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Biorefineries Using Agricultural Residue Feedstock in the Great Plains [1]

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Abstract

Rising prices and uncertain supplies of petroleum, together with environmental concerns regarding fossil fuel combustion, has enhanced interest in biobased products and fuels. The work reported here analyzes the feasibility of a multi-product biorefinery using wheat straw as feedstock that produces ethanol, electricity, and cellulose nanofibers. The nanofibers (nanowhiskers) would be used as reinforcements in a biobased nanocomposite material that could substitute for fiberglass in many applications. The analysis indicates that, at 2005 prices and costs, the biorefinery would be marginally profitable. Anticipated advances in bioprocessing technology would enhance profitability. The facility would also make a substantial contribution to the biorefinery site area economy, as a high percentage of operating expenses would be payments to local entities. The growth of a biobased industry could have major economic development implications for the Great Plains/Midwest region.

Key Words: biomass, biomaterials, ethanol, wheat straw, cellulose nanowhiskers (CNW), economic development

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Introduction

Recent changes in world energy markets have led to heightened awareness of U.S. dependence on foreign supplies of petroleum. While consuming approximately 25 percent of world oil production, the U.S. has only about 3 percent of known reserves (Greene et al. 2004). Concerns about foreign oil costs and supply disruptions are leading to revived interest in alternative energy sources. One of the sources that has attracted particular interest is biofuels derived from agricultural biomass.

Environmental concerns also support renewed interest in renewable energy sources (Schneider and McCarl 2003). While consuming fossil fuels releases greenhouse gases into the atmosphere, biofuels and other products derived from biomass are essentially carbon-neutral, as the carbon dioxide (CO_2) released during processing is offset by the CO_2 drawn from the atmosphere by the growing plants.

The recent growth of the ethanol industry demonstrates the potential of biofuels. From an annual production capacity of 1.1 billion gallons in 1990, ethanol production is expected to reach 5.0 billion gallons in 2006 (Eidman 2006). However, corn supply will likely limit ethanol's role in U.S. energy markets. While the Energy Policy Act of 2005 included a renewable fuels standard (RFS) which mandates 7.5 billion gallons of biofuels production annually by 2012, ethanol-based corn demand will exceed corn exports when the 7.5 billion gallon RFS is fully implemented. If bioenergy is to expand its role in national energy markets, a broader resource base and corresponding processing technologies are clearly needed.

As noted earlier, the Energy Policy Act of 2005 included a renewable fuels standard (RFS) starting at 4 billion gallons in 2006 and reaching 7.5 billion in 2012. The 2005 Act also created a Cellulosic Biomass Program to encourage production of cellulosic ethanol. The program provides federal government loan guarantees for new production facilities and grants for research on cellulosic ethanol production.

Midwest/Great Plains states with the largest potential supplies of agricultural biomass are particularly interested in developing bio-mass based energy and products (Walsh et al. 2000). A consortium led by North Dakota State University (NDSU) is currently engaged in a project that would use cellulose nanofibers derived from wheat straw to make a product that could substitute for fiberglass and plastics in many applications, including automotive parts. The work described here analyzes the economic value of adding a cellulose nanofiber production system to an ethanol biorefinery (see Figure 1). The addition appears to significantly improve the economics of the overall production process by capturing additional value from the wheat straw feedstock.

Cellulose Nanofibers Biorefinery Process Flow Diagram

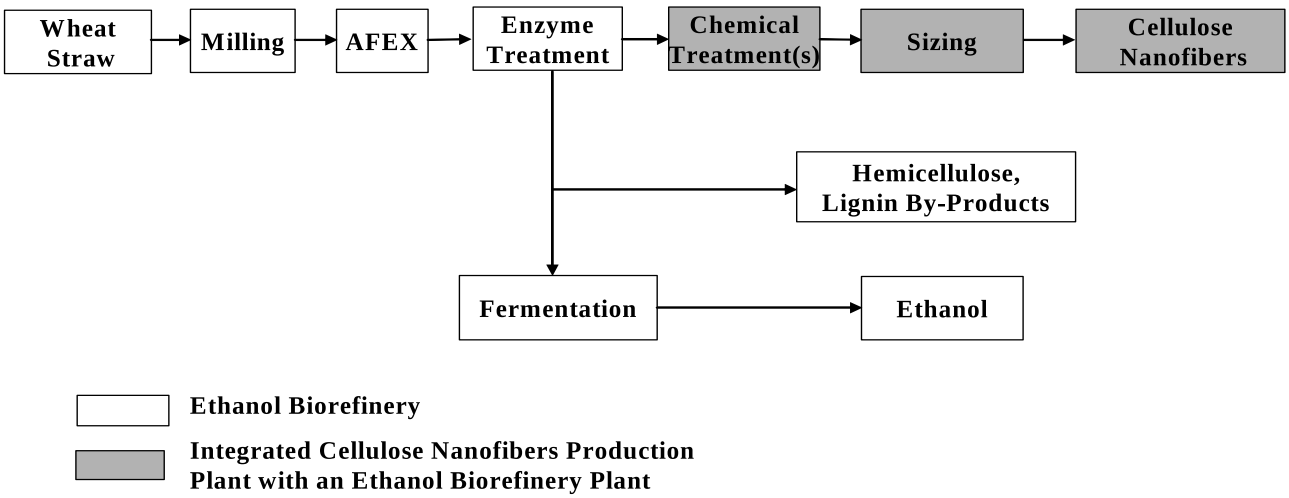

Figure 1. Cellulose Nanofibers Biorefinery Process Flow Diagram

Methods

In the remaining sections of this paper, the cellulose nanowhisker (CNW) product is described, and its potential uses and market are briefly discussed. Then, the integration of CNW production into an ethanol biorefinery using ammonia fiber expansion (AFEX) pretreatment of cellulosic biomass feedstock is described. An ASPEN Plus-based process model was developed to evaluate technical and economic performance of ethanol production from AFEX treated biomass (ASPEN Technology Inc. 2001). Basic engineering and economic parameters have been established for a 50 million gallons per year (MGPY) ethanol process (Leistritz et al. 2006), based on work reported by Aden et al. (2002), with updates as appropriate. The same model, slightly modified, was used to evaluate adding CNW production to the biorefinery.

Feedstock is expected to be the largest single operating cost component for a biorefinery. Accordingly, historical data on North Dakota wheat acreage and yield were used to estimate wheat straw production and available supply. Current costs for baling, transportation, and nutrient replacement were used to estimate the cost of wheat straw feedstock delivered to the plant. To determine the cost of alternative, potentially competing feedstocks, an extensive review of recent studies of feedstock availability and cost was undertaken.

Construction and operation of a biorefinery would result in substantial expenditures in the area where the facility is sited. The operating expenditures were examined, and those that would represent expenditures to in-state entities were identified (e.g., payments for feedstock, wages and salaries). The North Dakota Input-Output Model was used to estimate secondary economic impacts based on these data. The input-output (I-O) model consists of interdependence coefficients or multipliers that measure the level of business activity generated in each economic sector from an additional dollar of expenditures in a given sector. (A sector is a group of similar economic units, e.g., the firms engaged in retail trade make up the retail trade sector.) For a complete description of the input-output model, see Coon and Leistritz (1989). This model estimates the changes in gross business volume (gross receipts) for all sectors of the area economy that arise from the direct expenditures associated with construction and operation of the biorefinery. The increased gross business volumes are used to estimate secondary employment based on historic relationships.

Results and Discussion

Production of Cellulose Nanowhiskers from Wheat Straw

CNW are defined as fibrous, high-purity, single crystals with nanometric dimensions (Liu et al. 2005). Nanowhisker length ranges from 150 to 300 nanometers (nm) and the width is approximately 5 nm (Helbert et al. 1996). A nanometer is very, very small, 10^{-9} meter or 1 billionth of a meter. Dispersion of CNW in a polymer matrix, such as Latex, enhances the physical properties of the material at temperatures above the glass transition (Helbert et al. 1996).

The biobased composites developed from the cellulose nanofibers could have widespread applications, replacing fiberglass and similar materials. MBI International, a scientific participant in the NDSU project consortium, has begun analyzing the automotive industry for CNW applications, focusing on components such as interior elements, exterior panels, and suspension parts. CNW have several advantages over fiberglass components. CNW have a superior strength to weight ratio (greater strength at the same weight), are biodegradable, recyclable, carbon dioxide neutral, and potentially cost less to produce. The maximum market size for biobased fibers as a replacement for fiberglass has been estimated to be 1.67 billion pounds per year (Knudson and Peterson 2005).

MBI has proposed a process flow diagram (PFD) that uses ammonia fiber explosion (AFEX) treatment followed by enzymatic hydrolysis. The hydrolysate, rich in pentose and hexose sugars, is sent to ethanol fermentation, and the hydrolysate solids are further processed to produce CNW. This process is environmentally benign and does not have the waste stream issues of acid hydrolysis, the process previously used to isolate CNW from wheat straw (Helbert et al. 1996).

Ethanol Production from Wheat Straw

Fuels are likely to be the main product of a mature biorefinery industry, as there are few organic chemicals and polymers with markets large enough to serve as primary products for even one full-scale biomass refinery (Lynd et al. 2005). Thus, this analysis assumed that ethanol would be the primary product from a wheat straw biorefinery.

Prices for ethanol, biomass feedstock, and other inputs were based on a number of sources (Leistritz et al. 2006). The ethanol price was $1.80/gallon, which was the average price in 2005, F.O.B. Omaha. Wheat straw feedstock was assumed to cost $40 per U.S. ton, delivered to the plant (analysis of harvest and transportation costs are discussed subsequently). Other input costs are reported by Leistritz et al. (2006).

Other updates to the base case model (Aden et al. 2002) included:

- Steam will be generated in-house using wheat straw fermentation residue with 65 percent combustion efficiency.

- Consistent with existing dry mill ethanol plant designs, the ethanol production process will not generate any major liquid waste stream. Gaseous wastes from the boiler will be filtered in bag-houses and vented.

- Operating hours will be 8,400 hours per year, consistent with industrial standards.

- AFEX treated wheat straw is converted to ethanol in simultaneous saccharification and fermentation (SSF) using genetically engineered microorganisms capable of converting both glucose and xylose to ethanol.

The unit operations included in the process model are feedstock cleaning, AFEX pretreatment, ammonia separation, SSF, ethanol distillation, molecular sieve separation, stillage concentration, lignin separation, and combustion. The process would begin with wheat straw bales delivered by trucks and stored under cover. The process flow diagram used for the model, as well as the design basics and technical assumptions, are reported in Leistritz et al. (2006).

Some key assumptions were 60 percent conversion of cellulose to fermentable sugars and 55 percent conversion of xylan. The ethanol production target was set at 50 MGPY of anhydrous ethanol. At the assumed production efficiencies, this would require slightly more than 110 tons of straw per hour (900,000 tons per year).

The mass and energy balance results generated by the model were exported to a separate spreadsheet to evaluate the process economics. Equipment costs and key process variables such as the raw material costs, utilities costs, fixed operating costs, by-products revenue, and annual depreciation were estimated using standard engineering/economic methods. A straight line annual depreciation for 10 years of project life was assumed. No salvage value was considered at the end of the project life.

The base case model generated 54.418 MGPY denatured ethanol. The capital cost was estimated at $185 million. Total operating costs, excluding by-product credits, were $92.35 million per year. Revenue from sales was estimated at $97.95 million per year from ethanol and $7.5 million per year from electricity. The earnings before interest and income tax (EBIT) were $13.05 million per year providing a return on investment (ROI) of 7.06 percent. The production cost of ethanol, including by-product credit, was estimated to be $1.56 per gallon. The results from the economic analysis are shown in Table 1.

Producing Cellulose Nanowhiskers as a Secondary Product

The CNW production model assumes processing 50 tons of wheat straw hydrolysate solids per day and generates 1,050 tons of CNW per year. Projected selling price was $0.85 per pound, given that glass fibers sold at prices ranging from $0.59 to $0.91 per pound in 2005. Capital costs were estimated at $1.306 million, and total operating costs, excluding by-product credits, were $1.193 million per year. Revenue from sales of CNW was estimated to be $1.785 million per year. Earnings before interest and income tax (EBIT) were $591,849. The production cost of CNW was determined to be $0.57 per pound. The Consolidated Pro Forma Income Statement indicates that the production of CNW would enhance the economic performance of a wheat straw to ethanol mill (Table 2).

Feedstock Supply and Cost

The cellulose-based biorefinery is expected to be a large-scale facility with a feedstock requirement of approximately 900,000 tons of wheat straw per year. Accordingly, an assessment of the potential availability and cost of wheat straw feedstock was undertaken (for a complete description, see Leistritz et al. 2006).

Production of wheat straw was estimated based on grain yield, using a Harvest Index formula (Ottman et al. 2000). Using the Harvest Index formula and the 2004 statewide average wheat yield of 39.4 bushels per acre, an estimated 3,355.6 pounds per acre of straw would be produced. However, only a portion of this straw can be baled and removed from the field. A sustainable rate of straw recovery for North Dakota has been estimated to be 43 percent (Lundstrom 1994), and this value was used throughout the analysis. Over the past decade, estimated wheat straw production in North Dakota has ranged from 9.2 to 16.8 million tons. Using a 43 percent recovery rate, from 4 million to 7 million tons of wheat straw should be recoverable.

Table 1. Financial Summary

AFEX Pretreatment and Ethanol Production from Wheat Straw			
Construction Costs	**Ethanol MGPY**	**54,418,608**	
	Equipment		$81,998,665
	Installation		$82,489,640
	Engineering/Supervision		$4,400,000
	Land Preparation		$1,250,000
	General Construction		$3,200,000
	Fees/Licenses		$1,400,000
	Contingency		$1,730,000
Other Capital Costs			**$176,468,305**
	Land Cost		$250,000
	Start-up Costs		$1,600,000
	Start-up Inventory		$1,600,000
	Working Capital		$5,000,000
			$8,450,000
	Total Capital		**$184,918,305**
Projected Statement of Earnings:			
Sales:			
$1.80 Per gal	Ethanol		$97,953,495
0 Per ton	CO_2		$0
0.05 Per kWh	Electricity		$7,454,749
	Total Sales		**$105,408,244**
Production & Operating Expenses:			
40.00 Per ton	Feedstock (907,443 ton)		$36,297,720
25.00 Per ton	Liquid Feed Syrup		$5,676,522
0.05 Per lb	Cellulase		$6,333,000
0.10 Per lb	Cellobiase		$7,772,255
0.125 Per lb	Ammonia		$3,402,914
	Other Raw Materials		$8,358,427
	Utilities		$87,155
	Labor, Supplies & Overhead		$6,779,249
10 yr	Depreciation		17,646,830
	Total Production Cost		$92,353,491
Net Income:	EBIT		$13,054,753
	EBITDA		$30,701,583
Return on Investment (EBIT/Total Capital)			7.06%

Source: Raj and McCalla (2006).

Table 2. Consolidated Pro Forma Income Statement

Consolidated Economic Model: Wheat straw to ethanol plus Cellulose nanowhiskers from Wheat Straw Hydrolysate Solids

		Wheat Straw to Ethanol Model 50 mm gal/yr	Nanowhiskers from Wheat Straw Hydrolysate	Wheat Straw to Ethanol Plus Nanowhiskers
	Total capital	$184,918,305	$1,306,520	$186,224,825
Revenue/sales ($)		$105,408,244	$1,785,000	$107,193,244
Cost of sales				
	Total cost of sales	$67,927,412	$531,327	$68,458,739
Gross margin		$37,480,832	$1,253,673	$38,734,505
Operating costs				
	Total operating costs	$6,779,249	$531,172	$7,310,421
Amortization cost		$17,646,830	$130,652	$17,777,482
EBIT		$13,054,753	$591,849	$13,646,602
Return on investment (EBIT/total capital)		7.06%	45.30%	7.33%
EBITDA		$30,701,583	$722,501	$31,424,084
Return on investment (EBITDA/total capital)		16.60%	55.30%	16.87%

Source: McCalla (2006).

Various methods could be used to determine the selling price of straw to the biorefinery and hence the net return to producers. This analysis estimated nutrient value as well as baling and transportation costs to determine a selling price. Based on nutrient values estimated by Jones (2003) and fertilizer prices in the spring of 2006, the nutrient value of wheat straw was estimated to be $12.27 per ton (Leistritz et al. 2006). When farmers wish to save wheat straw either for their own use or for sale, the most common method is to have the combine drop the straw into windrows for baling. Based on current custom baling rates, baling costs were estimated to be $12.14 per ton (Leistritz et al. 2006).

The cost for hauling semi loads of straw was estimated at $3.72 per loaded mile, reflecting fuel costs prevailing in 2005 (Leistritz et al. 2006). The draw area for the plant was assumed to be a 50-mile radius. If straw suppliers were evenly distributed over this area, the average haul distance would be 36 miles, giving a transportation cost of $9.72 per ton.

A straw price of $40 per dry ton delivered to the plant would cover costs of baling and transportation and provide the producer with a payment of $18.14 per ton to cover nutrient replacement and provide an incentive to supply straw. For purposes of subsequent analysis, straw cost to the plant was assumed to be $40 per dry ton.

Alternative Feedstocks

The competitiveness of a biorefinery using wheat straw feedstock will depend substantially on the relative cost of wheat straw, compared to competing feedstocks. Several studies have examined the availability and cost of alternative biomass feedstocks (Walsh et al. 2000; Gallagher et al. 2003; Sheehan et al. 2004; Perlack et al. 2005; Gallagher 2006). Crop residues (e.g., corn stover, wheat straw) appear to be the lowest cost agricultural biomass sources. Dedicated energy crops (e.g., switchgrass) could be grown on land not suitable for annual crops, but at costs higher than those for crop residues (Gallagher 2006).

Recent analysis (Leistritz et al. 2006) indicates that North Dakota wheat straw can be delivered to a biorefinery at a cost of $40.00 per dry ton, after paying harvest, nutrient replacement, and transportation costs and providing the producer with $18.14 per ton to cover nutrient replacement and an incentive. When this is compared to recent estimates for corn stover, wheat straw appears to have a $5 to $10 per ton cost advantage. Similarly, when wheat straw costs are compared with those for switchgrass, wheat straw appears to have a cost advantage of $10 to $15 per ton or more.

In addition to cost considerations, wheat straw appears to have an advantage over switchgrass based on its higher content of both cellulose and lignin. Cellulose is the major source of fermentable sugars while lignin will be utilized as fuel for the biorefinery.

Regional Economic Impact

Construction and operation of the biorefinery would result in substantial expenditures for feedstock and a variety of supplies and materials, as well as wages and salaries for the workforce. Total operating expenditures for the biorefinery were estimated to be $74.6 million annually, of which $53.01 million was estimated to represent expenditures to North Dakota entities (Table 3). The largest single expenditure item was for the wheat straw feedstock ($36.3 million). This expenditure was allocated between the *agriculture crops* sector (baling costs – $11.07 million) and the *transportation* sector (hauling – $8.82 million), with the balance to the *households* sector ($16.41 million). Other substantial in-state expenditures would be for ammonia, ammonium phosphate, and potassium phosphate ($9.9 million), salaries and wages ($2.05 million), and employee benefits ($0.68 million).

Facility construction also represents a substantial outlay. Plant construction costs were estimated to total $176.5 million, of which 15 percent was estimated to represent expenditures to in-state entities, based on experience with other large agricultural processing facilities recently constructed in North Dakota (Coon and Leistritz 2001). Thus, the direct economic impact of plant construction was estimated to be $26.48 million (Table 3).

Table 3. Direct Economic Impacts Associated with Biorefinery Construction and Operation, by Input-Output Sector (million $)

		Operations	
Sector	Construction	Biorefinery	Biorefinery with CNW
Agriculture, crops		11.07	11.07
Construction	26.48		
Communications & utilities			0.12
Transportation		8.82	8.82
Wholesaling, ag. processing, & misc. manufacturing		9.94	9.94
Retail trade		1.84	1.89
Finance, insurance, & real estate		2.16	2.30
Business & personal services		0.36	0.36
Professional & social services		0.36	0.36
Households		18.45	18.92
Total direct impacts	26.48	53.01	53.78

When production of CNW is added to the biorefinery, the direct economic impacts are somewhat enhanced (Table 3). Direct impacts are estimated to increase from $53.01 million annually to $53.78 million, an increase of $0.77 million or 1.5 percent. The sectors receiving added expenditures include *households* ($0.47 million), *finance, insurance, and real estate* ($0.14 million), *communications and utilities* ($0.12 million), and *retail trade* ($0.05 million).

The North Dakota Input-Output Model was used to estimate the secondary economic impacts based on these data. Estimated direct impacts were applied to the I-O model coefficients to estimate the total impacts of construction and operation of the biorefinery facility (Table 4). Biorefinery operations were estimated to result in a total economic impact (contribution) to the North Dakota economy of $183 million annually. That is, the $53 million of direct economic impacts results through the multiplier process in an additional $130 million in secondary (indirect and induced) impacts, for a total of $183 million. Addition of CNW production results in somewhat larger total impacts ($185.2 million compared to $182.8 million). Construction of the biorefinery would result in a one-time total economic impact of $64.7 million to the North Dakota economy (Table 4).

The levels of economic activity reflected in Table 4 would support substantial levels of secondary employment in various sectors of the state economy. Biorefinery operations were estimated to lead to about 2,448 secondary jobs while with CNW production added, this figure rises to 2,474 (Table 4). These jobs are in addition to the persons employed directly by the facility (77 jobs for the biorefinery and 86 if CNW production is added). Facility construction is estimated to result in 793 person years of additional secondary employment.

Table 4. Regional Economic Impacts (Direct Plus Secondary) Associated with Biorefinery Construction and Operation (million $)

		Operations	
Sector	Construction	Biorefinery	Biorefinery with CNW
Gross Business Volume by Sector:			
Construction	27.8	3.9	3.9
Transportation	0.3	9.4	9.4
Wholesaling, ag. processing,			20.4
& misc. manufacturing	0.5	20.4	
Retail trade	10.9	37.9	38.4
Finance, insurance, & real estate	2.2	10.0	10.3
Households	16.1	58.1	59.1
Other[1]	6.9	43.1	43.7
Total	64.7	182.8	185.2
	-person years-	--------------------jobs---------------	
Secondary employment	793	2,448	2,474

[1]Includes agriculture, mining, communications and public utilities, services, and government.

Conclusions and Implications

The aim of the project is to commercialize MBI's technology for producing bio-based cellulose nanowhiskers (CNW) from wheat straw in an integrated biorefinery with ethanol and electricity as co-products. The first major milestone in the effort was to address key engineering and economic questions to determine the technical and economic feasibility of a pilot scale production process, while at the same time analyzing the integration of components made from biomaterials into the automotive supply chain. Preliminary results have been very encouraging and include:

- Wheat straw is a preferred feedstock for a biorefinery as it has a higher content of both cellulose and lignin than alternative feedstocks, such as switchgrass.

- Wheat straw can be supplied to a North Dakota biorefinery at costs lower than for alternative feedstocks (e.g., corn stover, switchgrass).

- A biorefinery producing 50 million gallons of ethanol per year would use 900,000 tons of wheat straw annually, employ 77 workers, and result in more than $50 million in annual payments to North Dakota entities.

- At an ethanol price of $1.80 per gallon (2005 average), the biorefinery would earn a positive net return (7 percent).

- Adding CNW production to the biorefinery would add several jobs and would enhance the profitability of the venture.

This project also has wider implications for economic development in the Midwest/Great Plains region. A recent national study indicated that the top six states in potential agricultural biomass were Illinois, Iowa, Nebraska, Kansas, Minnesota, and North Dakota (Walsh et al. 2000). An emerging biomass-based economy would represent a major economic development opportunity for rural areas of these states. Because of the bulk of the biomass feedstock, biorefineries and related processing facilities will almost certainly be sited near the source of the feedstock, offering the prospect of substantial new investment and job opportunities in rural areas. Further, because the biomass feedstock represents a major portion of the operating costs for these facilities, a large portion of the operating costs will be payments to in-state entities, including substantial payments to local farmers, custom baling operators, and truckers. For example, for the North Dakota biorefinery just examined, $53 million of the estimated $74.6 million annual operating costs (71 percent) were assumed to represent payments to in-state entities. The largest single expenditure was for wheat straw ($36.3 million or 49 percent of total operating costs), all of which would be payments to farmers and to those baling and transporting the feedstock.

It must be recognized that the technology for biomass-based energy and bioproduct production is still in its infancy. The biorefinery analysis reported here is based on the best levels of performance demonstrated to date, at the laboratory scale. Substantial work remains to scale-up these processes, first to a pilot plant scale and then to a commercial scale. Using the assumed yields incorporated in this analysis, the biorefinery would be marginally profitable (ROI of 7 percent). Given the pioneering nature of the technology involved, and associated risks, this level of return likely would be unsatisfactory to many investors. However, programs authorized in the Energy Policy Act of 2005 provide for loan guarantees, grants, and other incentives to make first-generation plants a more attractive investment.

Industry experts anticipate that biofuel production processes will be improved, increasing yields and reducing costs of cellulosic ethanol production. Areas where gains are expected include (1) development of a new generation of cellulose-hydrolizing enzymes, (2) development of genetically-engineered organisms capable of fermenting C5, as well as C6, sugars, and (3) higher yields of sugars from hemicellulose (90 percent vs. 67.5 percent today) and cellulose (90 percent vs. 63.5 percent) (Sheehan et al. 2004). Overall, these authors believe ethanol yields could ultimately approach 100 gallons per ton of biomass feedstock, compared to 60 gallons per ton in this study. Such improvements would obviously enhance the profitability of biorefinery operation.

A second major avenue for enhancing the profitability of biorefineries is through developing high-value co-products that will enable greater value to be derived from the biomass feedstock. The CNW studied here represents one of those co-products.

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