DOI: 10.1155/2014/537408

Hindawi Publishing Corporation
International Journal of Chemical Engineering
Volume 2014, Article ID 537408, 11 pages
http://dx.doi.org/10.1155/2014/537408

Research Article

A New Proposal of Cellulosic Ethanol to Boost Sugarcane Biorefineries: Techno-Economic Evaluation

Juliana Q. Albarelli,[1] Adriano V. Ensinas,[2] and Maria A. Silva[1]

[1] *School of Chemical Engineering, University of Campinas (UNICAMP), Cidade Universitária Zeferino Vaz, Avenida Albert Einstein 500, 13083-852 Campinas, SP, Brazil*
[2] *Federal University of ABC (UFABC), R. Santa Adélia 166, Bangu, 09210-170 Santo André, SP, Brazil*

Correspondence should be addressed to Juliana Q. Albarelli; jualbarelli@gmail.com

Received 17 February 2014; Accepted 22 April 2014; Published 21 May 2014

Academic Editor: Anuj K. Chandel

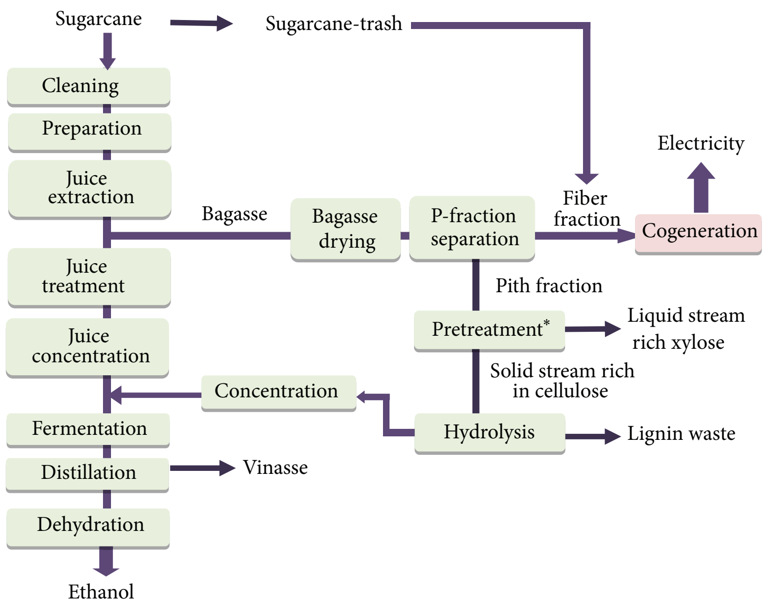
Commercial simulator Aspen Plus was used to simulate a biorefinery producing ethanol from sugarcane juice and second generation ethanol production using bagasse fine fraction composed of parenchyma cells (P-fraction). Liquid hot water and steam explosion pretreatment technologies were evaluated. The processes were thermal and water integrated and compared to a biorefinery producing ethanol from juice and sugarcane bagasse. The results indicated that after thermal and water integration, the evaluated processes were self-sufficient in energy demand, being able to sell the surplus electricity to the grid, and presented water intake inside the environmental limit for São Paulo State, Brazil. The processes that evaluated the use of the bagasse fine fraction presented higher economic results compared with the use of the entire bagasse. Even though, due to the high enzyme costs, the payback calculated for the biorefineries were higher than 8 years for all cases that considered second generation ethanol and the net present value for the investment was negative. The reduction on the enzyme load, in a way that the conversion rates could be maintained, is the limiting factor to make second generation ethanol competitive with the most immediate uses of bagasse: fuel for the cogeneration system to surplus electricity production.

1. Introduction

Sugarcane bagasse is an important byproduct from sugarcane industry. It can be used as raw material at different production processes; however its main use is as fuel for the sugarcane mill cogeneration system [1]. It has been broadly studied as raw material for second generation ethanol production processes. In Brazil, a large number of scientific and technological innovations in this extend have been generated by the increasing research incentive promoted by governmental funding agencies, research institutes, and private companies [2–6].

The use of bagasse to second generation process in the Brazilian scenario furthers the integration of conventional ethanol production with cellulosic ethanol production, eliminating shipping cost of the cellulosic material and allowing the simultaneous use of equipment. Different alternatives for integrated processes using sugarcane bagasse to ethanol production with the conventional sugar mill had been studied using simulation tools [7–10]. Most of these studies were accomplished using the software for process simulation Aspen Plus. Among the commercial process simulators, Aspen Plus stands out for its friendly user interface, vast database of equipment, and thermodynamic models.

In general, 1 t of sugarcane generates 280 kg of bagasse with 50% moisture [11]. After juice extraction, the formed bagasse has wide particle size dispersion. The typical chemical composition, on a dry basis, is 38 to 43% of cellulose, 25 to 32% of hemicellulose, 17 to 24% of lignin, and 1.6 to 7.5% of ash [12]. These values have a range of variation depending on many factors such as the variety of the sugarcane, stage of plant growth, weather conditions before and after the harvest, and the harvesting system. In addition to the ashes, organic extractives and minerals also are found in small quantities such as greases, gums, starches, alkaloids, resins, and essential oils. Bagasse physical composition is approximately 50% of



*Pretreatment step is not considered for Case 1

Figure 1: Block diagram of the P-fraction studied processes (Cases 1, 2, and 3).

moisture, 45% of fibrillar structures, and 5% of extractives and inorganic components. The fibrillar fraction comprises 55 to 60% fiber and 30 to 35% pith particles [13]. The fibers correspond mostly to stalk fibro-vascular cells; they have high length-width ratios (lengths up to a few centimeters). The pith particles are finer, with near unitary length-width ratio, and originated from stalk parenchyma.

Recent studies [14–16] indicated better results for cellulose saccharification using only the pith fraction of bagasse when compared with the use of the entire bagasse. These cells have a lower lignin content compared to the bagasse fiber, which facilitates the enzymatic attack to cellulose. Another advantage is that these particles have small particle size distribution in which it facilitates the transport and handling of the biomass without the need for prior grinding.

This new scenario needs evaluation and the results should be compared to the alternatives that have been evaluated for bagasse use in the sugarcane sector until now. In this context, the present study aims at evaluating the use of bagasse pith for second generation ethanol production using flowsheeting software (Aspen Plus). This new proposal of cellulosic ethanol is compared with the use of bagasse as fuel to the cogeneration system or the use for second generation ethanol production without separation of the pith fraction. Additionally, water balance in the whole process, including second generation plant, was analyzed as it is an important environmental restriction to the installation of new sugarcane mills in Brazil. An economic analysis was performed in order to compare the cases studied. Sensitivity analyses were carried out to assess the impact of raw material prices and investment on the economic feasibility of the process.

2. Materials and Methods

2.1. Process Modeling Strategy. For this study second generation ethanol production with bagasse pith fraction (P-fraction) as raw material using no pretreatment, steam explosion pretreatment, or LHW pretreatment was analyzed. Second generation ethanol production was integrated to first generation. The overall process is shown in Figure 1. Ethanol production from P-fraction was compared to ethanol production using sugarcane bagasse and also to the use of the entire bagasse to electricity production. In this extent, 5 different cases were analyzed. Table 1 shows the technology considered in each case studied.

A detailed description of each process is given as follows.

(i) Case 1: Use of P-fraction to second generation ethanol production integrated to the autonomous distillery, considering no pretreatment and enzymatic hydrolysis, and the use of sugarcane-trash as additional fuel to the cogeneration system with a condensing turbine and cooling towers to increase electricity in a thermally integrated autonomous distillery.

(ii) Case 2: Use of P-fraction to second generation ethanol production integrated to the autonomous distillery, considering steam explosion pretreatment and enzymatic hydrolysis, and the use of sugarcane-trash as additional fuel to the cogeneration system with a condensing turbine and cooling towers to increase electricity in a thermally integrated autonomous distillery.

(iii) Case 3: Use of P-fraction to second generation ethanol production integrated to the autonomous distillery, considering liquid hot water (LHW) pretreatment

Table 1: Summary of the technologies listed for the cases studied.

Case	1	2	3	4	5
1st generation ethanol production	X	X	X	X	X
P-fraction to 2nd generation ethanol production	X	X	X		
Bagasse to 2nd generation ethanol production				X	
Second generation process without pretreatment	X				
Steam explosion pretreatment		X			
Liquid hot water pretreatment			X	X	
Enzymatic hydrolysis	X	X	X	X	
Condensation turbine	X	X	X		X
Cogeneration using bagasse (50% w.b. moisture)				X	X
Cogeneration using bagasse fibers (8% w.b. moisture)	X	X	X		
Cogeneration using sugarcane-trash	X	X	X	X	X
Cogeneration using lignin waste				X	

and enzymatic hydrolysis, and the use of sugarcane-trash as additional fuel to the cogeneration system with a condensing turbine and cooling towers to increase electricity in a thermally integrated autonomous distillery.

(iv) Case 4: Second generation ethanol production from sugarcane bagasse integrated to the autonomous distillery, considering LHW pretreatment and enzymatic hydrolysis, using the surplus bagasse available after thermal integration of the process, and the use of sugarcane-trash as additional fuel to the cogeneration system.

(v) Case 5: Use of sugarcane-trash together with all the bagasse available as fuels for the cogeneration system with a condensing turbine and cooling towers to increase electricity in a thermally integrated autonomous distillery.

2.2. Process Simulation

2.2.1. Definition of the Simulation Parameters. The commercial simulator Aspen Plus [17] was used for the process modeling including mass and energy balance of each piece of equipment of the first and second generation ethanol plants. The thermodynamic properties method used to represent the process stream was UNIQUAC with modified binary parameters proposed by Starzak and Mathlouthi [18] to adequately represent the elevation of the boiling temperature of the sucrose-water mixture, except for pure water streams which used the model STEAMNBS method. The components cellulose, hemicellulose, lignin, and enzymes were added to simulator database using the data from Wooley and Putsche [19]. The average composition of sugarcane arriving at the process is presented in Table 2.

Table 2: Assumed composition for sugarcane at the beginning of the process, for the sugarcane-trash, and for the P-fraction.

		Sugarcane	Sugarcane-trash	P-fraction
		Composition (% w/w)		
Water		70.5	15.0	8.0
Fibers	Cellulose	5.9	35.7	46.0
	Hemicelluloses	3.5	28.1	22.1
	Lignin	3.2	19.8	9.2
Solids	Sucrose	13.9	—	—
	Dextrose	0.6	—	—
	K_2O	0.4	—	—
	KCl	0.2	—	—
	SiO_2	0.3	—	14.7
	Acronitic acid	0.6	—	—
Dirt	SiO_2	1.0	1.4	—

All the reducing sugars as dextrose, impurities as potassium salt, minerals as K_2O and SiO_2, organic compounds as acronitic acid, and the inorganic material dragged along with sugarcane from the field as SiO_2 were considered.

2.2.2. Description of the Analyzed Processes. The evaluated processes and the data used for its simulation are described in detail hereafter.

Autonomous Distillery Considered in All Cases Studied for Production of 1st Generation Ethanol. An autonomous distillery with processing capacity of 500 tonnes of sugarcane per hour was considered as it represents the processing capacity of a standard mill in São Paulo State [6, 8]. The distillery is dedicated to the production of anhydrous ethanol with 99.3% (w/w) of purity, which is the specification for blending with automotive gasoline. For the first generation ethanol production process dry cleaning of sugarcane followed by sugar extraction in a mill tandem was considered. Physical and chemical juice treatments were accomplished by screening, heating, liming, decantation, and mud filtration. After treatment clarified juice was concentrated until 20° Brix in a 5 effect evaporator. It was then sterilized in high temperature short time (HTST) process. The Melle-Boinot fermentation process (cell-recycle batch fermentation) was considered. The distillation step considered 5 distillation columns for production of hydrated ethanol (93.7% wt. of ethanol). For production of anhydrous ethanol (99.4% wt. of ethanol), a process of extractive distillation with MEG (monoethylene glycol) was simulated. A more detailed description of the considered process can be found at [9, 10, 20]. Data required for simulation of these steps were obtained in the literature [21, 22]. Main process parameters considered for the 1st generation ethanol production are displayed in Table 3.

Integrated 1st and 2nd Generation Ethanol Production from Bagasse P-Fraction. According to researches [14, 15] 35 to 40% of the bagasse mass is comprised by the pith particles. The average composition of these particles is show in

Table 3: Main parameters adopted for simulating first generation ethanol production.

Parameter	Value	Unit
Sugarcane processed	500	t/h
Efficiency of impurities removal on sugarcane cleaning	60	%
Efficiency of sugars extraction on the milling system	97	%
Sugarcane bagasse moisture content	50	% w.b.
Recovery of sugars on juice treatment	99.4	%
Fermentation yield	89	%
Ethanol recovery on distillation and dehydration	99.7	%

w.b.: wet basis.

Table 2. So, as a first step to access these particles for second generation processes, the separation of bagasse pith from fibers was considered. To have an efficient separation, first bagasse was dried in order to lower its moisture content from the initial 50% w.b., after sugar extraction to 8% w.b. (equilibrium moisture of bagasse at temperatures around 298 K and atmospheric pressure 1 atm). Dry bagasse was then considered introduced to a horizontal circular motion sieve to perform P-fraction separation. Horizontal circular motion sieves has proven to be more efficient than regular vibrating sieves to perform this separation experimentally [14]. Also pneumatic separation of bagasse showed good results in separation a bagasse fine fraction rich in pith particles [15]. Even so, in the present simulation study, a horizontal circular motion sieve was considered as experimentally could promote the best results in separating P-fraction so far [14].

After separation, P-fraction was sent to the second generation ethanol production process and bagasse fibers were sent to the cogeneration system. At the second generation process, P-fraction went thought a pretreatment process without any prior washing or treatment. In Case 1 no pretreatment unit was considered, this possibility was analyzed as experimental work [15, 16] indicated that reasonable good yields could be achieved using bagasse fine fraction, rich in pith particles, without pretreatment. Case 2 considered steam explosion pretreatment and Case 3 considered liquid hot water (LHW) pretreatment. The pretreated mass obtained in Cases 2 and 3 was washed to remove the xylose formed during the pretreatment. The process was followed by the enzymatic hydrolysis, where cellulose present in the P-fraction goes through a saccharification process to form fermentable sugars. It was admitted that the enzymatic hydrolysis was conducted under temperature of 50°C with residence time of 24 h using cellulase concentration of 15 FPU/g of biomass (enzyme activity 65 FPU/g) and β-glucosidase concentration of 0.9 IU/g of biomass (17 IU of enzyme activity/g) [23]. Pretreatment and hydrolysis conversion parameters were admitted based on data available in the literature for bagasse [24] and preliminary experimental tests [14–16]. It was assumed that higher yields than the ones found in the literature for sugarcane bagasse could be achieved for P-fraction since the evaluation of the processes are still incipient and probably, with further experimental analysis, better yields will be achieved by the optimization of process parameters.

The liquid stream resulted from hydrolysis was concentrated in a four-step evaporator until 20° Brix and the sugar rich solution was sent to the first generation fermentation process where it was mixed to the concentrated juice. The solid waste from the hydrolysis process contains lignin but is also rich in ashes, this material could be harmful for the cogeneration system, and therefore it was considered for use, together with the filter cake, as fertilizer for the sugarcane plantation. The parameters adopted in each step of the process are shown in Table 4.

A sensitivity analysis on the conversion parameters for Case 3 was analyzed and this new case was called Case 3L. In this analysis, lower parameters were evaluated considering a scenario where the experimental results obtained so far for the use of P-fraction could not be optimized and the conversion parameters at each step were just a little higher than the use of bagasse.

Bagasse fibers sent to cogeneration was mixed to sugarcane-trash; this process will be better described in item “cogeneration system”. Both biomasses were used as fuels to the cogeneration system from which 5% is saved for system startup or sugarcane crushing shutdowns. A steam-based cycle operating with live steam at 753 K and 6.5 MPa of temperature and pressure was considered, respectively, using a back-pressure turbine to generate electricity for the cogeneration system. Since the amount of fuel sent to the cogeneration was more than the necessary to supply the heat demand of the integrated process, the installation of a condensing turbine at the cogeneration system was considered, to use the surplus steam generated to increase electricity production. The parameters adopted at the cogeneration process are shown in Table 5.

Integrated 1st and 2nd Generation Ethanol Production from Bagasse. Ethanol production from sugarcane bagasse was simulated as a comparison case to the use of P-fraction as it has been largely studied experimentally and using simulation tools. This alternative was investigated in Case 4, where bagasse formed after juice extraction was separated in two flows, one sent to second generation process and the other to the cogeneration system. The amount sent to each function was set after thermal integration of the integrated 1st and 2nd generation processes.

The use of bagasse to ethanol production is considered a prior step of drying, until 8% w.b. of moisture content (equilibrium moisture of bagasse at temperatures around 25°C and atmospheric pressure) and milling in order to standardize, facilitate the transport, and increase the effectiveness of pretreatment. Prior to pretreatment, cleaning was considered once this step is important to remove impurities from the biomass and therefore increase pretreatment efficiency [26]. Second generation ethanol production was studied in Cases 3 and 4. LHW pretreatment was simulated followed by the biomass saccharification through enzymatic hydrolysis. The same enzyme concentration, temperature, and residence time described previews for the P-fraction process was admitted. After the hydrolysis reactor a concentration of the liquor produced was carried out in a multieffect evaporator. The resulting sucrose solution was sent to first generation

Table 4: Overall parameters adopted for the second generation ethanol production.

Case		Case 1	Case 2	Case 3	Case 3L	Case 4
Bagasse handle						
P-F from the total bagasse	%	35	35	35	20	—
Pretreatment		—	SE	LHW	LHW	LHW
Biomass used		—	P-F	P-F	P-F	B
Moisture content (SE)	%	—	70	—	—	—
Reactor solids load (LHW)	%	—	—	20	20	20
Reactor temperature	°C	—	205	180	180	180
Reaction time	min	—	5	15	15	15
Hemicellulose-xylose conversion	%	—	80.0	98.0	88.0	88.0
Cellulose-glucose conversion	%	—	3.2	3.2	3.2	3.2
Xylose-furfural conversion	%	—	18.0	0.1	0.1	0.1
Hemicellulose-acetic acid conversion	%	—	16.9	1.0	1.0	1.0
Enzymatic Hydrolysis						
Reactor solids load	%	10	10	10	5	5
Cellulose-glucose conversion	%	75	85.0	92.0	90.0	90.0
Hemicellulose-xylose conversion	%	35	35.7	35.7	35.7	35.7
Fermentation						
Glucose-ethanol conversion	%	92	92	92	89	89

B: bagasse; P-F: P-fraction; LHW: liquid hot water; SE: steam explosion.
Assumed parameters based on data available at [16, 24, 25].

fermentation process where it was mixed to the concentrated juice. The solid waste of hydrolysis is rich in lignin, and so cogeneration fuel was considered. The parameters adopted in each step of the process are shown in Table 4.

Bagasse set to the cogeneration system was mixed to sugarcane-trash; this process will be further described in item "cogeneration system". Also the lignin-rich stream residue from hydrolysis was mixed to the bagasse and trash fuel. The mixture was used as fuel to the cogeneration system where 5% is saved for system startup or sugarcane crushing shutdowns. The cogeneration system admitted is a steam-based cycle, biomass boiler producing steam at 65 bar and 480°C, and back pressure steam turbines for power production with exhaust steam used by the process. The parameters assumed for simulation of the cogeneration process are shown in Table 5.

1st Generation Ethanol Production Using Surplus Bagasse to Enhance Electricity Production. Case 5 evaluated the thermal integration of the autonomous distillery and the use of surplus bagasse together with sugarcane trash as fuels to the cogeneration system to enhance electricity production. As it seems the most developed opportunity to bagasse use, already performed in some extent in Brazilian mills, it was chosen as a comparative case to the use of P-fraction for ethanol production.

In this case, all bagasse after extraction is used as fuel at the cogeneration system. The use of 95% of the bagasse available and saving the remaining 5% for use during the cogeneration system startup or sugarcane crushing shutdowns was considered [27]. Sugarcane-trash was considered in a flow of 41.25 t/h. This flow was calculated based on the assumption that 50% of the sugarcane-trash available at the harvest is recovered and used at the cogeneration system. Although higher amount of sugarcane trash could be analyzed, the 50% value was assumed as, according to some experts, the other half of the trash should stay at harvest to protect the soil for the next sugarcane plantation [28]. The composition adopted for sugarcane-trash is presented in Table 2. A first cleaning step was considered, using vibrating screens, followed by the decrease of the particle size in a straw chopper blades and the mixture with bagasse.

Cogeneration System. For the cogeneration system a steam-based cycle operating with live steam at 480°C and 65 bars of temperature and pressure was considered, respectively, using a steam turbine to generate electricity, delivering steam as heating source for the process, and a condensation turbine dedicated to electricity production from the surplus steam. The parameters adopted for the cogeneration process are shown in Table 5.

2.3. Process Integration and Evaluation Indicators

2.3.1. Thermal Integration. All the process design case studies were thermally integrated using the pinch method [23], aiming at the reduction of process steam requirements and allowing the use of bagasse as raw material to enhance electricity production or for the second generation ethanol process. In this analysis, streams with less than 1,000 kW of heat load were included as independent process demand but not considered for thermal integration due to their low thermal integration potential.

Table 5: Main parameters adopted for simulating the cogeneration system of the studied cases.

	Case 1, 2, 3, and 3L	Case 4	Case 5	
Cogeneration cycle specification				
Steam temperature	480	480	480	°C
Steam pressure	65	65	65	bar
Turbines				
Steam turbine	Y	Y	Y	
Condensation turbine	Y	N	Y	
Fuels				
Bagasse	N	Y	Y	
Flow	—	c.s.	c.s.	t/h
Moisture	—	50	50	%
PCI	—	7.5	7.5	MJ/kg
Bagasse fiber	Y	N	N	
Flow	c.s.	—	—	t/h
Moisture	8	—	—	%
PCI	15.5	—	—	MJ/kg
Sugarcane-trash	Y	Y	Y	
Flow	41.25	41.25	41.25	t/h
Moisture	15	15	15	%
PCI	14.7	14.7	14.7	MJ/kg
Lignin cake	N	Y	N	
Flow	—	c.s.	—	t/h
Moisture	—	50	—	%
PCI	—	8.9	—	MJ/kg

c.s.: calculated by the simulation; N: no; Y: yes.

2.3.2. Water Consumption. Water balance of the studied cases was accomplished and the final water demand was calculated after identification of closed cycles and possibilities of water reuse. The water consumption of the process for the juice extraction imbibition, chemical treatment, fermentation, and second generation ethanol production was calculated with mass and energy balance in the flowsheeting model. The water consumption in specific equipment, such as the water consumption in boiler exhaust gas scrubbers, floors, and equipment cleaning, were obtained from Neto [29]. To achieve the overall water balance and check out possibilities of water reuse and/or recovery, effluent flows were estimated and analyzed as closed systems. Concentration of vinasse in a multieffect evaporator up to 30% of solids and reuse of water from pretreatment wash after chemical treatment were carried out in this study.

2.3.3. Economic Analysis. An economic study was undertaken considering fixed capital costs, production costs, and revenues. Initially, the investment cost for the first generation process using data from each part the industrial plant published by Dias et al. was analyzed [8]. Equipment for second generation, sugarcane-trash handling and modification on the cogeneration system, were calculated using the Aspen Economic Analyzer software [17] and data available in the literature [27, 33–35]. The equipment costs were updated to the year of 2013 using the chemical engineering process cost index [36] and reduction in the specific cost with the size considered scaling coefficient of 0.6. Tables 6 and 7 show the main parameters used in the economic analysis.

Table 6: Main parameters used in the economic analysis.

Data	Value
Project lifetime	25 years
Construction and startup	2 years
Depreciation	10 years
Interest rate	15% year
Sugarcane average cost	35.17[a] US$/t
Sugarcane-trash average cost	15.02[b] US$/t
Enzyme average cost	1.25[c] US$/kg
Ethanol average price	0.72[d] US$/L
Electricity average price	51[d] US$/MWh

[a][30]; [b][8]; [c][31]; [d][32].

3. Results and Discussion

Figure 2 shows the ethanol production and electricity available for sale at each case evaluated.

Analyzing the ethanol production in Case 3, that considered the use of P-fraction and LHW pretreatment, showed the best results. The other processes that evaluated the use of P-fraction to second generation processes, Cases 1 and 2, also presented higher ethanol production than Case 4,

Table 7: Main parameters evaluated in the sensitivity analysis.

Data	Initial value	Lower value			Higher value	Unit
Enzyme concentration						
cellulase	**15**	2	7	—	10	FPU/g of biomass
β-glicosidase	**0.8**	0.1	0.3	—	0.6	IU/g of biomass
Enzyme average cost	**1.25**	2.00	4.00	6.00	10.00	US$/kg
Increase in the cogeneration investment	**0**	20	40	—	60	%

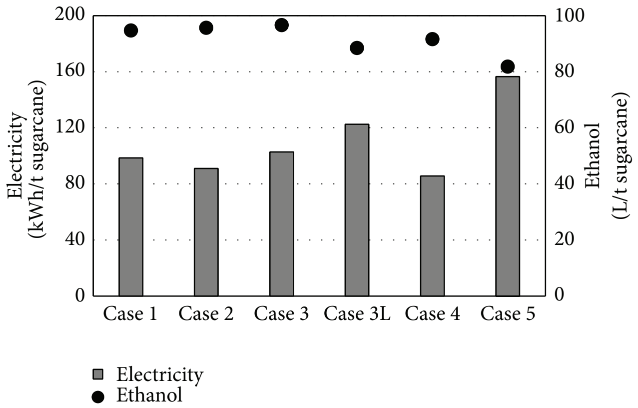


Figure 2: Electricity available for sale and production of ethanol for each case studied.

where all bagasse were used to second generation process. Although a smaller amount of bagasse was sent to the second generation in the P-fraction cases (Cases 1, 2, and 3) than for the use of the entire bagasse (Case 4), higher ethanol production was accomplished mainly due to the higher hydrolysis yields considered for the P-fraction technology. The higher yield assumption at hydrolysis for P-fraction comparing to bagasse was set based on preliminary experimental work [14–16].

Considering that lower P-fraction could be separated from bagasse due to possible future limitations on the separation technology and that not so optimistic yields could be achieved in the hydrolysis step, Case 3L, the overall ethanol production would be 3% lower than Case 4.

Case 4 ethanol production is highly dependable on the energy consumption of the process. As the amount of bagasse sent for the second generation process is set by the amount of fuel required at the cogeneration, ethanol production could be further increased by reducing even more the heat demand of the process. As this case is already thermally integrated, one option for further decrease in heat consumption would be the use of technologies with lower steam consumption as the substitution of the dehydration process for molecular sieves and other possibilities. If no water reuse from vinasse was accomplished for Case 4, it would present lower energy consumption and therefore the ethanol production would increase 5.6%, achieving a production of 97.1 L/t sugarcane. Therefore, without vinasse concentration, Case 4 would be the higher ethanol production case analyzed.

Analyzing the electricity production, Case 4 presented the lowest result of all evaluated cases. Case 4 is the only case where the use of a condensing turbine is not suitable as no surplus steam is generated to be used in the turbine. At the other configurations, more bagasse than the necessary was sent as fuel for the cogeneration; therefore more steam was produced and the excess, not used to supply the thermal demand of the process, was condensed at the condensing turbine producing electricity. Case 3L presented the highest electricity production from the second generation cases, due to the higher amount of bagasse sent for the cogeneration compared with the other cases that evaluated the P-fraction (Cases 1, 2, and 3). In Case 3L, only 20% of bagasse was separated as P-fraction, and therefore, the remaining 80% of bagasse rich in fibers was sent to cogeneration, in Cases 1, 2, and 3, only 75% of bagasse rich in fibers was sent to cogeneration. The case that presented the higher ethanol production, Case 3, produced 34% less electricity than Case 5, in which all bagasse is dedicated to electricity production. In Case 4, it was produced less 45% electricity than Case 5.

Water balance was accomplished for each case considering the practice for water reduction already performed in most mills and also water recovery from vinasse using a multieffect evaporator and 85% recovery of the water from pretreatment (Table 8). All cases presented water intake lower than 1 m^3/t of sugarcane, which is the maximum permitted for a new plant in the sugarcane sector for the São Paulo State [37]. The average water reuse is already high considering the common practice already undertaken at the sugarcane mills, the additional measures contribute with this panorama, enabling the installation of the processes.

The result of investment costs for the studied cases is presented in Table 9. The investment calculated for the second generation cases using P-fraction was very similar. Case 1 presented the highest second generation cost from the P-fraction evaluated cases. As P-fraction in Case 1 does not undergo a pretreatment process it was expected lower second generation investments cost, but without pretreatment the volume of the biomass sent to hydrolysis is bigger and, as solid concentration at the hydrolysis step is very low, it has a big impact on the hydrolysis reactors size. In fact, the hydrolysis equipment accounts for around 88% of the second generation calculated investment in all studied cases. Case 4 presented second generation cost 74% higher than the average cost for the cases that studied P-fraction. Again, the higher cost is manly due the higher amount of bagasse sent to second generation and lower solid content considered in the reactor which results in bigger hydrolysis reactors. The

Table 8: Water balance for the studied cases.

	Water consumption at the process (m^3/t sugarcane)	Conventional water reuse	Additional* water reuse	Total water intake necessary (m^3/t sugarcane)
Case 1	17.2	93%	5%	0.48
Case 2	17.0	89%	7%	0.66
Case 3	17.0	89%	7%	0.68
Case 3L	18.5	91%	6%	0.71
Case 4	23.6	89%	9%	0.59
Case 5	16.7	90%	4%	0.97

*Considering water recovery from vinasse and 85% recovery of the water from pretreatment.

Table 9: Investment cost separated by sector calculated for the evaluated cases.

	Case 1	Case 2	Case 3	Case 3L	Case 4	Case 5
			(Million US$)			
First generation ethanol production						
Sugarcane reception and juice extraction	25.9	25.9	25.9	25.9	25.9	25.9
Juice treatment and concentration	8.1	8.1	8.1	8.1	8.1	8.1
Cogeneration system	97.7	97.7	97.7	104.8	97.9	108.6
Buildings, laboratories, and water treatment	8	8	8	8	8	8
Control and instrumentation systems and insulation	11.2	11.2	11.2	11.2	11.2	11.2
Packaging and transport	5.4	5.4	5.4	5.4	5.4	5.4
Civil works and mechanical assembly	29.7	29.7	29.7	29.7	29.7	29.7
Spare parts, supervision, engineering, and so forth	4.3	4.3	4.3	4.3	4.3	4.3
Heat exchange network	3	3	3	3	3	3
Second generation ethanol production						
Pretreatment, hydrolysis, and concentration of the hydrolyzed	64.8	63.3	52.6	64.4	106.7	—
Shared equipment for first and second generation						
Fermentation and distillation	33.8	34.1	34.5	31.6	32.7	21.2
Vinasse concentration	0.6	0.6	0.6	0.6	0.6	0.5
Total	292.5	291.3	281	297	333.5	225.9

reduction on second generation investment costs is strictly related to decreasing the number and volume of the reactors at hydrolysis, to that extent, measures capable of increasing the reactor solid load and decreasing reaction time would be necessary to achieve this goal.

Economic analysis is presented in Figures 3 and 4 by the analysis of the payback time and the net present value (NPV).

Analyzing the second generation processes assuming the enzyme concentration of cellulase of 15 FPU/g of biomass and β-glucosidase of 0.9 IU/g of biomass, none of the second generation processes studied are economically attractive as payback is too high (higher than 10 years) and NPV is negative, indicating that the cash flow of the project is also negative at the assumed interest rate. Case 5 in which no second generation process was considered has shown good economic results, with reasonable NPV and the lowest payback time of the studied cases.

The enzyme concentration assumed in the present study was based on the experimental work of Carrasco et al. [24]. Usually high cellulase loadings are typically used to achieve economically viable sugar yields from pretreated biomass. According to Humbird et al. [38] the lower limit of enzyme loading is not well known, but by using advanced enzymes loadings as low as 0.02 g enzyme/g cellulose are possible attaining the same yields. The concentration evaluated by Humbird et al. [38] would represent a concentration around 15 times lower than the first admitted in the present study. Therefore, Figures 3 and 4 also show payback time and NPV for second generation considering lower enzymes load. P-fraction second generation cases start to present payback time in an acceptable range, when the concentration is lowered to 5 FPU/g biomass. For the concentrations of 2 and 5 FPU/g biomasses, the NPV calculated for the P-fraction cases is high. Case 3 even presents higher NPV than Case 5 at concentration 5 FPU/g biomass, representing that better profitability of the investment can be achieved in the long term by Case 3 compared to Case 5. Case 4 was the less economically alternative process evaluated at all concentrations. It only presents a positive NPV at concentration 2 FPU/g biomass and it is much lower than the other cases. Case 3 seems to be the best choice of investment of all second generation cases. Considering this case in its low conversion and separation parameters, Case 3L, the economic results are not so representative. Even considering the lowest enzyme concentration, the NPV for Case 3L is lower than Case 5, but Case 3L still represent a better alternative than using

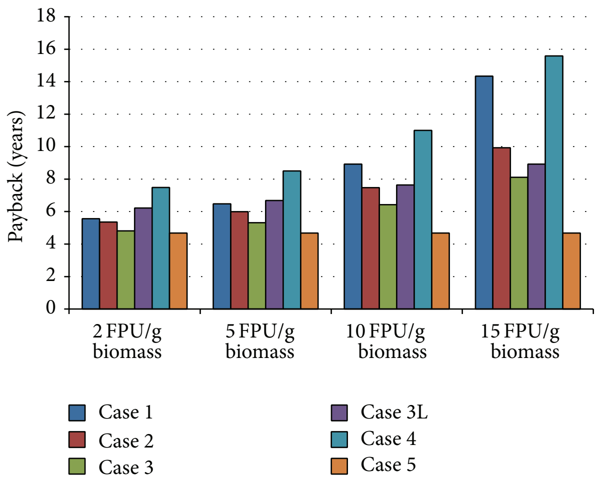


Figure 3: Payback calculated for the studied cases and its variation with the decrease in the enzyme concentration. Note: Enzyme concentration was expressed only regarding the cellulose load as it is the main enzyme used but β-glicosidase load also varies according with the cellulose concentration in accordance with the values described in Table 7.

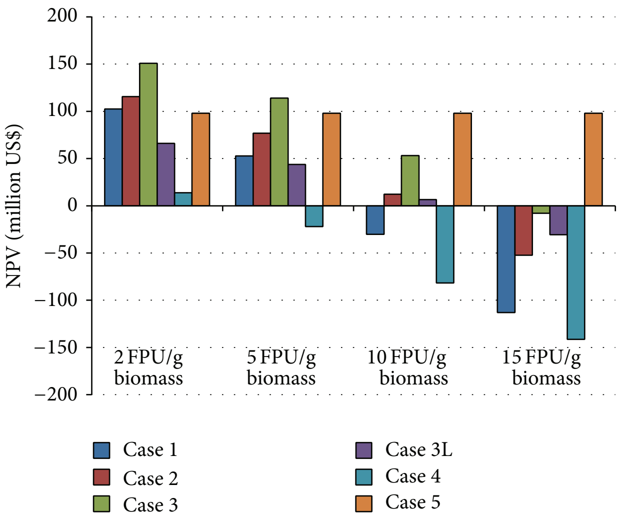


Figure 4: NPV calculated for the studied cases and its variation with the decrease in the enzyme concentration. Note: Enzyme concentration was expressed only regarding the cellulose load as it is the main enzyme used but β-glicosidase load also varies according with the cellulose concentration in accordance with the values described in Table 7.

Table 10: Maximum enzyme cost to have payback lower than 10 years for each case studied.

	Enzyme concentration*		
	2 FPU/g	5 FPU/g	10 FPU/g
		(US$/kg enzyme)	
Case 1	6	2	n
Case 2	6	2	n
Case 3	10	4	2
Case 3L	10	4	2
Case 4	4	2	n

*Enzyme cost analyzed were of 2, 4, 6, and 10 US$/kg enzyme; enzyme concentration was expressed only regarding the cellulase load but β-glicosidase load also varies in accordance with the values described in Table 7.
n: none of the studied values.

the entire bagasse (fibers and pith together) for second generation process as evaluated in Case 4.

The hydrolysis step proved to be the most expensive step in the second generation process studied, either due to the high investment cost linked to the low solid concentration and long reaction time of this step or due to the enzyme cost and concentration at the process. However, diminishing the enzyme cost initially admitted in this study would not be an option, and it is probable that the enzyme cost will be much higher than the one assumed. The value first assumed for enzyme cost equals the cost of one of the cheapest protein available today in the world market, the soybean protein. Analyzing the enzyme cost, calculated by some authors, of 4.24 US$/kg enzyme [38] and 10.14 US$/kg enzyme [31], the evaluated cases are deterrent as the payback ceases to exist, been the revenue obtained by the project lower than the operation cost, for the enzyme concentration firstly adopted. Therefore, it was calculated for each case studied and concentration evaluated the maximum cost possible for the enzyme among the evaluated cost values (values shown in Table 7) so payback would be lower than 10 years. The results of this analysis are shown in Table 10.

At the concentration of 10 FPU/g biomass only Cases 3 and 3L would be feasible with the lower cost of enzyme studied. Higher costs would result in a payback considerably higher than 10 years or inexistent. At lower concentrations higher values could be admitted for the enzyme cost, but only Cases 3 and 3L could admit enzyme cost near proposed by Klein-Marcuschamer et al. [31], 10 US$/kg enzyme. If enzyme concentration could be lowered to concentrations of cellulose 1 FPU/g and β-glicosidase 0.05 UI/g, all studied cases would present payback lower than 10 years for the enzyme cost of 10 US$/kg enzyme. Considering these concentrations and enzyme costs, Case 4 would present a payback of 10 years while Case 3 would present 6 years. Therefore, lowering the enzyme concentration represents a necessary action to enable the second generation process economically. Using concentrations as low as the one mentioned by Humbird et al. [38], would make the second generation process using P-fraction, Case 3, very competitive with only modification to the cogeneration system, Case 5, even with very high cost for the enzymes as proposed by Klein-Marcuschamer et al. [31].

In order to use sugarcane-trash as fuel to the cogeneration system, adaptation of the current burner used at sugarcane mills will be needed. The herbaceous nature of sugarcane trash, without pretreatment, can lead to high levels of fouling and slagging in conventional biomass boilers, decreasing considerably the boiler lifetime [38]. The investment admitted for the cogeneration system considered the current technology for bagasse burner. The use of an adequate burner for the

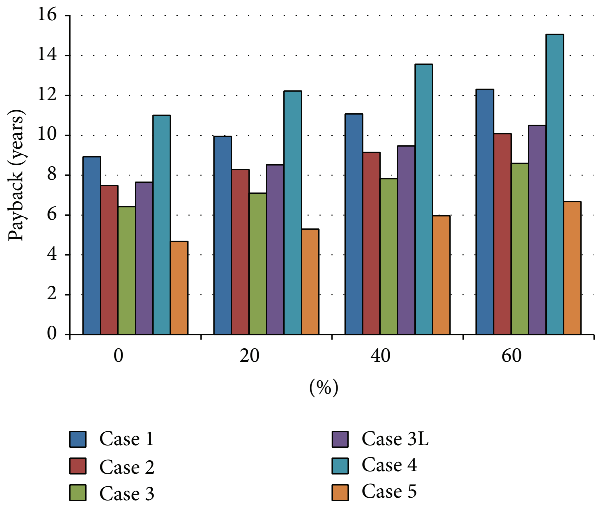


FIGURE 5: Sensitivity analysis of the studied processes with the increase in the cogeneration investment.

considered fuel could lead to a higher investment. Therefore a sensitivity analysis considering the increase of investments in cogeneration was carried out analyzing the impact in the payback time (Figure 5), considering the enzyme concentration of 10 FPU/g.

In the payback time calculated for Case 5, with the increase of 60% in the investment, additional two years in payback are found. For the cases that evaluated second generation ethanol production, with the increase of 60% in the investment, payback increased from 2.2 to 4.1 years. Thus, the increase in the cogeneration investment is a point that needs further verification in a more detailed economic analysis as it can increase significantly the payback time of the cases studied.

4. Conclusions

The evaluated processes after thermal and water integration were self-sufficient in energy demand, being able to sell the surplus electricity to the grid, and presenting water intake inside the environmental limit for São Paulo State, Brazil. It was decisive to consider the water recuperation from vinasse using a multieffect evaporator system to diminish the final water uptake of the evaluated processes to an accepted level regarding the local environmental laws. The use of P-fraction showed higher ethanol production than the use of sugarcane bagasse in the second generation process. Due to the high enzyme costs, for all cases that considered second generation ethanol, the payback calculated was higher than 8 years and the net present value was negative. The best configuration studied for P-fraction was the hydrothermal pretreatment LHW. Even by considering low conversion levels for this technology (Case 3L), it presented better economic results than the use of the entire bagasse for ethanol production. The reduction on the enzyme load, in a way that the conversion rates could be maintained, is the limiting factor to make second generation ethanol competitive with the most immediate use of bagasse: fuel for the cogeneration system to surplus electricity production.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

The authors acknowledge the financial support granted by the Agreement Unicamp-Brazil Shell Petroleum Ltd.

References

[1] K. Hofsetz and M. A. Silva, “Brazilian sugarcane bagasse: energy and non-energy consumption,” *Biomass and Bioenergy*, vol. 46, pp. 564–573, 2012.

[2] CTBE, Laboratório Nacional de Ciência e Tecnologia do Bioetanol, 2013, http://www.bioetanol.org.br/.

[3] CTC, Centro de Tecnologia Canavieira, 2013, http://www.ctcanavieira.com.br/.

[4] Dedini S/A Indústrias de Base, 2013, http://www.codistil.com.br/.

[5] Raízen, 2013, http://www.raizen.com/.

[6] Graalbio, “GraalBio cellulosic ethanol production project,” Alagoas, Brazil, 2012, http://www.chemicals-technology.com/projects/graalbio-cellulosic-ethanol-project-brazil/.

[7] F. F. Furlan, C. B. B. Costa, G. D. C. Fonseca et al., “Assessing the production of first and second generation bioethanol from sugarcane through the integration of global optimization and process detailed modeling,” *Computers & Chemical Engineering*, vol. 43, pp. 1–9, 2012.

[8] M. O. S. Dias, M. P. Cunha, C. D. F. Jesus et al., “Second generation ethanol in Brazil: can it compete with electricity production?” *Bioresource Technology*, vol. 102, no. 19, pp. 8964–8971, 2011.

[9] J. Q. Albarelli, A. V. Ensinas, and M. A. Silva, “Product diversification to enhance economic viability of second generation ethanol production in Brazil: the case of the sugar and ethanol joint production,” *Chemical Engineering Research and Design*, 2013.

[10] A. V. Ensinas, V. Codina, F. Marechal, J. Albarelli, and M. A. Silva, “Thermo-economic optimization of integrated first and second generation sugarcane ethanol plant,” *Chemical Engineering Transactions*, vol. 35, pp. 523–528, 2013.

[11] C. A. Cardona, J. A. Quintero, and I. C. Paz, “Production of bioethanol from sugarcane bagasse: status and perspectives,” *Bioresource Technology*, vol. 101, no. 13, pp. 4754–4766, 2010.

[12] A. P. de Souza, D. C. C. Leite, S. Pattathil, M. G. Hahn, and M. S. Buckeridge, “Composition and structure of sugarcane cell wall polysaccharides: implications for second-generation bioethanol production,” *BioEnergy Research*, vol. 6, no. 2, pp. 564–579, 2013.

[13] T. A. Chimenez, M. H. Gehlen, K. Marabezi, and A. A. S. Curvelo, “Characterization of sugarcane bagasse by autofluorescence microscopy,” *Cellulose*, vol. 21, no. 1, pp. 653–664, 2014.

[14] M. A. Silva, F. Maugeri, and F. A. Costa, “Processo de produção de etanol a partir de hidrólise enzimática de biomassa, processo de separação da matéria-prima de hidrólise e uso de células de parênquima para obtenção de etanol,” Brazil Patent PI 1004486-8, 2010.

[15] E. Almeida, L. A. B. Cortez, and M. A. Silva, "Sugarcane bagasse pneumatic classification as a technology for reducing costs on enzymatic hydrolysis process," in *Proceedings of the 28th International Society of Sugar Cane Technologists Congress*, vol. 28, São Paulo, Brazil, 2013.

[16] E. Almeida, "Estudo da separação pneumática de frações de bagaço de cana e sua influência na hidrólise enzimática," 2012, http://www.bibliotecadigital.unicamp.br/document/?code=000866267.

[17] AspenTech, "Aspen Plus: Users Manual V. 7.2," 2010.

[18] M. Starzak and M. Mathlouthi, "Temperature dependence of water activity in aqueous solutions of sucrose," *Food Chemistry*, vol. 96, no. 3, pp. 346–370, 2006.

[19] R. J. Wooley and V. Putsche, Development of an Aspen Plus physical property database for biofuels components, 2010, http://www.nrel.gov/docs/fy99osti/26157.pdf.

[20] R. Palacios-Bereche, K. J. Mosqueira-Salazar, M. Modesto et al., "Exergetic analysis of the integrated first- and second-generation ethanol production from sugarcane," *Energy*, vol. 62, pp. 46–61, 2013.

[21] P. Rein, *Cane Sugar Engineering*, Dr. Albert Bartens KG, Berlin, Germany, 2007.

[22] A. V. Ensinas, M. Modesto, S. A. Nebra, and L. Serra, "Reduction of irreversibility generation in sugar and ethanol production from sugarcane," *Energy*, vol. 34, no. 5, pp. 680–688, 2009.

[23] B. Linnhoff, *User Guide on Process Integration for the Efficient Use of Energy*, IChemE, Rugby, UK, 1st edition, 1982.

[24] C. Carrasco, H. M. Baudel, J. Sendelius et al., "SO_2-catalyzed steam pretreatment and fermentation of enzymatically hydrolyzed sugarcane bagasse," *Enzyme and Microbial Technology*, vol. 46, no. 2, pp. 64–73, 2010.

[25] M. A. Neves, T. Kimura, N. Shimizu, and M. Nakajima, *State of the Art and Future Trends in Bioethanol Production*, Dynamic Biochemistry, Process Biotechnology and Molecular Biology, Global Science Books, 2007.

[26] H. M. Baudel, "Hidrólise para Produção de Etanol," Workshop tecnológico sobre hidrólise de materiais lignocelulósicos, 2012, http://www.inovacao.unicamp.br/etanol/report/Hidrolise%20-Baudel%20Pr%C3%A9%20Tratamento%20e%20Hidr%C3%B3lise.pdf.

[27] L. F. Pellegrini, S. de Oliveira Júnior, and J. C. Burbano, "Supercritical steam cycles and biomass integrated gasification combined cycles for sugarcane mills," *Energy*, vol. 35, no. 2, pp. 1172–1180, 2010.

[28] W. A. Pippo, C. A. Luengo, L. A. M. Alberteris, P. Garzone, and G. Cornacchia, "Energy recovery from sugarcane-trash in the light of 2nd generation biofuels. Part 1: current situation and environmental aspects," *Waste and Biomass Valorization*, vol. 2, no. 1, pp. 1–16, 2011.

[29] A. E. Neto, *Manual de Conservação e Reúso de Água na Agroindústria Sucroenergética*, Agência Nacional de Águas (ANA), Brasilia, Brazil, 2009.

[30] UNICA, "Preço médio da cana-de-açúcar," 2012, http://www.unicadata.com.br/listagem.php?idMn=61.

[31] D. Klein-Marcuschamer, P. Oleskowicz-Popiel, B. A. Simmons, and H. W. Blanch, "The challenge of enzyme cost in the production of lignocellulosic biofuels," *Biotechnology and Bioengineering*, vol. 109, no. 4, pp. 1083–1087, 2012.

[32] UNICA, Preço-teto de leilão de energia desencoraja investimentos em bioeletricidade, 2012, http://www.unica.com.br/noticias/show.asp?nwsCode=%7B3985304E-7262-4ED3-8ED-E-D85A38934B72%7D.

[33] A. Aden, M. Ruth, K. Ibsen et al., "Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover," National Renewable Energy Laboratory (NREL), 2010, http://www.nrel.gov/docs/fy02osti/32438.pdf.

[34] J. H. Sosa-Arnao and S. Nebra, "Bagasse dryer role in the energy recovery of water tube boilers," *Drying Technology*, vol. 27, no. 4, pp. 587–594, 2009.

[35] T. P. A. Luz, L. F. B. Bonan, R. Passolongo, and R. A. V. Ramos, "Avaliação termodinâmica e termoeconômica do aproveitamento energético da vinhaça num sistema de cogeração de energia de uma usina sucroalcooleira," in *Proceedings of the Brazilian Conference on Dynamics, Control and their Applications*, vol. 9, pp. 707–803, Rio Claro, Brazil, 2010.

[36] CEPCI, Chemical Engineering Plant Cost Index, 2012, http://www.che.com/pci/.

[37] Secretaria de Estado do Meio Ambiente (SMA), Zoneamento Agroambiental para o Setor Sucroalcooleiro, 2012, http://www.ambiente.sp.gov.br/etanolverde/zoneamento-agroambiental/.

[38] D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, and A. Aden, "Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol," Tech. Rep. NREL/TP-5100-47764, National Renewable Energy Laboratory, Golden, Colo, USA, 2011.