Co-location of a Cellulosic Ethanol Biorefinery in an Pulp and Paper Facility using Sugarcane Bagasse and Straw - Brazilian Case

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Abstract

Literature shows that the co-location of a cellulosic ethanol biorefinery inside an existing pulp and paper mill may result in high financial returns by combining the convenience of using existing infrastructure with available low cost biomass. Sao Paulo state in Brazil is remarked by a strong presence of wood (especially eucalyptus) and sugarcane plantations, creating a good environment for the integration of sugarcane and pulp and paper industries, especially in the central area of the state. Sugarcane biomass availability has increased since 2002 when a law was created to eliminate sugarcane burning practices until 2021. In this study, an ethanol biorefinery based on dilute acid pretreatment and enzymatic hydrolysis was co-located in a pulp and paper mill. Six cases were studied considering sugarcane straw or bagasse as feedstock based and three different process capacities for the ethanol biorefinery. The pulp and paper mill was hypothetically placed in Jau region where the availability of sugarcane is about 10 OD tonne/hectare. Among all studied cases, the minimum observed IRR was 13.2% when sugarcane straw was used as feedstock considering the smallest plant capacity. The highest IRR observed was 20.9% when sugarcane bagasse was consumed considering the biggest plant capacity. Capital, enzyme and biomass are the most important cost drivers. Sensitivity analysis show that IRR is very sensitive to capital investment and ethanol price.

Keywords: bioethanol, biorefinery, co-location, pretreatment, enzymatic hydrolysis, economic analysis.

Introduction

Wood production in Brazil represents 17% of the world production occupying a total area of 7.6 million of hectares (2013). Among different species, plantations of Eucalyptus and Pinus are the most common occupying 72% and 20.7% of this total area respectively. 185 million of m^3 of wood were consumed in 2013 and pulp and paper industry is the biggest consumer with 35% of this total. Among the Brazilian states, Sao Paulo is the second biggest producer of eucalyptus comprehending 18% of total eucalyptus forestry in the country (1 million of hectares) [1].

Brazil is also the biggest producer of sugarcane in world with a production of 635 million tonne (sugarcane stalk) during 2014/2015 season and Sao Paulo state is responsible for 54% of this production [2]. 1 tonne of sugarcane stalk generates 145 kg of dry sugars (mainly sucrose) used to produce sugar and ethanol, 130 kg of dry fibers (sugarcane bagasse) mainly used as an energy source to produce steam and electricity and 140 kg of dry sugarcane straw or trash (tops and leaves) [3]. Sugarcane straw is either burned in the field before harvesting or left on the ground after mechanical harvesting. In 2002 a law was created in Sao Paulo state (law 11.241) to eliminate the burning practices until 2021. Recent numbers show that the percentage of mechanization during 2013/2014 season was 84.8% [4]. As a result, the availability of biomass from sugarcane industry has increased along the last years creating opportunity to use sugarcane bagasse and trash as a source for bioenergy production.

Figure 1 shows the distribution of sugarcane and eucalyptus in Sao Paulo state divided by 39 regions. Most of the sugarcane plantations are located in the center-north area of Sao Paulo State, on the other hand, eucalyptus plantations are located mainly in the center-south. Both agricultures exist in the central area of the state.

During 2014/2015 season, 28.6 million of m^3 of ethanol were produced in Brazil and Sao Paulo is the biggest producer with 49.4%. Despite its oscillation, the average growth of ethanol production in Brazil during the last ten years is about 6.8% [2].

Literature shows that the co-location of a cellulosic ethanol biorefinery in an existing pulp and paper mill may result in attractive opportunity to generate high financial returns. Different sources of biomass (sawdust, excess pulp, paper sludge, waste wheat straw) were studied. The convenience of using existing pulp and paper mill infrastructure, combined with the availability of low cost biomass, create opportunities for new profitable businesses. [5, 6, 7].

Eucaliptus Production Area (1.02 Mha)

Legend	Region %	Total %
▲	6-12	49.7
▲	3-6	24.7
▲	1-3	20.7
	< 1	5.0

Sugarcane Production Area (5.54 Mha)

Legend	Region %	Total %
●	6-8	21.3
●	3-6	50.6
●	1-3	23.8
	< 1	4.3

Figure 1: Eucalyptus and sugarcane production area in Sao Paulo state (2014) [3].

This study discusses the co-location of a cellulosic ethanol biorefinery in a hypothetical pulp and paper mill located in Sao Paulo state - Brazil. The industrial process for ethanol biorefinery is based on dilute acid pretreatment followed by enzymatic hydrolysis according to the technical report published by NREL (National Renewable Energy Laboratory - USA) [8]. Sugarcane bagasse and straw were used as feedstock. The process model was built using the software Aspen Plus and economic analysis was performed to compare the financial results of both biomasses considering 3 different capacities for the ethanol biorefinery.

Experimental

a) Process Description:

The hypothetical pulp and paper mill (Sao Paulo P&P) is an integrated bleached kraft facility with an annual production of 950 ktonne/year, representing the biggest producers of pulp and paper in Sao Paulo state. The cellulosic ethanol biorefinery is composed by a feedstock storage area, dilute acid pretreatment, ammonia conditioning, enzymatic hydrolysis, co-fermentation, ethanol distillation and dehydration, product storage, additional utilities (cooling water, air, chilled water) and turbogenerator based on NREL report [8]. Figure 2 shows the process diagram for the ethanol biorefinery. In this configuration, sugarcane bagasse, sugarcane straw and enzymes are purchased from external supplier. The produced stillage (beer column bottom) is composed by unconverted insoluble and soluble solids. After filtration, the solid material is burned in an existing biomass boiler to produce the steam necessary to fulfill the process demand. An additional turbogenerator produces electricity necessary to run the process. Excess energy produced is consumed by the pulp and paper mill. The stillage water and pretreatment condensate are directed to the existing waste water treatment. Water used in the process is supplied by the pulp and paper mill.

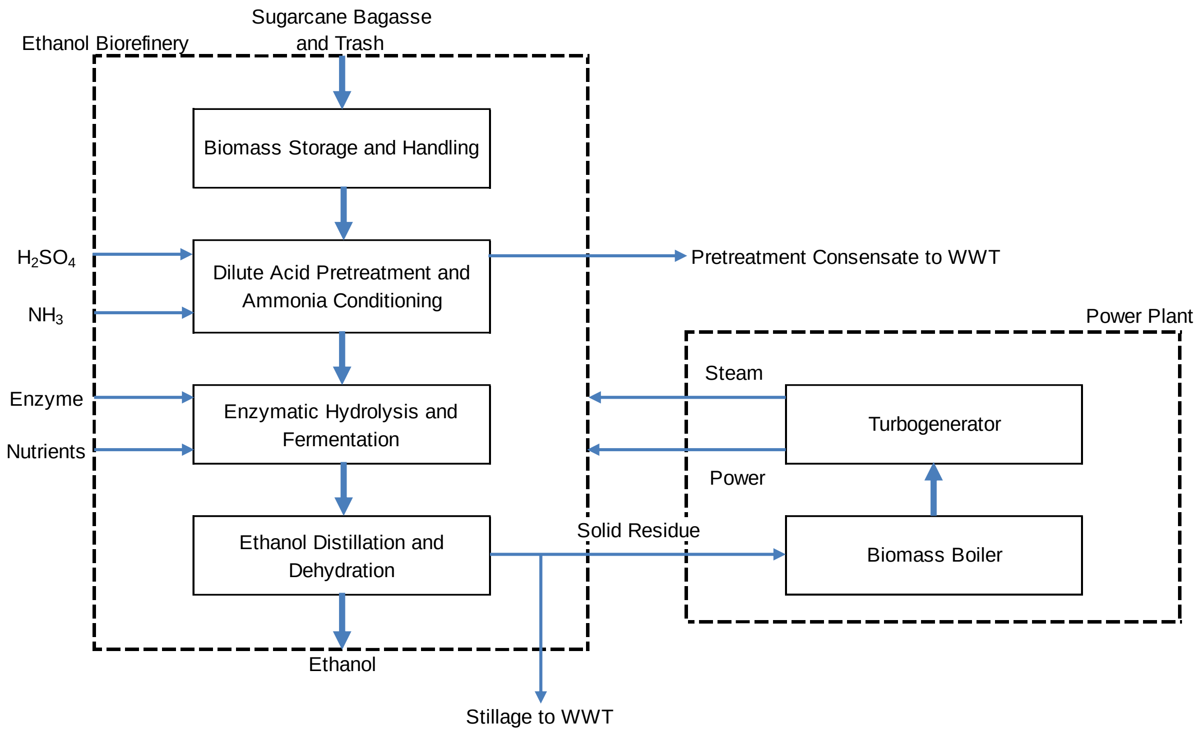

Figure 2: Dilute acid ethanol biorefinery process diagram.

b) Biomass Recovery, Agronomic Issues, Availability and Composition:

Despite the energetic potential associated with sugarcane straw, very little efforts have been made so far to develop an appropriate process for its collection in Brazil. Even though, two opposite collection routes can be highlighted: 1)Sugarcane is harvested without straw separation. Cane stalks and straw are collected and transported together to the sugarcane mill. Inside the sugarcane mill a dry cleaning station separates stalks and straw before cane crushing; 2)Sugarcane is harvested with trash separation. After harvesting, sugarcane straw is baled and transported. A report published by CTC (Copersucar Technology Center) shows that alternative 2 would have lower costs. Another aspect involved is the discussion regarding the amount of straw to be left in the field to take advantage of the agronomic and industrial benefits. Protection against soil erosion, increase of soil carbon content, increase of soil macro fauna (worms and ants) and weed inhibition are pointed as positives aspects. On the other hand, increases in pest population have a negative impact. Due to the number of variables involved in this analysis, it is not possible today to stablish the proper amount of straw that should be left on the soil [9]. Based on other publications [3], this study assumes that 50% of the total available straw would be collected to be used in the ethanol biorefinery.

Sugarcane bagasse is a byproduct produced in the sugarcane mill after cane crushing. The majority is consumed by the sugarcane mill as an energy source to produce steam and electricity. As a result, sugarcane bagasse availability depends on the configuration (type of mill, boiler configuration, process configuration) and energy consumption of each particular sugarcane mill. However, in this study it was assumed that the availability of sugarcane bagasse would be the same as the availability of sugarcane straw.

The location of Sao Paulo P&P was arbitrary chosen in the Region of Jau, where we have a strong presence of sugarcane and eucalyptus plantations (Figure 1), and where sugarcane availability is around 10 OD tonne/hectare. Table 1 brings the adopted composition for sugarcane bagasse and trash in dry basis. It was considered that their moisture content is 50% and 15% respectively.

Table 1: Sugarcane bagasse and trash composition.

Biomass Compostion (dry basis)		
Components	Bagasse (wt %) [3]	Straw (wt %)
Cellulose	43.4	34.3
Pentosan	23.2	26.9
Acetate	2.4	2.5
Lignin	23.2	21.5
Extractives	4.8	8.7
Ash	2.9	6.1
Total	100	100

c) Process Simulation and Financial Model:

Process simulation for the ethanol biorefinery was built using Aspen Plus 8.2.3 software. Mass and energy balance were obtained from a steady state simulation. Main process parameters were exported to the financial spreadsheet built using Microsoft Excel software.

d) Process Parameters:

Table 2 shows the parameters adopted in the simulation for the main process areas (pretreatment, enzymatic hydrolysis and fermentation) such as solids concentration, temperature, residence time, chemicals charge and components yields based on NREL report [8].

Table 2: Process parameters for the ethanol biorefinery

Process Parameters	
Dilute Acid Pretreatment	
Total Solids - %	30
Temperature - °C	158
Time - min	5
Sulfuric Acid charge - % w/w	2.2
Cellulose to Oligomers - %	0.3
Cellulose to Glucose - %	9.9
Cellulose to HMF - %	0.3
Pentosan to Oligomers - %	2.4
Pentosan to Monomers - %	90
Pentosan to Furfural - %	5
Acetate to Acetic Acid - %	100
Lignin to Soluble Lignin - %	5

Process Parameters	
Enzymatic Hydrolysis	
Total Solids - %	20
Temperature - °C	48
Time - h	84
Enzyme charge - mg/g cellulose	20
Cellulose to Oligomers - %	5
Cellulose to Glucose - %	75

Process Parameters	
Fermentation	
Total Solids - %	20
Temperature - °C	32
Time - h	36
Corn Steep Liquor charge - %	0.25
Diammonium Phosfate charge - g/L	0.33
Glucose to Ethanol - %	95
Glucose to Microorganism - %	2
Glucose to Glycerol - %	0.4
Glucose to Succinic Acid - %	0.6
Xylose/Arabinose to Ethanol - %	85
Xylose/Arabinose to Microorganism - %	1.9
Xylose/Arabinose to Glycerol - %	0.3
Xylose/Arabinose to Xylitol - %	4.6
Xylose/Arabinose to Succinic Acid - %	0.9
Sugar Loss - %	3

e) Financial Analysis:

Financial analysis was performed for each studied case. Table 3 shows the main financial assumptions adopted such as project year, capital spending schedule, depreciation, capital reinvestment, working capital, other costs, maintenance, taxes, discount rate, and inflation (RAV = Replacement Asset Value). The actual anhydrous ethanol market price in Sao Paulo state was adopted [10]. Prices for sugarcane bagasse and straw were calculated based on their potential revenue for electricity production. A sensitivity analysis was used to monitor the financial metric (IRR, Internal Rate of Return) while perturbing revenue and costs drivers.

Table 3: Financial assumptions

Financial Assumptions - 2015			
Start up year	2,015	Working Capital - % Direct Costs + Revenue	10
Terminal Year	2,025	Other Fixed Costs and Overhead - %	3
Operated hours per year	8,400	Maintenance - % RAV	2
Capital Spent in year -2 - %	20	Taxes - %	35
Capital Spent in year -1 - %	50	Terminal Value - Year 10 EBITDA Multiple	5
Capital Spent in year 0 - %	30	Discount Rate - %	12
Process Capacity at year 0 - %	60	Inflation - %	6.48
Process Capacity at year 1 - %	90	Anhydrous Ethanol Price - U$/L	0.60
Depreciation Schedule - straight years	10	Sugarcane Straw Price - U$/OD tonne	44.12
Capital Reinvestment - % RAV	1	Sugarcane Bagasse Price - U$/OD tonne	39.17

e) Capital Investment:

Capital investment for the ethanol biorefinery was based on the costs of equipment presented in NREL report [8]. Equipment costs were escalated to 2015 and scaled according to the capacity of each process area. An average installation factor of 3.56 was used to calculate the capital investment. The following areas were considered in this estimative: feedstock storage, dilute acid pretreatment, ammonia conditioning, enzymatic hydrolysis, co-fermentation, ethanol distillation and dehydration, product and chemicals storage, additional utilities (cooling water, air, chilled water) and turbogenerator. No capital was considered for infrastructure (land, roads and offices), biomass boiler, waste water treatment and water plant for the co-location of the ethanol plant in an existing pulp and paper mill.

f) Ethanol Biorefinery Capacity:

The number of sugarcane mills in Sao Paulo state is around 176. Dividing the sugarcane production during 2014/2015 season by the number of mills, it is possible to calculate the average consumption of sugarcane (approximately 582 OD ktonne/year). This number was adopted to calculate the average biomass availability (sugarcane straw and bagasse) per sugarcane mill.

Six biorefineries were studied. Cases S2, S3 and S5 consider that the ethanol biorefinery will consume sugarcane straw collected from 2, 3 or 5 sugarcane mills respectively. Cases B2, B3 and B5 consider the consumption of sugarcane bagasse and straw purchased from 2, 3 or 5 mills. As a tentative to avoid storage problems with sugarcane bagasse decomposition due the presence of around 1% of free sugars and 50% moisture content, it was considered that bagasse is consumed during 8 months (harvesting season) and straw is consumed during 4 months for cases B2, B3 and B5. According to the availability of sugarcane in Jau region (10 OD tonne/hectare), the amount of bagasse and straw consumed in all studied cases would be collected in an average radius of 30~35 km.

Results and Discussion

a) Capital Investment:

Capital investment, biomass consumption and ethanol production are presented in Figure 3 and Table 4 for each studied case. The co-location scenario is more economic when compare to a Greenfield facility due to the use of existing infrastructure. Sugarcane bagasse has a higher content of carbohydrates when compared to straw. As a result, more ethanol is produced increasing the capital investment for ethanol purification area. The solid material separated from stillage has a higher amount of organic compounds for the case of sugarcane bagasse, resulting in bigger steam production and higher capital investment for turbogenerator.

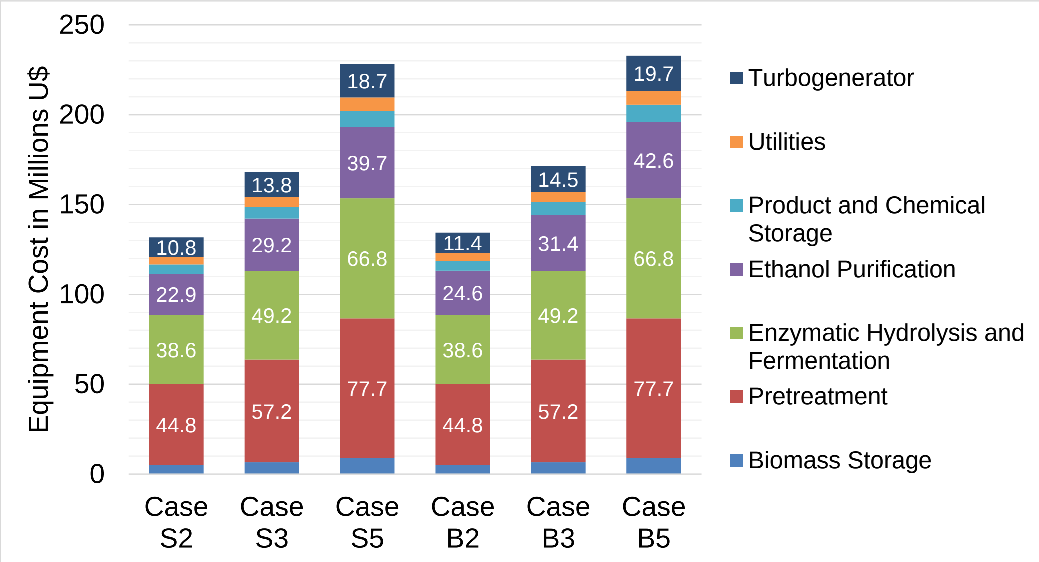

Figure 3: Equipment cost by process area for studied cases.

Table 4: Biomass consumption and ethanol production for studied cases.

	Case S2	Case S3	Case S5	Case B2	Case B3	Case B5
Straw Consumption - OD k tonne/year	271.7	407.6	679.3	90.6	135.9	226.4
Bagasse Consumption - OD k tonne/year	-	-	-	181.1	271.7	452.9
Ethanol Production - L/OD tonne biomass	318.7	318.7	318.7	345.4	345.4	345.4

b) Production Costs:

A breaking down of all costs (direct and indirect) is presented in Figure 4. Depreciation, biomass, and enzyme are the major cost drives. It is possible to see that the increase in plant capacity reduces the total costs due to scale economy.

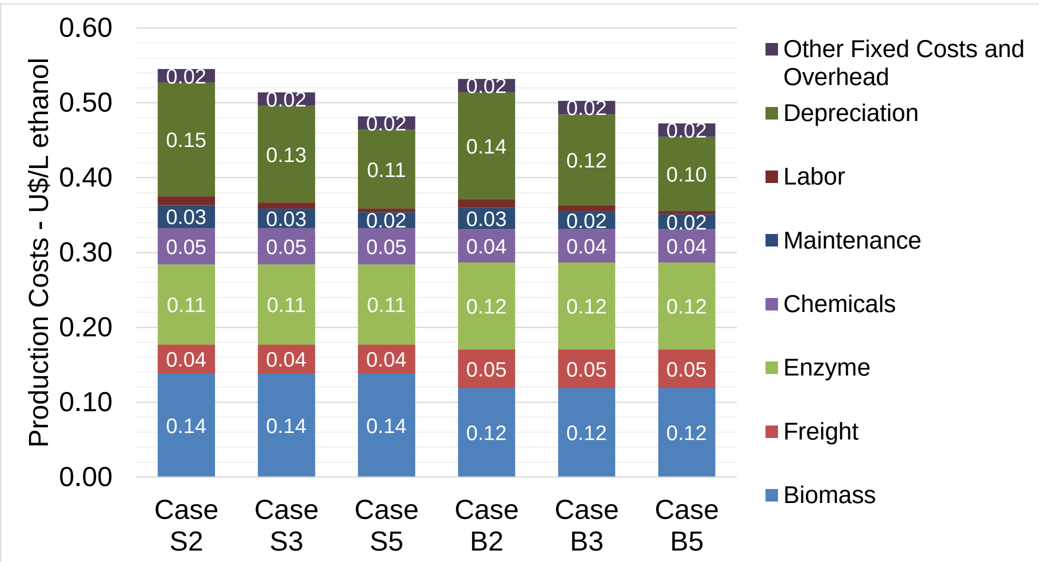

Figure 4: Production costs per liter of ethanol for studied cases.

c) Internal Rate of Return and Sensitivity Analysis:

Internal Rate of Return (IRR) was calculated for each studied scenario. Table 5 shows that the increase in plant capacity improves the financial return. A sensitivity analysis was performed using a variation of ±25% of the central values for capital investment, ethanol price and main cost drivers (biomass, enzyme, chemicals and freight) to understand the impact on IRR. According to Figure 5, IRRs for cases S5 and B5 are most sensitive to ethanol price and capital investment.

Table 5: Internal Rate of Return (S2, S3, S5 – sugarcane straw from 2, 3 and 5 sugarcane mills. B2, B3, B5 bagasse and straw from 2, 3 and 5 sugarcane mills).

Case	IRR	Case	IRR
S2	13.2%	B2	14.3%
S3	16.1%	B3	17.2%
S5	19.8%	B5	20.9%

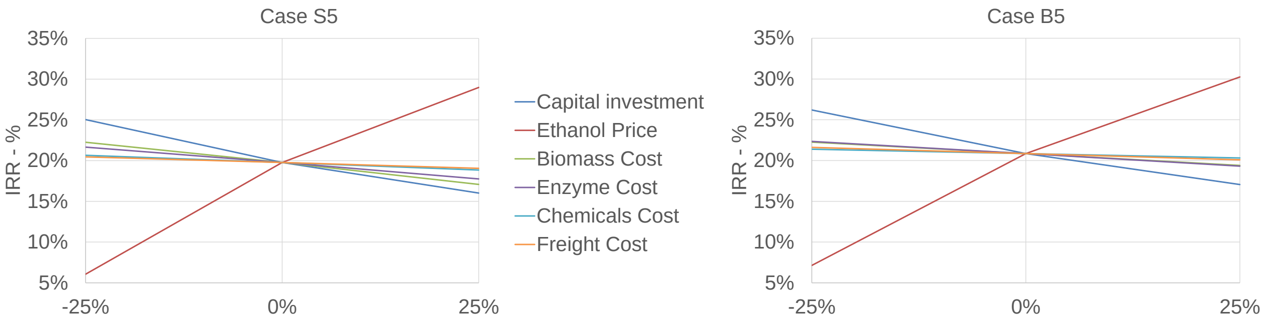

Figure 5: IRR sensitivity to capital investment, ethanol price and main costs drivers (biomass, enzyme, chemicals and freight) for cases S5 and B5.

Conclusions

The co-location of a dilute acid pretreatment biorefinery in an existing pulp and paper mill for cellulosic ethanol production using sugarcane bagasse and straw as feedstock showed interesting IRRs ranging from 13.2 % (S2) to 20.9% (B5). The availability of sugarcane biomass in Sao Paulo state and the convenience of using existing infrastructure in a pulp and paper mill are important economic drivers. The ethanol cost breakdown shows that scale economy has contributed for cost reduction. Any future effort to reduce ethanol cost would involve capital, biomass and enzyme, which are the main cost drivers. IRR has showed to be very sensitive to ethanol price and capital for cases S5 and B5. Despite these attractive numbers, further evaluation need to be addressed in order to better estimate the impact of main cost drivers. Also, the success of the co-location scenario will be determined by the existing infrastructure and biomass availability for a specific pulp and paper mill. Industrial validation of the current technology needs to be address to confirm process yields, especially for enzymatic hydrolysis.

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