Thermoeconomic Analysis of Combined Production of Electricity and Second Generation Ethanol Based on the Dilute Acid Hydrolysis of Sugarcane Bagasse

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Abstract

In this study, a thermoeconomic assessment of an integrated ethanol production from sugarcane bagasse and traditional sugarcane juice is developed and discussed. An integrated distillery, which works with first and second generation ethanol production routes, is modeled and simulated. The thermoeconomic model assumes that the only agricultural input to the processes is the sugarcane itself (straw or other wastes recovered from the field were not considered in the analysis). The analyses are carried out for three operating scenarios: scenario I describes a traditional distillery or a first generation distillery; scenario II takes into account an integrated distillery operating with current acid hydrolysis technology; scenario III describes an improved distillery which operates with future technology for hydrolysis and pentose fermentation. Exergy analysis, production cost analysis and economic viability assessment are carried out for each scenario. As a result, it can be concluded that the global exergy efficiency decreases with the bagasse hydrolysis for scenario II. This situation is reversed when pentose fermentation is considered in scenario III. The economic viability assessment shows that hydrolysis is not viable in the present Brazilian economic scenario because it causes a drop of 4.0% in the internal rate of return (IRR) for scenario II and 2.3% for scenario III, when compared to scenario I.

Keywords: Exergy; acid hydrolys; biofuel; cogeneration; second generation ethanol.

1. Introduction

Brazil is the second largest ethanol producer in the world, the largest exporter, the international leader in terms of biofuels and the first economy that has reached a sustainable use of it. Brazil and the United States lead the ethanol production worldwide. In 2006, they accounted for 89% of the global output and nearly 90% of ethanol as fuel [1].

In 2011, Brazil produced nearly 21 billion liters of ethanol [2]. Brazilian ethanol industry has 90 years of history and sugarcane is the main agricultural raw material. Going further, regulation enacted by the Federal Government states that all gasoline sold in the country must be blended with 25% ethanol, and since July 2009, more than 8 million vehicles can run on 100% ethanol or any combination of ethanol and gasoline. These cars are popularly called "flex".

Currently, ethanol production in Brazil is based on first generation technologies, i.e., it uses only sucrose, which represents one third of energy stored in sugarcane [3]. The bagasse is used primarily as an energy source for steam generation in boilers. However, it is possible to transform cellulose present inside the bagasse to sucrose through a hydrolysis reaction, which is known as second generation technology.

Second generation biofuels are produced from lignocellulosic materials such as cereal straw, forest residues, bagasse, and purpose-grown energy crops such as vegetative grasses and short rotation forests. This technology could avoid many of the concerns that first generation biofuels face and potentially offers greater cost reduction in the long term.

In the sugarcane industry, another advantage for the use of lignocellulosic material as feedstock for bioethanol production is clear: since it is already available in plant site (for bagasse), or close to it (trash), second generation bioethanol production may share part of the infrastructure where first generation ethanol production takes place, for instance, concentration, fermentation, distillation, storage and cogeneration facilities [4].

An important factor in the current Brazilian ethanol program is the production of large amounts of electricity by burning the excess bagasse. In the early days of the program, bagasse was burnt inefficiently to produce heat and work required for the industrial process (crushing, fermentation and distillation), and a good portion of it was then wasted. Nowadays high-pressure boilers can operate around 100 bar (in contrast with 20 bar in the past). As a result, a portion of the energy can be supplied to the local electricity grid.

2. Objectives

In this study, a thermoeconomic model that evaluates the integrated ethanol production from sugarcane bagasse and traditional sugarcane juice is developed. The model is applied to a hybrid distillery, which works with both first and second generation juices. The model assumes that the only agricultural feedstock to processes is the sugarcane itself, i.e. straw or other waste recovered from the field were not considered in the analysis and the surplus

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electricity will be sold to the public grid. The analysis will be carried out considering three complementary approaches; (i) The exergy analysis evaluates exergy use of the inputs until the final products and then identifies the main sources of irreversibilities in a given production route; (ii) The cost analysis that aims to obtain the production cost of ethanol and electricity; (iii) The economic viability assessment intends to assess the viability in terms of return on investment.

Three different scenarios were defined. Scenario I depicts a traditional distillery or a first generation distillery, scenario II represents a hybrid distillery that operates with current technology for hydrolysis (base case), and scenario III takes into account an improved distillery which operates with future technology for hydrolysis and pentose fermentation. Exergy analysis, production cost analysis and economic viability assessment will be carried out for each scenario.

3. Methods
3.1 Exergy and Thermoeconomic Analysis
Assuming all processes in steady state and neglecting variations in kinetic and potential energies, the mass, energy, exergy and cost balances for each control volume and every production route, take respectively, the form of Eqs. (1) – (4):

$$\sum_{i=1}^{n} \dot{m}_{in} - \sum_{i=1}^{n} \dot{m}_{out} = 0 \qquad (1)$$

$$\sum_{i=1}^{n} \dot{Q}_i - \dot{W} + \sum_{i=1}^{n} \dot{m}_{in} h_{in} - \sum_{i=1}^{n} \dot{m}_{out} h_{out} = 0 \qquad (2)$$

$$\sum_{i=1}^{n} \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) - \dot{W} + \sum_{i=1}^{n} \dot{m}_{in} b_{in} - \sum_{i=1}^{n} \dot{m}_{out} b_{out} = \dot{I} \qquad (2)$$

$$\sum_{i=1}^{n} (\dot{m}bc)_{in} + c_W \dot{W} + \dot{Z} = \sum_{i=1}^{n} (\dot{m}bc)_{out} + c_Q \dot{Q} \qquad (4)$$

Where $\dot{m}_{in\,(out)}$ represents mass flow rate entering (exiting) the control volume (kg/s), $\dot{Q}_i$ heat transfer rate (kW), $\dot{W}$ shaft power (kW), h specific enthalpy (kJ/kg), b specific exergy (kJ/kg), T_0 ambient temperature (K), $\dot{I}$ irreversibility rate (kW), c specific monetary exergy cost (R\$/kJ) and $\dot{Z}$ the depreciation rate of equipment (R\$/s) which is calculated by Eqs. (5) and (6):

$$\dot{Z} = \frac{C_e(f_a + f_{omf} + FC f_{omv})}{T_{oper} 3{,}600} \qquad (5)$$

$$f_a = \frac{j(1+j)^N}{(1+j)^N - 1} \qquad (6)$$

where C_e is the acquisition cost of the equipment (R\$), f_a capital recovery factor, f_{omf} fixed cost associated with

the equipment operation (9%), f_{omv} variable cost of the equipment (1%), FC the load factor (0.75), j interest rate (12 %), T_{oper} expected yearly operation time (5,000 hours) and N equipment lifetime (20 years). The set of equations was solved simultaneously using EES® software [5].

3.2 Development of the Model
The thermodynamic model used in this study is based on performance prediction models of three plants available in the literature. The first one is a utilities plant with subcritical Rankine cycle [6], the second one is a distillery plant [7], and the third one is a hydrolysis plant [8]. Each one of them will be explored separately and the complete model to be solved in this study arises from the assembly of these three sub-models. The implementation of the model corresponds to mass, energy, exergy, and monetary exergy cost balances for each control volume, as stated before.

3.2.1 Distillery
Ethanol is produced by fermentation of the sugarcane juice as well as the juice obtained from the bagasse hydrolysis. Thus, the modelled distillery can be considered a hybrid one, i.e., a combination of first and second generation production routes, as shown in Fig. 1 and described in detail by [9]. The following processes were modelled thermodynamically: (i) washing, (ii) extraction, (iii) juice treatment, (iv) evaporation (v) fermentation, (vi) distillation and rectification, and (vii) cooling. Table 1 shows data related to these processes.

Table 1. Distillery Parameters.

Parameter	Value
Capacity [2]	2 500 000 TC/year[a]
Sugarcane Processed (wet basis)[2]	500 TC/h[a]
Yearly Operation	5000 hours/year
Sugarcane Fiber Content (wet basis)[2]	14.0%
Sugarcane Sucrose Content (wet basis)[2]	14.0%
Sugarcane Moisture Content	70.5%
Juice Extraction Efficiency (Fermentable sugar recovery)[2]	97.0%
Sucrose Fermentation Efficiency (Sucrose mass converted to alcohol)[2]	89.0%
Bagasse Moisture Content[1]	50.0%
Hydrated Ethanol Purity[2]	93.7%
Process Steam Pressure[2]	2.5bar
Sugarcane Bagasse Cellulose Content (dry basis)[1]	43.4%
Sugarcane Bagasse Hemicellulose Content (dry basis)[1]	25.6%
Sugarcane Bagasse Lignin Content (dry basis)[1]	23.2%
Sugarcane Bagasse Ash Content (dry basis)	1.0%
Distillation Steam Consumption (Distillery Plant)[3]	2.5 kg/kg of ethanol
Distillation Mass Recovery Efficiency (Distillery Plant)[3]	99%

a - TC - metric tons of sugarcane.
1 – [4]
2 – [7]
3 – [6]
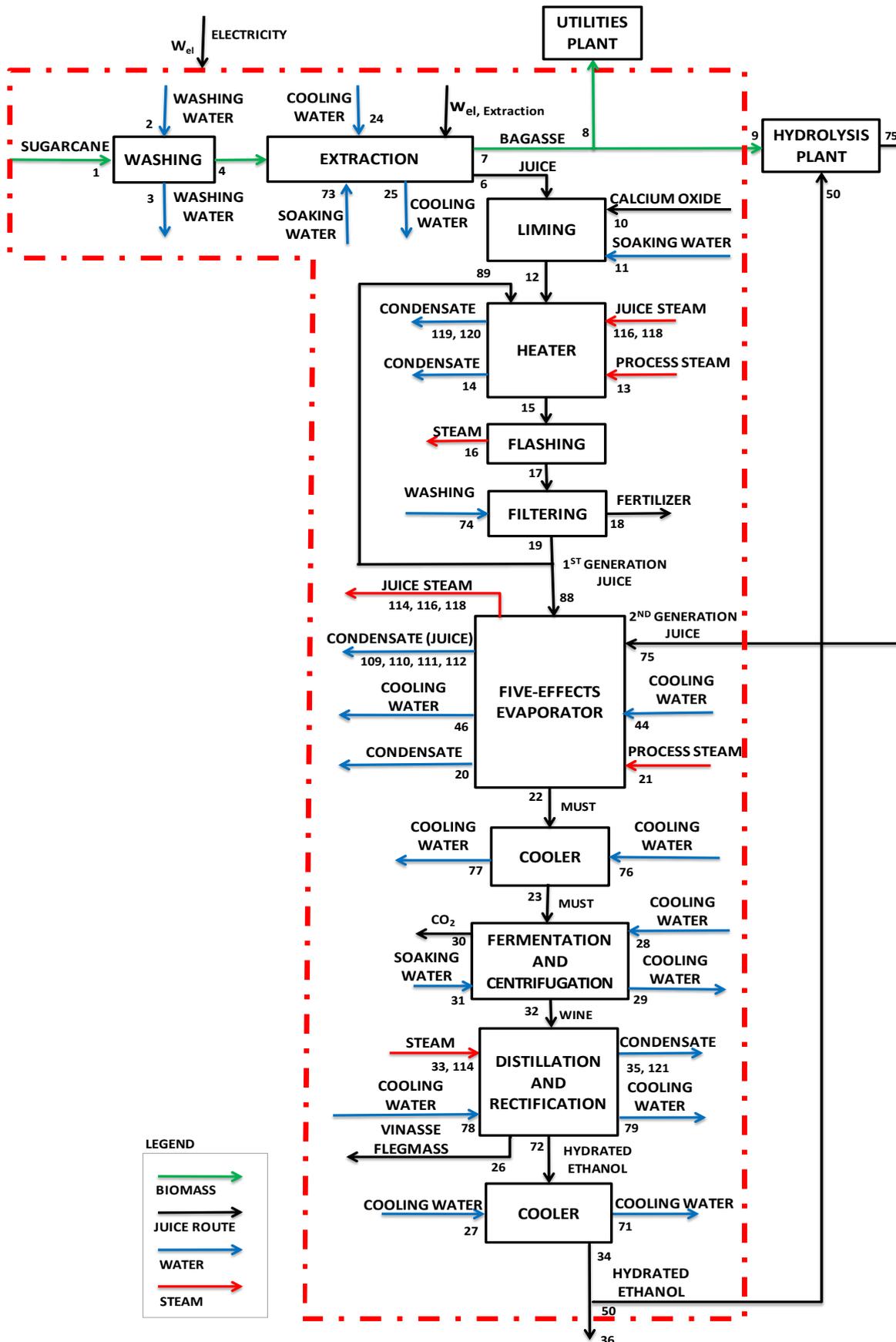
Figure 1. Distillery plant.

3.2.2 Utilities Plant

In Brazil, backpressure systems normally operate at 21 bar and 300°C. Steam is expanded in single-stage turbines (turbo pumps and mills) and / or multistage (turbo) until the process pressure, around 2.5 bar [6] is reached.

By increasing steam temperature and pressure in the boiler, the surplus electricity generated can be sold to the grid in greater amounts. Furthermore, the use of extraction-condensing turbines makes it possible to generate and sell electricity in the period between harvests.

New plants and units, seeking to improve their energy balances, opt to use boilers with pressures up to 100 bar in order to facilitate the sale of surplus electricity. The use of higher pressures is limited to 180 bar due to equipment cost and to economic and financial issues related to the sale of surplus electricity. The efficiency of these new boilers is 85-87% (based on Lower Heating Value, LHV), and it can be raised to 89-90% in case of burning dry bagasse [6].

The utilities plant modelled in this study, differently from the standard Brazilian backpressure system, operates on a Rankine cycle with a condensing-extraction turbine. The extraction is done twice: steam at 13 bar is required to provide heat to the hydrolysis plant, and steam at 2.5 bar is used for the remainder heat demands, e.g. distillation, evaporation and heating, as shown in Fig. 2. No pressure drop in the piping and heat exchangers was considered for the simulation. The main parameters used to model the utilities plant are presented in Table 2.

Table 2. Utilities Plant Operating Parameters.

Parameter	Value
Steam Generation Pressure	60 bar
Steam Generation Temperature	450ºC
Boiler Efficiency (LHV basis)[1]	82%
Turbine Isoentropic Efficiency[1]	85%
Pump Isoentropic Efficiency	80%
Make up Water[1]	5%
Electric Generator Efficiency[2]	95%

1 – [6]
2 – [4]
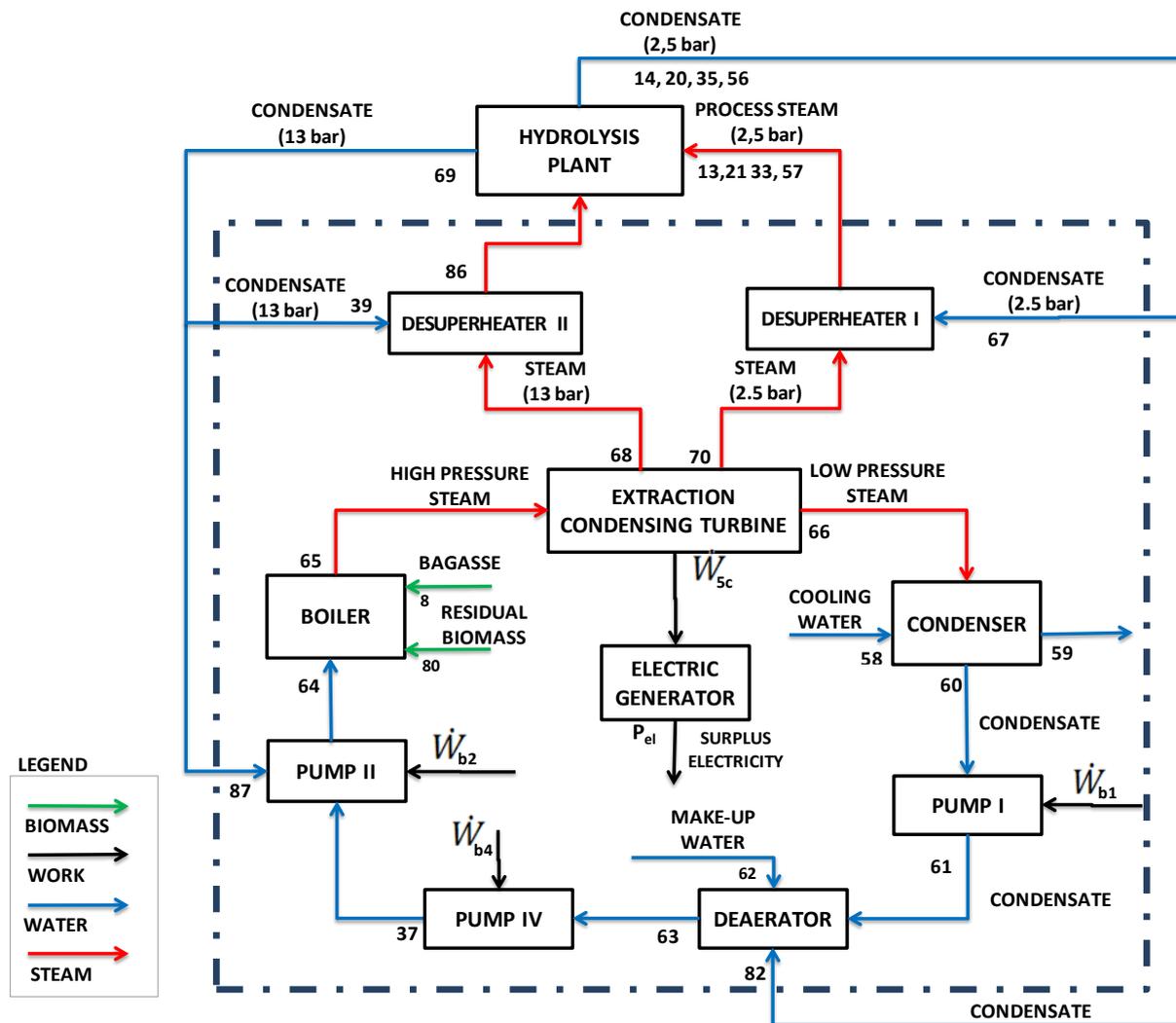
Figure 2. Utilities plant.

3.2.3 Hydrolysis Plant

The hydrolysis plant operates on the process DHR (Dedini Rapid Hydrolysis), which combines the organosolv pre-treatment of bagasse with the dilute acid rapid hydrolysis [10].

The pre-treatment process and the hydrolysis of cellulose and hemicellulose occurs simultaneously in a counter current reactor fed with bagasse from the top and with a mixture of ethanol (75% weight/weight) and diluted sulphuric acid (0.25 - 0.5% weight/weight), under pressure of 25-28 bar and temperature of 180 - 200°C [11]. The fluxes meet in the middle part of the reactor, where cooking takes place between the lignocellulosic biomass and the ethanol-water mixture responsible for promoting delignification and the hydrolysis reaction. The weight ratio bagasse, ethanol-water mixture, sulphuric acid at 98%, is 100:600:0.1 [11]. The time that the mixture remains in the reactor varies from a few seconds to a few minutes. The residual biomass, composed primarily of lignin, is recovered and burnt in the boiler.

Upon leaving the reactor, the slightly acid solution with high sugar content is immediately cooled as a result of the expansion in the valve, which is modelled as isenthalpic,

thereby preventing degradation of formed sugars. The cold liquor is routed to a distillation column where ethanol is recovered at the top of the column and returned to the process. The aqueous solution containing sugar is removed from the bottom of the reactor. Fig. 3 shows the hydrolysis synthesis plant.

Steam consumption in the distillation column is determined by applying the first principle of thermodynamics Eq. (2) in the distillation control volume. Due to the small amount of sulfuric acid, only ethanol, water and sucrose were taken into account to assess steam consumption. The parameters used in this control volume are detailed in Table 3.
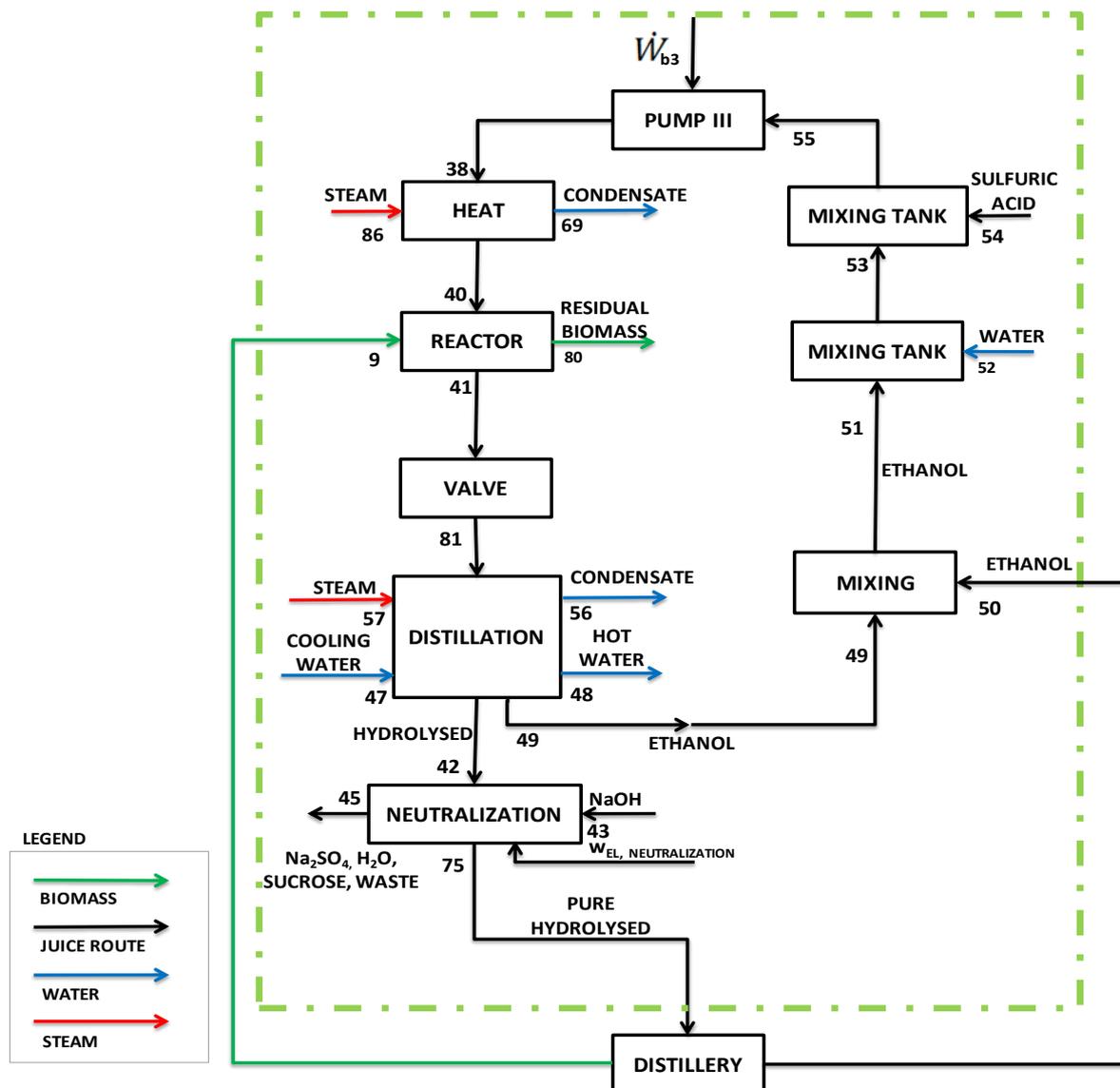
Figure 3. Hydrolysis synthesis plant.

Table 3. Hydrolysis Juice Distillation Parameters.

Parameter	Value
Ethanol Concentration in the Reactor (% weight/weight)	72.20
Sulfuric Acid Concentration in the Reactor (% weight/weight)	0.35
Pressure in the Reactor (bar)	27
Temperature in the Reactor (ºC)	190.0
Hydrolysed Juice Exit Temperature (ºC)	99.8
Ethanol Exit Temperature (ºC)	77.8
Ethanol Exit Concentration (% weight/weight)	93.7
Ethanol Condensation Thermal Load (kJ/kg of ethanol)[1]	2133

1 – [7]

The plants are designed to minimize external water consumption. A cooling tower system collects the condensate of juice steam as well as the water used in cooling processes in order to reuse it by providing cool water for the processes. As a result, the external water

consumption represents less than 10% of the water needed for the processes.

4. Results and Analysis

Three scenarios were defined in order to analyse the results. Table 4 shows the parameters of each scenario.

Because of most fermentable sugar is from the first generation plant, steam consumption in the distillery plant is slightly affected by hydrolysis yield or pentose fermentation. The simulation shows that for scenarios II and III, steam consumption in the hydrolysis plant limits to 18% the amount of bagasse that can be hydrolysed. This is a direct consequence of the steam requirement in the distillation and heating process inside the hydrolysis plant, which is approximately the same for both scenarios II and III. Table 5 presents key points process values obtained from the base case simulation.

4.1 Exergy Analysis - Base Case

- Distillery

Sugarcane exergy is the main input for the distillery. It represents 87.4% of the overall input, followed by process steam, 3.3%. From the perspective of exergy destruction, irreversibilities consume 16.8%, followed by 12.4% in wastes. The product (ethanol) and by-product (bagasse) take 30.2% and 40.8% respectively.

The detailed study of each control volume reveals that the main source of irreversibility is the fermentation process that consumes 13.2% of the input exergy.

- Utilities Plant

Sugarcane bagasse represents 97.6% of the total exergy input for the utilities plant. From the perspective of exergy destruction, irreversibilities are responsible for 72.7%. They are mainly concentrated in the combustion process, inside the boiler control volume, with 69.3%.

The products carry 27.2% of the input exergy, 14.1% for process steam, 13.1% for the electricity and 2.3% for the sugarcane crushing work.

- Hydrolysis Plant

Sugarcane bagasse is the main input for the hydrolysis plant. It represents 60.7%, followed by process steam with 21.5%. The irreversibilities, concentrated mainly in the reactor and in the distillation process, consume 27.6% of the total input. The residual biomass composed primarily of lignin takes 33.6% and the juice composed of fermentable sugars takes 13.1%.

- Global Plant

The plant composed of the distillery, utilities plant and hydrolysis plant destroys 55.1% of the input exergy. The products take 38.2% of the input exergy, being 34.2% for ethanol and 4.1% for the surplus electricity.

Table 4. Scenarios.

Description	Scenario I	Scenario II (Base Case)	Scenario III
	First Generation	Current Hydrolysis Technology	Future Hydrolysis Technology
Pentose Fermentation	-	No	Yes
Hydrolysis - Cellulose Conversion[3]	-	50%	70%
Hydrolysis - Hemicellulose Conversion[3]	-	-	70%
Pentose Fermentation Efficiency[1]	-	-	80%
Filters - Soluble Solids Losses[1]	-	90%	90%
Investment (R$ Million)[2]	317.7	381.2	381.2
Residual Biomass Burning	-	Yes	Yes
Electricity Consumption (Hydrolysis Plant)[1]	-	24 kWh/TC	24 kWh/TC
Reaction Temperature	-	190°C	190°C
Reaction Time	-	5 min	5 min
Sugarcane Bagasse Hydrolysed	0%	15%	15%
Capacity (Dry Basis)	-	100 t/year	100 t/year

1 – [4]

2 – Changes in equipment capacity were correlated to costs considering a coefficient of 0.6 and exchange rate of 2.00 R$/US$ [12]

3 – [13]

Table 5. Key Points Process Parameters - Base Case.

Key Points	ṁ (kg/s)	P (kPa)	T (°C)	b (kJ/kg)	c (10⁻⁶R$/kJ)
1	138.9	101.3	25.0	5,695.0	13.0
6	143.6	600.0	35.0	2,931.0	15.1
8	31.4	101.3	35.0	9985.0	15.1
12	147.0	600.0	36.5	2,865.0	16.5
23	107.7	101.3	28.0	3,725.0	24.8
32	137.7	101.3	32.0	2,041.0	39.9
34	9.9	101.3	35.0	27,618.0	47.8
37	72.1	1,300.0	114.0	97.0	70.6
38	33.3	2,700.0	64.7	22,014.0	105.1
40	33.3	2,700.0	190.0	22,136.0	105.0
41	34.4	2,700.0	190.0	21,739.0	104.5
42	7.9	101.3	99.8	1,593.0	104.8
51	26.5	101.3	77.8	27,626.0	104.8
53	33.1	101.3	64.4	22,090.0	105.0
55	33.3	101.3	64.2	22,011.0	105.1
60	7.7	8.2	42.0	51.9	66.0
61	7.7	250.0	42.0	51.9	66.4
63	72.1	250.0	113.9	96.7	69.8
64	80.2	6,000.0	124.4	108.5	80.5
65	80.2	6,000.0	450.0	1,353.0	62.1
66	7.7	8.2	42.0	165.6	67.7
68	8.1	1,300.0	261.7	973.6	67.7
70	64.4	250.0	127.4	662.0	67.7
75	7.6	101.3	99.8	1,577.0	130.5
88	149.1	600.0	97.0	2,658.0	18.3

The definition of global exergy efficiency $\left(\eta_B\right)$ for a distillery is presented in Eq. (7): the ratio between the exergy of products (alcohol, $\dot{B}_{ETHANOL}$, and surplus electricity, P_{EL}) and the difference of sugarcane exergy (input process) and the waste exergy (part of exergy that is not used in the process). Fig. 4 summarizes the results of the exergy analysis for scenario II.

$$\eta_B = \frac{\dot{B}_{ETHANOL} + P_{EL}}{\dot{B}_{SUGARCANE} - \dot{B}_{WASTE}} \tag{7}$$

The global exergy efficiency can be compared among the scenarios I, II and III. Fig. 5 presents this result as a function of the amount of hydrolysed bagasse. It can be concluded that, from a perspective of the rational use of the exergy, scenario III is better than scenarios II and I.

4.2 Production Cost Analysis - Base Case

Ethanol and electricity production cost can be assessed by doing the cost balance for each control volume. In case of a control volume with more than one product, e.g. steam turbine, the equality cost partition criteria was adopted. Table 6a and 6b show the global cost balance for scenario II. It can be inferred that the primary source of cost is the sugarcane as feedstock followed by the distillery amortization.

Another interesting analysis that can be performed at this point is a production costs comparison between first and second generation sugarcane juice. The production cost

of the latter reaches extremely high values for small values of the percentage of hydrolysed sugarcane bagasse. This comes from the fact that all the fixed cost of the hydrolysis plant is discharged in a small amount of produced juice

(a) - Distillery

(b) – Utilities Plant

(c) – Hydrolysis Plant

(d) – Global Plant
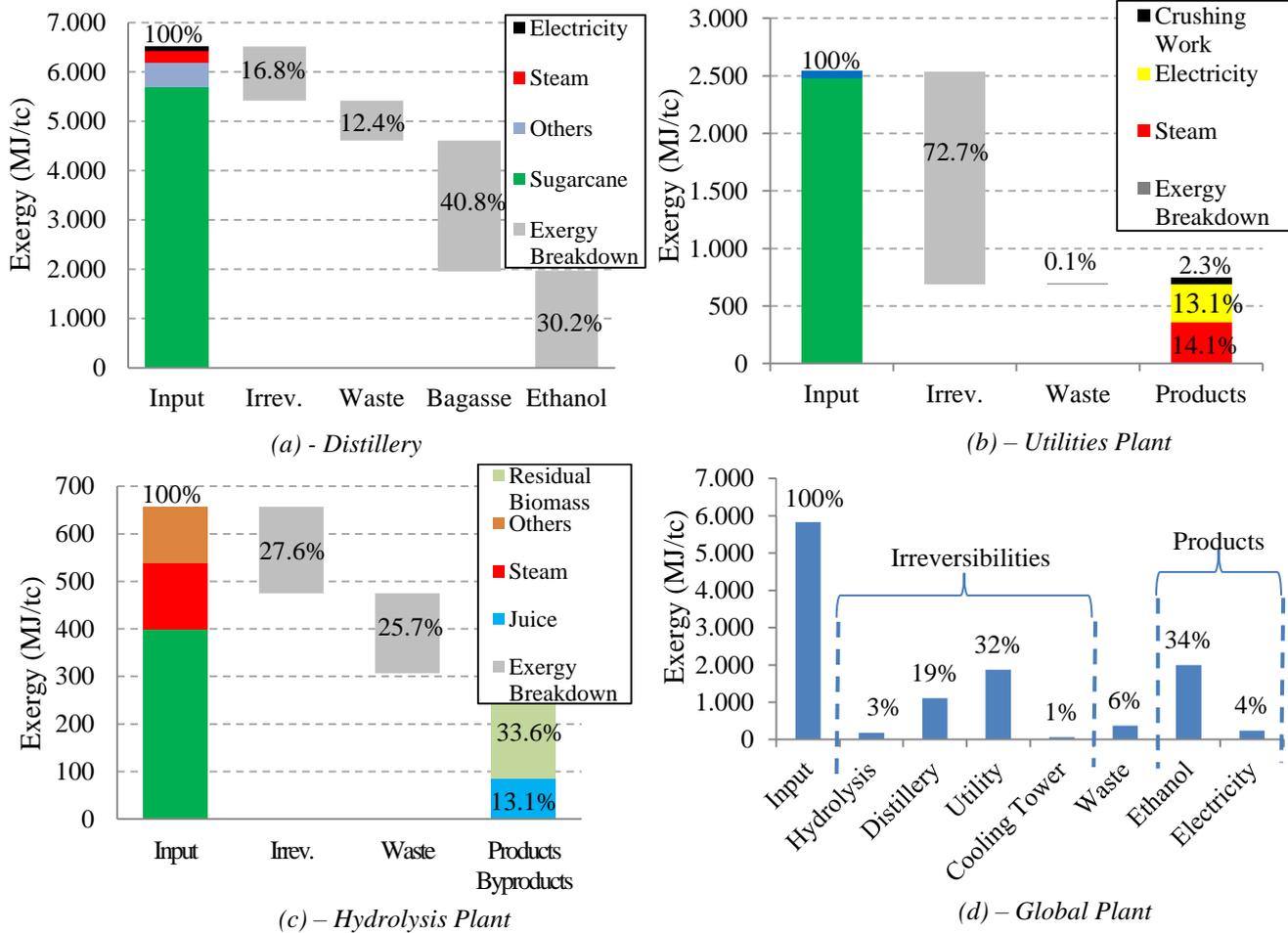
Figure 4. Exergy analysis for scenario II (15% of hydrolysis).
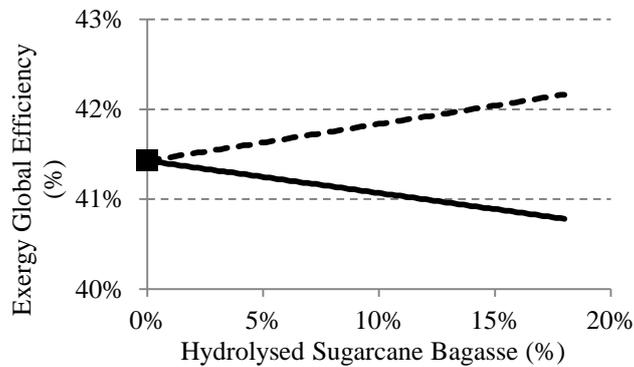
Figure 5. Global exergy efficiency for scenarios I, II and III.

Table 6a. Input Costs for Scenario II - Base Case.

Input	Monetary Exergy Cost (10⁻⁶ R$/kJ)	Specific Exergy (kJ/kg)	Specific Cost (R$/kg)	Cost Rate (R$/s)	Specific Cost (R$/tc)	Flow
Sugarcane[1]	13.0	5695	0.074	10.29	74.09	m_1
H_2SO_4[1]	360.1	1666	0.60	0.07	0.51	m_{54}
NaOH[1]	738.5	2113	1.56	0.13	0.91	m_{43}
CaO[1]	142.5	1965	0.28	0.04	0.31	m_{10}
Replacement Water[1]	5.20	50	0.00	0.04	0.29	m_{84} and m_{62}
Distillery	-	-	-	3.00	21.59	Amortization
Hydrolysis Plant	-	-	-	0.82	5.87	Amortization
Utilities Plant	-	-	-	1.08	7.81	Amortization
Total Input	-	-	-	15.5	111.3	

1- [14]

Output	Monetary Exergy Cost (10^{-6} R$/kJ)	Specific Exergy (kJ/kg)	Specific Cost (R$/kg)	Cost Rate (R$/s)	Specific Cost (R$/tc)	Flow
Ethanol	47.8	27618	1.32	13.06	93.99	m_{36}
Electricity	73.4[a]	-	-	2.39	17.21	W_{el}
Total Output	-	-	-	<u>15.5</u>	<u>111.2</u>	

a - 264.30 R$/MWh
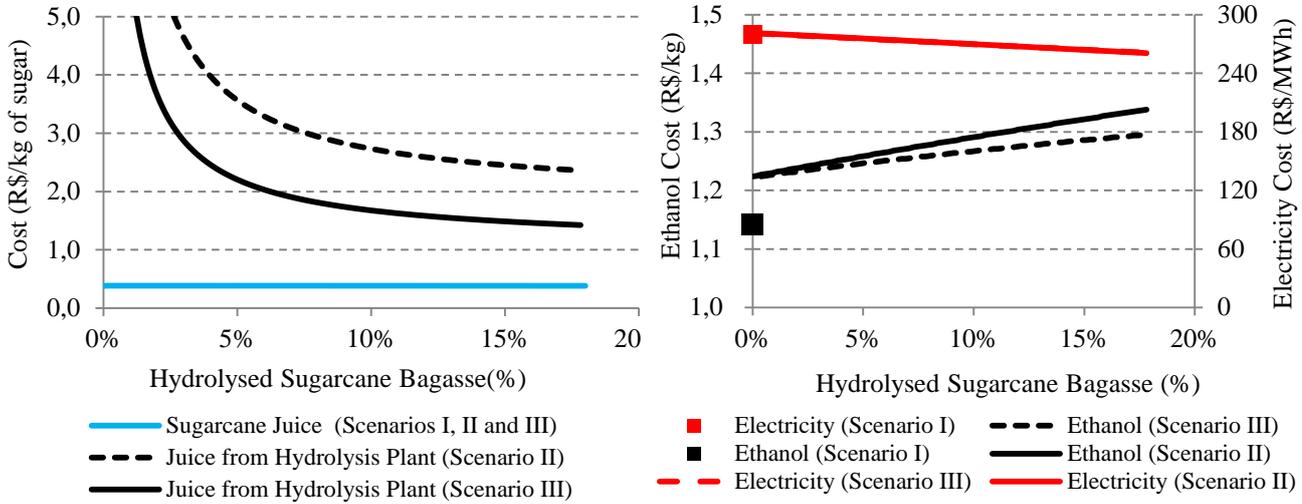
Figure 6. Juice (a), electricity and ethanol (b) production costs.
(Note: Electricity costs for scenarios II and III are overlapped in the chart)

For scenarios II and III, as shown in Fig. 6, production cost of the juice tends to stabilize when a large amount of bagasse is hydrolysed. Although the cost tends to decrease with the amount hydrolysed, it is still much more costly than the first generation juice. Scenario III shows a 40% cost reduction in relation to scenario II. This is a consequence of the higher hydrolysis yield and the use of the pentose for obtaining ethanol.

4.2.1 Sensitivity Analysis - Base Case
In order to compare the impact of changes in the main parameters, a dimensionless sensitivity coefficient is defined as in Eq. (8):

$$\beta = \frac{\frac{\Delta Product}{Product}}{\frac{\Delta Input}{Input}} \qquad (8)$$

where:

- *Product* is a result obtained by the model. Four products were analyzed: (i) sugarcane juice cost, (ii) hydrolysed juice cost, (iii) ethanol cost, and (iv) electricity cost.

- *Input* is a specific process variable. Seven inputs were considered: (i) sugarcane price, (ii) investment, (iii) boiler LHV efficiency, (iv) cellulose conversion efficiency, (v) steam turbine isentropic efficiency, (vi) distillation steam consumption, and (vii) sucrose fermentation efficiency.

An array can be obtained by calculating β for all possible combinations of Product-Input. Table 7 shows the dimensionless sensitivity array. As can be seen, sugarcane plays a key role in determining the cost of all products. In addition, the control volumes that present the highest irreversibility rate, i.e. boiler, steam turbine, fermentation and hydrolysis reactor, also present the highest dimensionless sensitivity coefficient.

Table 7. Dimensionless Sensitivity Array for Scenario II - Base Case.

Input \ Product	Sugarcane Juice Cost	Hydrolysed Juice Cost	Ethanol Cost	Electricity Cost
Sugarcane Price	**<u>0.84</u>**	**<u>0.47</u>**	**<u>0.64</u>**	**<u>0.74</u>**
Investment	0.15	**<u>0.56</u>**	0.36	0.25
Boiler LHV Efficiency	-0.07	-0.32	-0.21	**<u>-0.92</u>**
Cellulose Conversion Efficiency	-0.01	**<u>-0.56</u>**	-0.02	0.00
Steam Turbine Isentropic Efficiency	-0.04	-0.23	-0.16	**<u>-0.47</u>**
Distillation Steam Consumption	0.00	-0.03	0.04	-0.04
Sucrose Fermentation Efficiency	-0.04	-0.24	**<u>-0.96</u>**	-0.07

Note: The most significant coefficients are highlighted

4.3 Economic Viability Assessment
The economic viability assessment is based on the cash flow generated by the construction and operation of the plants for scenarios I, II and III as described in Table 4. During the first two years, cash flow is negative because of the investment expenses. From the third year until the end of operation, cash flow is generated by the sale of electricity and ethanol. The Internal Rate of Return (IRR) is then calculated to decide which scenario is the best one in terms of return on investment. Fig. 7 illustrates that although the IRR increases with the hydrolysis for scenario III, the best choice is still scenario I with IRR of 13.4% in real terms. Table 8 shows the main parameters used in the economic viability assessment.

Table 8. Parameters Used in the Economic Analysis.

Parameters	Value
Ethanol Price[1]	1.31 (R$/l)
Tax on Revenue[2]	8.30%
Electricity Price[3]	102.10(R$/MWh)
Income Tax	34%
Depreciation (linear)	10 years
Start-up time	2 years
Salvage Value	0
Project lifetime	20 years

1- [14]

2- [15]

3- Public Auction 02/2011-ANEEL (Net of taxes) [16]
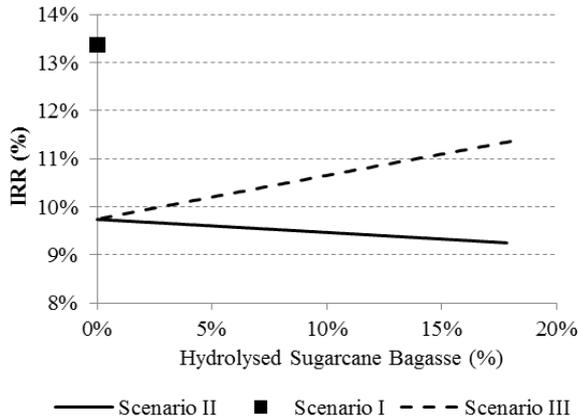
Figure 7. IRR for scenarios I, II and III.

4.3.1 Sensitivity Analysis

In order to evaluate the impact of changes in prices and investment expenses on the internal rate of return (IRR), taking into account eventual uncertainties on the investment of the hydrolysis plant and market fluctuations, a sensitivity analysis was carried out. For electricity price, sugarcane price and investment expenses, a variation of ±25% over the original value (displayed in Tables 4, 5a and 6) was assumed. For ethanol price, a variation of ±20% was

considered. Results are shown in Fig. 8. It can be verified that among the variables, the one that presents the most significant impact on the IRR, is the ethanol price: a variation of ±20% causes the largest changes on the IRR in all the scenarios evaluated. Changes of ±25% on sugarcane prices also affect the IRR significantly, but with less intensity than ethanol prices. Changes on investment of hydrolysis plant and electricity price have small impact on the IRR. An important conclusion at this point is that scenario I presents the highest IRR value among the three scenarios in the ±25% interval.

4.4 Comparison with Other Studies

Tables 9 to 11 show several comparison parameters between results obtained in this model and previous publications.

As expected, the exergy efficiency varies significantly as a function of the hydrolysed biomass. Table 9 shows that lignocellulosic materials such as banana peduncle and sugarcane bagasse present exergy efficiency ranging from 13.1% to 28.7% depending on the analysed scenario.

In terms of global exergy efficiency (Table 10), scenario II actually is worse than scenario I. When compared with previous publications, global exergy efficiency is close to a first generation plant. This is due to the fact that most input exergy from sugarcane in the model is still processed in a traditional first generation distillery and only the surplus bagasse is hydrolysed.

Table 11 compares main efficiency parameters of the model with a 50/50 ethanol/sugar first generation plant [6] with different utilities plant configurations. As a result, global exergy efficiency in the model is lower than value obtained for an extraction-condensing system. This is mainly due to the choice 100/0 ethanol/sugar in the model, which is more irreversible. For the other parameters, it can be concluded that the results are consistent with this study

Figure 8. Sensitivity analysis.

Table 9. Exergy Efficiency Comparison (Hydrolysis Only).

	Acid Hydrolysis[1]		Enzymatic Hydrolysis[1]	Acid Hydrolysis[2]	
Origin	Banana Skin	Banana Pulp	Peduncle	Bagasse (Scenario II)	Bagasse (Scenario III)
Biomass	Starch	Starch	Lignocellulose	Lignocellulose	Lignocellulose
η_B (%)	51.3	57.4	20.3	13.1	28.7

1 – [8];

2 – Results from the model

Table 10. Global Exergy Efficiency Comparison.

Biomass	Products	Exergy Efficiency (%)
Palm Tree[1]	Biodiesel	74.7
Sugarcane[3]	Sugar and Ethanol	43.5
Banana Skin (Starch)[1]	Ethanol	35.1
Banana Pulp (Starch)[1]	Ethanol	24.5
Banana Peduncle (Lignocellulose)[1]	Ethanol	12.2
Sugarcane (Scenario I)[2]	Electricity and Ethanol	41.4
Sugarcane (Scenario II - 15% of hydrolysis)[2]	Electricity and Ethanol	40.9
Sugarcane (Scenario III - 15% of hydrolysis)[2]	Electricity and Ethanol	42.0

1 – [8]
2 – Results from the model
3 – [6]

Table 11. Key Results Comparison.

Parameter	Backpressure System[1]	Extraction-Condensing System[1]	Supercritical System[1]	Scenario I[2]	Scenario II[2]	Scenario III[2]
Ethanol Exergy Cost (kJ/kJ)	3.08	2.91	2.54	2.23	2.42	2.36
Electricity Exergy Cost (kJ/kJ)	5.01	5.16	3.66	4.58	4.23	4.22
Steam Exergy Cost (kJ/kJ)[3]	4.77	4.78	3.78	4.35	4.02	4.01
Steam Consumption (kg/tc)	490	392	278	322.2	526.0	526.0
Sugar Exergy Cost (kJ/kJ)[3]	1.62	1.56	1.39	-	-	-
Exergy Efficiency (%)	45.8	44.7	50.0	41.4	40.9	42.0
Surplus Electricity (kWh/tc)	48.5	64.9	142.3	90.5	65.4	62.3
Surplus Sugarcane Bagasse (%)	12.8	3.0	3.0	0.0	0.0	0.0

1 - Different configurations for a 50/50 sugar/ethanol plant [6]
2 - Results from the model
3 - Differently from the monetary exergy cost (R$/kJ), the exergy cost (kJ/kJ) measures the amount of input Exergy necessary to produce one kJ of product Exergy, in this case electricity and ethanol.

5. Conclusions

The simulation shows that for scenarios II and III, steam consumption in the hydrolysis plant limits to 18% the amount of bagasse that can be hydrolysed. This is a direct consequence of the steam requirement in the distillation and heating process inside the hydrolysis plant, which is approximately the same for scenarios II and III. Because of most fermentable sugar is from the first generation plant, steam consumption in the distillery plant is slightly affected by hydrolysis yield or pentose fermentation. In terms of productivity improvement, hydrolysis can increase the net ethanol production by 3.7% and 8.1%, for scenarios II and III respectively, which leads, respectively, to 136 and 286 liters of ethanol per dry ton of sugarcane.

Regarding the exergy analysis, hydrolysis under scenario II causes a small drop in global exergy efficiency, from 41.4% (scenario I) to 40.9% (scenario II). The situation is reversed for scenario III in which the global exergy efficiency increases from 41.4% to 42.0%. This is a direct consequence of higher saccharification yield and pentose fermentation. Exergy analysis still shows that, for all three scenarios, the main source of irreversibility is the utilities plant, notably the boiler. This is an expected result because the combustion reaction is highly irreversible.

The economic viability assessment based on the IRR shows that scenario I, which is a first generation plant, is the best choice with IRR of 13.4%, followed by scenarios III and II with IRR of 11.1% and 9.3% respectively. Sensitivity analysis shows that the scenario I is still the best choice even if main parameters change ±25%.

Nomenclature

b	Specific exergy (kJ/kg)
$\dot{B}_{ETHANOL}$	Ethanol exergy flow rate (kW)
$\dot{B}_{SUGARCANE}$	Sugarcane exergy flow rate (kW)
$\dot{B}_{WASTE}$	Waste exergy flow rate (kW)
c	Specific monetary exergy cost (R$/kJ)
C_e	Acquisition cost of the equipment (R$)
f_a	Capital recovery factor
f_{omf}	Operational and maintenance fixed cost factor
f_{omv}	Operational and maintenance variable cost factor
FC	Load factor
h	Specific enthalpy (kJ/kg)
$\dot{I}$	Irreversibility rate (kW)
IRR	Internal rate of return (%)
j	Interest rate (%)
$\dot{m}$	Mass flow rate (kg/s)
N	Equipment lifetime (year)
P	Pressure (kPa)
P_{EL}	Electrical power (kW)
$\dot{Q}$	Heat transfer rate (kW)
T	Temperature (K, °C)
T_0	Ambient temperature (K, °C)
T_{oper}	Expected yearly operation time (h)
$\dot{W}$	Shaft power (kW)
$\dot{Z}$	Equipment depreciation rate (R$/s)

Greek Symbols

β	Sensitivity Coefficient
Δ	Variation
η_B	Exergy efficiency

Subscripts

in	Inlet
out	Outlet
Q	heat
W	work

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