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Conversion of paper sludge to ethanol, II: process design and economic analysis

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Abstract Process design and economics are considered for conversion of paper sludge to ethanol. A particular site, a bleached kraft mill operated in Gorham, NH by Fraser Papers (15 tons dry sludge processed per day), is considered. In addition, profitability is examined for a larger plant (50 dry tons per day) and sensitivity analysis is carried out with respect to capacity, tipping fee, and ethanol price. Conversion based on simultaneous saccharification and fermentation with intermittent feeding is examined, with ethanol recovery provided by distillation and molecular sieve adsorption. It was found that the Fraser plant achieves positive cash flow with or without xylose conversion and mineral recovery. Sensitivity analysis indicates economics are very sensitive to ethanol selling price and scale; significant but less sensitive to the tipping fee, and rather insensitive to the prices of cellulase and power. Internal rates of return exceeding 15% are projected for larger plants at most combinations of scale, tipping fee, and ethanol price. Our analysis lends support to the proposition that paper sludge is a leading point-of-entry and proving ground for emergent industrial processes featuring enzymatic hydrolysis of cellulosic biomass.

Introduction

Biomass is the only foreseeable low cost, abundant resource for production of organic fuels, chemicals and materials [1]. Moreover, production of renewable fuels from biomass offers benefits in terms of sustainable resource supply, energy security, and rural economic development. Paper sludge is a solid by-product of pulping and/or paper-making operations. As discussed in a companion paper in this issue, it is also an attractive biomass feedstock for production of fermentation products such as ethanol [1–8]. Total paper sludge production in the US is on the order of 5 million tons, but not all are suitable for biological conversion. Thus, paper sludge is available at a smaller scale than many other potential cellulosic feedstocks and will not by itself solve challenges associated with energy supply. However, paper sludge has some distinctive advantages among cellulosic feedstocks including negative cost at many locations, no requirement for dedicated pretreatment at many mills, and the potential availability of preexisting infrastructure.

In this study, we consider design and economic analysis for ethanol production from paper sludge at the Fraser paper mill in Berlin/Gorham, New Hampshire under two scenarios. Scenario one is based on technology demonstrated at lab scale. Scenario two is based on technology that is not yet demonstrated, but it is

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expected to be available by the time a plant is brought into production, assuming an aggressive development effort.

Design context

Fraser's Gorham paper mill is located in Gorham, New Hampshire and has the capacity to produce 200,000 tons of paper products per year. Sludge from the Gorham paper mill originates from paper making only (not pulping), and is obtained from the underflow of a primary clarifier. As currently operated, sludge containing about 3% dry weight is dewatered to about 25–32% dry weight by a belt press before being disposed of via landfill. Paper sludge is now generated at 15 dry ton per day; the current cost of disposal is $25 per wet ton. Main components of the sludge include glucan, xylan, lignin, and minerals including TiO_2, $CaCO_3$ and Kaolin [9]. The Lynd lab began testing the sludge from the Gorham Paper mill in 1992 and found that the composition and amenability to enzymatic hydrolysis have remained reasonably constant for over a decade [7]. Data obtained since earlier report support this conclusion, although some differences in the amount of cellulase required has been documented for sludge samples taken out at different times.

An ethanol plant at the Gorham mill is expected to be sited within the paper mill. Utilities available at the paper mill could potentially provide to the ethanol plant electricity, steam, cooling water and process water. At this site, an ethanol plant would need its own wastewater treatment system to reduce the oxygen demand. We anticipate that the ethanol plant could be incorporated into existing process monitoring and maintenance functions of the plant. It is estimated that one dedicated employee on an 8 h shift and 5 days a week basis is sufficient for running the ethanol facility assuming operation with a significant degree of automatic operation.

Experimental results and parameters used in the design and economic analysis

Glucan conversion, enzyme loading and feeding frequency

The design presented here uses a feeding frequency (feeding per residence time) of 1.33, and a residence time of 4 days. The reactor is fed once every 3 days and three-fourths of the fermentation broth is harvested at the end of the 3-day cycle. Cellulase loading is set at 10 FPU/g Cellulose. Glucan conversion of 92% and ethanol yield of 0.46 g/g glucose are used in the design based on the experimental data presented in a companion paper.

Mineral recovery

Recovery of minerals from the residue remaining after ethanol production could potentially create extra revenue by mineral reuse or sale, while at the same time decreasing waste generation resulting in decreased disposal costs. A mineral recovery method in which SSF process residues are first centrifuged and the mineral rich solids from the pellet are reincorporated into the paper making process was investigated. Paper hand sheets were prepared with SSF residues in various portions. The burst strength, brightness, opacity, and whiteness of the paper hand sheets prepared with SSF residues in various portions changed very little with up to 10% of the mineral content originating from SSF residues. Since the rate of production of sludge is less than 10% of the rate of production of paper at the Gorham mill, we anticipate that the fraction of minerals originating from paper sludge would not exceed 10%.

Although other approaches could be incorporated to recover minerals, only the reuse of un-fractionated sludge is considered in our scenarios. Based on the encouraging preliminary data in Fig. 1, mineral recovery is evaluated assuming 90% recovery with recovered minerals valued at 50% that of their virgin counterparts in scenario 2, while no mineral recovery is assumed in scenario 1. Further investigation of the impact of mineral recovery and reuse would be

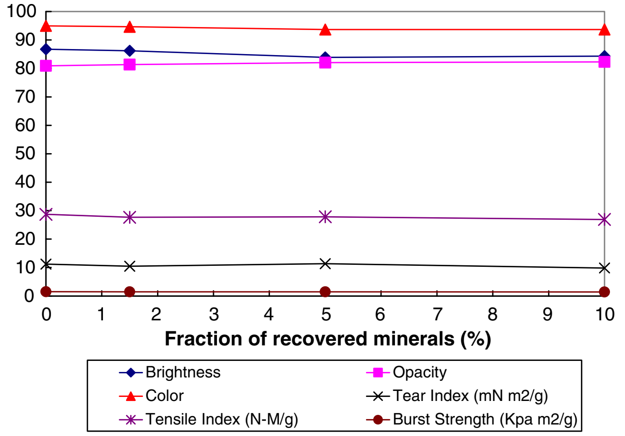

Fig. 1 Paper quality in relation to percent of substitution of recovered mineral [7]

required before this could be done at full scale. It may be noted that recovery and reuse of the mineral component of paper sludge is considerably easier from residues following enzymatic hydrolysis as compared to the original sludge.

Xylose conversion

A substantial amount of xylose results from enzymatic hydrolysis, which cannot be utilized by *Saccharomyces cerevisiae*. In particular, we note that effluents of SSF carried out with this organism contain xylan solubilization products at levels corresponding to that expected based on the xylan present in the feed [8]. It is thus desirable to consider incorporating into the process microorganisms able to use xylose as well as glucose. Candidate microbes for use in this capacity include: *Zymomonas mobilis* [10], *Saccharomyces* sp. 424A (LNH-ST) [11], *S. cerevisiae* strains [12], and *Escherichia coli* KO11 [13]. Consistent with data from the literature, but with no direct supporting data, xylose conversion is included in scenario 2 assuming 90% of xylan conversion and 90% of ethanol yield from xylose, but xylose conversion is not included in scenario 1. The simple medium used in our studies (1% corn steep liquor) is assumed to be adequate to support growth of xylose-converting microbes.

Ethanol and cellulase costs

The price of ethanol sold at 2007 is uncertain at this point, but is projected to be $1.50 per gallon based on historic data and strong prospects for ethanol market demand. The cost of cellulase for bioconversion processes cannot be known with certainty at this time, as cellulase at prices consistent with this application is not a commercial product today. Information released by commercial enzyme suppliers provides a sense of the current cost of cellulase. For example, Genencor reported that cellulase cost is at the range of 10–20 cents per gallon of ethanol for a cellulase loading of about 15 IU/g cellulose (Genencor press release, October 2004), which corresponds to $1.6–3.2/million IU. In the analysis reported herein, a base cellulase purchase cost of $2.4/million IU is assumed with sensitivity analysis to this cost reported. Since experimental results suggest that a loading of 5–10 IU/g is required for paper sludge, a cellulose cost of $0.17 per gallon ethanol is used for scenario 1 and $0.085 per gallon assumed for scenario 2. Sensitivity analysis was conducted to evaluate how economics change as a function of ethanol price and cellulase costs.

Definition of scenarios

Three variables differentiate scenario two from scenario one: conversion of five carbon sugars, mineral recovery, and the cost of cellulase. Table 1 presents the parameters used for the two scenarios, with the rationale for the choice of parameter value as presented in the prior section.

Process design

Approach

Process flow diagrams (PFD) were specified and corresponding mass and energy balances developed using Aspen Plus and an Excel spreadsheet. Reactors are modeled based on experimentally determined conversions and yields obtained at the same conditions used in the design. Distillation columns and scrubber are modeled using APSEN based on stage-by-stage mass, energy and vapor–liquid equilibrium calculations. Liquid and solid separations are modeled with specified solids removal and liquid retention based on experimental data.

Process overview

Paper sludge (solid content ~3%) is sterilized and cooled in a continuous sterilizer/cooler operated in a counter-current flow configuration, and then dewatered to about 20% solids content before being fed to the SSF reactor. Additional inputs to the reactor include a cellulase preparation (produced off-site) and a steam-sterilized nutrient solution. Following conversion to ethanol in the bioreactor, broth containing ethanol, microbial cells, and residual solids are fed to an equalization tank and subsequently to a distillation column. Two distillation columns are used to distill the ethanol away from the water and residual solids. A nearly azeotropic ethanol/water mixture is purified to pure ethanol using vapor phase molecular sieves. A water scrubber is used to remove ethanol from vents associated with fermentation and distillation with subsequent release of CO_2. The bottoms from the distillation column flow through a counter-current heat exchanger, and then are centrifuged to separate wastewater from solids. Solids are either disposed of via landfill or further processed for mineral recovery depending on the scenario. Wastewater goes to an anaerobic digester to decrease BOD before discharge to the Androscoggin River. A flow chart for the process analyzed herein is presented in Fig. 2.

Table 1 Specifications of scenarios

	Scenario 1	Scenario 2
Carbohydrate converted	Glucan and mannan	Glucan, mannan and xylan
Cellulase cost	\$0.17/gallon ethanol produced	\$0.085/gallon ethanol produced
Mineral recovery/residue disposal	None, process residues disposed of by landfill	90% Mineral recovery, 50% of the mineral value recovered

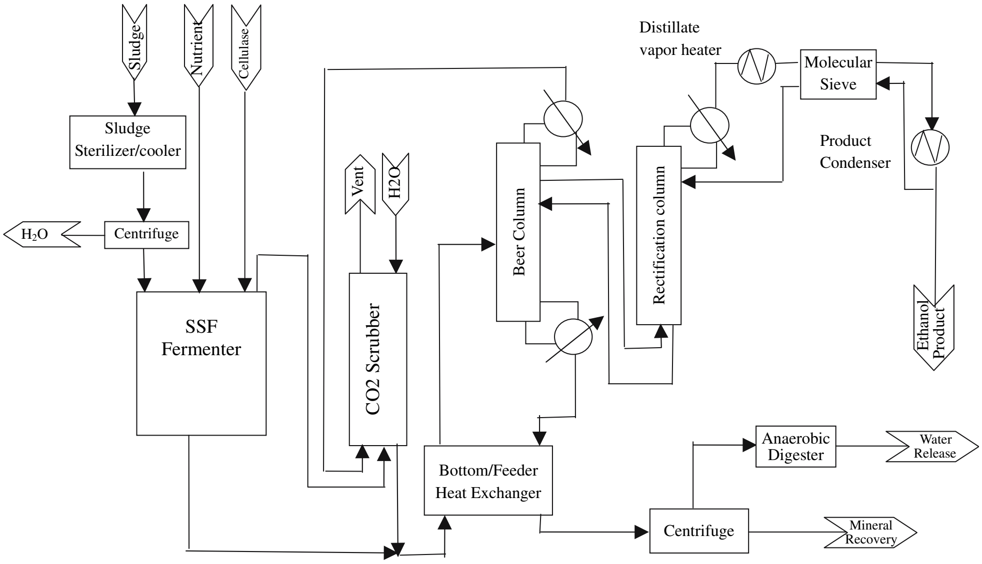

Fig. 2 Overall process flow diagram

Sludge and nutrient pasteurization

Figure 3 presents the process flow diagram for sludge and nutrient sterilization process. Paper sludge from the mill's primary clarifier is pausteurized by heating to 105°C and subsequently cooled to 37°C using a continuous sterilization and cooling system composed of a heat exchange unit and a holding unit. Sludge from the primary clarifier containing about 3% solids is heated from 25°C to about 95°C by the hot sterile sludge flowing on the hot side of the heat exchanger. Steam is supplied to heat the slurry from 95 to 105°C in the final stage of the heat exchanger. The 105°C slurry flows to the holding unit to keep the temperature for 30 min before entering the heat exchange unit where it heats the incoming sludge. The slurry exiting the heat exchanger unit is cooled to about 37°C. Sterile sludge is dewatered by a decanter centrifuge (C101) to about 20% solids. The dewatered sludge is collected in a 300 m^3 sludge storage tank before being fed to the SSF fermenter.

Corn steep liquor is sterilized in a jacketed tank with an agitator designed to have a volume of 1 m^3, which is also used as the seed fermentor. The sterilized corn steep liquor is stored in a 2 m^3 CSL storage tank with an agitator, which corresponds to 24 days supply of CSL. Cellulase is stored in the enzyme storage tank (T102) as received. The tank is designed to have a volume of 20 m^3 and has the capacity to hold a volume of cellulase necessary to operate for 12 days.

SSF

In the SSF subprocess, hydrolysis of cellulose to sugars and fermentation of sugars occur simultaneously in the reactor. Cellulase enzymes are stabilized solutions used as-received form (without additional sterilization) as per standard industrial practice for industrial enzymes (Mike Knauf, Genencor, personal communication). *S. cerevisiae* used for sugar fermentation is grown in a batch seed fermenter for 1 day before being inoculated into the SSF fermenter at 0.1% (v/v) to initiate the culture. SSF is conducted semi-continuously. pausteurized sludge, nutrient and enzyme from the sludge and nutrient sterilization subprocess are fed to the SSF fermenter every 3 days, and the resulting ethanol broth is collected in an equalization tank before being fed to a continuously-operated distillation column (Figs. 4, 5, 6).

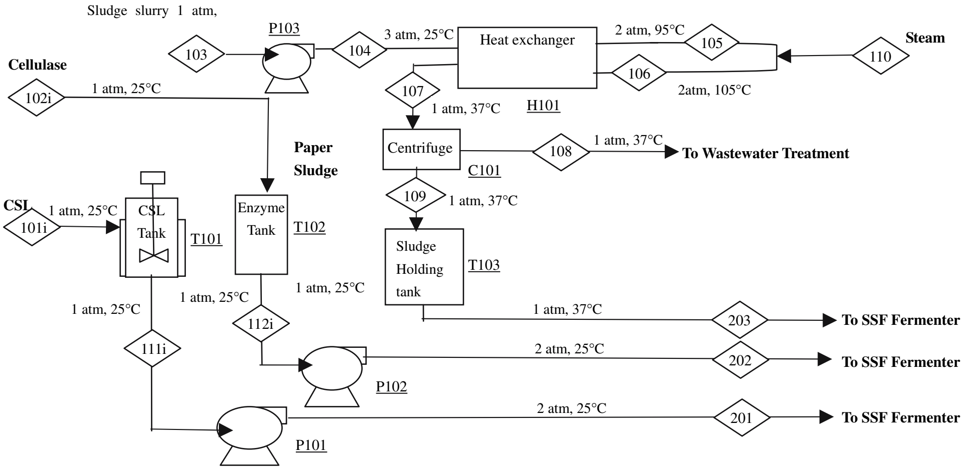

Fig. 3 Process flow diagram of feedstock and nutrient sterilization sub-process

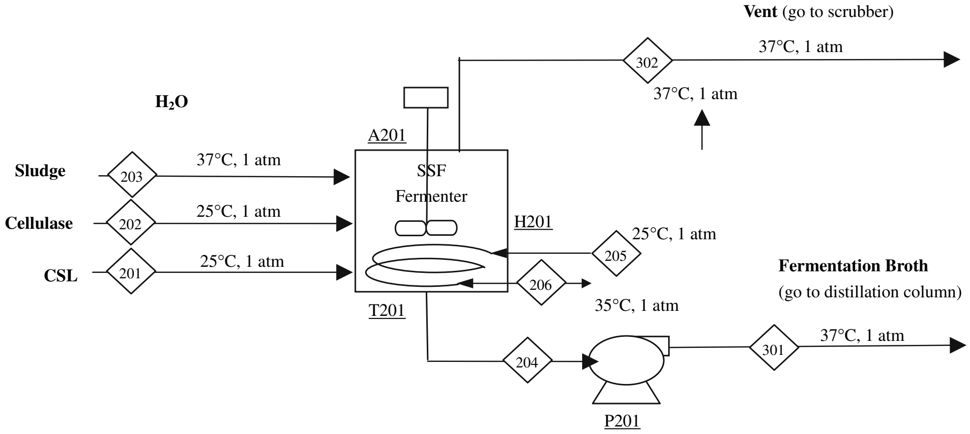

Fig. 4 Process flow diagram of SSF sub-process

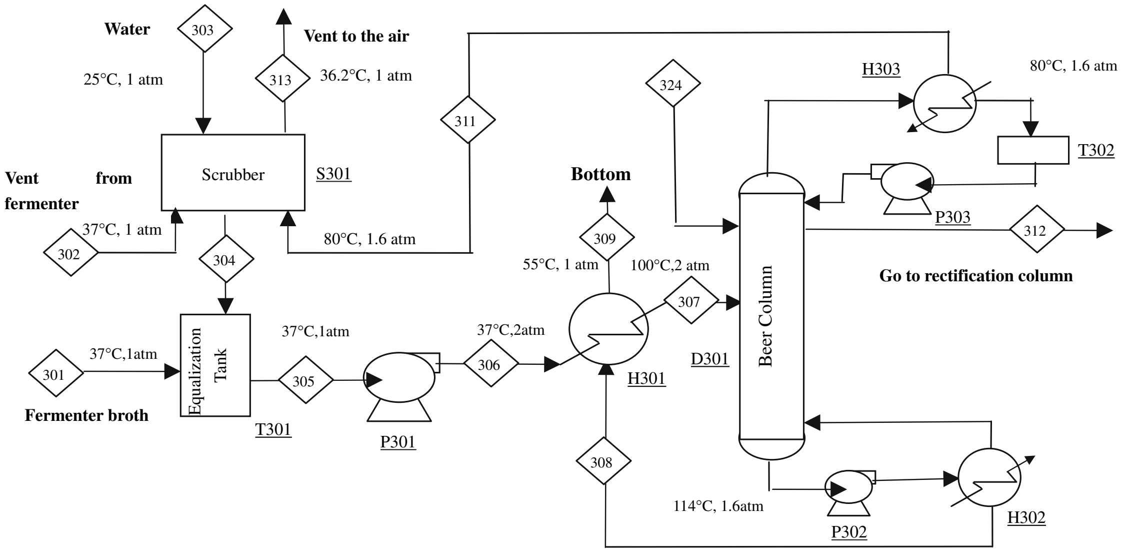

Fig. 5 Process flow diagram for the product recovery sub-process (1)

The SSF fermenter is designed to be a vessel with a total volume of 450 m^3, and a working volume of 400 m^3. A vent on top of the reactor keeps the fermentation head space pressure at about 1 atm. Vents from the SSF fermenter are fed to a scrubber to recover most of the ethanol before releasing CO_2. The

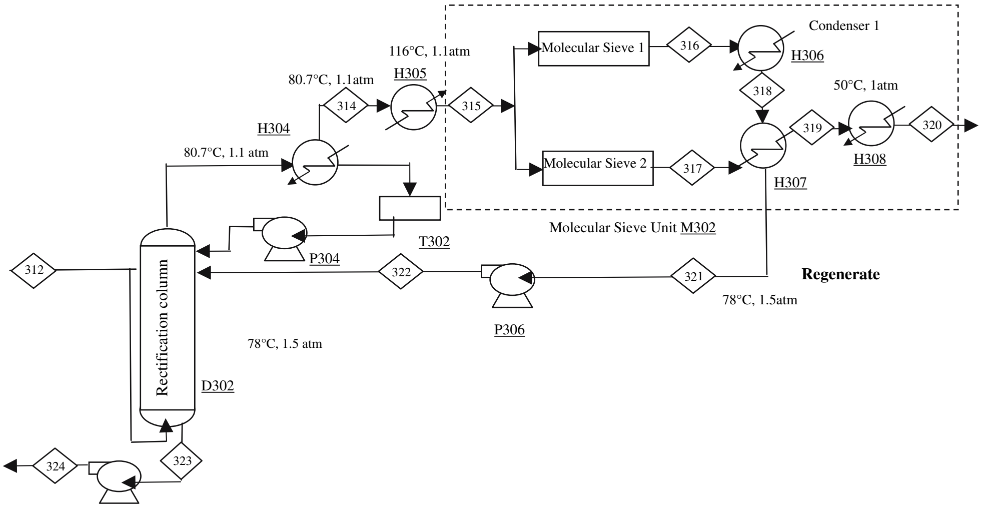

Fig. 6 Process flow diagram for the product recovery sub-process (2)

fermenter uses a submerged coil to remove heat by cooling water. The fermenter is also equipped with two side mounted marine stirrers to provide moderate mixing. Fermentation broth is withdrawn from the system by a pump (P201) to an equalization tank.

Product recovery

Product recovery process was modified from the NREL design [14]. Distillation and molecular sieve adsorption are used to recover ethanol from the raw fermentation beer and produce 99.5% ethanol. Two column are designed to accomplish distillation. The first column, the beer column, has the both the reboiler and condenser and 24 actual trays. It removes most of the water and dissolved CO_2. The second column, the rectification column, has 24 trays as well. But, it contains a condenser but no reboiler. The vapor side drawn from the second tray of the beer column is fed directly to the bottom of the rectification column, while the bottom of the rectification column is fed to the second tray of the beer column. The rectification column enriches ethanol to 92.5% purity. Water contained in the near azeotropic mixture from the rectification column is removed by vapor phase molecular sieve adsorption. The molecular sieve is regenerated by pure ethanol, and the resulting ethanol and water mixture is recycled to recover ethanol in the rectification column. The fermentation vent (containing most of the CO_2 produced in the fermentation and some ethanol) and the first distillation column vent are introduced to a water scrubber to recover nearly all ethanol and release the CO_2. The scrubber effluent is combined with the fermentation broth before being fed to the first distillation column. The bottoms stream from the beer column contains all the unconverted insoluble solids, cells and other minor components. The heat contained in the bottom stream is used to preheat the feed stream to the first distillation column. Then, solids and liquids in the bottom stream are separated by a decanter centrifuge. The resulting solids go to mineral recovery or landfill and the liquid goes to wastewater treatment. The vent streams from the distillation column and the fermenter are sent to the water scrubber. The scrubber is designed to be a packed column using Jaeger Tri-Pack plastic packing, and contains four theoretical stages. The column recovers 99.5% of the ethanol it receive.

Economic analysis

Approach

Revenues and operating costs are evaluated first; and the affordable capital cost for a specified return on investment is then calculated based on net income. Total capital cost is estimated thereafter. By comparing the affordable capital cost with the estimated capital cost, the gaps between estimated and allowable capital costs are calculated. All the costs are presented in 2007 dollars.

Estimation of revenues and operating costs

Revenues come from the sales of ethanol, savings from avoided sludge disposal, and (for scenario 2) mineral sales. Yearly revenues are presented in Table 2.

Operating costs include raw material consumption, water, electricity, labor, maintenance, and administration. Among these, variable operating costs include costs for raw material, waste treatment, and energy consumed (electricity and steam), which are incurred only when the process is operating. Fixed operating costs, incurred whether or not the plant is operating at full capacity, include labor and various overhead items. All material and energy flows are determined based on the process design and mass and energy balances. Table 3 summarizes the variable operating costs, fixed operating costs and total operating costs under different scenarios.

Table 2 Summary of revenues

	Scenario 1	Scenario2
Ethanol from glucan and Mannan	$457,976	$457,976
Ethanol from xylan	–	$40,874
Avoided sludge disposal	$416,667	$416,667
Mineral sales	–	$83,300
Total revenue	$874.643	$998,817

Estimation of working capital

Working capital is estimated to be about 5% of the total capital investment, which is about $197,131 as suggested by Wooley et al. and Allen et al. [14, 15]. The working capital will be sufficient to cover the cost for 2 months' of chemicals, cellulase, finished products in storage, accounts receivable and payable, cash on hand for monthly payments and accounts payable.

Estimation of the affordable capital cost

Table 4 presents the affordable capital costs at a 15% internal rate of return calculated using discounted cashflow analysis.

The following assumptions are incorporated in the discounted cash flow modeling: plant capacity of 15 dry tons of sludge per day; tipping fee of $25/wet ton; no cost for G&A (assuming the facility can use existing G&A at no cost); ethanol price $1.10/gallon; one dedicated employee to the process (assuming that 24-h monitoring of the facility is incorporated into existing mill operations); plant life 20 years; depreciation method: 7 year DB 200%; tax rate of 39%; the construction and start-up of the plant takes 1 year and the facility is running at full capacity after year 1; internal rate of return 15%.

Capital cost estimation

Methodology

Equipment purchase and installation costs were estimated based on process specifications. The purchase cost of individual equipment is estimated by one of several methods: (a) using ASPEN ICARUS Process Evaluator software; (b) quotes from vendors; (c) scaling up or down based on similar equipment with cost estimated elsewhere [NREL] but of a different size using the following exponential scaling expression:

$$C_{\text{new}} = C_{\text{original}} \left(\frac{\text{Size}_{\text{new}}}{\text{Size}_{\text{original}}} \right)^n \quad (1)$$

C_{new}	cost of the new equipment
C_{original}	cost of the original equipment
Size_{new}	size of the new equipment
$\text{Size}_{\text{original}}$	size of the original equipment.

After determining the individual equipment cost, an installation factor is applied to determine the installed

Table 3 Summary of operating costs

	Cost ($/kg)	Scenario 1			Scenario 2		
		kg/h	$/year	cents/gallon ethanol	kg/h	$/year	cents/gallon ethanol
$MgSO_4$	$0.466	2.6	$9,622	2.31	2.58	$9,622	2.12
Corn steep liquor	$0.191	13.0	$18,458	4.43	13	$19,873	4.38
Cellulase	$0.147	60.0	$70,778	17.00	30	$35,389	7.80
Residual disposal	$0.025	567.8	$113,553	27.27	–	–	–
Steam	$0.011	926.4	$81,309	19.53	935.7	$82,127	18.11
Electricity	$0.005/kWh	95.1 kW	$3,804	0.91	95.1 kW	$3,804	0.84
Labor			$83,600	20.08		$83,600	18.43
Wastewater treatment operating cost[a]			$41,634	10.00		$41,634	9.18
Insurance @1% of total capital cost[b]			$39,426	9.47		$39,426	8.69
Mainteinence @ 3% of total capital cost[b]			$118,279	28.41		$118,279	26.08
Total operating cost	$580,463	139.42				$433,754	95.65
Total revenue/operating cost			1.5			2.4	

[a] Wastewater treatment operating cost include chemicals and electricity

[b] Estimated capital cost reported in Table 3 is used

Table 4 Summary of affordable capital costs

	Scenario 1	Scenario 2
Affordable capital cost	$1,240,000	$2,606,000

equipment cost. The scaling exponent *n* in Eq. 1 and installation factors for equipment were obtained from an NREL technical report [14, 15] or suggested by vendors. After determining the installed equipment costs, we applied various overhead and contingency factors to determine the total capital investment.

The cost of a wastewater treatment facility based on anaerobic digestion was quoted as an individual item from Ecovation, Inc (Victor, New York). The estimated capital cost includes all the equipment, buildings, instrumentation, and remote monitoring. Hence, the total capital cost the whole project is obtained by adding the quoted wastewater treatment facility cost in 2007 dollars on top of the total capital costs excluding the wastewater treatment facility.

Installed equipment estimation

Detailed equipment costs, sources of cost information are presented in Table 5. It is estimated that the total installed equipment is about $1,939,452.

Table 5 Equipment costs summary

Equip. no.	Equipment name	Equipment category	Equip cost	Installation factor	Total installed cost in 2002	Total installed cost in 2006	Cost method
H101	Sterilization/Cooling System	Heatx	$16,000	2.1	$33,600	$36,050	Icarus
C101	Centrifuge	Centrifuge	$90,000	1.2	$108,000	$115,875	Vendor quote
P101	CSL pump	Pump	$3,500	2.8	$9,800	$10,515	Icarus
P102	Enzyme pump	Pump	$3,500	2.8	$9,800	$10,515	Icarus
P103	Paper sludge slurry pump	Pump	$7,900	2.8	$22,120	$23,733	Icarus
T101	CSL storage tank	Tank	$39,400	1.2	$47,280	$50,728	Icarus
T102	Enzyme storage tank	Tank	$18,900	1.2	$22,680	$24,334	Icarus
T103	Sludge storage tank	Tank	$151,400	1.2	$181,680	$194,928	Icarus
A201	SSF fermenter agitator	Agitator	$113,300	1.2	$135,960	$145,874	Icarus
H201	SSF fermenter Heat Exchanger	Heatx	$16,700	1.2	$20,040	$21,501	Icarus
P201	Circulating pump	Pump	$9,000	2.8	$25,200	$27,038	Icarus
T201	SSF fermenter	Tank	$125,200	1.2	$150,240	$161,195	Icarus
T202	Seed fermenter	Tank	$33,900	1.2	$40,680	$43,646	Icarus
A301	Beer storage tank agitator	Agitator	$49,800	1.2	$59,760	$64,118	Icarus
C301	Centrifuge	Centrifuge	$115000	1.2	$138,000	$148.063	Vendor quote
D301	Beer column	Column	$53,400	2.1	$112,140	$120,317	Icarus
D302	Rectification column	Column	$52,900	2.1	$111,090	$119,190	Icarus
H301	Preheater	Heatx	$19,700	2.1	$41,370	$44,387	Icarus
H302	Beer column condenser	Heatx	$5,350	2.1	$11,235	$12,054	Icarus
H302	Reboiler	Heatx	$20,400	2.1	$42,840	$45,964	Icarus
H304	Rectification condenser	Heatx	$19,400	2.1	$40,740	$43,711	Icarus
M301	Molecular sieve unit	Miscell.	$96,000	1	$96,000	$103,000	NREL
P301	Feed pump	Pump	$3,500	2.8	$9,800	$10,515	Icarus
P302	Reboiler pump	Pump	$4,200	2.8	$11,760	$12,618	Icarus
P303	Beer column reflux pump	Pump	$3,900	2.8	$10,920	$11,716	Icarus
P304	Rectification reflux pump	Pump	$4,000	2.8	$11,200	$12,017	Icarus
P305	Rectification column bottom pump	Pump	$4,100	2.8	$11,480	$12,317	Icarus
P306	Recycle pump	Pump	$4,100	2.8	$11,480	$12,317	Icarus
P307	Scrubber pump	Pump	$4,100	2.8	$11,480	$12,317	Icarus
P308	Product pump	Pump	$3,500	2.8	$9,800	$10,515	Icarus
S301	CO_2 scrubber	Column	$9,900	2.1	$20,790	$22,306	NREL
T301	Equalization tank	Tank	$115,000	1.2	$138,000	$148,063	Icarus
T302	Beer column reflux drum	Tank	$4,000	1.2	$4,800	$5,150	Icarus
T303	Rectification reflux drum	Tank	$9,800	1.2	$11,760	$12,618	Icarus
T304	Product tank	Tank	$26,100	1.2	$31,320	$33,604	Icarus
R401	Reboiler refurbish cost	Boiler	$44,000	1.2	$52,800	$56,650	Matches*

Matches* software: http://www.matche.com/EquipCost/Boiler.htm

Table 6 Total project investment

Estimation of total capital cost exclusive of wastewater treatment	
Total installed equipment cost	$1,939,452
Warehouse (1.5% of TIEC)	$29,092
Site development (9% of TIEC)	$174,551
Capital cost contigency (30% of TIEC)	$581,836
Total installed cost (TIC)	$2,724,931
Indirect cost	
Legal and administration fee (10% of TIC)	$272,493
Construction regulation fee (25% of TIC)	$408,740
Subtotal capital cost (SCC)	$3,406,163
Capital cost for wastewater treatment	$536,458
Total capital cost (TCC)	$3,942,622

Table 7 Comparison of affordable and estimated capital

	Scenario 1	Scenario 2
Affordable capital cost	$1,240,000	$2,606,000
Estimated capital cost	$3,943,000	$3,943,000
Gap	$2,703,000	$1,337,000

Estimation of additional cost

Other costs of total installed investment include warehousing, site development and a contingency of 30% of the total installed equipment cost. Indirect costs include legal and administration fees and construction regulation fees. The rates used are lower than expected for a green field facility, and are further lowered in anticipation of substantial design work being accomplished prior to the initiation of construction. Table 6 presents a capital cost summary.

Investment analysis

According to our estimation, the total capital cost for this project is about $3.94 million, and the affordable capital cost for scenario 1 is about $1.24 million, and about $2.61 for scenario 2. Hence the gap between affordable capital with a 15% IRR and actual capital is about $2.70 million and $1.34 million for scenario 1 and 2, respectively as shown in Table 7.

It is anticipated that funding to fill this gap may be available from a combination of governmental sources and/or equity investors in a position to realize value beyond plant cash flow.

Economic analysis of a sample plant of 50 dry ton per day capacity

The processing capacity of 15 dry ton per day of Fraser Paper is relatively small in scale, we evaluate the economics of a plant with the capacity varies from 15 to 100 dry tone per day.

The total capital cost for such a facility is scaled up based a 15 day ton capacity plant with known total capital cost using the following exponential scaling expression:

$$\mathrm{TCC}_{\mathrm{new}} = \mathrm{TCC}_{\mathrm{original}} \left(\frac{\mathrm{Capacity}_{\mathrm{new}}}{\mathrm{Capacity}_{\mathrm{original}}} \right)^{0.6}. \qquad (2)$$

The operating costs excluding the insurance and maintenance is linearly scaled up from that of the 15 dry ton facility. Insurance is calculated at 1% of total capital cost calculated using Eq. 2, and maintenance is calculated at 3% of the total capital cost calculated using Eq. 1. Internal rate of returns for both scenarios is shown in Fig. 7.

Sensitivity of affordable capital costs for a 50 dry ton per day processing capacity plant to ethanol selling price, cellulase cost, electricity cost, sludge disposal costs, processing capacity are studied. It was found that the internal rate of returns (IRRs) are very sensitive to ethanol selling price and scale, rather sensitive to tipping fee as shown in Fig. 8, and rather insensitive to the electricity and cellulase costs. Of particular note, the plant with scenario 2 assumptions exceeded the 15% IRR threshold even at lowest ethanol price or lowest tipping fee analyzed. While plant with scenario 1 assumptions exceeded the 15% IRR at favorable

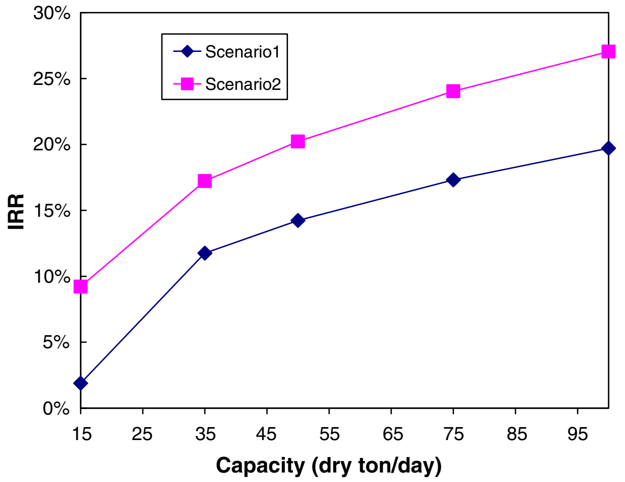

Fig. 7 Sensitivity of IRR to capacity

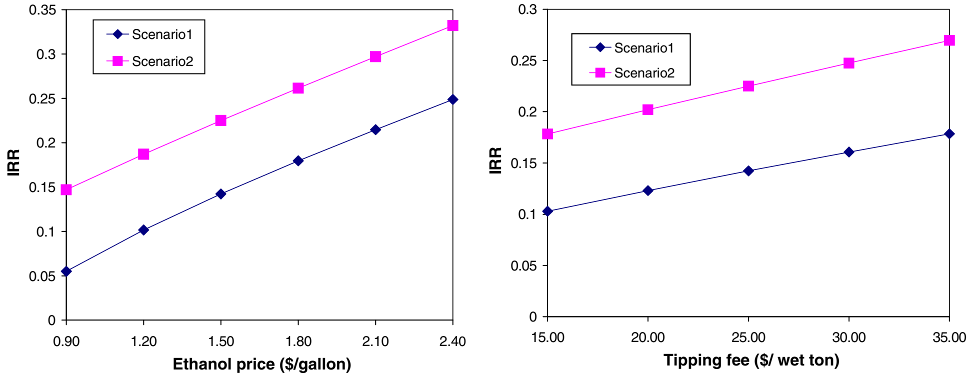

Fig. 8 Sensitivity of IRR to **a** ethanol price and **b** tipping fee

ethanol price (>$1.6/gallon) or at very favorable tipping fee (>$29/wet ton).

Discussion

Biomass conversion to ethanol has been advocated for a long time due to its potential to foster sustainable energy supply, reduce green house gas emissions, boost rural economies and reduce the country's dependence on foreign oil. But there are no commercial facilities today featuring enzymatic hydrolysis of cellulose. A key reason for this is the very large size, and hence capital cost, required to realize positive cash flow using most feedstocks. Investors are reluctant to invest large amounts of capital on first-of-a kind technology without substantial risk mitigation. Although other feedstocks are potentially available at much larger scales, paper sludge conversion likely represents the lowest cost opportunity to realize a commercial facility with positive cash flow-in essence, a pilot plant that one could not afford to shut down. In particular, the total investment of less than $4 million, estimated here results from a combination of the large negative feedstock cost, small scale, a relatively simple process (e.g., not requiring pretreatment), and utilization of preexisting infrastructure. In light of these considerations, paper sludge conversion to ethanol appears to be a uniquely well-suited to serve as a point-of-entry and proving ground for nascent industries based on enzymatic hydrolysis of cellulosic biomass.

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