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Use of Agricultural Residue Feedstock In North Dakota Biorefineries

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Rising prices and uncertain supplies of petroleum, together with environmental concerns regarding fossil fuel combustion, have enhanced interest in biobased products and fuels. This study analyzes the feasibility of a multi-product biorefinery that uses wheat straw as feedstock to produce ethanol, electricity, and cellulose nanofibers. Nanofibers (nanowhiskers) would be used as reinforcements in a biobased nanocomposite material that could substitute for fiberglass in many applications. The growth of a biobased industry could have major economic development implications for the Great Plains/Midwest region.

Key Words: biomass, biomaterials, cellulose nanofibers (CNFs), economic development, ethanol, wheat straw

Recent changes in world energy markets have led to heightened awareness of U.S. dependence on foreign supplies of petroleum. Although the United States consumes approximately 25% of the world's oil production, it holds only about 3% of known reserves (Greene et al., 2004). Costs of foreign oil and supply disruptions have revived interest in alternative energy sources. Thus, biofuels derived from agricultural biomass have attracted much attention.

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 was expected to exceed 10 billion gallons in 2009 (Renewable Fuels Association, 2009). However, corn supply will likely limit ethanol's role in U.S. energy markets (Tokgoz et al., 2007). If bioenergy is to expand its role in national

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energy markets, a broader resource base and corresponding processing technologies are clearly needed.

The Energy Policy Act of 2005 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. The Energy Independence and Security Act (EISA) of 2007 continued federal support for cellulosic ethanol production through enhanced R&D funding and through increased mandates for biofuel use. The EISA established a renewable fuel standard (RFS) of 36 billion gallons of biofuels by 2022, of which 21 billion gallons must be advanced biofuels with a minimum of 16 billion gallons of cellulosic biofuels. Expansion of the biofuels industry to this capacity within the specified time frame poses major challenges as technology for cellulosic ethanol production has yet to be demonstrated on a commercial scale. Moreover, technology for producing alternative biofuels appears to be even less advanced. However, several pilot and demonstration-scale facilities are currently being developed, some with support from the U.S. Department of Energy.

Developing a commercial biomass-based fuel industry is not without risks. The profitability of a biorefinery will depend on a number of factors, including (*a*) price of the biofuel product (which may be affected by world energy markets and by national policies), (*b*) feedstock costs, (*c*) yields of product or co-products, and (*d*) capital and operating costs of the biorefinery. Recent developments in the corn ethanol industry underscore the sensitivity of industry profitability to fluctuating product prices and feedstock costs.

Midwest/Great Plains states with the largest potential supplies of agricultural biomass could have a major interest in developing biomass-based energy and products (Milbrandt, 2005; Walsh et al., 2000). Several states have made substantial commitments to biofuels development, as have several major energy companies. A consortium led by North Dakota State University (NDSU) is currently engaged in a project that would use wheat straw as a feedstock for an integrated biorefinery to produce ethanol, electricity, and other high-value products—specifically cellulosic nanofibers. The work described here analyzes the economic value of adding a cellulose nanofiber production system to a cellulosic ethanol biorefinery (see figure 1).

Objective

Our research objectives are to estimate the cost of producing ethanol in a biorefinery using wheat straw as feedstock. Then, the addition of cellulose nanofibers as a co-product is modeled to determine whether this would improve the financial performance of the biorefinery. Finally, the potential economic impact of the biorefinery is estimated.

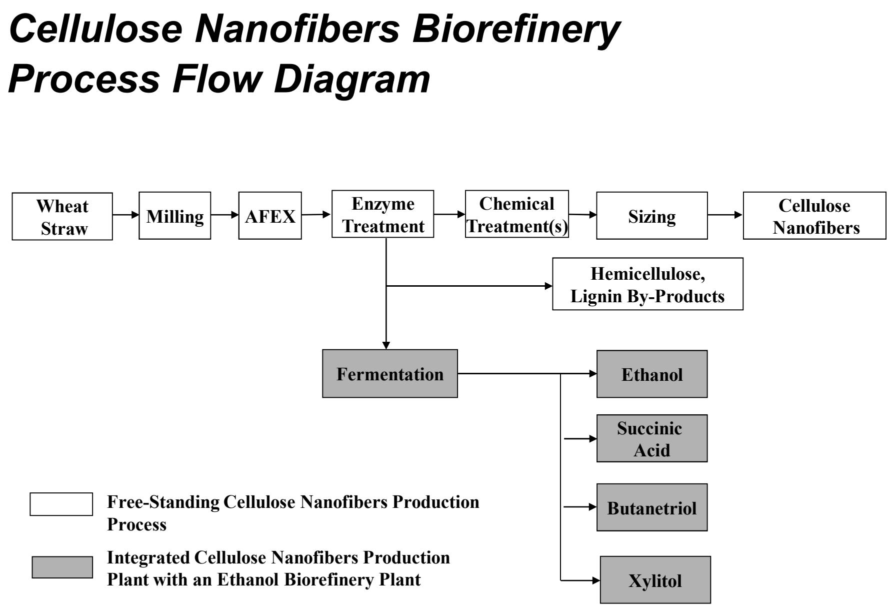

Figure 1. Flow diagram of cellulose nanofibers biorefinery process using AFEX pretreatment of cellulosic biomass feedstock

Prior Studies

Several studies have examined prospects for producing ethanol from lignocellulosic biomass. Aden et al. (2002) investigated yields and input costs needed to achieve the U.S. Department of Energy's (DOE's) ethanol break-even price goal of $1.07/gallon by 2010. This goal would require a yield of 90 gallons of ethanol per dry ton of feedstock and a feedstock cost of $33/metric ton (MT) ($30/U.S. ton). Economies of scale are evident in biorefinery operation. The authors found that an increase of plant size from 2,000 MT/day of feedstock to 10,000 MT would reduce non-feedstock costs by $0.19/gallon, but increases in feedstock costs (because of longer haul distances) would offset these savings by $0.13/gallon.

Sheehan et al. (2004) evaluated production of ethanol using corn stover as feedstock. Ethanol yields would need to rise to 80 gallons/ton of feedstock from the 60 gallons/ton that had been achieved in laboratory and pilot-scale experiments to date. This can be accomplished through (*a*) developing a new generation of cellulose-hydrolizing enzymes to attain higher yields of sugars from cellulose (90% vs. 63.5% today) and hemicellulose (90% vs. 67.5%), and (*b*) developing organisms capable of fermenting C5 as well as C6 sugars. With these improvements in processing efficiency and a feedstock cost of $41.60 per ton delivered to the plant, Sheehan et al. conclude that ethanol could be produced from corn stover at a cost of $1.21/gallon.

Lynd et al. (2005) examined the potential of multi-product biorefineries for conversion of cellulosic biomass. They argue that 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-sized biomass refinery. Their study focused on biorefineries with ethanol as the primary product, and with co-generated power and fermentation-derived co-products. Based on their findings, per unit capital costs decrease substantially with increasing scale, and power co-generation using the feedstock's lignin fraction significantly lowers processing costs. Lynd et al. argue that ethanol selling price can be lowered substantially by co-producing higher value, lower volume products, such as succinic acid. They assume a yield of 85 gallons/ton for initial plants, but believe yields could be improved to 104 gallons with advanced technology.

Kaylen et al. (2000) also note the importance of co-products for an economically viable biorefinery. Using agricultural residues as feedstock and assuming a feedstock cost of $25/ton and ethanol price of $1.25/gallon, a plant producing only ethanol was not found to be profitable. However, when furfural (starting point for producing nylon) was added as a co-product, the plant was profitable at feedstock costs up to $45/ton.

A key to successful commercialization of ethanol and co-product production from lignocellulosic feedstocks is development of processes to obtain high yields of sugars from the cellulose and hemicellulose that make up a large part of these materials. The usual approach is a pretreatment process to alter the structure of the biomass, making the cellulose more accessible to the enzymes that convert the cellulose polymers to sugars (Mosier et al., 2005). Research to date has evaluated several forms of pretreatment (Eggeman and Elander, 2005; Mosier et al., 2005). Dilute acid pretreatment has been used most widely in pilot-scale plants, but the ammonia fiber expansion (AFEX) process appears to have substantial advantages for pretreatment of agricultural residues and grasses. AFEX pretreatment separates lignin from cellulose in the feedstock, thus lowering enzyme requirements. The potential for high yields of sugars and ethanol and the fact that formation of sugar degradation products (which inhibit downstream processes such as fermentation) is minimized are particularly strong points for the AFEX pretreatment.

Methods

In the remaining sections of this paper, the cellulose nanofiber (CNF) product is described, and its potential uses and market are briefly discussed. Then, the integration of CNF production into an ethanol biorefinery using 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 gallon 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 CNF 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 I-O 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

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

The biobased composites developed from cellulose nanofibers could have widespread applications, replacing fiberglass and similar materials. CNFs offer several advantages over fiberglass components. CNFs 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 International (MBI) has proposed a process flow diagram that uses AFEX treatment followed by enzymatic hydrolysis (Raj and McCalla, 2006). The hydrolysate, rich in pentose and hexose sugars, is sent to ethanol fermentation, and the hydrolysate solids are further processed to produce CNF. This process is environmentally benign and does not have the waste stream issues of acid hydrolysis, the process previously used to isolate CNF from wheat straw (Helbert, Cavaille, and Dufresne, 1996).

Because fuels are likely to be the primary product of a mature biorefinery industry (Lynd et al., 2005), this analysis assumed 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 of $1.80/gallon was the average price of ethanol in 2005, FOB 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. Additional updates to the base case model (Aden et al., 2002) included the following:

- Steam will be generated in-house using wheat straw fermentation residue with 65% 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 more fully reported in Leistritz et al. (2006).

Key assumptions were 60% conversion of cellulose to fermentable sugars and 55% conversion of xylan [based on laboratory data from MBI International (Raj and McCalla, 2006)]. 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. Capital costs were estimated at $185 million with total operating costs, excluding by-product credits, of $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. Earnings before interest and income tax (EBIT) were $13.05 million per year providing a return on investment (ROI) of 7.06%. 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.

The CNF production model assumes that 50 tons of wheat straw hydrolysate solids are processed per day, which would generate 1,050 tons of CNF per year. Given that glass fibers sold at prices ranging from $0.59 to $0.91 per pound in 2005 (Knudson and Peterson, 2005), projected selling price was $0.85 per pound. 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 CNF was estimated to be $1.785 million per year with earnings before interest and income tax (EBIT) of $591,849. The production cost of CNF was determined to be $0.57 per pound. The consolidated pro forma income statement (table 2) indicates that the production of CNF would enhance the economic performance of a wheat straw-to-ethanol mill.

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, Dorge, and Martin, 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% (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% recovery rate, from 4 million to 7 million tons of wheat straw should be recoverable.

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.). The cost for hauling semi

Table 1. Financial Summary: CNF Base Case Model

AFEX pretreatment and ethanol production from wheat straw		
Ethanol MGPY = 54,418,608		
Construction Costs:		
	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
		$176,468,305
Other Capital Costs:		
	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 Costs	**$184,918,305**
Projected Statement of Earnings:		
Sales:		
$1.80 / gallon	Ethanol	$97,953,495
$0 / ton	CO_2	$0
$0.05 / kWh	Electricity	$7,454,749
	Total Sales	**$105,408,244**
Production and Operating Expenses:		
$40.00 / ton	Feedstock (907,443 tons)	$36,297,720
$25.00 / ton	Liquid Feed Syrup	$5,676,522
$0.05 / lb.	Cellulase	$6,333,000
$0.10 / lb.	Cellobiase	$7,772,255
$0.125 / lb.	Ammonia	$3,402,914
	Other Raw Materials	$8,358,427
	Utilities	$87,155
	Labor, Supplies, and Overhead	$6,779,249
10 years	Depreciation	$17,646,830
	Total Production Costs	**$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).

loads of straw was estimated at $3.72 per loaded mile, reflecting fuel costs prevailing in 2005 (Leistritz et al.). 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, with a transportation cost of $9.72 per ton.

Table 2. Consolidated Pro Forma Income Statement

Consolidated economic model: Wheat straw to ethanol plus cellulose nanofibers from wheat straw hydrolysate solids			
Description	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
Total Cost of Sales	$67,927,412	$531,327	$68,458,739
Gross Margin	**$37,480,832**	**$1,253,673**	**$38,734,505**
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).

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 give an incentive to supply straw. For purposes of subsequent analysis, straw cost to the plant was assumed to be $40 per dry ton.

The plant was designed to have feedstock storage capacity of three weeks (i.e., approximately 2,300 tons). The remainder of the feedstock was assumed to be stored at field side until needed. No separate cost was estimated for the field-side storage, although this issue will be explored further in subsequent analysis. If it is deemed necessary to provide covered field storage, the bale piles could be covered with plastic tarps at a cost of $2 per ton (Mapemba et al., 2007).

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).

Recent analysis (Leistritz et al., 2006) suggests North Dakota wheat straw can be delivered to a biorefinery at a cost of $40 per dry ton, after paying harvest 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 has a higher content of both cellulose and lignin than switchgrass. Cellulose is the major source of fermentable sugars, while lignin will be utilized as fuel for the biorefinery.

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 (table 1), of which 15% 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 at $26.48 million (table 3).

When production of CNF 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%. 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—i.e., the $53 million of direct economic impacts, through the multiplier process, results in an additional $130 million in secondary (indirect and induced) impacts, for a total of $183 million. Addition of CNF production yields 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. With CNF production, this figure rises to 2,474 (table 4). These jobs are in addition to

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

		Operations	
Sector	Construction	Biorefinery	Biorefinery with CNF
Agriculture (crops)		11.07	11.07
Construction	26.48		
Communications & Utilities			0.12
Transportation		8.82	8.82
Wholesaling, Ag Processing & Misc. Manu.		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 (pymts. to farmers, wages & salaries)		18.45	18.92
Total Direct Impacts	**26.48**	**53.01**	**53.78**

Table 4. Regional Economic Impacts (direct plus secondary) Associated with Biorefinery Construction and Operation, by Input-Output Sector ($ mil.)

		Operations	
Description	Construction	Biorefinery	Biorefinery with CNF
Gross Business Volume by Sector:			
Construction	27.8	3.9	3.9
Transportation	0.3	9.4	9.4
Wholesaling, Ag Processing & Misc. Manu.	0.5	20.4	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 [a]	6.9	43.1	43.7
Total	**64.7**	**182.8**	**185.2**
	Person Years	— Number of Jobs —	
Secondary Employment	793	2,448	2,474

[a] "Other" includes agriculture, mining, communications and public utilities, services, and government.

direct employment at the facility (77 jobs for the biorefinery and 86 if CNF production is added). Facility construction is estimated to result in 793 person years of additional secondary employment.

At first glance, the estimates of secondary employment may appear excessive, but these estimates include the labor required for baling and transporting the straw. Straw harvest would involve baling the straw from more than one million acres, which could easily involve more than 200 farmers and custom baling operators during the two- to three-month harvest window. Transporting the straw to the plant would require at least 100 full-time equivalent (FTE) truckers and loaders. If these workers were considered to be part of the project's direct employment, the employment multiplier would be consistent with values reported for corn ethanol plants [Swenson and Eathington (2006) report employment multipliers of 6.8 to 8.4, depending on the level of local ownership].

Conclusions and Implications

The aim of the project is to commercialize MBI's technology for producing bio-based cellulose nanofibers (CNFs) 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%).
- Adding CNF production to the biorefinery would add several jobs and would enhance the profitability of the venture.

As we have discussed, the analysis presented here is dependent on a number of assumptions regarding output prices, input costs, and yields of products obtained. An ethanol selling price higher than that assumed ($1.80/gallon) would make the biorefinery a more attractive investment, while a lower selling price would obviously reduce its profitability. Similarly, if the wheat straw feedstock could be obtained at a cost lower than the $40/ton used in the analysis, profitability would be enhanced, whereas a higher cost for feedstock would reduce profitability. Perhaps an even greater degree of uncertainty surrounds the yields of ethanol and co-products that may be obtained, given the current state of development of conversion technologies.

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%) were assumed to represent payments to in-state entities. The largest single expenditure was for wheat straw ($36.3 million, or 49% of total operating costs), all of which would be payments to farmers and to those baling and transporting the feedstock.

The local economic impacts of an ethanol biorefinery using agricultural residues as feedstock would be substantially greater than those of the recently constructed corn ethanol plants. For example, a recent study estimated the annual direct economic impacts (payments to in-state entities) of a 50 MGPY corn ethanol plant to be $16.8 million, compared to $53 million for the cellulosic ethanol facility (Hodur, Leistritz, and Hertsgaard, 2006).

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%). 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 under the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 provide for loan guarantees, grants, and other incentives to make first-generation plants a more attractive investment. The first series of grants under these programs was announced in February of 2007, providing $385 million to support six demonstration projects.

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