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2012

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Treasure, Trevor; Gonzalez, R.; Venditti, Richard; Pu, Y.; Jameel, H.; Kelley, Steve; and Prestemon, Jeffrey, "Co-production of electricity and ethanol, process economics of value prior combustion" (2012). *USDA Forest Service / UNL Faculty Publications*. 242.
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Co-production of electricity and ethanol, process economics of value prior combustion

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ARTICLE INFO

Article history:

Received 10 January 2012

Received in revised form 4 April 2012

Accepted 5 April 2012

Available online 26 June 2012

Keywords:

Value prior to combustion

Power

Ethanol

Hemicellulose

Autohydrolysis

Softwood

Hardwood

Minimum ethanol selling price

ABSTRACT

A process economic analysis of co-producing bioethanol and electricity (value prior to combustion) from mixed southern hardwood and southern yellow pine is presented. Bioethanol is produced by extracting carbohydrates from wood via autohydrolysis, membrane separation of byproducts, enzymatic hydrolysis of extracted oligomers and fermentation to ethanol. The residual solids after autohydrolysis are pressed and burned in a power boiler to generate steam and electricity. A base case scenario of biomass combustion to produce electricity is presented as a reference to understand the basics of bio-power generation economics. For the base case, minimum electricity revenue of \$70–\$96/MWh must be realized to achieve a 6–12% internal rate of return. In the alternative co-production cases, the ethanol facility is treated as a separate business entity that purchases power and steam from the biomass power plant. Minimum ethanol revenue required to achieve a 12% internal rate of return was estimated to be \$0.84–\$1.05/l for hardwood and \$0.74–\$0.85/l for softwood. Based on current market conditions and an assumed future ethanol selling price of \$0.65/l, the co-production of cellulosic bioethanol and power does not produce financially returns. A risk analysis indicates that there is a probability of 26.6% to achieve an internal rate of return equal or higher than 12%. It is suggested that focus be placed on improving yield and reducing CAPEX before this technology can be applied commercially. This modeling approach is a robust method to evaluate economic feasibility of integrated production of bio-power and other products based on extracted hemicellulose.

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1. Introduction

The effective conversion of cellulosic biomass into different forms of energy has been the target for many researchers in the last decades [1–7]. Although several pathways have been developed (biomass to power, lignocellulosic biomass to ethanol, etc.) [1,2,5,8–10], very few technologies meet the key requirements to become commercial: being both profitable under current market conditions and environmentally friendly. The success of corn ethanol in the US and sugar cane ethanol in Brazil has been widely discussed [1,11–14]. Nevertheless, it is important to note that the economics of both processes benefit from the commercialization of byproducts, as well as a continued improvement in the efficiency of the conversion process (efficient conversion of the feedstock into ethanol and different byproducts) [1,10,15]. Production of goods in addition to ethanol from lignocellulosic biomass may increase profitability and reduce investment risks which will attract investors. This paper presents a process economic analysis of co-producing cellulosic ethanol and electrical power. This production process evaluated is accomplished via autohydrolysis

and extraction of hemicelluloses (carbohydrate extraction for alcohol production) and burning the residues for power generation; a process termed value prior to combustion (VPC).

The hot-water extraction process, also known as autohydrolysis, can extract hemicellulose oligomers and monomers (mainly xylo-oligomers with different degrees of polymerization) from wood while leaving other components intact [16–20]. Temperature and reactor residence time are critical parameters to minimize sugar degradation and extraction yield. During hot-water extraction, acids are produced by the hydrolysis of hemicelluloses [18]. These acids, coupled with the dissolution of extractives in the biomass, cause the liquor pH to drop and effectively self-catalyze the hydrolysis process [21]. The sugar degradation products (furfural and hydroxymethylfurfural) are easily volatilized and may result in a loss of yield. The extracted xylose and other hemicellulose sugars can undergo fermentation to ethanol and can be considered a potential renewable resource for bio-based fuels [22,23]. Although we have focused on fermentation of extracted sugars to produce ethanol, hemicellulosic sugars can also be used to produce biodegradable plastics and chemicals that are currently derived from petroleum [18,19,24]. The residues after hot water extraction can be burned to produce steam and electricity or alternatively can be used as a raw material for wood and paper products.

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The concept of liquid fuel and power production from the same feedstock has several advantages in comparison to traditional second generation ethanol production technologies that are only focused on producing cellulosic ethanol or traditional bio-power platforms for electricity generation. Previous studies have indicated that liquid biofuel and bio-power production could profitably co-exist in an integrated process as technology improvement occurs [25–27]. From an efficiency point of view, hot water extraction removes components of the feedstock (hemicelluloses) that have low heating value but can potentially be converted to valuable by-products such as ethanol [28]. By removing the low heating value components from the raw material, the heating value of the residual solids is actually higher per unit mass and therefore a smaller boiler can be used to produce the same amount of power. From a revenue point of view, VPC diversifies the portfolio of products and reduces risk of the biorefinery in regards to fluctuations in main product selling prices. Previous research efforts in co-production of power and ethanol concluded that high capital investment and high enzyme costs limit the potential of this combined production process [28]. However, in comparison to traditional second generation cellulosic ethanol technologies, the cost of enzyme hydrolysis may be substantially lower since enzymes are only being used on soluble oligosaccharides which hydrolyze in less time with less enzyme than hydrolysis of insoluble pretreated lignocellulosics used in traditional second generation technologies. The co-production of high value bio-based products from the extracted hemicelluloses would also increase the profitability of combined production processes and may lead to greater diversity in product portfolio as the technology for bio-based product production becomes more mature [29].

The aim of this paper is to present the economics of co-producing power and lignocellulosic ethanol in an integrated process using southern mixed hardwood and southern yellow pine as feedstocks. The economics of standalone power generation from biomass in a greenfield plant is explored first and represents a base case analysis. The following economic indicators were determined to gauge the economic performance of the base case and proposed cases: internal rate of return (IRR), net present value (NPV), pay-back period, and minimum power selling price (to achieve a specific internal rate of return). After developing the base case, the proposed scenario involving biomass autohydrolysis and sugar extraction to produce ethanol while burning the residual solids was developed and analyzed. The discussion provides novel information needed to understand the tradeoff between producing power and ethanol in an integrated conversion process.

2. Materials and methods

In order to offer a guide for the information provided in this paper a brief description of each section is presented here. The “Feedstock” section provides the chemical composition, moisture content and delivered cost of the raw materials. The “Basis for Evaluation” section establishes the framework for comparison across the paper; defining the base case (power generation only) and alternative case (power and ethanol production). The “Proposed Pathway” section describes the integrated process for power and ethanol production in more detail by identifying the major unit operations as well as process conditions. The “Conversion Factors” section deals with wood component yields through autohydrolysis and defines the composition of both extraction liquor and solid residues. The process modeling framework, including software used, inputs, and constraints, is presented in the “Process Simulation” section. Within the “Economics Analysis” section, the variables used for the estimation of the economic indicators and the methods to estimate cost drivers are presented.

2.1. Feedstock

Feedstocks used in this analysis are softwood (southern yellow pine) and hardwood (natural southern mixed hardwood) in the form of forest residues (also called hog fuel). The moisture content estimated for hog fuel was about 40% [30–32].

The chemical composition of the feedstock (softwood and hardwood) used for this study is a normalized version of compositional analysis data collected in the lab (Table 1). The original compositional analysis was determined at the Department of Forest Biomaterials at North Carolina State University and is explored in greater detail by Pu et al. [21]. Proportional normalization of the feedstock composition was performed to satisfy mass balance constraints within the process model.

2.2. Basis for evaluation

As previously mentioned, this paper presents the economics of an integrated process producing power and ethanol. The economics of standalone power generation from biomass is explored first. In an alternative case, power and ethanol are produced in the same facility. For the economic analysis, a greenfield concept was used. Further explanation for each case is presented next.

2.2.1. Base case

Power generation from biomass is evaluated in the base case for softwood and hardwood, separately. The conversion process of a greenfield plant was simulated in WinGEMS [33] and the economics in an Excel spreadsheet. An annual input of 500,000 dry short tons (abbreviated as BDT) (or 453,592 dry metric tons), is fed into the system to achieve a power generation rate of ~72 MW. The facility was assumed to operate for 350 days per year which results in ~605 GWh of power produced annually.

2.2.2. Alternative case

In the alternative case, power and ethanol are co-produced in an integrated plant. The model was built in order to recalculate the amount of feedstock required to produce ~72 MW. The amount of biomass fed to the facility is higher than the Base Case because some of the material that was previously burned to produce electricity is now being converted to ethanol. A total of six alternative cases were evaluated as outlined in Table 2. For all the cases, the model estimates the amount of feedstock required to produce 95% of the power capacity (~72 MW), an additional production capacity of 5% has been assumed for capital investment (CAPEX) estimation. The same excess capacity and additional CAPEX requirement are also assumed in the base case.

2.3. Proposed pathway

The proposed pathway for integrated power and cellulosic ethanol production is illustrated in Fig. 1. Lignocellulosic biomass is fed into the autohydrolysis reactor for 1 h residence time at the specified temperature (Table 2). For all alternative cases, ~13% of the incoming feedstock is assumed to contain a share of under-/

Table 1
Chemical composition of softwood and hardwood feedstocks.

Component	Hardwood (%)	Softwood (%)
Lignin	27	29
Glucan	46	46
Hexan	4	14
Xylan	19	7
Extractives	3	3
Ash	1	1

Table 2

Alternative cases in power and ethanol production.

Case	I	II	III	IV	V	VI
Feedstock	Hardwood	Hardwood	Hardwood	Softwood	Softwood	Softwood
Autohydrolysis temperature (°C)	160	170	180	160	170	180
Reaction time	1 h	1 h	1 h	1 h	1 h	1 h
Product	Power	Power	Power	Power	Power	Power
Co-product	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol

Fig. 1. Proposed integrated system for power and lignocellulosic ethanol production.

over-sized chips and generated saw dust that would not process well in the water hydrolysis reactor and is therefore sent directly to the combustor in the power plant (this might also include high heating value materials usually purchased by bio-power companies as treated and dry wood). Thus, 87% of the total feedstock brought into the facility is fed to the water hydrolysis reactor for sugar extraction. After autohydrolysis, the slurry is passed through a washing-screw press system to recover dissolved carbohydrates and reduce the moisture content of the solid residue to 40% before it is sent to the combustor for power generation. In this stage of processing, it is assumed that 91% of the sugars are recovered in the filtrate for conditioning and fermentation to ethanol during washing and that 9% of the dissolved carbohydrates are burned, as opposed to being conditioned and fermented to produce ethanol. The filtrate, containing both monomeric and oligomeric carbohydrates as well as dissolved wood solids, is passed through a membrane system to remove undesired products generated during autohydrolysis such as furfural, hydroxymethylfurfural, acetic acid and formic acid. It was assumed that ~90% of the undesired byproducts are removed in the membrane system although laboratory studies have reported higher separation efficiencies [18]. Oligomeric sugars are then hydrolyzed using enzymes. The resulting

filtrate (~16% sugar concentration, water removal by means of membrane filtration) is fermented and distilled to produce anhydrous fuel grade ethanol. Conversion efficiency during enzymatic hydrolysis was 100% for pentoses (five carbon sugar) and hexoses (six carbon sugars) with a total residence time of 48 h; 48 h is a conservative estimate as this residence time is typical for enzymatic hydrolysis of insoluble lignocellulosic substrates and therefore may be significantly less for the soluble oligomeric sugar stream in this process. Conversion efficiency used for fermentation was 95% for hexoses and 80% for pentoses with a total residence time of 36 h. Fermentation experiments were not performed in the lab and modeling conversion factors were assumed using data from previous reports [1,34].

2.4. Mass balance of extract and residues

After the autohydrolysis reactions take place, pentoses and hexoses are partially extracted into the liquid phase. Degradation of sugars into non-desirable products also occurs (furfural, hydroxymethylfurfural, acetic acid and formic acid). These products are not desirable because they constitute a yield loss and can inhibit downstream fermentation. As more degradation products are

formed the material balance data collected in the lab becomes more open. Presumably, this results from volatilization of degradation products. To account for this lack of material balance closure, a “Volatiles” component was incorporated into the dissolved solids stream structure of the process model. Dry matter loss to volatiles for hardwood is larger compared to softwood and increases as temperature increases; as the autohydrolysis temperature increases from 160 °C to 180 °C, the amount of dry hardwood that degrades to a volatile component increases from 6.3% to 17.5% [21]. The complete mass balances for hardwood at 160 °C, 170 °C, and 180 °C are illustrated in Table 3. The mass balances are reported on a 1000 oven dry kg of raw material basis.

The amount of material extracted from hardwood, at all temperatures, was more than softwood. The amount of material degraded to unspecified volatiles is lower for softwood compared to hardwood; as the autohydrolysis temperature for softwood increases from 160 °C to 180 °C the amount of material converted to volatiles increases from 0% to 5.0% [21]. The complete mass balances for softwood at 160 °C, 170 °C and 180 °C are illustrated in Table 4. Again the mass balances have been recreated with an initial starting material of 1000 kg for illustration purposes. Lignin content in the filtrate and residues was measured for the lower temperature conditions for both species and then assumed as the same for the other pretreatment conditions. This is not an unreasonable assumption since lignin is known to have a low solubility in acidic water.

2.5. Process simulation

A complete steady-state mass and energy balance process model for the integrated power plant and biorefinery facility was produced using WinGEMS V.5.3 [33,35]. This process simulation software was originally developed for use in the pulp and paper industry and therefore has specialty blocks and unit operations (solid/liquid handling washing and separation) particularly useful for application in pulp and paper and biorefinery facilities [1,2]. The simulation results were exported to a Microsoft Excel spreadsheet where it could be referenced for the economic evaluations.

Table 3
Extract and residues mass balance for hardwood after autohydrolysis.

Mass balance hardwood								
Starting material 1000 kg (O.D.)			Temperature 160 °C Solids		Temperature 170 °C Solids		Temperature 180 °C Solids	
Component	%	kg	Component	kg	Component	kg	Component	kg
Lignin	27	270.0	Lignin	264.6	Lignin	264.6	Lignin	264.6
Glucan	46	460.0	Glucan	448.9	Glucan	449.0	Glucan	358.4
Hexan	4	40.0	Hexan	0.0	Hexan	0.0	Hexan	0.0
Xylan	19	190.0	Xylan	86.8	Xylan	24.2	Xylan	0.0
Extractives	3	30.0	Extractives	0.0	Extractives	0.0	Extractives	0.0
Ash	1	10.0	Ash	1.0	Ash	1.0	Ash	1.0
Total		1000.0	Sub total	801.3	Sub total	738.7	Sub total	624.0
			Dissolved solids		Dissolved solids		Dissolved solids	
			Lignin	5.4	Lignin	5.4	Lignin	5.4
			Glucan	1.9	Glucan	4.3	Glucan	6.8
			Hexan	6.1	Hexan	10.0	Hexan	9.0
			Xylan	3.7	Xylan	19.0	Xylan	29.2
			Extractives	3.0	Extractives	3.0	Extractives	3.0
			Ash	9.0	Ash	9.0	Ash	9.0
			Oligomers	82.6	Oligomers	90.5	Oligomers	65.6
			Acetic acid	11.0	Acetic acid	24.0	Acetic acid	40.0
			Furfural	1.0	Furfural	5.0	Furfural	13.0
			HMF	1.0	HMF	1.0	HMF	2.0
			Formic acid	11.0	Formic acid	16.0	Formic acid	18.0
			Volatiles	63.0	Volatiles	74.0	Volatiles	175.0
			Sub total	198.7	Sub total	261.3	Sub total	376.0
			Total material	1000.0	Total material	1000.0	Total material	1000.0

Two main simulation models were built: (i) the base case in which only power was produced, and (ii) an integrated process in which power and alcohol are coproduced and the steam and electrical demands of the alcohol production facility are met by the power plant. The heating value of the feedstock both for the base case and alternative cases was estimated based on its composition (cellulose, hemicellulose, lignin, extractives and ash) following the methodology proposed by Jimenez and Gonzalez [36].

2.5.1. Capital investment power plant

Capital investment for biomass power plants vary greatly depending on the power generation capacity and process technology. Capital investment was estimated based on reported values found in the literature (based on dollars per kilowatt), with figures ranging from \$1500/kw (year 2007) [37], \$3235/kw (year 2007) [38] and \$2500/kw (year 2009) [39]. Capital investment (CAPEX) for this project was estimated based on a production capacity of 72 MW (plus an additional 5% for CAPEX estimation). A CAPEX value of \$2800 (as of 2011) per kw of electricity was assumed. The CAPEX was inflated to year 2012, using the civil works construction cost index system of the US Army Corps of Engineers [40]. Total CAPEX (including 2% of indirect costs and 2% of contingency, as well as land) was estimated at \$241.7 million. The value of the land alone was estimated at \$1.1 million. A sensitivity analysis on the assumed value of CAPEX is presented in the Results and Discussion.

2.5.2. Capital investment biorefinery

Capital investment for the biorefinery plant includes: land purchase, land preparation, raw water treatment, waste water treatment, water hydrolysis extraction, enzymatic hydrolysis, membrane clean up, fermentation, beer column, rectification column, dehydration, and product storage and shipment. This yielded a \$47 million investment (as of 2012) for an ethanol production capacity of 7 million gallons (26.5 million liters), including 2% of indirect costs and 2% of contingency. The CAPEX of the biorefinery is recalculated for each feedstock and autohydrolysis treatment temperature, so the model sizes the CAPEX of the biorefinery depending on the total ethanol output. The estimated CAPEX for the biorefinery complex

Table 4

Extract and residues yield for softwood after autohydrolysis.

Mass Balance Softwood								
Starting material 1000 kg (O.D.)			Temperature 160 °C Solids		Temperature 170 °C Solids		Temperature 180 °C Solids	
Component	%	kg	Component	kg	Component	kg	Component	kg
Lignin	29	290.0	Lignin	284.2	Lignin	284.2	Lignin	284.2
Glucan	46	460.0	Glucan	448.7	Glucan	440.3	Glucan	434.1
Hexan	14	140.0	Hexan	68.0	Hexan	39.8	Hexan	11.1
Xylan	7	70.0	Xylan	40.0	Xylan	23.9	Xylan	16.8
Extractives	3	30.0	Extractives	27.0	Extractives	7.0	Extractives	0.0
Ash	1	10.0	Ash	1.0	Ash	1.0	Ash	1.0
Total		1000.0	Sub total	868.9	Sub total	796.2	Sub total	747.2
			Dissolved solids		Dissolved solids		Dissolved solids	
			Lignin	5.8	Lignin	5.8	Lignin	5.8
			Glucan	1.9	Glucan	9.8	Glucan	19.2
			Hexan	13.6	Hexan	20.1	Hexan	25.2
			Xylan	4.6	Xylan	17.0	Xylan	20.7
			Extractives	3.0	Extractives	3.0	Extractives	3.0
			Ash	9.0	Ash	9.0	Ash	9.0
			Oligomers	66.6	Oligomers	87.7	Oligomers	72.9
			Acetic acid	8.6	Acetic acid	14.0	Acetic acid	23.0
			Furfural	0.9	Furfural	2.0	Furfural	5.0
			HMF	0.9	HMF	1.5	HMF	4.0
			Formic acid	16.2	Formic acid	14.0	Formic acid	15.0
			Volatiles		Volatiles	20.0	Volatiles	50.0
			Sub total	131.1	Sub total	203.8	Sub total	252.8
			Total material	1000.0	Total material	1000.0	Total material	1000.0

producing 7 million gallons of ethanol per year (26.5 million liters per year) is presented in Table 5. CAPEX for the biorefinery was built based on previous techno-economic reports and by consulting experts [8,34,41,42]. CAPEX estimation was based on green tons of feedstock for autohydrolysis and enzymatic hydrolysis, autohydrolysis filtrate flow for membrane clean-up, and beer flow for fermentation, beer column, rectification column and dehydration.

2.6. Economic analysis

The major cost drivers and assumptions are listed for the economic analysis of the base and alternative case in Tables 6 and 7.

For all cases, the evaluation horizon has been set for 15 years. A terminal value in year 15 of seven times year 15 EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortization) was assumed. The discount rate used for the biomass to electricity production case (Table 7) was 6%; this was based on the value of the weighted average capital costs (WACC) for electric utility companies on the east coast of the US [43] and the market return of “risk free” portfolios (based on the return of US treasury bills) [44]. In the case of ethanol production, a discount rate of 12% has been as-

Table 5

Capital investment for an ethanol biorefinery producing 7 million gallons per year (Softwood 170 °C). Source: [8,34,41,42].

Description	Scale factor	Green field US\$
Land purchase	0.9	36,953
Land preparation	0.9	1,011,525
Raw water treatment	0.7	433,417
Waste water treatment	0.7	650,126
Water hydrolysis	0.7	12,707,471
Enzymatic hydrolysis	0.7	11,628,920
Membrane clean up	0.7	8,895,230
Fermentation	0.8	5,630,195
Beer column	0.8	1,278,155
Rectification column	0.8	1,186,793
Dehydration	0.7	1,293,582
Product storage and shipment	0.6	1,658,609

Table 6

Operative and financial assumption for power plant (base case).

Description	Value
Feedstock supply, BDT/year	500,000
Startup year	2013
Terminal year	2027
% of CAPEX spending in year-2	30%
% of CAPEX spending in year-1	50%
% of Spending in year 0	20%
% of Nominal capacity, project year 1	80%
% of Nominal capacity, project year 2	90%
Working capital per cent of direct cost	10%
Years depreciation schedule	10
Tax rate, with tax loss carryforward	35%
Discount rate	6%
Terminal value, year 15 EBITDA multiple	7
Hours per year	8400
Biomass Cost, \$ per dry Ton	38.2
Moisture content%	40%
Hourly and administrative staff (non-maintenance)	16
Salaried staff	4
Maintenance expense, including labor, % of replacement asset value	1.0%
Capital reinvestment, % of replacement asset value	0.5%
Other fixed costs, % of sales	1.0%
Sales and other overhead, % of sales	1.0%

sumed for this project because this is a technology yet to be demonstrated on commercial scale and this discount rate is consistent with other studies [1,2,45,46]. All costs have been scaled up to year 2012. The analysis has been constructed to estimate the minimum power or ethanol selling price to achieve a specific rate of return (or discount rate) rather than assuming a price for ethanol (or power). A discussion of how these minimum selling prices compare to current prices found in the market is presented in Section 3.9 of this manuscript.

3. Results and discussions

In order to understand the tradeoff between producing power and cellulosic ethanol in an integrated process, it is important to

Table 7

Operative and financial assumption for the biorefinery.

Description	Value	S	Description	Value	S
Additional wood	Backcalculated		Biomass cost, \$ per dry ton	38.2	E
Startup year	2013	A	Moisture content, % of green ton	40%	E
Terminal year	2027	A	Enzyme cost, \$ per gallon ethanol	0.20	A
% of Spending in year-2	30%	E	Yeast Cost, \$ per Gallon Ethanol	0.07	1
% of Spending in year-1	50%	E	Hourly and administrative staff (non-maintenance)	21	E
% of Spending in year 0	20%	E	salared staff	4	E
% of Nominal capacity, project year 1	80%	E	Maintenance expense, including labor, % of replacement asset value	1.0%	E
% of Nominal capacity, project year 2	90%	E	Capital reinvestment, % of replacement asset value	0.5%	E
Excess material use in project year 1	30%	E	Other fixed costs, % of sales	1.0%	E
Working capital per cent of direct cost	10%	E	Sales and other overhead, % of sales	1.0%	E
Years depreciation schedule	10	E	Hydrolysis residence time	1 h	2
Tax rate, with tax loss carryforward	35%	E	Sugar loss during washing/screw press	9.1%	E
Discount rate	12%	A	Filter efficiency	90%	A
Terminal value, year 15 EBITDA multiple	7	A	Fermentation efficiency C5	85%	A
Hours per year	8400	A	Fermentation efficiency C6	95%	A

S = Source; A = Assumption; E = Expert consultation [41,42]; 1 = [1]; 2 = [21].

review some aspects of stand-alone biomass power production costs, profitability as well as effect of feedstock and moisture content.

3.1. Feedstock cost

The average feedstock delivered cost was estimated at \$38.2 per dry short ton (\$42.1 per dry metric tonne) for both softwood and hardwood. The estimation of the feedstock delivered cost was based on the cost per green ton [free on board (FOB)] and transportation cost (for an average transportation distance of 40 miles and transportation fee at \$0.13 per green ton per loaded mile) taken from the last eight quarterly publications of Timber Mart-South [47]. This average delivered cost was similar to the price paid for hog fuel in several locations in the Southern US as of the third quarter of 2011 [32]. Though an average price of \$38.2 per dry short ton (BDT) was used, there is an expected distribution of feedstock cost following a Lognorm distribution (Fig. 2). The distribution model fit was done using the distribution fit function of the @Risk software [48]. Note from the top of the graph (Fig. 2) that

70% of the values exist in an interval between \$20 and \$40 per BDT delivered.

3.2. Power generation

Power generation varies depending on the chemical composition and moisture content of the feedstock. In our process simulation, the same annual input of hardwood or softwood at the same moisture content produced slightly different amounts of electricity. An annual supply of 500,000 BDT of softwood produced ~73.3 MW, while the same quantity of hardwood produced ~72.8 MW, with an efficiency of 22.8% and 22.7% respectively (based on low heating values). These values are consistent with other publications [37,49,50].

3.3. Power generation costs

Power generation cost using an annual input of 500,000 BDT of softwood (40% moisture content) is presented in Fig. 3 (bars show absolute values while pie chart shows percentage values). Major

Fig. 2. Distribution of feedstock delivered cost in US\$ dollars per BDT, (1 dry metric tonne = 1.1023 BDT).

Fig. 3. Power generation costs using softwood feedstock.

cost drivers are biomass and depreciation (\$34.3 and \$42.2 per MWh, respectively) adding up to ~88% of total costs. A similar cost structure was observed for hardwood (not shown here). The relative importance of feedstock cost in the total power generation cost is one of the major limitations to increase the size of biomass power plants. Higher tonnage input of biomass would require longer feedstock hauling distances and increased delivered costs. One major handicap of biomass power compared to coal power is the cost of delivered raw material. Coal can be delivered at a cost relatively insensitive to the quantity demanded while biomass becomes increasingly more expensive as more biomass at a single location is demanded. In this analysis the feedstock cost was held

constant with no additional cost for higher volumes supplied to the market.

3.4. Minimum selling revenue required

The minimum selling revenue analysis estimates the required minimum wholesale price of electricity to achieve a specific internal rate of return. The minimum revenue of electricity required in order to achieve an internal rate of return of 6%, 8%, 10% and 12%, using softwood or hardwood, are shown in Fig. 4. In general, minimum revenue required values are lower in softwood because softwood has a slightly higher heating value resulting in more power

Fig. 4. Minimum revenue required per MWh of electricity at different values of internal rate of return (IRR).

generation per unit biomass. Minimum revenue required for softwood ranges from \$70 per MWh (at 6% IRR) to \$95 per MWh (at 12% IRR), while minimum electricity revenue for hardwood ranges from \$71 per MWh (at 6% IRR) to \$96 per MWh (at 12% IRR).

3.5. Moisture content effect on power generation and minimum whole selling price

One of the major factors influencing biomass to power generation efficiency is the moisture content of the feedstock. It is expected that feedstock with lower moisture content will produce higher energy output compared to feedstock with higher moisture content. Fig. 5 shows the effect of moisture content on electricity generation and minimum electricity revenue required (using hardwood as feedstock) to achieve a specific rate of return of 6% and 12%. For this sensitivity analysis, a range of 20–55% moisture content is presented. As moisture content increases, electricity generation (MW) decreases. Feedstock at 20% moisture content would produce ~79 MW, whereas the outcome for feedstock at 55% moisture would be 66.6 MW. When moisture content is lower and electricity generation is higher (20% moisture content), the minimum electricity whole sale revenue required is \$65 and \$88 per MWh to achieve a 6% and 12% IRR respectively. When moisture content increases to 35%, the minimum whole sale electricity revenue required rises to \$78 per MWh (6% IRR).

3.6. Ethanol production cost

Ethanol production costs, minimum ethanol revenue and other economic indicators are analyzed for each of the alternative cases (as listed in Table 2). The ethanol production costs for softwood at 170 °C are shown in Fig. 6. The method for distributing production cost for ethanol, specifically for feedstock and energy, is as follows: the model estimated the amount of feedstock required to produce ~72 MW, all additional wood (additional wood relative to the base case input of 500,000 BDT per year) was charged to the cost center of ethanol feedstock. Energy cost was estimated from the energy used (by the biorefinery facility), and it was considered as a cost

to the biorefinery assuming a cost rate of \$64 per MWh (power and process steam were calculated using the engineering software WinGEMS). In other words, the electrical demand of the ethanol production equipment is satisfied by the electricity produced by the biomass power facility and sold at whole sale price. In Fig. 6 it can be observed that feedstock (35% of production costs), depreciation (26%) and energy (14%) are the major cost drivers accounting for ~75% of total production costs.

The main findings of the economic analysis focus on the interaction between the different extraction conditions, feedstocks and the economic indicators for ethanol production. Fig. 7 shows additional wood input, ethanol production and total wood sent to the autohydrolysis reactor for sugar extraction (87% of total wood input). The highest ethanol production scenario is observed for softwood at 170 °C (26.6 million liters per year). Both softwood and hardwood had the highest ethanol output at 170 °C. Lower additional wood input was determined for softwood because the amount of material extracted to produce ethanol is lower at a given temperature compared to hardwood. For the two feedstocks, the additional wood input increases at higher temperature (more material extracted during autohydrolysis) [21]. However, higher extraction rates do not necessarily translate into greater ethanol production because of yield loss to sugar degradation products at higher temperatures. Additional wood input ranged from 118 thousand BDT per year (softwood 160 °C) to 249 thousand BDT per year (hardwood 180 °C). Ethanol yields (wood sent to hydrolysis) for hardwood at process conditions of 160, 170 and 180 °C were 37.2, 41.6 and 31.6 l of ethanol per BDT of feedstock, respectively. Ethanol yield for softwood at process conditions of 160, 170 and 180 °C were 32.9, 45.6 and 39.9 l per BDT respectively.

3.7. Minimum ethanol revenue required, cash cost and production cost

Fig. 8 shows production costs, cash cost and minimum ethanol revenue required (estimated to achieve 12% IRR). The lowest production costs, cash costs and minimum ethanol revenue required are observed at 170 °C for both feedstocks. Overall lower values are observed for softwood, explained by less sugar degradation to

Fig. 5. Effect of moisture content on electricity production for 500,000 BDT and minimum revenue required (to achieve 6% and 12% IRR).

Fig. 6. Ethanol production costs per gallon of ethanol (Softwood 170 °C), 1 gallon = 3.785 l.

Fig. 7. Ethanol production, wood to hydrolysis and additional wood purchased for each autohydrolysis condition.

unwanted components, producing more ethanol output and requiring less additional wood input. Minimum ethanol revenue required (MER) ranged from ~ \$0.74–1.05 per liter of ethanol (FOB) at the plant for the cases considered.

3.8. Return on investment and payback

Returns on investment, payback and minimum ethanol revenue were estimated for all cases. Return on investment (ROI) is a popular financial indicator calculated as the ratio between the after tax income with respect to the assets used to generate such revenue in

the project. Across the fifteen year evaluation horizon, both feedstocks at 170 °C present the higher ROI with values of ~7% for year nine (Payback period). Lower ROI was observed for both feedstocks at the highest temperature (180 °C), with values of ~6% for year nine. Payback is the time required to offset the initial investments. In other words, it is the time required such that the accumulated free cash flow at historical values becomes positive. As expected the lower payback periods are observed in those conditions with lower production costs, cash costs and minimum ethanol revenues, with payback around 9 years (softwood 170 °C followed by hardwood 170 °C).

Fig. 8. Minimum ethanol revenue required (12% IRR), cash cost and production cost for each autohydrolysis condition.

3.9. By-products

As discussed previously, degradation of sugars occurs at elevated temperatures in the presence of acid leading to the formation of byproducts of which furfural, hydroxymethylfurfural, acetic acid, and formic acid are the most abundant. Table 8 illustrates the amount of these four components recovered after separation from the hydrolyzate stream (using membranes). More byproducts are produced from hardwoods relative to softwoods at a given temperature. More byproducts are produced from a given feedstock as the autohydrolysis temperature increases. No revenue has been considered from these byproducts but they could be purified with additional equipment and then sold.

3.10. Sensitivity analysis

A sensitivity analysis describes how the system variables impact the economic forecast of a project. An analysis of this kind also helps to guide future development to mitigate risk. The response variable chosen to understand sensitivity impact was the minimum ethanol revenue required (estimated to achieve a 12% IRR). The sensitivity analysis was built with a variation of $\pm 25\%$ of the central values for CAPEX, ethanol yield, biomass cost and enzyme cost (Fig. 9).

The MER is most sensitive to ethanol yield, followed by biomass cost and CAPEX. In the most favorable case, a 25% increase in yield may drop the MER to \$0.64 per liter. Reducing feedstock cost and enzyme cost individually by 25% can decrease the MER to ~\$0.67 per liter of ethanol.

Ethanol market prices have varied considerably in the past decade. A key consideration when conducting simulations in which prices are allowed to randomly vary requires an understanding of the shape of the probability distribution of these prices. The shape of the probability distribution of ethanol market price in the period between January 2002 and July 2011 was estimated using the distribution fit function of @Risk software, which determines the parameters of the probability distribution that is most consistent with observed data. The distribution indicated that approximately 20% of the ethanol selling prices fall in the range of \$0.64 + liter. Fig. 10 presents the historic selling price for ethanol and regular gasoline in Omaha, Nebraska, US [51]. Although the selling price for ethanol has increased drastically over the past decade, a reasonable estimate of future ethanol selling price is likely around \$0.60–\$0.70/l.

If a future ethanol selling price of \$0.65/l is assumed, the technology outlined herein to produce bioethanol via autohydrolysis of wood would have to have a 25% higher yield to achieve a 12% IRR (Fig. 9). This technology is relatively insensitive to enzyme cost but a reduction of CAPEX and biomass costs are other variables in addition to yield that have potential to improve the financial prospects of a VPC project. Note that the calculated minimum ethanol revenue required calculations ranged from \$0.74 to \$1.05 per liter of ethanol for the six cases, indicating that it is not economically feasible under current ethanol prices to pursue VPC.

In order to provide a measure of the probability of investment failure or success, the probability distribution of the NPV is presented as a function of all operational data and the probability distribution of enzyme cost, feedstock cost, CAPEX, and yield. All

Table 8
Formation of acetic acid, formic acid, furfural and hydroxymethylfurfural for each autohydrolysis condition.

Byproducts (ton/year)	Hardwood 160 °C	Hardwood 170 °C	Hardwood 180 °C	Softwood 160 °C	Softwood 170 °C	Softwood 180 °C
Acetic acid	4486	10,399	17,827	3132	5585	9708
Formic acid	5098	7880	9117	6723	6347	7196
Furfural	463	2461	6585	395	906	2397
Hydroxymethylfurfural	463	492	1012	395	682	1918

Fig. 9. Sensitivity of minimum ethanol revenue required (12% IRR) with variation of $\pm 25\%$ for CAPEX, yield, biomass cost and enzyme cost (Case: Softwood 170 °C).

Fig. 10. Historic ethanol and regular gasoline price FOB Omaha, Nebraska, US.

distributions were fit using @Risk software [48]. The probability distribution of the feedstock cost is the same as presented in Fig. 2. The probability distribution of enzyme cost (\$ per liter), CAPEX, and ethanol output (in liters) were modeled following rectangular distributions based on the assumption of $\pm 25\%$ with respect to the central assumption listed in the methodology section. These potential sources of variations affect the distribution of the NPV values of the project (Fig. 11). The simulation was performed with 500 iterations using the simulation module of @Risk. For this evaluation, instead of evaluating the minimum revenue required per

liter of ethanol, a wholesale selling price of \$0.65 per liter of ethanol was used along with a discount rate of 12%. From the distribution of the NPV listed in Fig. 11, it was possible to assign a percentage of failure or success for the project. It can be observed that only 26.6% of the distribution of the NPV is above zero, which means that there is a probability of 26.6% to achieving an internal rate of return equal or higher than 12%. Previous studies addressing the co-production of power and ethanol have concluded that mature technologies could be profitable in the long term [52,53]. One main influence that may lead to improved economics of the

Fig. 11. Probability distribution of the NPV value of the project (discount rate 12%).

biorefinery is increased plant capacity [52], although higher feedstock costs will then become a major limitation [9].

4. Conclusions

The concept of VPC (value prior to combustion) is technically feasible but the minimum ethanol revenues required to produce a 12% internal rate of return are high enough to discourage investors if future prices are distributed similarly to the last decade's historical prices. Under the current assumptions and scenarios evaluated, the lowest minimum ethanol revenue required to achieve a 12% IRR (\$0.74/l) occurs for softwood at an extraction temperature of 170 °C. This revenue requirement is higher than the assumed future ethanol selling price of \$0.65/l. The base case analysis showed that electrical power from biomass must sell for \$70–\$96/MWh to achieve internal rates of return of 6–12%. The financial performance of this autohydrolysis technology appears to be most sensitive to ethanol yield followed by CAPEX and biomass cost. Biomass cost, much like ethanol selling price, is subject to rules of the open market. Therefore, it is suggested that focus be placed on improving yield and reducing CAPEX before this technology can be applied commercially.

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