the equation that primary product selling price is reduced by lower raw material costs (*F*+*E*), higher yields ($Y_{P/F}$), and higher coproduct values ($\sum_i S_i f_i Y_{i/F}$). Figure 7 presents ethanol price as a function of relative process margin for coproduction scenarios involving both power and succinic acid for the two cases at full scale (9,500 dry ton/yearr, near-term case; 8,300 dry ton/year, advanced case; 300 MM gal ethanol/year). To provide useful benchmarks, relative margin values for petroleum refining, corn wet milling, and both cellulosic ethanol process designs are indicated in the figure. The operating lines in the figure can be used to estimate the price benefit of process maturation, which corresponds to decreasing process margin values. The near-term technology case with power cogeneration, for example, has a relative margin of 1.65 and an ethanol price of \$0.85/gallon when scaled to 300 MM gal ethanol/year and when feedstock is priced at \$30/dry ton. If the near-term case matures such that its relative margin is equal to that of the advanced technology case, 0.75, then the corresponding ethanol price would drop to \$0.65/gallon. If the feedstock cost is increased to \$40/dry ton, both the slope and the intercept of the near-term operating line increase significantly, as indicated in the figure. (Note: when the feedstock cost for the near-term case is \$30/dry ton, the slope and intercept are comparable to that for the advance technology case having a feedstock cost of \$38/dry ton—slope equals 0.33 \$/gallon, near-term, 0.37 \$/gallon, advanced; intercept equals 0.24 \$/gallon, near-term, 0.25 \$/gallon, advanced.) The figure also shows the benefit of coproduction for each level of maturity. For example, when 0.4% of the feedstock is allocated to succinic acid coproduction—

corresponding to 10 MM lb of succinic acid, or approximately 30 percent of the current market size—the price of ethanol for the advanced case with power cogeneration fall from $0.51/gallon to $0.42/gallon.

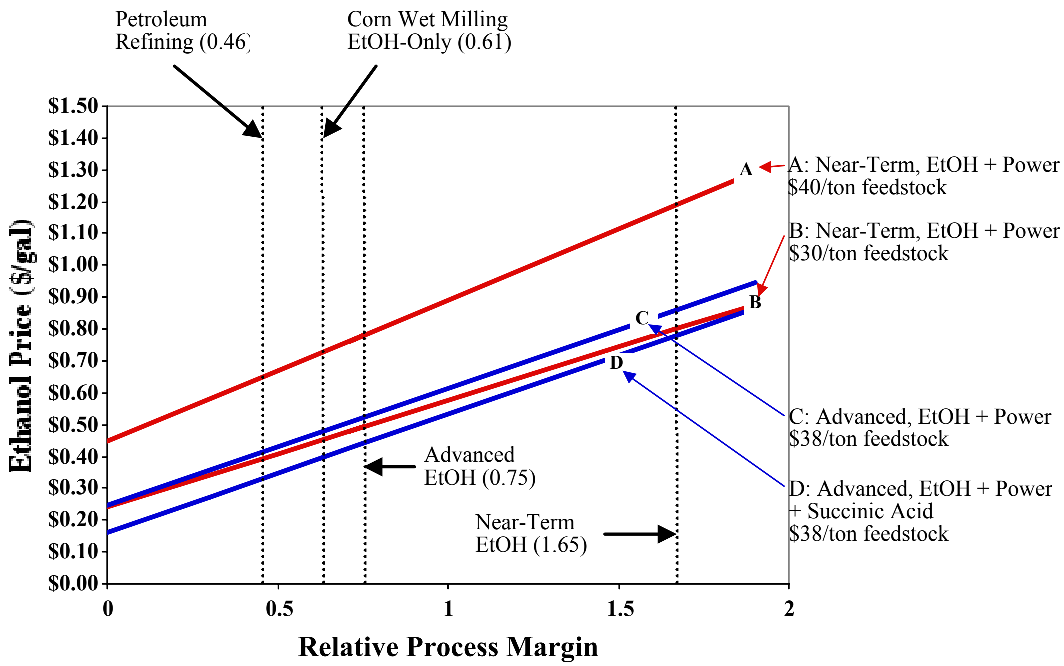

Figure 7. Ethanol price as a function of relative process margin.

Thoughts on Biorefinery Product Slate Selection

Given that a coproduct such as succinic acid can significantly lower the primary product selling price, one might ask, "Why not make even more of the coproduct?" and "Why not make only high-value coproducts?" As mentioned above (see Figure 2), the market size for most potential high-value coproducts is not large enough to support full-scale dedicated production. And, if the market were to increase to the extent that it could support dedicated production, the coproduct would cease to be high-value, having become a commodity itself.

Figure 8 presents a price versus market size curve for succinic acid. The function represents an estimate based on the present market sizes and prices of potential succinic acid derivative, calculated as follows:

$$P_{SA}(D) = \frac{\sum_i D_i Y_{i/SA}(P_i - C_i)}{\sum_i D_i} \qquad [7]$$

where

$P_{SA}(D)$ = succinic acid price as a function of market demand ($/lb succinic acid)

D_i = succinic acid needed to produce market demand of i^{th} derivative (MM lb/year)

$Y_{i/SA}$ = yield of i^{th} derivative (lb derivative/lb succinic acid)

P_i = price of i^{th} derivative ($/lb derivative)

C_i = production cost of i^{th} derivative exclusive of feedstock ($/lb derivative)

The market sizes, prices, yields, and production costs of the derivatives included in this calculation are listed in Table 4.

Recall that for a full-scale biorefinery with power cogeneration, the allowable selling price of succinic acid at a coproduction level of 10 MM lb/year is estimated at $0.21/lb for the near-term case and $0.16 for the advanced technology case. In Figure 8, succinic acid price drops from $2.68/lb to $0.33/lb—well above the estimated allowable selling price for both cases—as the market volume increases from 33 million to 3 billion pounds per year. This suggests that a full-scale biorefinery producing succinic acid as a primary product may indeed be economically viable.[2] It should be noted, however, that even if market conditions were such that a full-scale facility could be supported, the biorefinery process configuration would likely still allocate 30 percent of feedstock—or greater—to ethanol production, since succinate fermentation requires carbon dioxide, a by-product of ethanol fermentation. This underscores that process integration synergies help determine process design and represent yet another potential benefit of biorefineries.

[2] There are several factors—lower prices for derivatives and higher production costs, for example—that might cause the selling price to decline further with market expansion than estimated in Figure 8.

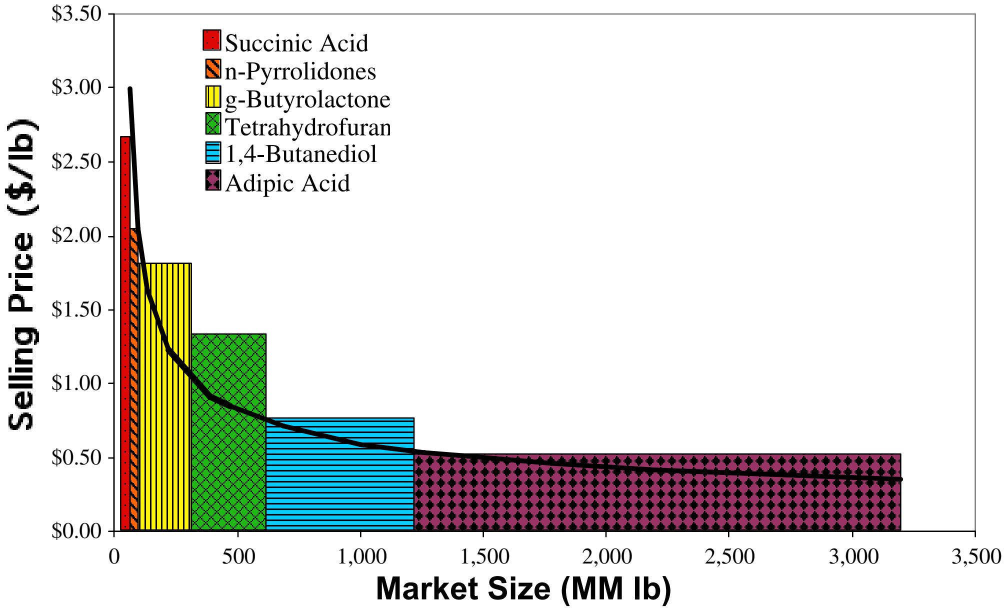

Figure 8. Estimated succinic acid price as a function of market size.

Table 4. Market size, price, and yield for succinic acid and its derivatives.

Derivative	Market Size (MM lb)	Price ($/lb derivative)	Yield (lb/lb SA)	Production Cost ($/lb derivative)
Succinic Acid	33[a]	$2.68[a]	-	-
n-Pyrrolidones	50[b]	$2.00[b]	0.71[b]	$0.26[e]
γ-Butyrolactone	200[b]	$1.80[b]	0.71[b]	$0.30[f]
Tetrahydrofuran	300[b]	$1.33[b]	0.59[b]	$0.30[f]
1,4-Butanediol	615[c]	$0.75[c]	0.64[d]	$0.29[e]
Adipic Acid	2,000	$0.51	1.02	$0.30[f]

[a] From (23).
[b] From (24).
[c] From (17).
[d] From unpublished model of Landucci.
[e] Based on unpublished cost analyses of Landucci. Production cost = required selling price - cost of succinic acid feedstock.
[f] Estimated based on production costs for n-pyrrolidones and 1,4-butanediol.

Though this article is concerned more with demonstrating why coproduction is beneficial and less with discussing the pros and cons of potential biorefinery products—others have done this (e.g. 22, 25)—a few general remarks regarding product slate selection are nonetheless in order. The first is that assembling a diverse product slate is important, both because capturing modest market share of several coproducts can have a profound impact on the primary product selling price, and because product diversity helps protect the biorefinery from seasonal demand cycles and market downturns. Table 5, which lists the reduction in ethanol price for a full-scale biorefinery coproducing succinic acid, lactic acid, and butanol, illustrates the first half of this point. Though in this example, only 16 to 18 percent of the total feedstock is allocated to coproduction, the ethanol selling price is reduced from $0.85/gallon to $0.62/gallon for the near-term technology case and from $0.51/gallon to $0.21/gallon for the advanced case. Product slate diversity—see Report 1—is a defining characteristic of today's petroleum refining and corn wet milling industries; mature biorefineries of tomorrow will also likely produce a wide array of products.

Table 5. Impact on ethanol selling price of coproducing small amounts of succinic acid (SA), lactic acid (LA), and butanol (BuOH) in a full-scale (300 MM gal) ethanol biorefinery.

Coproduction Scenario	Coproduct Produced (MM lb)	Feedstock to Coproduct Near	Feedstock to Coproduct Advanced	Coproduct Price ($/lb)	Ethanol Price Near ($/gal)	Ethanol Price Advanced ($/gal)
Ethanol + Power	-	-	-	-	0.85	0.51
+ SA	10	0.5%	0.4%	2.68[a]	0.78	0.42
+ LA	30	1.2%	1.1%	0.64[b]	0.81	0.45
+ BuOH	100	16.3%	15.0%	0.50[c]	0.79	0.37
+ SA + LA + BuOH	10/30/100	18.0%	16.5%	-	0.62	0.21

[a]From (23).
[b]From (26).
[c]From (18).
Key process parameters and economic values for succinic acid recovery are listed in Table 3. Those for lactic acid and butanol recovery are presented in Appendix B.
Succinic acid yields are: 0.29 lb/lb dry feedstock (near-term); 0.42 lb/lb dry feedstock (advanced).
Lactic acid yields are: 0.37 lb/lb dry feedstock (near-term); 0.46 lb/lb dry feedstock (advanced).
Butanol yields are: 0.09 lb/lb dry feedstock (near-term); 0.12 lb/lb dry feedstock (advanced).
Butanol process also produces acetone (0.315 lb/lb butanol) and ethanol (0.095 lb/lb butanol). Acetone valued at $0.39/lb (18).

A second point to consider is that selecting coproducts having the potential to become platform intermediates makes strategic sense for the biorefining industry. Doing so will foster the commoditization of these chemicals by taking advantage of the economies of scale provided by producing small amounts of the coproduct in an ethanol biorefinery. Thus, early generation ethanol biorefineries can serve as incubators for chemicals that can then become high-volume products in their own right. Both succinic acid—as noted above—and lactic acid are good examples of such products. In fact, lactic acid's move from specialty chemical to commodity is already underway: Cargill Dow recently brought its 300 million pound polylactic acid plant online, increasing worldwide lactic acid demand by approximately four-fold. Such market expansion, in light of the above discussion, will serve as a particularly useful example of how product price changes with increasing market size.

Yet another product slate strategy worth considering is to produce two or more large volume products in addition to smaller-volume, higher margin coproducts. The ability to swing production from one major product to another depending on market conditions—especially if the major products are not closely related—would make the refinery more resilient to demand cycles and downturns. Petroleum refineries, for example, typically maximize gasoline production during the summer months and shift to heating oils during the winter months to capitalize on seasonal demand. The corn wet milling industry also experiences seasonal market cycles: demand for high fructose corn syrup (HFCS), which is used extensively in the soft drink industry, is heaviest during the summer; during this time, wet mills can swing production from ethanol and starch to HFCS. Butanol—which is used primarily as a feedstock for organic chemicals such as butyl acrylate, methyl acrylate, glycol ethers, and butyl acetate (18)—represents an example of a chemical that might serve as such a major "swing" biorefinery product. U.S. demand for butanol is currently 2 billion pounds (18). Lactic acid is another, especially given its current rapid expansion. Yet another is acetic acid, though fermentation-derived acetic acid is not considered to be economically attractive at this time (22).

Concluding Remarks

In this study, using two ethanol biorefinery process designs and a few targeted coproduct examples, we have sought to show the advantages of the biorefinery concept as compared to dedicated production of a single product. Table 6 provides a summary of these considerable advantages. The essential message is that integrated coproduction is beneficial for *all* the products manufactured in a biorefinery, resulting in lower prices for both primary products and coproducts. It should be emphasized that several classes of products can be produced within a biorefinery—fuels, chemicals, power, and feed. While the relationship between the production of these product types is often portrayed as competitive, our analysis suggests the opposite: that coproduction of multiple product classes in a single facility will be beneficial, and in many cases will likely be necessary for cost-competitiveness in the long run.

Table 6. Advantages of integrated biorefinery configurations as compared to dedicated facilities producing a single product.

- Revenues from high-value coproducts reduce the selling price of the primary product (Figure 5, Table 5).

- The economies of scale provided by a full-size biorefinery lowers the processing costs of low-volume, high-value coproducts (Figure 6).

- Less fractional market displacement is required for cost-effective production of high-value coproducts as a result of the economies of scale provided by the primary product.

- Biorefineries maximize value generated from heterogeneous feedstock, making use of component fractions.

- Common process elements are involved in producing fermentable carbohydrate, regardless of whether one or more products are produced.

- Coproduction can provide process integration benefits (e.g. meeting process energy requirements with electricity and steam cogenerated from process residues).

As indicated in Table 6, the economic viability of biomass refineries is enhanced by coproduction of mutliple products, as coproducing high-value chemicals with a commodity such as ethanol—a less attractive investment when considered as a stand-alone product—can provide economies of scale that lower the manufacturing costs of the high-value coproducts. Owing to this economic enhancement, multi-product refineries are the likely long-term end point for the industry, much like today's petroleum refining and corn wet milling industries. In the near-term, however, commercial installations may well add one new product or process at a time in order to avoid compounding risk, just as petroleum refining and corn wet milling developed incrementally over time, evolving from single to multi-product industries.

Multiple product biorefineries also can help improve societal well-being by enhancing resource sustainability, energy security, and rural economic development. The realization of these benefits, however, is largely dependent on producing energy since the consumption of energy dwarfs that of either chemicals or materials (recall Figure 1). As a result, the indirect long-term contribution of biobased chemicals and materials resulting from increasing the economic viability of energy production may well be larger than the direct contribution from fossil fuel displacement per se.

As illustrated in Figure 9, for biomass refining to become commercial viable, two key technical objectives must be met: 1) overcoming the recalcitrance of cellulosic such that the carbohydrate fraction can be easily preserved and converted into reactive intermediates (i.e. sugars and oligomers), and 2) developing a diverse array of value-added bioproducts from such reactive intermediates. There is currently strong economic incentive for industry to pursue the second objective, and many companies such as Cargill Dow and DuPont are already doing so using corn as a feedstock. Further technical progress in the area of product diversification, however, provides minimal benefit with respect to the first objective, an area for which there is minimal economic incentive at present: today, cellulosic feedstocks offer little if any price advantage. (In the long term, however, as biomass refining technology matures, the transfer cost of soluble sugars derived from cellulosics has the potential to be half that derived from corn—reference 6.) In light of this limited economic incentive and the profound societal benefits that stand to result from biomass refining, we submit that the first objective represents an appropriate target for government-sponsored R&D, as technical progress in this area will benefit most potential biomass refineries and help to establish the industry.

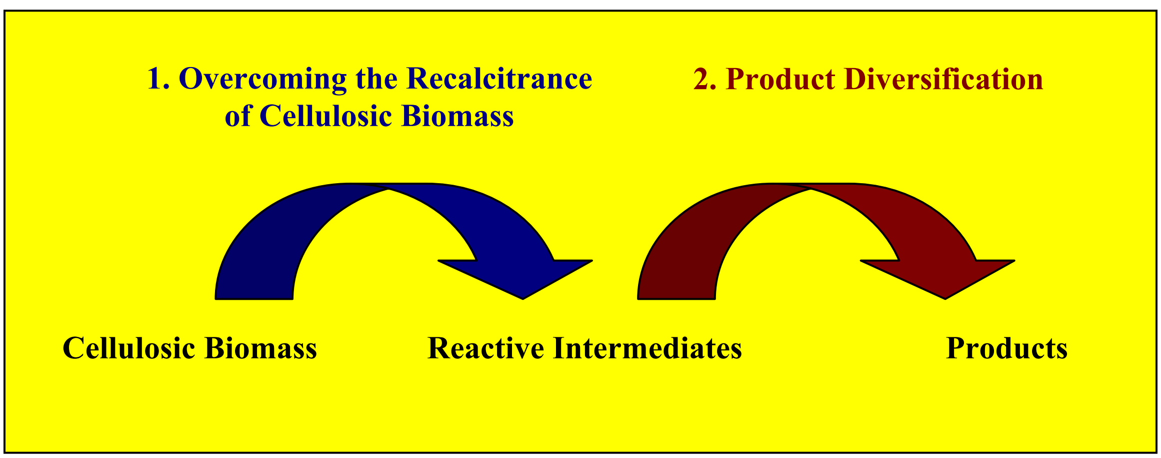

Figure 9. An important choice for biomass refining research and development: Overcoming the recalcitrance of biomass vs. product diversification.

Acknowledgments

This project was funded by the National Renewable Energy Laboratory (NREL). For help on Report 1, we thank John Jechura of NREL, John Marano of the University of Pittsburgh, and Ed Sughrue of Phillips Petroleum for their expertise and insights regarding the petroleum refining industry, and to John for his helpful comments on early drafts of both reports. Thanks also to Kelly Ibsen of NREL for her insightful reading of early drafts of the reports. We also thank Ki Park of Cargill, Inc. for helping us with several questions concerning the corn wet milling industry. Finally, for help on Report 2, we thank Kelly for providing spreadsheet documentation of the near-term cellulosic ethanol process design and to Haiming Jin of Dartmouth who helped us run NREL's near-term ASPEN model.

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Appendix A: Calculation of Biomass Transport Costs versus Plant Capacity

Calculation of Transport Radius

$$\text{transport radius (mi)} = \left(\frac{\text{plant capacity (ton / day)} * \text{operating days (days / yr)}}{\pi * \text{biomass yield (ton / mi}^2\text{ / yr)} * \text{fraction land used}} \right)^{1/2}$$

Table A.1. Biomass yield and fraction land used for energy crop production for near-term and advanced technology cellulosic ethanol process designs.

Case	Biomass Yield (ton/acre/year)	Biomass Yield (ton/mi^2/year)	Fraction Land Used
Near-Term[a]	2.0	1,280	0.375[c]
Advanced[b]	10.0	6,398	0.05

[a]Source: 20.
[b]Source: 21.
[c]Source: 27

Calculation of Transport Costs

Table A.2. Transportation cost versus one-way miles as calculated from parameters in Table A.3.

One-Way Miles	Transportation Cost ($/dry ton)
5	$4.95
50	$8.07
100	$11.53
200	$18.46

Table A.3. Key parameters used in calculation of biomass transport costs.

Item	Value
Year Basis:	2001
Fuel Economy [a]	6 mi/gallon
Fuel Cost [b]	$1.00 low cost, $/gallon diesel fuel $2.00 high cost, $/gallon diesel fuel
Maintenance Cost [a]	$1,000 per year
Oil Change Cost [a]	$20 per 5000 miles
Driver's Salary [a]	$50,000 per year
Driver Benefits [a]	$25,000 per year
Driver Hours [a]	3,120 per year (60 hr/wk; 52 wk yr)
Local Speed [a]	15 mph ave.
Highway Speed [a]	45 mph ave
Local Miles [a]	5 per trip
Loading/Unloading Time [a]	2 hours/trip
Truck Life [a]	10 years
Lease Rate	10% (APR)
Truck Residual Value [a]	$11,300 at end of lease
Capital Recovery Factor	0.16
Truck Capital Cost [a]	$113,000
Truck Capacity [a]	29 tons
Biomass Moisture Content [a]	50%
Capital Recovery	$17,681

[a]Source: 22.
[b]Source: 13.

Appendix B: Key process parameters and economic values for lactic acid and butanol recovery.

Table B.1. Key process parameters and economic values of lactic acid recovery model.

Process Area		Units	Values
Scale		MM lb lactic acid/year	100
Lactic Acid Yield		lb/lb glucose	0.96
		lb/lb dry feedstock	0.36 (near-term)
			0.46 (advanced)
Installed Capital Cost		$	15,844,532
Operating Costs			
	Raw Materials	$/lb lactic acid	0.0088
	Electricity	$/lb lactic acid	0.0042
	Steam	$/lb lactic acid	0.0006
	Maintenance	$/lb lactic acid	0.0032
	Taxes & Insurance	$/lb lactic acid	0.0024
	Capital Recovery	$/lb lactic acid	0.0279
Total		$/lb lactic acid	0.0471

Capital recovery = 0.176*installed capital cost, (20). Electricity valued at $0.04/kWh, (21). Steam valued at $2.00/1000 lb. Capital installation factor = 2.75 (27). Equipment scaling exponent = 0.7. Taxes and insurance = 0.015*installed capital cost, (20). Maintenance = 0.02*installed capital cost, (20).

Table B.2. Key process parameters and economic values of butanol recovery model.

Process Area		Units	Values
Scale		MM lb butanol/year	338
Butanol Yield		lb/lb glucose	0.24
		lb/lb dry feedstock	0.09 (near-term)
			0.12 (advanced)
Installed Capital Cost		$	24,436,134
Operating Costs			
	Electricity	$/lb butanol	0.0169
	Steam	$/lb butanol	0.0242
	Maintenance	$/lb butanol	0.0014
	Taxes & Insurance	$/lb butanol	0.0011
	Capital Recovery	$/lb butanol	0.0128
Total		$/lb butanol	0.0564

Capital recovery = 0.176*installed capital cost, (20). Electricity valued at $0.04/kWh, (21). Steam valued at $2.00/1000 lb. Capital installation factor = 2.75 (27). Equipment scaling exponent = 0.7. Taxes and insurance = 0.015*installed capital cost, (20). Maintenance = 0.02*installed capital cost, (20).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
October 2005

2. REPORT TYPE
Subcontract Report

3. DATES COVERED *(From - To)*
1/24/2002 - 7/1/2002

4. TITLE AND SUBTITLE
Strategic Biorefinery Analysis: Analysis of Biorefineries

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
L.R. Lynd; C. Wyman; M. Laser; D. Johnson; and R. Landucci

5d. PROJECT NUMBER
NREL/SR-510-35578

5e. TASK NUMBER
BBA3.4220

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Dartmouth College
11 Rope Ferry Road
Hanover, NH 03755-1404

8. PERFORMING ORGANIZATION REPORT NUMBER
ADZ-2-31086-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-510-35578

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES
NREL Technical Monitor: J. Jechura

14. ABSTRACT *(Maximum 200 Words)*
Subcontract report prepared by Dartmouth College that identifies and discusses the advantages of producing ethanol in a biomass refinery as compared to a single-product facility.

15. SUBJECT TERMS
biorefinery; Dartmouth; wet milling

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		
					19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18