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Preliminary Feasibility Analysis for an Integrated Biomaterials and Ethanol Biorefinery Using Wheat Straw Feedstock

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Abstract

Biobased products and fuels appear to have a very bright future. A consortium led by 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 producing cellulose nanowhiskers (CNW) as a co-product in an ethanol biorefinery. An ASPEN Plus-based process model was developed to evaluate ethanol production from wheat straw. The base case model generated 54.418 million gallons per year (MGPY) of denatured ethanol, using approximately 900,000 tons per year of wheat straw feedstock. The capital cost was estimated at $185 million. Total operating costs, excluding by-product credits, were $92.4 million per year. Revenue from sales was estimated at $98.0 million per year from ethanol and $7.5 million per year from electricity. The earnings before interest and income tax (EBIT) are $13.1 million per year providing a return on investment (ROI) of 7.06 percent. The production cost of ethanol including by-product credit was determined at $1.56 per gallon. When production of CNW was added to the base case model, the manufacturing cost of producing CNW from wheat straw was estimated to be $.57 per pound. Economic analysis indicated that production of CNW would be an enhancement to the economic performance of a wheat straw to ethanol mill.

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

Glossary

AFEX	ammonia fiber explosion
CNW	cellulose nanowhiskers
EBIT	earnings before interest and income taxes
EBITDA	earnings before interest, income taxes, depreciation, and amortization
MGPY	million gallons per year
MM	million
NREL	National Renewable Energy Laboratory (U.S. Dept. of Energy)
PFD	process flow diagram
ROI	return on investment
T_g	glass transition temperature

Executive Summary

Biobased products and fuels appear to have a very bright future. Concerns about the price and security of petroleum supplies and environmental concerns associated with the use of hydrocarbon fuels and feedstocks (e.g., CO_2 emissions) enhance the outlook for bioproducts. While interest in biobased fuels and products is high, extensive adoption of biofuels using only current technologies could have major impacts on agricultural commodity markets. For example, recent national estimates indicate that if fuel ethanol were to be used at the normal 10 percent ratio in all domestic gasoline consumed, over half of the 2005 record corn crop would be required as raw material. Accordingly, technologies that can produce biofuels and bioproducts from crop residues and other biomass are generating great interest. Technologies are nearing commercialization that would allow a crop residue, such as wheat straw, to be processed in a biorefinery to produce a variety of products including ethanol, cellulose nanofibers (to be used in a fiberglass-substitute product), and high value chemicals as succinic acid, butanetriol, and xylitol. The biorefinery concept is economically attractive because it offers the potential to capture greater value from the biomass feedstock.

A consortium led by 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 producing cellulose nanofibers as a co-product in an ethanol biorefinery. The addition of cellulose nanowhiskers as a co-product in an ethanol biorefinery appears to significantly improve the economics of the overall production process by capturing additional value from the what straw feedstock.

Cellulose nanowhiskers (CNW) are defined as fibrous, high-purity, single crystals with nanometric dimensions. Because of the quantity and crystalline nature of wheat straw cellulose, there is a potential to produce cellulose nanowhisker fibers for the structural enhancement of polymer matrices. CNW would reinforce a polymer-based molded component like fiberglass reinforces a car bumper. Many industries, such as automotive parts, railway, aircraft, irrigation systems, furniture, and sports and leisure, could utilize and benefit from CNW reinforced components.

Wheat straw CNW have several advantages when compared to inorganic fillers. CNW fillers are: 1) renewable, 2) relatively low in cost, 3) supportive of an agricultural-based economy, 4) capable of improving the storage shear modulus in thermoplastics above the Tg (glass transition temperature) (fibers bond well with polymers and make a strong rigid reinforcement), 5) comparatively easy to process, 6) generally lighter in weight than other comparable fillers, and 7) relatively reactive (pertaining to the addition of chemical functionality). The potential market for CNW is also substantial. The current market for fiberglass in automobiles is 1.67 billion pounds with a market value of $1 billion. While CNW components would not be suitable in all applications or likely to completely displace fiberglass anytime in the foreseeable future, these figures demonstrate that the potential market is significant. The worldwide market for polymer nanocomposites was valued at $90.8 million in 2003 and could be as large as $211.1 million by 2008.

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. Accordingly, this analysis assumed that ethanol would be the primary product from a wheat straw biorefinery. An ASPEN Plus-based process model was developed to evaluate technical and economic performance of ethanol production from AFEX treated biomass. Basic engineering and economic parameters have been established for a 50 million gallon per year (MGPY) ethanol process. The base case model generated 54.418 MGPY of denatured ethanol. The capital cost was estimated at $185 million with total operating costs, excluding by-product credits, of $92.35 million per year. Revenue from sales was estimated at $98 million per year from ethanol and $7.5 million per year from electricity. The earnings before interest and income tax (EBIT) was $13.1 million per year providing a return on investment (ROI) of 7.06 percent. The earnings before interest, income tax, depreciation, and amortization (EBITDA) was $30.7 million per year. The production cost of ethanol including by-product credit was estimated to be $1.56 per gallon.

Production of CNW was then added to the base case model. The 50 MGPY wheat straw to ethanol plant would process over 100 tons of wheat straw per hour. The model assumes that 50 tons per day of wheat straw hydrolysate solids would be processed to produce 1,050 tons of CNW per year. The model thus assumes utilizing only a small portion of the hydrolysate solids for CNW production. With the limited information available on the most efficient way to produce quantities of CNW, it seems prudent to project a smaller than maximum amount of CNW product. Also by processing only a small amount of solids into CNW, the power generating assumptions in the base model would not be affected The manufacturing cost of producing CNW from wheat straw was estimated to be $.57 per pound. Economic analysis indicated that production of CNW 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. 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 should be recoverable. Baling costs were estimated to average $12.14 per ton, and transportation costs (based on a 50-mile draw radius) were estimated to average $9.72 per ton. A grower payment of $18.14 per ton to cover nutrient value and an incentive would supply the plant with straw feedstock at a cost of $40 per ton.

An extensive examination of recent literature provides insight regarding competitive feedstocks. Corn stover and switchgrass are feedstocks most likely to compete with wheat straw, at least in the short term. Comparing cost estimates for corn stover and switchgrass from the literature with cost estimates calculated for North Dakota wheat straw indicated that wheat straw appears to have a $5 to $10 per ton cost advantage over corn stover and a $10 to $15 per ton or more advantage over switchgrass.

Construction and operation of the biorefinery would result in substantial expenditures. Total operating expenditures for the biorefinery were estimated to be $74.6 million annually, of which $53 million were expenditures made to North Dakota entities. The largest single expenditure item was for the wheat straw feedstock ($36.3 million). 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 increases total impacts to $185.2 million. Employment estimates for the biorefinery were estimated at 77 jobs; 86 jobs with the addition of CNW. In addition to jobs directly related to biorefinery and CNW production operation, biorefinery operations were estimated to lead to about 2,448 secondary jobs. With CNW production included, this figure rises to 2,474 jobs.

North Dakota's relative ability to attract industrial participants in the biobased economy also has been analyzed. Key attractiveness factors were combined to make a composite ranking which was then compared to other states in the region. This comparison is not only applicable to the wheat straw to biomaterials effort specifically studied here but to other initiatives in the bioindustry sector as well. The factors found to be most critical were: (a) Level of state funding of bioprocessing research and promotion, (b) Presence of a formal strategic plan for local bioprocessing, (c) Commitment of the local commercial sector, (d) Presence of nationally recognized bioprocessing research institutions, (e) Scale of local life sciences industry, (f) Training and education facilities for bioprocessing, (g) Risk capital availability, (h) Biofuels industry scale, and (i) Raw material availability. North Dakota's competitive position was analyzed relative to seven states deemed to be its likely competitors: South Dakota, Minnesota, Iowa, Wisconsin, Illinois, Nebraska, and Michigan.

Although North Dakota ranked the lowest overall among the states analyzed, this does not mean that the state does not possess significant resources. Specific resources include:

- Emerging bioprocessing programs at North Dakota State University and University of North Dakota
- NDSU's nationally recognized Polymers and Coatings Department
- Successful implementation of the Technology Corridor and its rapid growth
- Recognition of the opportunities in bioprocessing by key state leaders
- Recent announcements of significant investment in biofuels production
- Identification of potential private venture investors in the wheat straw biomaterials project
- Raw material supply likely superior to the other states

While North Dakota posses significant resources, considering the state's current overall attractiveness, the conclusion must be drawn that significant efforts and investment by both the public and private sectors are required for North Dakota to reach parity with its likely competitors.

While North Dakota is ranked low in overall attractiveness, its positioning for the wheat straw biomaterials project is significantly higher. A different profile emerges when considering this specific initiative. For this specific opportunity, North Dakota appears to be quite competitive. Three factors (North Dakota's wheat straw supply, significant interest by commercial investors, and the NDSU Polymers and Coatings Department resource) work to overcome the deficiencies noted earlier for overall industry competitiveness. The recent emergence of a significant biofuels sector will help to improve the state's attractiveness and strengthen its position relative to this initiative.

The project team has reached two key conclusions. First, commercial investment is feasible at this stage of the enterprise development process The project team will be working with private investor organizations to facilitate commercialization. Second, the wheat straw to biocomposite business should be developed in conjunction with a biorefinery, the primary product of which will be fuel ethanol, initially converting starch to ethanol and advancing to cellulosic raw materials. The team will also initiate discussions with participants in North Dakota's emerging ethanol industry to explore co-location possibilities and possible business configurations.

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Introduction

Biobased products and fuels appear to have a very bright future. Forces that enhance the outlook for bioproducts include (1) concerns about prices and security of supplies of petroleum products and (2) environmental concerns associated with the use of hydrocarbon fuels and feedstocks (e.g., CO_2 emissions). The recent growth in ethanol production (3.9 billion gallons nationwide in 2005, up 144 percent from 2000) exemplifies the potential for rapid growth of biobased fuels.

Extensive adoption of biofuels, based on current technologies, could have major impacts on agricultural commodity markets. For example, recent national estimates indicate that if fuel ethanol were to be used at the normal 10 percent ratio in all domestic gasoline consumed, over half of the 2005 record corn crop would be required as raw material. Similarly, it is estimated that if biodiesel blends at recommended ratio levels were used for all domestic diesel needs, raw material requirements would exceed the 2005 record soybean crop by over 50 percent. Not surprisingly, technologies to produce bioproducts from crop residues and other biomass are generating great interest. Technologies are nearing commercialization that would allow a crop residue, such as wheat straw, to be processed in a biorefinery to produce a variety of products including cellulose nanofibers (to be used in a fiberglass-substitute product), ethanol, and such high value chemicals as succinic acid, butanetriol, and xylitol. The biorefinery concept is economically attractive because it offers the potential to capture greater value from the biomass feedstock (Lynd et al. 2005).

A consortium led by 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 an ethanol biorefinery plant (see Figure 1) to the cellulose nanofiber production system. The result appears to significantly improve the economics of the overall production process by capturing additional value from the wheat straw feedstock.

There is a growing interest in natural/bio-fibers as reinforcements for composites, potentially replacing the glass fibers used in industry today. Advantages of natural fibers include a superior strength to weight ratio, biodegradability, recyclability, carbon dioxide neutrality, and potentially lower cost to produce. The current NDSU project is focused on commercializing technology for producing biobased cellulose nanofibers (nanowhiskers) from wheat straw.

The biobased composites developed from the cellulose nanofibers could have widespread applications, replacing fiberglass and similar materials. The first market being analyzed is the automotive industry. MBI International, a scientific participant in the NDSU project consortium, is analyzing the integration of biomaterials into the automotive supply chain, focusing on components such as interior elements, exterior panels, and suspension parts.

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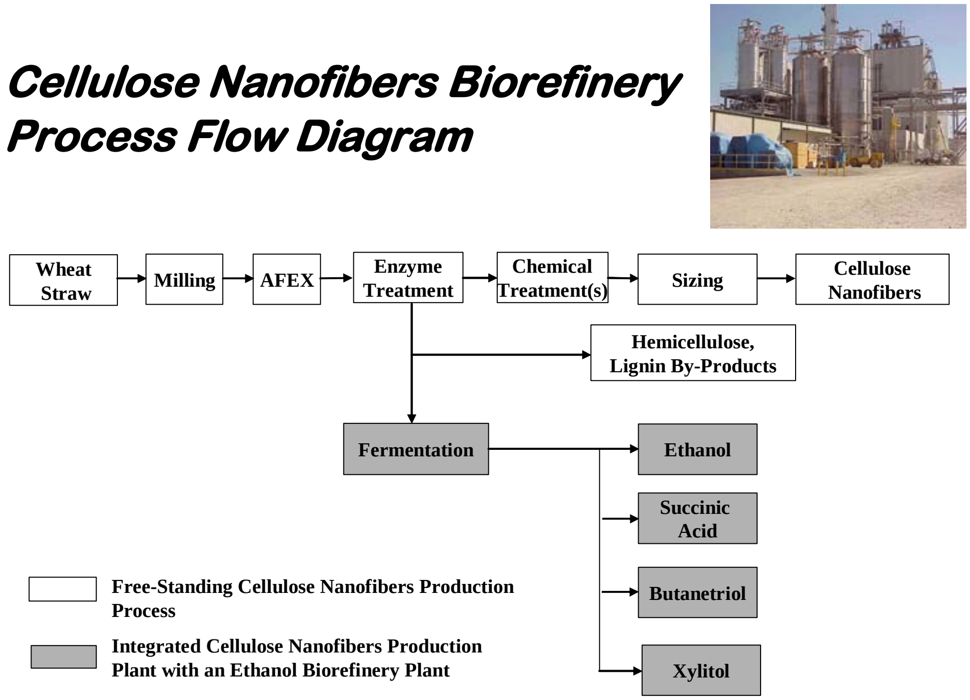

Figure 1. Cellulose Nanofibers Biorefinery Process Flow Diagram

In the remaining sections of this report, the cellulose nanowhisker (CNW) product is described, and its potential uses and market are briefly discussed. Then, an analysis of ethanol production from wheat straw feedstock is presented. The third section assesses the effects of producing CNW as a secondary product in a wheat straw ethanol plant. An assessment of the availability and cost of wheat straw feedstock is presented, followed by an assessment of availability and cost of competing feedstocks. Then, the potential economic impact of a 50 million gallon per year (MGPY) wheat straw biorefinery is presented. North Dakota's competitive position in biorefining is examined by comparing North Dakota with seven regional competitors on a number of criteria. Finally, the next steps for developing a biomaterials industry in North Dakota are discussed.

Potential Production of Cellulose Nanowhiskers from North Dakota Wheat Straw

Over the past decade (1995-2004), between 9.2 and 16.8 million tons of wheat straw are estimated to have been produced annually in North Dakota, of which 43 percent is estimated to be recoverable by current harvesting methods (Coon and Leistritz 2006). Harvesting this agricultural residue is justified provided value-added products can be generated. The potential profitability associated with converting wheat straw to ethanol is exemplified by Abengoa's facility which is planned to be operational in Spain by the autumn of 2006 (Biotechnology Industry Organization 2006). In addition to ethanol, other potentially valuable products can be generated from wheat straw. These include using the distillers stream as animal feed, converting the arabinoxylan fraction to xylitol or butanetriol, and combusting the lignin fraction to produce energy.

Because of the quantity and crystalline nature of wheat straw cellulose, there is a potential to produce cellulose nanowhisker fibers for the structural enhancement of polymer matrices. CNW are defined as fibrous, high-purity, single crystals with nanometric dimensions. Cellulose comprises 34 to 40 percent by weight (wt %) of wheat straw, and the crystallinity of this cellulose ranges from 43.2 to 47.4 percent (the crystallinity is determined from wide-angle X-ray diffraction) (Liu et al. 2005). Nanowhisker length ranges from 150 to 300 nanometers (nm) and the width is approximately 5 nm (Helbert et al. 1996).

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). Products in the automotive parts, railways, aircraft, irrigation systems, furniture industries, and sports and leisure industries could utilize and benefit from CNW reinforced components (Samir et al. 2005).

Wheat straw CNW have several advantages when compared to inorganic fillers. CNW fillers are: 1) renewable, 2) relatively low in cost, 3) supportive of an agricultural-based economy, 4) capable of improving the storage shear modulus in thermoplastics above the Tg (glass transition temperature) (fibers bond well with polymers and make a strong rigid reinforcement), 5) comparatively easy to process, 6) generally lighter in weight than other comparable fillers, and 7) relatively reactive (pertaining to the addition of chemical functionality) (Samir et al. 2005).

The potential market for CNW is also substantial. The current market for fiberglass in automobiles is 1.67 billion pounds with a market value of $1 billion. While CNW components would not be suitable in all applications or likely to completely displace fiberglass anytime in the foreseeable future, these figures demonstrate that the potential market is significant (Knudson and Peterson 2005). In order to compete with glass fibers in the current automotive supply chain, CNW must be cost competitive. Glass fibers were selling at prices ranging from $0.59 to $0.91 per pound in 2003.

The bench-scale method currently used to isolate CNW from wheat straw (Helbert et al. 1996) uses acid hydrolysis to isolate the crystalline cellulose. Acid hydrolysis produces gypsum, and gypsum disposal becomes an environmental concern and a burden to processing cost. Furthermore, the use of sulfuric acid in the acid hydrolysis process results in esterification, a functionality that can lead to difficulties when mixing with hydrophobic thermoplastics. This process can produce the fillers from wheat straw, but it is not likely that this process can become economically viable. Because of the issues associated with acid hydrolysis, MBI has developed an alternative process for isolating CNW.

Process Description

MBI has proposed a process flow diagram (PFD) that uses ammonia fiber explosion (AFEX) treatment followed by enzymatic hydrolysis (Figure 2). The hydrolysate, rich in pentose and hexose sugars, is sent to ethanol fermentation and the hydrolysate solids are further processed to produce CNW. To isolate CNW from these solids the following processes are followed: 1) Pulping, 2) Neutralization, 3) Filtration, 4) Bleaching, and 5) Filtration (MBI 2006b).

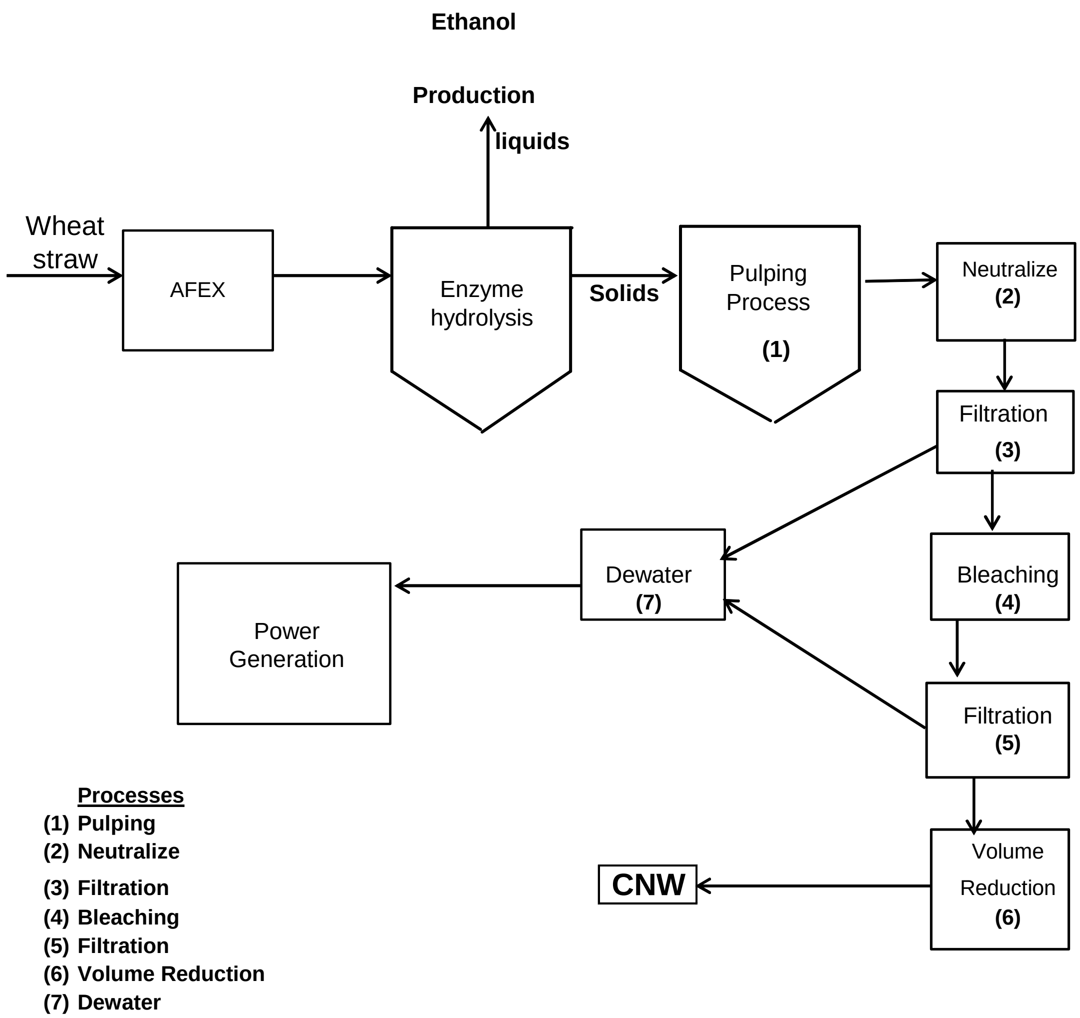

Figure 2. Process Flow Diagram - CNW from Wheat Straw Hydrolysate

This process is environmentally benign and does not have the waste stream issues of acid hydrolysis. Enzymatic hydrolysis of AFEX treated materials does not produce compounds that are inhibitory to fermentations, whereas acid hydrolysis produces furfural compounds that are generally inhibitory to fermentations and require a further step to remove the furfurals. The crystalline portion of the wheat straw cellulose is the source of the nanowhiskers, and a lesser enzymatic hydrolysis seems to breakdown the amorphous cellulose while leaving the crystalline cellulose intact. Further advantages of AFEX include some solubilization of the lignin and hemicellulose, allowing a portion of these materials to be removed in the hydrolysate. Application of a milder pulping step to extract the remaining lignin and hemicellulose decreases the manufacturing costs.

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. An ASPEN Plus-based process model was developed to evaluate technical and economic performance of ethanol production from AFEX treated biomass. Basic engineering and economic parameters have been established for a 50 MGPY ethanol process (MBI 2006a).

The biomass used for the study was wheat straw with 5 percent moisture. The average composition of wheat straw based on MBI's in-house analysis is provided in Table 1.

Table 1. Average Wheat Straw Composition (wt. basis)

Biomass Composition	
	Dry Basis
XYLAN	20.61%
H20	- -
CELLULOSE	35.44%
LIGNIN	19.80%
ARABINAN	2.84%
MANNAN	0.00%
GALACTAN	1.11%
STARCH	0.01%
OIL, ASH, & MISC	19.89%

The price of ethanol, biomass, and other market sensitive assumptions are listed in Table 2. Ethanol price was based on average price for ethanol F.O.B. Omaha, NE for 2005 as reported on the Official Nebraska Government Website at: http://www.neo.state.ne.us/statshtml/66.html. Average rack price for ethanol was $1.80 per gallon for 2005. Current market price for textile grade cellulase (Spezyme CP) is $5 per kg based on the Genencor International (GI) estimate. GI is currently working on reducing the cost of enzyme. The model assumption of $0.05 per lb. cellulase is based on Report TP-510-32438 (Aden 2002). Current market price of cellobiase (Novozyme 188) is $25 per liter. For simplicity, the cost was assumed at $0.10 per lb. These assumptions need to be validated by thorough investigation.

Table 2. Market Sensitive Assumptions for AFEX-Ethanol Process

Market Sensitive Assumptions		
Wheat Straw	$40.00	Per US ton
Ammonia	250.00	Per US ton
Liquid Feed Syrup	25.00	Per US ton
Cellulase	100.00	Per US ton
Cellobiase	200.00	Per US ton
Ammonium Phosphate	180.00	Per US ton
Potassium Phosphate	180.00	Per US ton
Make-up Water	1.00	Per mgal
Electricity	0.05	Per kWh
Natural Gas	5.00	Per mcf
Ethanol	1.80	Per gal

Process Description

The unit operations included in the process model are feedstock cleaning, AFEX pretreatment, ammonia separation, simultaneous saccharification and fermentation (SSF), ethanol distillation, molecular sieve separation, stillage concentration, lignin separation, and combustion. The process flow diagram used for the model is attached as Appendix Figure 1.

The process would begin with wheat straw bales delivered by trucks and stored under cover. The bales are broken, and the straw is ground to a 0.5"-1" particle size in mills. The ground straw then is mixed with recycled water and ammonia in a continuous AFEX reactor at 300-350 pounds per square inch gauge (psig), 90^{o}C, for 30 minutes. The mixture is exploded to a flash drum at 30 psig. The flash vapor comprised mostly of ammonia is compressed, condensed, and recycled to the reactor. The solids are dried using an indirect, rotary dryer that recovers most of the remaining ammonia. The dryer vapors are condensed and recycled to the reactor.

The dried solids are mixed with make-up water and converted to ethanol by *Zymomonas mobilis* or a suitable organism using SSF. In the fermentation step, sugars generated by the hydrolysis are converted to ethanol and carbon dioxide. Carbon dioxide is scrubbed to remove traces of ethanol and may be processed to liquid CO_2 in a separate facility.

The ethanol is recovered from the fermented beer by distillation and concentrated to approximately 95 percent (v/v ethanol). Ethanol is then dried in a molecular sieve and transferred to the storage and shipping area. Residue from the bottom of the first distillation column (Beer Column) is concentrated and filtered using Pneumapress to remove lignin residue. The thin stillage is partly recycled to the SSF fermentor, and the rest is concentrated by evaporation. The concentrated syrup is mixed with the lignin residue and used as boiler feed.

The following updates were made to the base case model.

- Steam will be generated in-house using wheat straw fermentation residue with 65 percent combustion efficiency. Design and capital cost for the boiler are based on Foster-Wheeler design reported in NREL's Technical Report TP-510-32438.

- 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. Further study is required in this area to verify boiler performance and emission levels.

- Ammonia loss associated with the AFEX process will be less than 2 percent of the feed.

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

- Dryer vapors containing ammonia and steam will be condensed and recycled to the AFEX reactor. Distillation process will not be required to separate water and ammonia. More experimental work is required to verify this assumption.

- AFEX reactor cost estimate is based on Foster-Wheeler design. Pilot plant study and more rigorous reactor design are required prior to scale-up and commercialization of the AFEX process.

- Pneumapress will be used to separate solids from stillage. Final lignin residue will have 50 percent moisture.

- AFEX treated wheat straw is converted to ethanol in SSF using genetically engineered microorganisms capable of converting both glucose and xylose to ethanol. Solid loading is assumed at 25 percent.

- Enzyme and nutrient loading in SSF are based on MBI's current experimental work on AFEX. Liquid Feed Syrup will be used as an inexpensive additive to enhance the fermentation efficiency.

- Capitalization costs were assumed at twice the costs of a 40 MGPY corn-based dry mill ethanol plant.

- Turbo generator capital estimate was based on NREL's report TP-510-32438.

- Installation factors for feed handling, fermentation, and ethanol recovery equipment were updated using MBI's dry mill ethanol model.

Base Case Model

For the base case, current experimental loadings of moisture, ammonia and enzymes, temperature, pressure, and reaction times were assumed. The effects of process parameters on the overall economics are dependent on the technical assumptions. The design basis and technical assumptions are summarized in Table 3.

Table 3. Design Basis and Technical Assumptions for AFEX-Ethanol Process

Technical Assumptions		
Cellulose Conversion	60%	
Xylan Conversion	55%	
Cellulase Loading	15.00	FPR/g cellulose
Cellobiase Loading	40.0	CBU/g cellulose
Ammonia Loading	1:1	wt/wt dry biomass
Ammonia Loss	1.5%	of feed ammonia
Moisture Loading	1.5:1	wt/wt dry biomass
AFEX Temperature	90	C
AFEX Pressure	200-250	psi
AFEX Reaction Time	30	min

For the base case scenario, 50 MGPY of anhydrous ethanol was set as the target. The feedstock is wheat straw. The list of all the raw materials used for the process is provided in Table 4.

Table 4. Raw Material – Consumption and Costs

	kg/hr	mm$/yr
Wheat Straw	103,143	36.29
Clarifier Polymer	29	0.67
Ammonia	1,470	3.41
Liquid Feed Syrup	24,496	5.76
Cellulase	6,838	6.34
Cellobiase	4,196	7.78
Ammonium Phosphate	1,960	3.27
Potassium Phosphate	1,960	3.27
NaOH	980	1.06
Boiler Chemicals	1	0.03
Chemicals	2	0.04
Wastewater Chemicals	3	0.01
Wastewater Polymers	0.2	0.01

Simulation runs provided the mass and energy balances for the process. Ethanol and by-products production rates and the annual revenue are provided in Table 5.

Table 5. Product Formation Rates and Annual Generated Revenue

	kg/hr	mm$/yr
Ethanol	18,318	97,953,495
CO_2	16,818	0.00

The process-generated lignin residue was used to generate steam in a circulating fluidized bed combustor. The original design reported in NREL's Technical Report TP-510-32438 was based on Foster Wheeler Energy specifications. The lignin heat content was assumed by NREL at 4,179 Btu per lb. Boiler efficiency was 65 percent. Part of the generated steam was used for process heating. Excess steam was converted to electricity using a turbo generator based on ABB Power Generation Systems design. The turbine efficiency was assumed at 80 percent. The performances of the boiler and turbine generator are provided in Table 6.

Table 6. Energy Balances for Lignin Boiler and Turbo-generator

Boiler Energy Balance

	kg/hr	lb/hr	Btu/lb	mmBtu/hr	
Feed	115,785	255,305	4,179	1,067	
Efficiency	65%				
Steam Output	314,512	693,499		693	
Ratio	3	3			

Turbine Energy Balance

	kg/hr	lb/hr	Btu/lb	mmBtu/hr	kW
Excess Steam	67,176	148,123		148	
Efficiency	80%				
Output				118	34,730

The mass and energy balance results generated by the model were exported to a separate spreadsheet to evaluate the process economics. AFEX reactor cost estimates were based on Foster Wheeler design. Pilot plant study and more rigorous reactor design are required prior to scale-up and commercialization of the AFEX process. 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 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. Equipment costs originally estimated by NREL and updated by Foster Wheeler for corn stover to ethanol process were used to calculate the capital costs. USDA, NREL, Chemical Marketing Reporter, and DOE data banks were used as sources for raw material costing.

Financial Summary

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, with earnings before interest, income tax, depreciation, and amortization (EBITDA) of $30.70 million per year. 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 7.

Producing Cellulose Nanowhiskers as a Secondary Product

The manufacturing cost of producing CNW from wheat straw has been estimated to be $.57 per pound (Appendix Table A). This estimate is based on:

1. The Yields, Process Parameters and Assumptions found in Appendix Table B
2. The Mass Balances found in Appendix Table C
3. The Capital Cost estimates in Appendix Table D
4. The manufacturing costs presented in Appendix Table A

This model assumes processing 50 tons per day of wheat straw hydrolysate solids, which produces 1,050 tons of CNW per year. The model assumes utilizing only a small portion of the hydrolysate solids from the 50 MGPY wheat straw to ethanol plant which processes over 100 tons of wheat straw per hour. With the limited information available on the most efficient way to produce quantities of CNW, projecting a smaller than maximum amount of CNW product is prudent. It is also believed that by processing only this small amount of solids, the power generating portion of the wheat straw ethanol plant would not be affected.

Table 7. 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%**

The cost of wheat straw hydrolysate solids was assumed to be zero. Electricity, steam, and water costs have yet to be determined. Estimates were used in this model. Currently, sodium hydroxide (NaOH) represents the largest material cost. The use of AFEX treatment may decrease the amount of NaOH needed to extract the remaining lignin and hemicellulose. Current bench scale experiments will better define this issue.

1. The model generates 1,050 tons of CNW per year with a projected selling price of $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 CNW was estimated to be $1.78 million per year. Earnings before interest and income tax (EBIT) are $591,849. The production cost of CNW was determined to be $0.57 per pound.
2. Filtration
3. Bleaching
4. Filtration

This model's production of CNW utilizes less than 1 percent of the available wheat straw hydrolysate solids from the Ethanol Mill model. Any expansion of CNW production would depend on the market for the product based on the comparative value for composites made from CNW vs. composites made from other structural fibers. The value of CNW fibers from wheat straw hydrolysate solids, as well as the actual costs of production for CNW from wheat straw, is yet to be determined.

The Consolidated Pro Forma Income Statement indicates that the production of CNW would be an enhancement to the economic performance of a wheat straw to ethanol mill (Table 8).

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.

During the period 1980-2004, the acreage of all wheat harvested in North Dakota has ranged from 7.2 million acres (1988) to 12.2 million acres (1996) (Table 9). State average wheat yields ranged from 41.1 bushels per acre (1994) to 14.3 bushels per acre (1988). North Dakota has been divided into nine crop reporting districts (Figure 3). In recent years, the Northeast and Northwest districts have reported the largest acreages of wheat harvested (Coon and Leistritz 2006).

Table 8. Consolidated Pro Forma Income Statement

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

	Wheat Straw to Ethanol Model 50 mm gal/yr	Nanowiskers From Wheat Straw Hydrolysate	Wheat Straw to Ethanol Plus Nanowiskers
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%

Table 9. Estimated Wheat Straw Production for All Wheat, Using the Harvest Index Formula, North Dakota, 1980-2004

Year	Area Harvested	Yield Per Acre	Straw Produced Per Acre	Total Straw Production[1]
	----acres-----	---bushels---	---pounds---	----tons----
1980	9,620,000	18.7	1,592.7	7,660,644.0
1981	11,690,000	28.4	2,418.8	14,137.787.6
1982	10,490,000	31.5	2,682.8	14,071,313.6
1983	7,205,000	26.9	2,291.0	8,253,437.5
1984	8,660,000	32.8	2,793.5	12,095,959.8
1985	8,870,000	36.4	3,100.1	13,749,078.9
1986	9,380,000	31.2	2,657.3	12,462,524.7
1987	9,300,000	29.5	2,512.5	11,682,978.2
1988	7,230,000	14.3	1,217.9	4,402,738.9
1989	10,330,000	23.5	2,001.5	10,337,530.0
1990	10,910,000	35.3	3,006.5	16,400,158.9
1991	9,790,000	31.0	2,640.2	12,923,882.1
1992	11,420,000	41.1	3,500.4	19,987,410.2
1993	10,800,000	31.0	2,640.2	14,257,193.7
1994	11,238,000	31.7	2,699.8	15,170,395.1
1995	11,114,000	27.0	2,299.6	12,778,584.7
1996	12,515,000	31.6	2,691.3	16,840,948.1
1997	11,025,000	24.3	2,069.6	11,408,629.4
1998	9,610,000	32.3	2,750.9	13,218,266.7
1999	8,657,000	28.0	2,384.7	10,322,242.3
2000	9,413,000	33.3	2,836.1	13,348,144.3
2001	9,080,000	32.2	2,742.4	12,450,601.1
2002	7,915,000	27.3.	2,325.1	9,201,574.9
2003	8,500,000	37.3	3,176.8	13,501,324.0
2004	7,775,000	39.4	3,355.6	13,045,034.1

[1] Dry weight basis. Estimates represent total straw production, only a portion of which is recoverable. Current estimate is that 43 percent of total straw production can be recovered through baling.

Source: National Agricultural Statistics Service. 2005. *Agricultural Statistics - Data Base - North Dakota*. U.S. Department of Agriculture, NASS Internet Web Site.

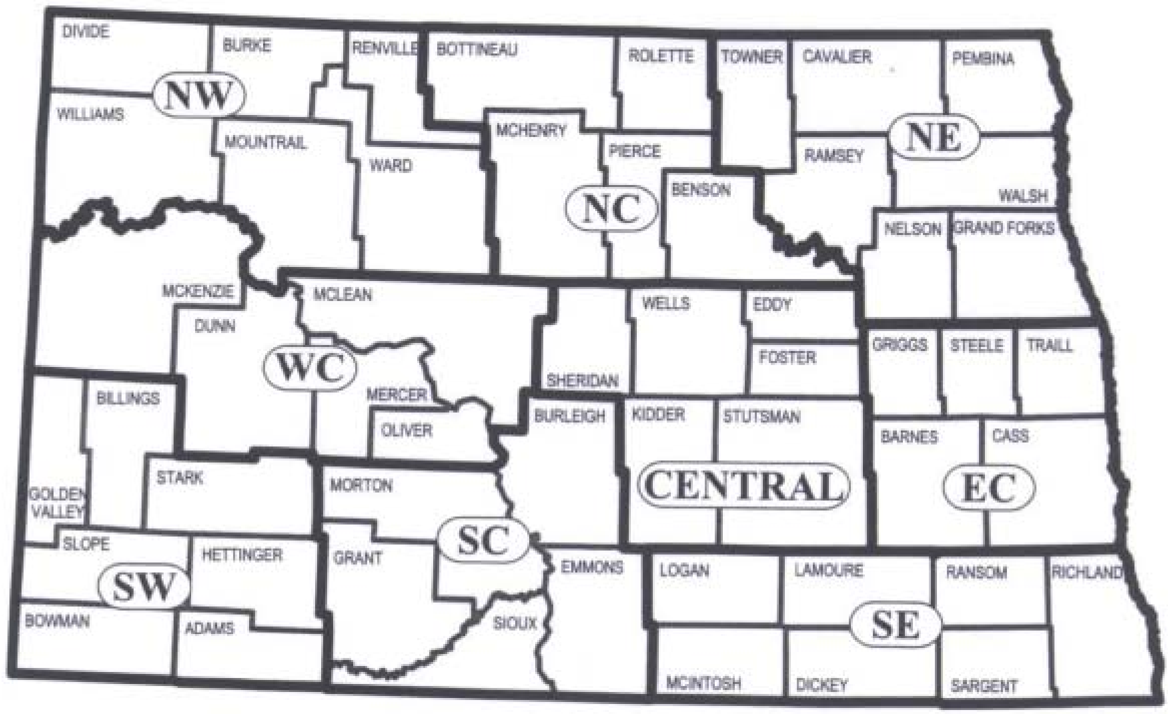

Figure 3. North Dakota's Nine Agricultural Statistics (Crop Reporting) Districts

Straw Production

Production of wheat straw can be estimated based on grain yield, using a Harvest Index formula (Ottman et al. 2000). The formula is as follows:

$$\text{Harvest Index} = \frac{\text{dry grain weight}}{\text{total plant dry weight}} = 0.38$$

For example, in 2004 the statewide average wheat yield of 39.4 bushels per acre, would produce an estimated 3,355.6 pounds per acre of straw. However, only a portion of this straw can be baled and removed from the field. A reasonable rate of straw recovery for North Dakota has been determined to be 43 percent (Lundstrom 1994), and this value will be 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 should be recoverable.

Nutrient Value of Wheat Straw

Wheat straw has potential nutrient value to the farmer. Jones (2003) indicates that the nutrient content of wheat straw is as follows:

N	=	0.75 percent of straw weight
P_2O_5	=	0.225 percent of straw weight
K_2O	=	1.625 percent of straw weight

Based on fertilizer prices for the spring of 2006, the nutrient value of straw was estimated at $12.27 per ton.

Cost of Baling Straw

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 (Coon and Leistritz 2006; North Dakota Agricultural Statistics Service 2004).

Cost of Hauling Straw

The cost per loaded mile for hauling semi loads of straw was estimated at $3.72 per loaded mile, reflecting fuel costs prevailing in 2005 (Coon and Leistritz 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.

Wheat Straw Price and Producer Net Returns

Various approaches could be taken to determine the selling price of straw to the biorefinery and hence the net return to producers. Coon and Leistritz (2006) obtained straw prices from the Rock Valley, IA, Hay and Straw auction and adjusted them to reflect North Dakota market conditions, arriving at a price of $36.92 per ton. This price would yield a producer net return of $2.79 per ton:

Price	$36.92 per ton
Transport cost	9.72 per ton
Baling cost	12.14 per ton
Nutrient value	12.27 per ton
Producer net return	$ 2.79 per ton

Another approach would be to establish a desired level of producer net return and use that together with the other costs to establish the straw price. Previous analyses have used $10 per ton as the producer net return (U.S. Department of Energy 2003). Using this approach, the cost to the plant would be $44.13 per ton, if the full nutrient value were included.

Transport cost	$ 9.72 per ton
Baling cost	12.14 per ton
Nutrient value	12.27 per ton
Producer net return	10.00 per ton
Total	$44.13 per ton

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

Alternative 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).

A recent study by Perlack et al. (2005) examined the potential of U.S. land resources to supply a biomass-based industry and concluded that agricultural and forest lands have the potential to provide in excess of 1.3 billion dry tons (dt) per year by mid-century (assuming a variety of technology and yield improvements and land use changes). Of the total, about 933 million dt (72 percent) would come from agricultural lands, comprised of 425 million dt of annual crop residues, 377 million dt of perennial crops, 56 million dt of grains used for biofuels, and 75 million dt of animal manures, process residues, and other miscellaneous feedstocks. Among the assumptions key to these estimates are: (1) increased yields, (2) harvest technologies capable of recovering a higher percentage of crop residues (up to 75 percent), (3) all cropland managed with no-till practices, and (4) 55 million acres of CRP and other cropland dedicated to perennial bioenergy crops (e.g., switchgrass).

Walsh et al. (2000) examined potential biomass supplies in each of the 48 states. The leading states in biomass availability were all in the Midwest/Northern Great Plains region. Illinois and Iowa were the leading states in biomass availability, followed by Nebraska, Kansas, Minnesota, and North Dakota in a virtual tie (all with between 21 and 22 million tons at $50 or less). (Note: This analysis was based on 1995 prices. Costs of biomass harvest, transportation, etc., would be considerably higher if current energy costs were taken into account.) In Illinois and Iowa, agricultural residues dominated the biomass supply at prices between $30 and $40 per dry ton. These residues were predominately corn stover (94 percent in Illinois and 99 percent in Iowa). As biomass prices rise to $50, energy crops assume a growing importance in both states, with switchgrass appearing to be the most attractive energy crop. The other states showed similar patterns, with agricultural residues being the first major source of biomass, followed by switchgrass as an energy crop.

Gallagher et al. (2003) estimated biomass supplies from crop residues. Supply functions are estimated for major agricultural production regions (Corn Belt, Great Plains, West Coast, Delta), considering harvest costs, livestock feed demand, and other values of residues (erosion control, nutrients). Key findings include:

1. Wheat straw in the Northern Great Plains can be an economical source of biomass.

2. Livestock demand is less of a factor for wheat straw than for most other forms of biomass, as the feed value is estimated to be only $21.21 per ton (compared to $41.90 per ton for corn stover).

3. The Corn Belt and Great Plains account for 90+% of the total potential crop residue supply.

The studies reviewed indicate that corn stover is the agricultural residue most likely to seriously compete with wheat straw as a feedstock, while switchgrass is the energy crop most likely to provide competition. In the sections that follow, these two competing feedstocks are addressed specifically.

Corn Stover

Sheehan et al. (2004) describe a life-cycle model for the production of ethanol from corn stover in Iowa. Corn stover is assumed to be harvested as round bales and transported to the plant with a 17-bale wagon. The cost to the plant includes: (1) direct cost of baling and transport, (2) farmer profit of $10 per dry metric ton (mt), and (3) fertilizer (nutrient) replacement cost of $7 per dry mt. The base cost for delivered feedstock is $46 per dry mt ($41.62 per ton), rising as more plants are built, requiring longer hauls. Adjusting for current costs of transportation and fertilizer replacement would likely raise these costs by several dollars per ton.

Sokhansanj et al. (2002) examine published data on collecting corn stover using field machinery to estimate collection efficiency and costs. Main collection operations for stover include cutting and shredding, windrowing, baling, and transport to a storage site. The shredding and windrowing operations can be combined, but at the risk of inadequate drying. The stover harvest season is shorter than the corn (grain) harvest season. In central Indiana, losses of stover become excessive (>50%) after November 10 (a date at which the grain harvest is only 57 percent completed in an average year). The fraction of stover available for harvest is estimated to be 45 percent of total stover produced. Baling can be with round or square bales (roughly 1,200# bales). For an assumed stover yield of 1.27 tons per acre, the estimated cost for round baling and delivery to a storage site 5 miles away would be $19.70 per dry ton. (Base year for costs is not specified.)

This paper points out, indirectly, two advantages of wheat straw: (1) one or two less harvest operations (bale straw direct from combine windrow) and (2) longer harvest window/less risk of losses due to weather.

Switchgrass

Perrin and his colleagues (2003) report on a study of switchgrass production in Nebraska, North Dakota, and South Dakota. Experimental plots were established at four sites in Nebraska, four in South Dakota, and three in North Dakota. Results to date indicate that yields of 2.5 to 4.5 tons per acre may be achievable by the second year after establishment. Production costs are estimated to be about $30 per ton, while land charges would add another $10 per ton (for non-tillable land) to $30 per ton (for marginal row cropland). Thus, the farm-gate price is estimated to fall in the range of $40 to $60 per ton. A transportation cost of $10 per ton is believed to be representative for the average producer, giving a delivered cost of $50 per ton or more. (These costs would need to be adjusted to account for current fuel and fertilizer costs.)

Implications

Examination of recent literature indicates that corn stover and switchgrass are the alternative feedstocks most likely to compete with wheat straw, at least in the short term. Recent analysis by Coon and Leistritz (2006) indicates that North Dakota wheat straw can be delivered to a biorefinery plant at a cost of $44.13 per dry ton, after paying harvest, nutrient replacement, and transportation costs and providing the producer with a $10 per ton net return. When this is compared to recent estimates for corn stover, wheat straw appears to have a $5 to $10 per ton cost advantage, after adjusting for recent increases in energy costs. 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 (Table 10). 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 are estimated to be $74.6 million annually, of which $53.01 million was estimated to represent expenditures to North Dakota entities (Table 11). The largest single expenditure item is 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).

Construction of the facility 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 11).

Table 10. Average Lignocellulosic Feedstock Compositions, Wheat Straw vs. Switchgrass (% dry wt basis)

Biomass Composition	Wheat Straw[a]	Switchgrass[b]
Cellulose	35.44	31.90
Xylan	20.61	21.09
Arabinan	2.84	2.84
Galactan	1.11	0.95
Mannan	0.00	0.30
Lignin	19.80	18.13
Other[c]	20.20	24.71

[a]Source: MBI International 2006a.
[b]Source: Hamelinck et al. 2005.
[c]Oils, ash, starch, and other.

Table 11. 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 11). 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. 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. The procedures used in the analysis are parallel to those used in estimating the impact of other facilities and activities (Coon and Leistritz 2005a; Bangsund and Leistritz 2005; Coon and Leistritz 2005b).

When the I-O model coefficients are applied to the estimated direct impacts, estimates of the total impacts of construction and operation of the biorefinery facility are obtained (Table 12). 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 12).

The levels of economic activity reflected in Table 12 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 12). These jobs are in addition to the persons employed directly in operating 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 12. Regional Economic Impacts (Direct Plus Secondary) Associated with Biorefinery Construction and Operation

		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, & misc. manufacturing	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[1]	6.9	43.1	43.7
Total	64.7	182.8	185.2
Secondary employment	793	2,448	2,474

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

North Dakota's Competitive Position for Biorefining: A Comparison to Other Regional Initiatives

The competitive position of North Dakota regarding the state's ability to attract industrial participants in the biobased economy has been analyzed as the composite of its relative ranking of key attractiveness factors compared to other states in the region. This comparison is not only applicable to the wheat straw to biomaterials effort specifically studied here but also to other initiatives in the bioindustry sector. Factors most critical to attracting commercial activity are the following:

A. Level of state funding of bioprocessing research and promotion
B. Presence of a formal strategic plan for local bioprocessing
C. Commitment of the local commercial sector
D. Presence of nationally recognized bioprocessing research institutions
E. Scale of local life sciences industry
F. Training and education facilities for bioprocessing
G. Risk capital availability
H. Biofuels industry scale
I. Raw material availability

The state's competitive position was analyzed relative to states deemed to be likely competitors (Figure 4): South Dakota, Minnesota, Iowa, Wisconsin, Illinois, Nebraska, and Michigan. The information for this analysis was drawn from a variety of sources including local reports of bioindustry promotion and research efforts, a comparative industry analysis conducted for the Biotechnology Industry Organization, trade journals, and reports and discussions with industry participants and observers.

Figure 4. Competitive Analysis of Overall Attractiveness for Bioprocessing – Selected States

Factor	SD	MN	IA	WI	IL	NB	MI	ND
A	❍	◒	●	◒	◒	❍	●	❍
B	❍	◒	●	●	◒	◒	●	❍
C	◒	◒	●	◒	◒	❍	●	❍
D	❍	◒	●	●	●	◒	●	❍
E	❍	◒	◒	◒	●	●	●	❍
F	❍	●	●	◒	◒	❍	◒	❍
G	◒	●	●	●	●	◒	●	❍
H	●	●	●	❍	◒	●	❍	❍
I	●	●	●	◒	●	●	◒	●
Composite	◒	●	●	◒	◒	◒	◒	◒

Note: ❍ = low, ◒ = medium, ● = high

Although North Dakota ranks the lowest of the states analyzed, this does not mean that the state does not possess significant resources. These include the following.

- Emerging bioprocessing programs at NDSU and UND
- NDSU's nationally recognized Polymers and Coatings Department
- Successful implementation of the Technology Corridor and its rapid growth
- Recognition of the opportunities in bioprocessing by key state leaders
- Recent announcements of significant investment in biofuels production
- Identification of potential private venture investors in the wheat straw biomaterials project
- Raw material supply likely superior to the other states

However, when the state's overall attractiveness at the present time is considered, the conclusion must be drawn that significant efforts and investment by both the public and private sectors are required for North Dakota to reach parity with its likely competitors.

While North Dakota is ranked low in overall attractiveness, its positioning for the wheat straw biomaterials project is significantly higher. When this single initiative is considered, a very different profile is presented (Figure 5).

Figure 5. Competitive Analysis of Overall Attractiveness for Wheat Straw Bioprocessing – Selected States

Factor	SD	MN	IA	WI	IL	NB	MI	ND
A	❍	◒	●	◒	◒	❍	●	❍
B	❍	◒	●	●	◒	◒	●	❍
C	◒	◒	●	◒	◒	❍	●	❍
D	❍	◒	●	●	●	◒	●	●
E	❍	◒	◒	◒	●	●	●	❍
F	❍	●	●	◒	◒	❍	◒	❍
G	◒	●	●	●	●	◒	●	◒
H	●	●	●	❍	◒	●	❍	❍
I	●	◒	◒	❍	❍	◒	❍	●
Composite	◒	◒	◒	◒	◒	◒	◒	◒

Note: ❍ = low, ◒ = medium, ● = high

Thus, for this specific opportunity, North Dakota appears to be quite competitive. Three heavily weighted factors work to overcome the deficiencies noted earlier for overall industry competitiveness. These are wheat straw supply, significant interest by commercial investors, and the NDSU Polymers and Coatings Department resource. The emergence of a significant biofuels sector in the state reinforces this conclusion.

Potential Steps to Enhance Competitiveness

North Dakota, as one of the major U.S. sources of biomass for fuels and materials, deserves a place among the states leading the establishment of this industry. An important first step would be to follow the example of many of the competing states which were analyzed here and create a formal strategic plan for addressing the biobased economy. With such a plan, the foundation would be laid to create partnerships dedicated to this initiative among government, industry, foundations, and research universities. Further, mechanisms would be identified to make the investment and provide the seed capital to put in place key elements critical to quick achievement and sustainability of short-term results that lead to long-term success. Investment is required in:

- Education at all levels for leadership, management, labor, and the public,

- Demonstration projects, such as a biorefinery that can be used to test concepts, develop applications, create prototypes for industry, train the growing workforce, and initiate technical expertise in the development and refinement of the conversion processes to spur innovation and engineering of next-generation equipment and technologies,

- Support of emerging bioeconomy entrepreneurs who are creating markets for their products and can attract other bio-based companies,

- Support for communities that may be highly impacted by transition, through both the shift in job skills and the introduction of new entrepreneurial enterprises and cultures to ensure that the changes they undergo are smooth, sustained, and advance the quality of life,

- Ongoing research and development, both at our research universities and in industry and through sponsored research that is conducted in partnerships between them, and

- Coordination of partnerships and facilitation of strategic market development by knowledgeable leaders whose jobs are to track and create opportunities to advance all aspects of the developing sector.

Conclusions and Next Steps for Developing a Biomaterials Industry in North Dakota

The aim of the project is to commercialize MBI's technology for producing biobased cellulose nanowhiskers (CNW) from wheat straw in an integrated biorefinery with ethanol and high-value chemicals 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.

The critical next step in a North Dakota-based biomaterials industry is the construction and operation of a pilot plant (in North Dakota) to demonstrate the commercial potential of this technology. With this information and expertise, full-scale commercialization can begin. Work planned for the near future includes (1) applied research to optimize the nanofiber production process, produce samples of the biobased nanocomposite material, and verify yields and production costs; (2) development/engineering to evaluate questions related to scale-up of processes, leading to an engineering design for construction of a pilot plant, as well as further testing and refinement of the biocomposite material; and (3) developing an investment analysis/prospectus. Estimated cost for completion of these tasks is $1,300,000. Specific tasks to be accomplished include:

- Preparation and evaluation of CNW samples
- Preparation and evaluation of composite materials
- Pre-Pilot plant design and engineering
- Develop a revised model for an ethanol biorefinery and CNW biorefinery from wheat straw
- Pilot plant design and engineering
- Evaluation of composite materials
- Review characteristics of composite products with potential customers
- Develop a Business Plan to enable implementation of the biorefinery model
- Solicit commercial partners for the business

The project team has reached two key conclusions. First, commercial investment is feasible at this stage of the enterprise development process. Second, the wheat straw to biocomposite business should be developed in conjunction with a biorefinery, the primary product of which will be fuel ethanol, initially converting starch to ethanol, and advancing to cellulosic raw materials. The project team will be working with private investor organizations to facilitate commercialization efforts. The team will also initiate discussions with participants in North Dakota's emerging ethanol industry to explore co-location possibilities and possible business configurations.

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Appendix

Appendix Table A. Manufacturing Costs

Production of CNW from Wheat Straw Hydrolysate Solids

Capacity	Capacity (tpy)	Tons of CNW
50 Tons per day	17,500	1,050

Variable costs	**units**	**units/year**	**$/unit**	**$/year**	**$/ton CNW**	**$/lb CNW**
Raw materials						
wheat straw hydrolysate solids	tons	17,500	0	- -	- -	- -
sodium hydroxide	tons	3,449	88.5	305,259	291	0.15
Membranes						
UF membranes 1	m2	276	200	55,200	53	0.03
UF membranes 2	m2	276	200	55,200	53	0.03
Utilities						
steam	tons	estimated	13.6	38,556	37	0.02
water	gallons	321,766	0.12	38,612	37	0.02
electricity	KWh	estimated	0.1	38,556	37	0.02
Total variable costs				**531,383**	**$506**	**$0.25**
Fixed costs						
Labor						
operating (2 tech/shift)	hr	17,520	12	210,240	200	0.10
control laboratory (1 tech/shift)	hr	4,200	15	63,000	60	0.03
maintenance (2% of fixed capital)				26,130	25	0.01
supervisory (15% of total labor)				44,906	43	0.02
benefits (33% of payroll)				113,611	108	0.05
Miscellaneous costs						
maintenance materials (2% of fixed capital)				26,130	25	0.01
operating materials (10% of operating labor)				21,024	20	0.01
local taxes & insurance (2% of fixed capital)				26,130	25	0.01
Total fixed costs				**$531,172**	**$506**	**$0.25**
Amortization cost (10 yr amortization)	Total capital	1,306,520		**$130,652**	**$124**	**$0.06**
Total manufacturing costs				**$1,193,207**	**$1,136**	**$0.57**

Appendix Table B. Yields, Process Parameters and Assumptions

Yields

wheat straw	35.44%	cellulose
cellulose	708.8	#s cellulose/ton wheat straw
hydrolysate	60.00%	of cellulose to eth production
hydrolysate solids	40.00%	of wheat straw cellulose
hydrolysate solids	283.52	#s cellulose/ton solids
CNW	129	#s CNW/ton solids
WNW	45.50%	yield of CNW from avail cellulose

Process parameters

		Units
processing capacity	50	tons per day
processing capacity	17,500	tons per year
overall yield	6.00%	mass cnw/mass biomass
CNW	1050	tons per year
base concentration	0.175	g NaOH/g suspension
biomass to base soln ratio	0.05	g/g
ratio of biomass to wash water	0.025	g/ml

Assumptions

1. Perfect separation of the hemicellulose and lignin from the cellulose
2. Nanowhiskers are not completely dry after filtration, no cost is established for drying, if necessary
3. Actual energy usage has not been estimated, \$0.06/lb of CNW used for utility costs
4. Lang factor of 4 for vertical tanks to estimate installation costs
5. Cost for dewatering the retentate off the filters is not estimated, this may be a waste stream

Appendix Table C. Mass Balances

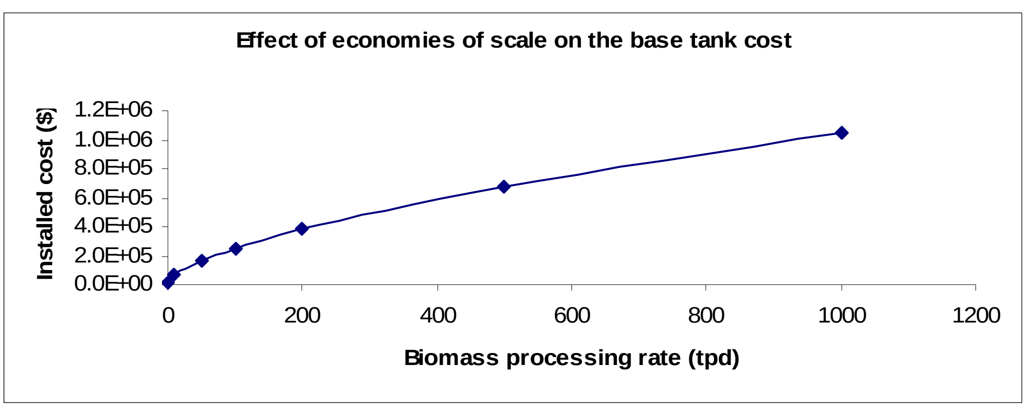
Mass Balances for PFD 4

Stream #	Wheat straw	Cellulose	Hemicellulose	Lignin	Crude protein	Fats & oils	Ash	Silica & sillicates	Glucose	NH_3	NaOH	Water	Cellulose soln	Whiskers
	tpd (d.b)	tpd	tpd	tpd	tpd	tpd	tpd	tpd	tpd	tpd	tpd	tpd	tpd	tpd
1	50	50	17.5	8.25	1.6	2.5	4	2.5	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	0	0.5	0	1	0	0
3	0	50	17.5	8.25	1.6	2.5	4	2.5	0	0	0	1	0	0
4	0	0	0	0	0	0	0	0	0	0.5	0	1	0	0
5	0	0	0	0	0	0	0	0	0	0	10.5	1.5	0	0
6	0	50	0	0					0	0	0	0	0	0
7	0	0	17.5	8.25					0	0	10.5	1.5	0	0
8	0	0	0	0					0	0	0	800	0	0
9	0	50	0	0					0	0	0	0	0	0
10	0	0	0	0					0	0	0	800	0	0
11	0	.0	0	0					0	0	0	1.05	1.05	0
12	0	0	0	0					0	0	0	178.05	4.21	0
13	0	3.2	0	0					18.67	0	0	180	5.26	3.2
14	0	3.2	0	0					0	0	0	0	5.26	3.2
15	0	0	0	0					18.67	0	0	180	0	0
16	0	3.2	0	0					0	0	0	178.05	5.26	3.2
17	0	0	0	0					0	0	0	178.05	0	0
18	0	3.2	0	0					0	0	0	0	0	3.2

Appendix Table D. Capital Cost Estimates

Pulping tank	unit	
Biomass processing capacity	tpd	50
Ratio of biomass to base	g/ml	0.05
Base solution flow rate	gal/d	239,654
Residence time	hr	1
Tank working volume	gal	9,986
Tank inside radius	in	72
Max internal pressure	psig	50
Max working stress	psi	13,700
Joint efficiency	- -	0.85
Corrosion allowance	in	0.125
Wall thickness	in	0.43
Major axis of ellipsoidal head	in	143
Thickness of ellipsoidal head	in	0.43
Density of steel	lb/in^3	0.28
Correction factor for ellipsoidal heads	- -	1.23
Mass of ellipsoidal head	lb	2,998
Volume of cylindrical shell	in^3	35,060
Mass of cylindrical shell	lb	9,922
Total mass of base tank	lb	12,920
Cost of tank	$/lb	3.20
Cost of tank f.o.b.	$	41,354
Lang factor	- -	4
Installed cost of base tank	$	165,417

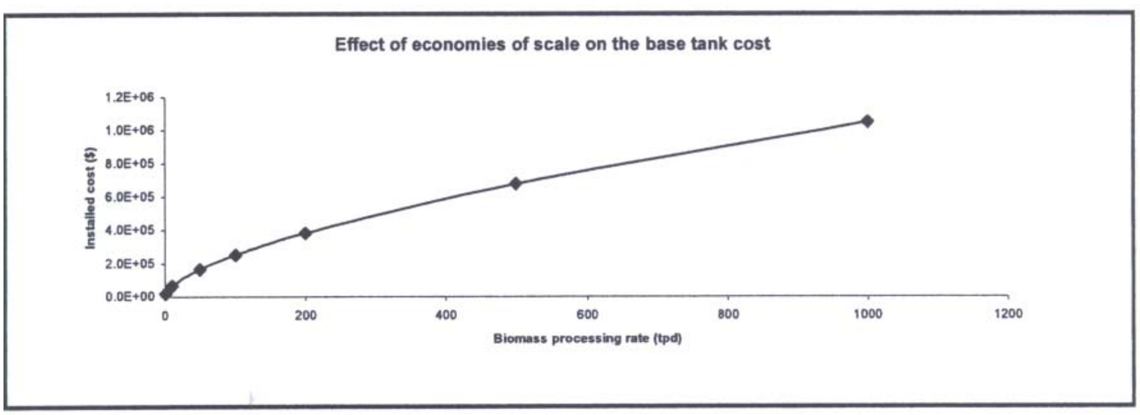
Biomass proc cap (tpd)	Installed cost ($)
1	18,313
10	64,711
50	165,417
100	250,947
200	383,193
500	676,406
1000	1,045,492



Appendix Table D. (Cont.)

Wash tank	unit	
Biomass processing capacity	tpd	50
Ratio of biomass to wash water	g/ml	0.025
Wash water flow rate	gal/d	479,308
Residence time	hr	0.25
Tank working volume	gal	4,993
Tank inside radius	in	57
Max internal pressure	psig	50
Max working stress	psi	13,700
Joint efficiency	- -	0.85
Corrosion allowance	in	0.125
Wall thickness	in	0.37
Major axis of ellipsoidal head	in	114
Thickness of ellipsoidal head	in	0.37
Density of steel	lb/in^3	0.28
Correction factor for ellipsoidal heads	- -	1.23
Mass of ellipsoidal head	lb	1,612
Volume of cylindrical shell	in^3	18,852
Mass of cylindrical shell	lb	5,335
Total mass of base tank	lb	6,947
Cost of tank	$/lb	3.95
Cost of tank f.o.b.	$	27,459
Lang factor	- -	4
Installed cost	$	109,835

Biomass proc cap (tpd)	Installed cost ($)
1	18,313
10	64,711
50	165,417
100	250,947
200	383,193
500	676,406
1000	1,045,492



Appendix Table D (Cont.)

Filter Unit	Unit	
Biomass processing capacity	Tpd	50
MSI 2005	- -	800
Inlet flow rate	Gal/hr	6,898
Transmembrane flux	Gal/(m^2-hr)	25
Membrane surface area	M^2	276
Purchased cost	$	218,285
bmf	- -	1.42
Installed cost of filter unit	$	309,964

Capital Investment

			Equipment	**Capital**
		capacity	50 tons raw material per year	
	Process		**Installed**	**Cost***
(1)	**Pulping**			$215,043
		tank	165,417	
(2)	**Neutralization**			$142,785
		wash tank	109,835	
(3)	**Filtration**			$402,953
		ultra filter 1	309,964	
(4)	**Bleaching**			$142,785
		wash tank	109,835	
(5)	**Filtration**			$402,953
		ultra filter 1	309,964	
(6)	**Volume reduction**		unknown	
(7)	**Dewater**		unknown	
		Total Capital	1,005,015	**$1,306,520**

*Includes building and accessories factor of 30%

Appendix Figure 1. Process Flow Diagram

[redacted]