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ANALYSIS OF OVERALL UTILIZATION OF SUGARCANE BIOMASS AND WASTE FROM THE PRODUCTION OF SUGAR AND ETHANOL FOR COGENERATION IN A BRAZILIAN SUGARCANE MILL

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ABSTRACT

This work presents thermodynamic, thermoeconomic and economic analyses of biomass gasification systems integration in a sugar-ethanol factory. Four configurations, combining the actual cogeneration plant with straw and stillage gasification systems, are considered. Case 1 represents a steam plant of a modern conventional power plant (base case), with a steam boiler of high-pressure and high-temperature, as well as an extraction-condensation steam turbine, being all mechanical driving electrified. In the other cases, gasification systems are associated to the actual plant using the energy from a gas turbine and a heat recovery steam generator to complete a combined cycle. In Case 2, the incorporation of a system for biodigestion of stillage is experimented. In Case 3, the incorporation of the sugar-cane straw gasification in the current plant is considered and Case 4 considers the gasification of straw and stillage.

NOMENCLATURE

BEN	[R$]	Annual benefit obtained
BSR	[t_{bag}/kg_{steam}]	Bagasse-Steam Ratio
c	[R$/kJ]	Average cost per unit of exergy
C	[R$]	Monetary Cost
$\dot{C}$	[R$/s]	Cost rate of exergy
ex	[kJ/kg]	Specific exergy
$\overline{ex}$	[kJ/kmol]	Molar exergy of a component in the mixture
$\dot{E}x$	[kW]	Exergy rate
f	[%]	Factor for amortization or operation and maintenance
h	[kJ/kg]	Specific enthalpy
I	[US$]	Total invested capital at the start of project operation
IRR	[%]	Internal rate of return on investment
j	[%]	Discount rate
L	[kJ/kg]	Enthalpy of vaporization
LF	[%]	Load Factor
LHV	[kJ/kg]	Lower Heat Value
$\dot{m}$	[kg/s]	Mass flow rate
N	[years]	Useful live / Number of years analyzed
NPV	[R$]	Net Present Value
P	[MPa]	Pressure
PHR	[-]	Power-Heat Ratio
$\dot{Q}$	[kW]	Heat transfer rate
$\overline{R}$	[kJ/molK]	Universal gas molar constant
PCR	[kWh/t_{cane}]	Power-Cane Ratio
s	[kJ/K]	Specific entropy
$\dot{S}$	[kW/K]	Entropy rate
SCR	[kg_{steam}/t_{cane}]	Steam-Cane Ratio
t	[h]	Time
T	[K]	Temperature
$\dot{W}$	[kW]	Power
x	[-]	Molar fraction of a component in the mixture
Z	[%]	Fraction in mass of a component in the mixture

Special characters

β	[%]	Function of the mass fraction of biomass components
η	[%]	Efficiency

Subscripts

a	Amortization
bag	Bagasse
$biom$	Biomass
ch	Chemical
$comp$	Compressor
$cons$	Consumed
cv	Control Volume
e	Equipment or Electric
ele	Electrical
exp	Exported
fom	Fixed cost for operation and maintenance
gen	Generated
i	In or Component index
o	Out
$oper$	Operation
k	Component index
ph	Physical
$pump$	Pump
q	Heat index
t	Thermal
vom	Variable cost for operation and maintenance
w	Work index
0	Reference state

INTRODUCTION

According to the Brazilian Ministry of Mines and Energy (MME), the consumption of electricity in Brazil has increased more than the Gross Domestic Product (GDP) due to the population growth concentrated in urban areas and the modernization of the economy. Because of this situation, incentives for the use of other energy sources and the search to increase the efficiency of energy production have been increased in the last years. In this context, the conversion of biomass into energy vectors is an interesting alternative.

The straw burning in the sugarcane sector is a common practice to facilitate the harvest, but in Sao Paulo State an environmental law for the gradual elimination of this practice was approved in 2002, appearing the interest in their recovery for use as fuel in addition to the bagasse. More recently, in July 2007, a Green Protocol to minimize the effects of pollution was signed, stipulating that the burn must be stopped in mechanizable areas (areas with steepness smaller than 12 %) and completely abolished in all areas by 2017 ([1]). Figure 1 shows the gradual elimination of straw burning in Sao Paulo state, according to the previous mentioned law and protocol ([1]).

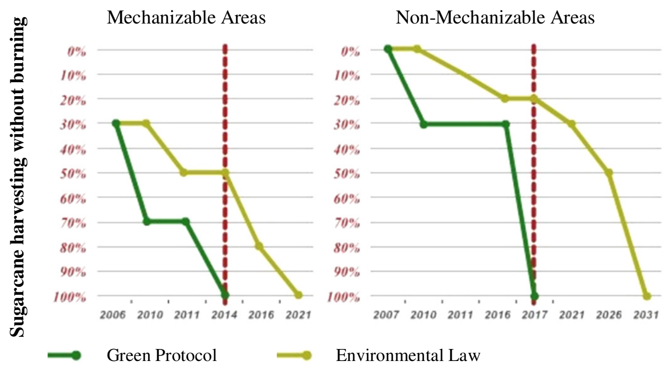

Figure 1 Elimination of straw burning in Sao Paulo state.

The solid biomass gasification is a chemical process of converting biomass into a fuel gas of low calorific value, consisting mainly of carbon monoxide, hydrogen, carbon dioxide and methane. The integration of this system in sugarcane factories can be made by using the technology BIG-GTCC (Biomass Integrated Gasification Gas Turbine, Combined Cycle), which uses a combination of gas and steam turbines integrated with a biomass gasifier for the production of gas.

There is also a great potential for utilization of stillage, which is a byproduct of the ethanol production process, through the process of biodigestion. The stillage is generated in large quantities (10 to 15 m^3 by each m^3 of ethanol produced) and currently it is only used as fertilizer. The biodigestion process of the organic load of stillage generates biogas, which can be used for power generation, and the stillage digested retains its fertilizer power yet.

Considering that 1 ton of sugarcane generates 1 m^3 of stillage and taking into account that is generated 7.2 kg of methane during the process of digestion of 1 m^3 of stillage, the chemical energy produced would be about 100 kWh per ton of sugarcane, if totally converted in electrical energy would promote an increase of approximately 20 kWh per ton of cane.

The process of biogas production starts with the effluent to be treated being distributed uniformly on the base of the reactor, passing by the sludge layer, transforming the organic matter into biogas. In the practice, by means of the stillage it is obtained 0.3 liters of CH_4 per gram of oxygen chemical demand, being the proportion of CH_4 in the biogas about 50 to 65 %. As the biogas presents some contaminants immediately after its production, it is necessary a depuration by using filters, compressors, coolers, pumps e other equipment.

The objectives of this work are performing thermodynamic, thermoeconomic and economic analyses for utilization bagasse, straw gasification and stillage biodigestion for energy cogeneration in a sugarcane mill. The literature contains several studies related to the subject of this paper, some of which will be outlined in the sequence.

Salomon ([2]) conducted an economic and environmental evaluation of technologies for energy recovery from stillage biogas. An analysis of biogas production, considering theoretical and experimental results, was carried out, in addition to modeling the production of electricity from biogas, for different temperatures of the reactor operation. Analyses showed the great potential for generation of biogas by stillage, showing that an internal combustion engine presents themselves as the best option for electricity generation from biogas.

Seabra ([3]) investigated the technological options involving the use of bagasse and cane straw considering various technologies such as electric power generation through cogeneration steam cycle; cogeneration with biomass integrated gasification combined cycle; increment in the ethanol production through bagasse hydrolysis and of the production of fuels from biomass gasification. It was assessed that, with the options currently available, it could have a generation of surplus power in excess of 140 kWh/t_{cane}, costing around US$ 55.00/MWh for systems with high pressure cogeneration and use of some straw in conjunction with the bagasse. Going forward, cogeneration systems with integrated gasification combined cycle biomass should allow the levels of surplus to exceed 200 kWh/tc, but production costs should be also higher (greater than US$ 75.00/MWh).

Romão Júnior ([4]) examined the possibility of utilization of straw as a supplementary fuel in sugar-ethanol factories. It was found that the use of straw as a supplementary fuel to bagasse in conventional high pressure enabling an increase in generation of electrical energy surplus with the possibility to be exported for commercialization. For this, studies of losses, gains and investments were carried out with the introduction of straw in the industry through thermodynamics analysis to generate energy, production of alcohol and sugar, efficiencies of equipment like as mechanical cane harvest, washing system of cane to be dried, mincer of straw, high-pressure boiler, milling of sugar cane, among others.

Pellegrini, Oliveira Jr. and Burbano ([5]) presented thermodynamic and thermoeconomic comparative studies of new technologies applied in sugar-ethanol factories. The configurations studied include supercritical steam cycles, with high pressure and steam temperature reaching 30 MPa and

600 °C, respectively, and technologies for biomass gasification, considering atmospheric and pressurized gasification. The technologies of supercritical cycles and atmospheric gasification allow to generate electricity surplus about 150 kWh/t_{cane}, whereas with pressurized gasification could reach up to 202 kWh/t_{cane} surplus of electricity. Moreover, the exergy cost of electricity generated could be reduced by 50% with supercritical steam cycle and in more than 60% with pressurized gasification.

METHODOLOGY

Thermodynamic Analysis

Considering a steady-state process and assuming overall negligible kinetic and potential energy, the mass conservation as well as First and Second Laws of Thermodynamics for a control volume are represented in a simplified form by ([6]):

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{1}$$

$$\dot{Q}_{c.v} - \dot{W}_{c.v.} + \sum \dot{m}_i h_i - \sum \dot{m}_o h_o = 0 \tag{2}$$

$$\dot{S}_{gen,c.v.} + \sum \left(\dot{Q}_{c.v,k} / T_k \right) + \sum \dot{m}_i s_i - \sum \dot{m}_o s_o = 0 \tag{3}$$

Energy analysis alone is incapable of taking into account the energy quality and the sources of irreversibility for the processes. The combination of the First and Second Laws leads to the exergy inventory and to the evaluation of the irreversibility of the processes.

According to [7], total specific exergy is composed by physical and chemical exergies.

$$ex_{total} = ex_{ph} + ex_{ch} \tag{4}$$

Disregarding effects of kinetic and potential energy, the specific physical exergy of a flow is evaluated based on a restricted equilibrium state of the system with a standard environment (P_0, T_0), by means of:

$$ex_{ph} = (h - h_0) - T_0 (s - s_0) \tag{5}$$

In this work the reference temperature and pressure for the ground state are T_0 = 298.15 K and P_0 = 101.3 kPa, as usually.

For an ideal solution of pure substances, the molar chemical exergy is given by ([8]):

$$\overline{ex}_{ch} = \sum_k x_i \, \overline{ex}_{ch;k} + \overline{R} \, T_0 \sum_i \left(x_i \ln x_i \right) \tag{6}$$

The specific chemical exergy of the bagasse and straw are evaluated with the help of the expression presented by [7] that takes into account the correlation between the chemical exergy and *LHV* of the fuel, considering its elementary composition, the ash content and the humidity, as follows:

$$ex_{ch} = \beta (LHV_{fuel} + L_{water} Z_{water}) + ex_{water} Z_{water} \tag{7}$$

being:

$$\beta = \frac{1.0412 + 0.2160\left(\frac{Z_{H_2}}{Z_C}\right) - 0.249\left(\frac{Z_{O_2}}{Z_C}\right)\left[1 + 0.7884\left(\frac{Z_{H_2}}{Z_C}\right)\right] - 0.0450\left(\frac{Z_{N_2}}{Z_C}\right)}{1 - 0.3035\left(\frac{Z_{O_2}}{Z_C}\right)} \tag{8}$$

In order to evaluate the plant performance some indexes are defined, permitting to compare products from different thermodynamic qualities, such as thermal energy and power produced ([9]).

The overall efficiency of the plant is the ratio of useful energy, either thermal or electrical power available to exportation (total produced minus the quantity consumed by compressors, pumps and electrical installation), and the power supplied to the system by the fuel that is being utilized in the plant, in general just the bagasse, according to:

$$\eta_{overall} = \frac{\dot{W}_{ele} + \dot{Q}_{useful} - \dot{W}_{comp} - \dot{W}_{pump} - \dot{W}_{cons}}{\dot{m}_{bag} \, LHV_{bag}} \tag{9}$$

This definition of overall efficiency is based only in the power supplied to the plant, disregarding the energy from other sources available in the industry that could be used for energy purposes, but are not being used. Thus, it is also considered an efficiency of biomass utilization as the ratio of useful energy, either thermal or electromechanical, total biomass and energy available for utilization, regardless of whether or not it is being used in the plant (straw, bagasse, and biogas of stillage), being defined by:

$$\eta_{biom} = \frac{\dot{W}_{ele} + \dot{Q}_{useful} - \dot{W}_{comp} - \dot{W}_{pump} - \dot{W}_{cons}}{\dot{m}_{bag} \, LHV_{bag} + \dot{m}_{straw} \, LHV_{straw} + \dot{m}_{biogas} \, LHV_{biogas}} \tag{10}$$

Another important index is the Power-Heat Ratio (*PHR*), which is the ratio between the electrical power available to exportation (as defined in the text previously) and the thermal energy used in the process, namely:

$$PHR = \frac{\dot{W}_{export}}{\dot{Q}_{useful}} \tag{11}$$

The specific consumption of bagasse, or Bagasse-Steam Ratio (*BSR*), is an important parameter linked to the efficiency of boilers. This parameter is calculated from the amount of bagasse (in ton) that is required to produce one kilogram of steam at a desired temperature and pressure, as follow:

$$BSR = \frac{\dot{m}_{bag}}{\dot{m}_{steam}} \tag{12}$$

With respect to the thermal demand for the sugar-ethanol production, the Steam-Cane Ratio (*SCR*) represents the heat that is being used in the process, expressed by kilograms of steam per ton of sugarcane, as follow:

$$SCR = \frac{\dot{m}_{steam}}{\dot{m}_{cane}} 1000 \quad (13)$$

It is recommendable to reduce this number, so that the plant is able to process the cane with the lowest possible steam demands.

Another important parameter is the ratio of the electrical power available to exportation and the quantity of cane milled (*PCR*), given in kWh/t_{cane}:

$$PCR = \frac{\dot{W}_{exp}}{\dot{m}_{cane}} \quad (14)$$

Thermoeconomic Analysis

The thermoeconomic evaluation of the plant is based on the theory of exergy cost, which involves the balance of costs for each component of the same. Thus, for a given component (*k*) that receives heat and generates power, the balance of cost should take into account the cost rates (R$/s) associated with the exergy input and output, and the rates associated with power and heat transfer, beyond the rate of cost of equipment, considering the equipment cost and factors related to amortization, fixed and variable expenses with operation and maintenance, according to the load factor and the number of hours of operation, is given by ([8]):

$$\sum\left(\dot{C}_i\right)_k + \left(\dot{C}_w\right)_k = \left(\dot{C}_q\right)_k + \sum\left(\dot{C}_o\right)_k + \left(\dot{C}_e\right)_k \quad (15)$$

being:

$$\dot{C}_i = c_i \dot{E}x_i = c_i \left(\dot{m}_i ex_i\right) \quad (16)$$

$$\dot{C}_o = c_o \dot{E}x_o = c_o \left(\dot{m}_o ex_o\right) \quad (17)$$

$$\dot{C}_w = c_w \dot{W} \quad (18)$$

$$\dot{C}_q = c_q \dot{Q} \quad (19)$$

$$\dot{C}_e = \frac{\left[C_e \left(f_a + f_{fom} + LF\, f_{vom}\right)\right]}{t_{oper}\, 3600} \quad (20)$$

The depreciation factor can be calculated using the annual percentage rate of interest and number of years of useful life of equipment, according to the following equation ([8]):

$$f_a = \frac{\left[j\left(1+j\right)^N\right]}{\left[\left(1+j\right)^N - 1\right]} \quad (21)$$

Economic Analysis

Usually, the financial analysis of projects is based on estimates of future cash flow, derived from forecasts for several variables. The initial analysis of cash flow is done by representative values for the variables considered, allowing the calculation of financial indicators deterministic. However, these variables cannot be predicted with accuracy, indicating the importance of considering, in greater or lesser degree, the risk associated with expected financial return for the project.

The more sophisticated techniques for analyzing capital investment, according to [10], consider the time factor in the amount of money and involve the concepts of cash flow supposedly known throughout the lifetime of the project.

Techniques based on the cash flows are the most frequently utilized to describe the interaction between capital expenditures and the benefits received in each year with the implementation of a project. These benefits are obtained through the use of fuel in a more rational way. The method is to upgrade to the zero years of operation the benefits achieved during the life of the project at a discount rate, then these values are added and deducted from capital spending initially, and the resulting value is defined as Net Present Value (*NPV*). The *NPV* method explicitly demonstrates the real net profit that investors must receive over the lifetime of the project, being calculated by:

$$NPV = \sum_{k=1}^{N} \frac{BEN}{\left(1+j\right)^k} - I \quad (22)$$

The criterion when *NPV* is used to make decisions like "accept" or "reject" the project is the following: if the *NPV* is greater than or equal to zero, the project must be accepted because the company will obtain a return equal to or greater that the cost of capital invested and the project will retain or increase its equity; otherwise, if the *NPV* is less than zero, the project should be refused.

Probably the most used technical analysis to evaluate investment alternatives is the Internal Rate of Return (*IRR*), determined iteratively according to the expression ([10]):

$$\sum_{k=1}^{N} \frac{BEN}{\left(1+IRR\right)^k} - I = 0 \quad (23)$$

The internal rate of return of an investment is the rate *j* presented in Eq. (22) that returns the present value of net cash inflow associated with the project equal to the initial investment or, equivalently, the rate *j* that makes the *NPV* of the project equal to zero. This is a more objective criterion on which the decision to evaluate the project is based on the cost of capital. If the *IRR* is greater than or equal to the cost of capital or discount rate adopted, the project can be accepted; otherwise, the project should be rejected.

Numerical Solution

The solution of the equation system resulting from the thermodynamic analysis of each of the cases is obtained by employing the software IPSEpro® [11], whereas for the thermoeconomic and economic analyses was employed the software EES - Engineering Equation Solver [12].

Cases Studied

The first case studied is a conventional steam plant of a sugarcane mill (base Case), shown in Figure 2. This plant uses modern and efficient equipment, including a boiler that produces 160 t/h of steam at 6.86 MPa and 530 °C, being 125 t/h of steam consumed in an extraction-condensation steam turbine connected to a generator of 32 MW. There is an extraction of 97 t/h of steam at a pressure of 0.245 MPa for utilization in the evaporation process of sugarcane juice and the remaining steam continues to expand until 7 kPa and, then, it is condensed. The remaining steam (35 t/h) is directed to a backpressure turbine, which is coupled to a generator of 12 MW. The steam is discharged at a pressure of 0.245 MPa, also designed to meet the demand of steam for the industrial process. It is interesting to note that the industrial process currently consumes 130 t/h of steam (about 450 kg of steam per ton of sugarcane), at a temperature of 135 °C. As the steam exhaust temperature is close to 160 °C a desuperheater is required to reduce the steam temperature to 135 °C (close to the saturation temperature) by injecting a quantity of liquid water at 38 °C in the steam. From the energy point of view there is no loss, since reduced energy due to the temperature drop is compensated by increasing the flow of steam leaving the desuperheater.

Table 1 presents some data from harvest of the plant.

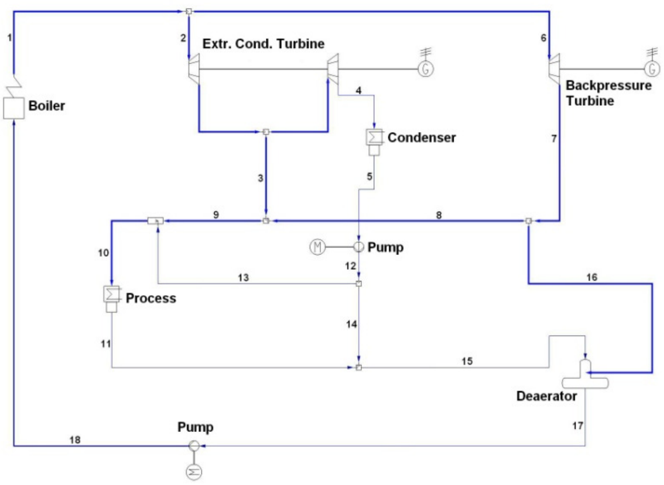

Figure 2 Conventional thermal power plant (Case 1).

Table 1 Plant harvest data for Case 1.

Parameter	Value	Units
Sugarcane milled at harvest	1,500,000	t
Sugarcane milled per hour	286.0	t/h
Flow of bagasse produced	81.0	t/h
Flow of bagasse in the boiler	75.2	t/h
Flow of surplus bagasse	6.3	t/h
Flow of steam in the boiler	160.0	t/h
Steam consumption in the process	130.0	t/h

Figure 3 shows in a compact form the steam power plants proposed for Cases 2, 3 and 4.

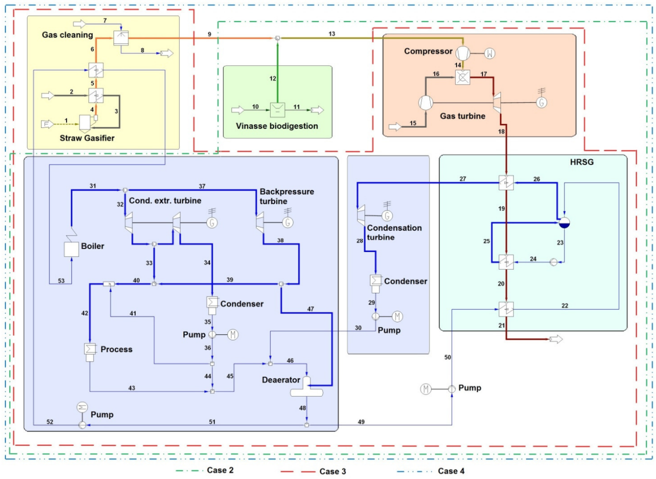

Figure 3 Modified thermal power plants (Cases 2, 3 and 4).

Case 2 presents the incorporation in the plant of Case 1 of a system for bio-digestion of stillage. In this plant, the biogas is utilized in a gas turbine to generate electricity, heat and exhaust gas, which is utilized in a recovery boiler, generating steam to drive a condensation steam turbine. Considering that the production of ethanol is about 14 m^3/h, and that for every m^3 of ethanol are produced 13 m^3 of stillage, the stillage flow that can be utilized in the bio-digester is about 180 m^3/h. So, the biogas produced is utilized for electric energy generation by using a gas turbine, being selected the Rolls Royce, model 501 KB7, with pressure ratio 13.5 and nominal capacity of 5.2 MW. The heat from this turbine exhaust is utilized in a recovery boiler, generating steam to drive a condensation steam turbine (steam turbine and condenser). The condensate of this turbine joins with the condensates of the sugar-ethanol production process and of the extraction-condensation steam turbine in the deaerator before be pumped to the boiler.

In Case 3 is studied a configuration in which is inserted in the plant of Case 1 a system for straw gasification. According to [4], considering a harvester operating without ventilation and taking into account the percentage of straw in the sugarcane and that it is necessary to leave some straw in the farming for the soil fertilization, for 286 t of sugarcane milled per hour it is reasonable the straw flow that can be utilized in the gasifier is about 30 t/h. The gasifier model considered is the circulating fluidized bed, working at atmospheric pressure. As the gas is produced at a temperature range of 700 °C it is necessary a cooling before being compressed. Thus, the gas passes through an air preheater and by a heat exchanger, which should preheat the boiler feed water. This process allows an increase of steam flow generated from 160 to 170 t/h, considering that the boiler does not show a reduction in its efficiency. Then the gas passes over a cooling system with a gas cleaning system before be compressed and utilized in the gas turbine from Hitachi, model PG6561B, with a pressure ratio equal 12.0 and nominal capacity of 39.6 MW. The remaining processes are the same as in the previous case

Case 4 considers a plant for gasification of straw and stillage. The processes of bio-digestion and gasification are the same as described in Cases 2 and 3, respectively, as well as the flow rates of straw and stillage. In this case is considered a gas mixture for use in a single gas turbine from Siemens model W251B11/12 with pressure ratio 15.3, and nominal capacity of 49.5 MW. The utilization of the exhaust gases and steam plant are similar to Cases 2 and 3, with the difference that in this case it is utilized a greater condensing turbine to the combined cycle, since the gas flow to the gas turbine is greater so that the flow of exhaust gases will be so.

RESULTS

Preliminary Considerations

In this work, it was considered that the lower heating value (*LHV*) of straw and bagasse are 13,151 kJ/kg and 7,736 kJ/kg, respectively ([13]). In the cases with digestion of stillage, calculations were made based on the *LHV* of the biogas, which was calculated by using the software IPSEpro® taking into account its composition, resulting 26,022 kJ/kg. The equipment costs for the systems of cogeneration, biodigestion and gasification were estimated according to [14], [2] and [15], respectively, and are presented in Table 2.

The annual cost of equipment with amortization was calculated taking into account a depreciation period of 20 years and a discount rate of 12 % per year. It was still considered a percentage of 9 % and 1 % for the annual cost related to fix and variable costs, respectively, for operation and maintenance, with a load factor of 0.75. For the economic analysis of the plant, it was considered a useful life of 20 years and the discount rate was maintained at 12 % per year.

Table 2 Estimated costs of the main equipment (Million R$).

Equipment	Case 1	Case 2	Case 3	Case 4
Boiler (Conventional)	28.00	28.00	28.00	28.00
Boiler (HRSG)	-	3.51	21.40	26.80
Steam Turbine (Extraction-Cond.)	17.00	17.00	17.00	17.00
Steam Turbine (Backpressure)	3.00	3.00	3.00	3.00
Steam Turbine (Condensation)	-	0.95	5.00	4.90
Gas Turbine	-	3.25	19.80	24.75
Gasifier	-	-	39.00	39.06
Biodigestor	-	3.30	-	3.30
Gas Compressor	-	1.20	6.70	6.70
Condenser	0.80	0.80	0.8	0.8
Condenser (Steam Turbine)	-	0.20	1.00	1.00
Pump (Condensate)	0.10	0.10	0.10	0.10
Pump (Boiler)	1.80	1.80	1.80	1.80
Pump (HRSG)	-	0.15	0.70	0.80
Desuperheater	0.15	0.15	0.15	0.15
Evaporator (Juice)	1.00	1.00	1.00	1.00
Mixer (Condensate)	0.20	0.20	0.20	0.20
Deaerator	2.00	2.00	2.00	2.00
Pump (Cond. Steam Turbine)	0.05	0.50	0.10	0.10
Gas Cooler	-	-	2.80	2.79
Gas Cleaner	-	-	5.60	5.58

Thermodynamics Results

Table 3 shows the power generated by equipment of the plant in kW for each case studied. Table 4 illustrates the power demanded by the thermal evaporation process of the juice and the thermal condensation and in Table 5 are presented the indexes of performance for the cases studied.

Table 3 Power generated/consumed in the plant, in kW.

Equipment	Case 1	Case 2	Case 3	Case 4
Compressors	0	- 373	- 10,180	- 11,563
Pumps	- 504	- 529	- 670	- 651
Gas Turbine	0	5,512	31,046	40,838
Steam Turbine (Ext.-Cond.)	27,147	25,930	26,262	26,274
Steam Turbine (Backpressure)	6,527	7,460	9,325	9,325
Steam Turbine (Condensation)	0	2,796	14,317	14,128
Power Consumed by the Plant	-10,000	-12,000	-17,000	-19,000
Total	**23,170**	**28,798**	**53,100**	**59,351**

Table 4 Thermal power lost in the plant, in kW.

Process	Case 1	Case 2	Case 3	Case 4
Juice Evaporation	79,791	79,791	79,791	79,791
Steam Condensation	16,372	21,740	50,452	50,067

Table 5 Plant performance indexes.

Performance index	Case 1	Case 2	Case 3	Case 4
$\eta_{overall}$ (%)	61.4	58.7	48.1	47.3
η_{biom} (%)	34.9	36.1	44.2	46.3
PHR	0.29	0.36	0.66	0.74
BSR (kg_{bag}/kg_{steam})	0.49	0.49	0.47	0.46
SCR (kg_{steam}/t_{cane})	454	454	454	454
PCR (kWh/t_{cane})	81	101	186	207

For a better understanding, in Figures 4 to 7 are presented graphically the results for global efficiency, efficiency of biomass utilization, power-heat ratio and power-cane ratio, respectively, for each case considered.

From the point of view of overall efficiency of the plant it is found that the integration of the gasification plant fosters a reduction in this plant efficiency, since this index considers only the relationship between the useful energy and energy actually delivered to the plant, disregarding other energy sources available in the plant that could be used. However, the advantages of gasification, from the thermodynamic viewpoint, can be noticed through the efficiency of the biomass utilization, since this index is higher than Case 1 for all other cases. This increase was expected since the gasification enables an increase in the generation of electricity in all cases, and also due to the fact that the efficiency of utilization of biomass is based on all the available biomass at the plant, which results in better use in cases with gasification.

It was also observed a significant increase in power-to-heat ratio (*PHR*) and electric-power ratio sugarcane (*PCR*) of the plant. This index could reach 207 kWh/t_{cane} with gasification of straw and stillage.

In all cases, the specific consumption (*SCR*) vapor was maintained constant at 454 kg_{steam}/t_{cane}, because there were no changes in the sugar and ethanol production processes.

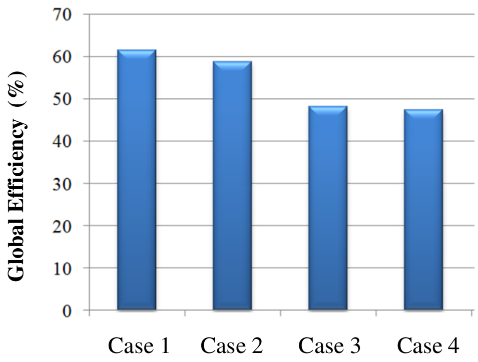

Figure 4 Global efficiency for each case considered.

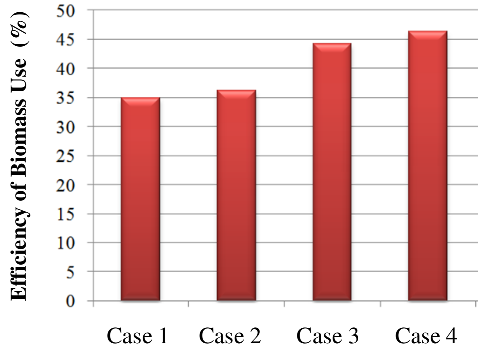

Figure 5 Efficiency of biomass use for each case considered.

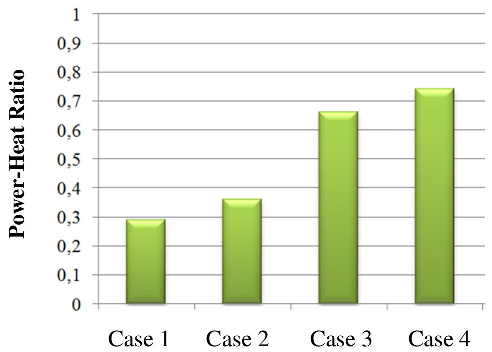

Figure 6 Power-Heat Ratio for each case considered.

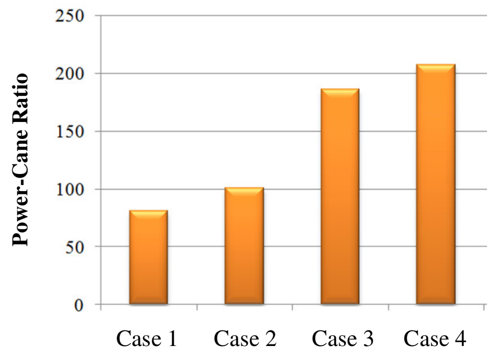

Figure 7 Power-Cane Ratio for each case considered.

Thermoeconomic and Economic Results

In order to perform a more thorough evaluation will be presented in the sequence a sensitivity analysis of the electricity generation average cost as a function of input costs.

Figures 8, 9 and 10 show the sensitivity graphs of the electricity generation average cost for Case 1, 2 and 3, respectively, due to the bagasse cost variation between R$ 0.00/t and R$ 20.00/t, and considering the costs of stillage between R$0.00/m^3 and R$10.00/m^3 (for Case 2) and of straw between R$10.00/t and R$40.00/t (for Case 3).

According to Figure 8, the electricity generation average cost for Case 1 shows to be quite sensitive to the bagasse cost, because a variation of R$ 20.00/t promotes a rise of R$ 47.00/MWh in the electricity. Observing Figures 9 and 10, it can be note that the electricity generation average cost is much more sensitive to the stillage than to the straw costs, because a variation of R$ 10.00/m^3 in the stillage results in a cost difference of R$ 39.00/MWh, while a variation of R$ 30.00/t in the straw results in a difference of only R$ 11.00/MWh.

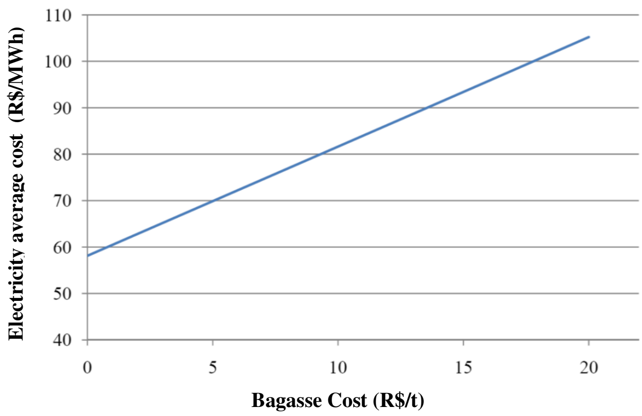

Figure 8 Electricity average cost as a function of bagasse cost (Case 1).

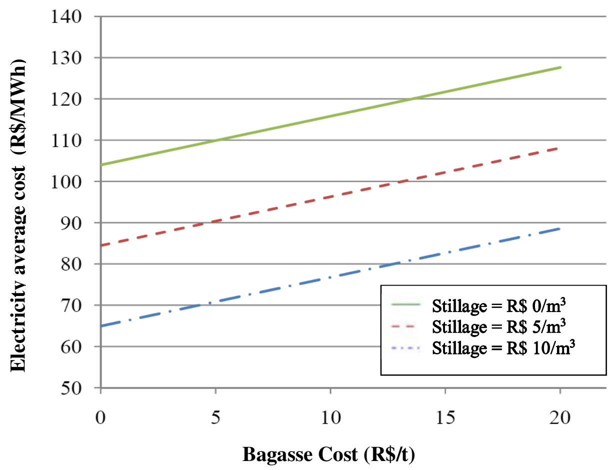

Figure 9 Electricity average cost as a function of bagasse and stillage costs (Case 2).

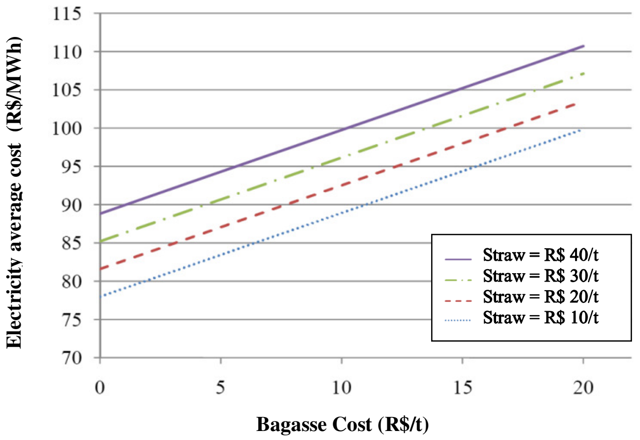

Figure 10 Electricity average cost as a function of bagasse and straw costs (Case 3).

In Figures 11, 12 and 13 are shown the sensitivity analysis of electricity generation average cost for Case 4, depending on the cost of bagasse and straw, and for stillage costs of R$ 0.00/m³, R$ 5.00/m³ and R$ 10.00/m^3, respectively.

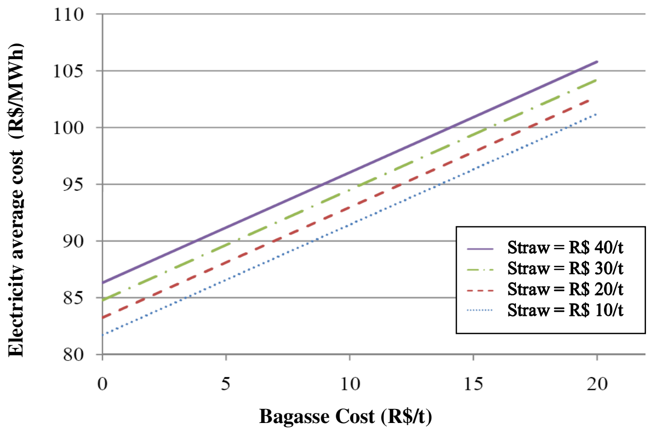

Figure 11 Electricity average cost as a function of bagasse and straw costs, for stillage cost of R$ 0.00/m³ (Case 4).

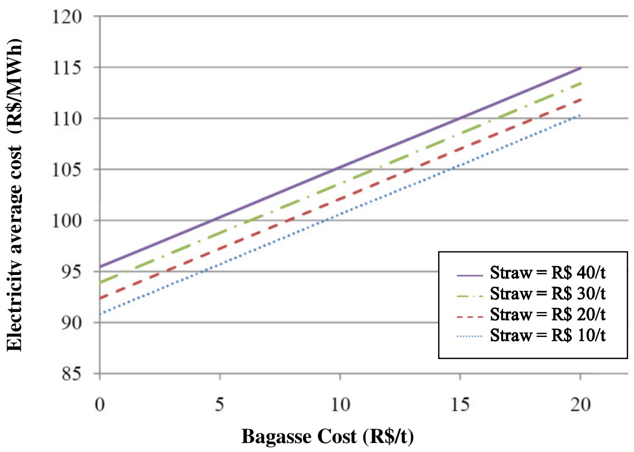

Figure 12 Electricity average cost as a function of bagasse and straw costs, for stillage cost of R$ 5.00/m³ (Case 4).

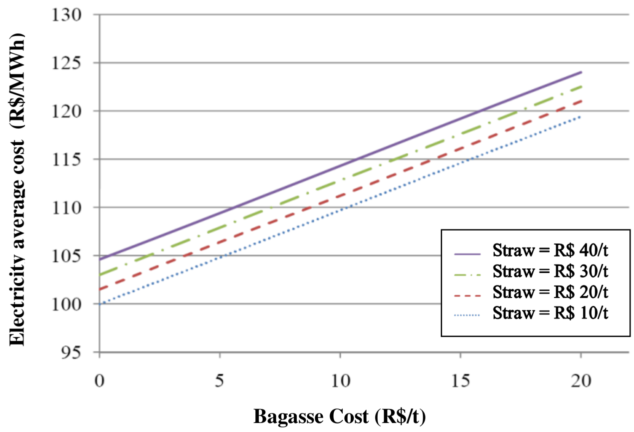

Figure 13 Electricity average cost as a function of bagasse and straw costs, for stillage cost of R$ 10.00/m³ (Case 4).

These figures show that, similarly to Cases 2 and 3, the average cost of electricity generation proved more sensitive to the cost of stillage than in relation to the cost of straw, since, for a change the cost of straw from R$ 10.00/t to R$ 40.00/t, the average cost of electricity generation increased only R$ 5.00/MWh, while for increased stillage cost from R$ 0.00/m³ to R$ 10.00/m³ increase was approximately R$ 18.00/MWh.

For each case considered, the analyzes were performed considering four values of selling electricity, with prices ranging from R$ 150.00/MWh up to R$ 180.00/MWh, thus allowing to evaluate the economic performance of the system for various of electricity sales contracts options.

Tables 6 to 9 show the results for the net present value (*NPV*), internal rate of return on investment (*IRR*) and the payback time of the investment, in years, for each one of the cases studied.

Figures 14 to 17 show the performance of the cash flow for each one case studied, for different values of sales of electricity, whereas a period of implementation of the system two years, during which time the disbursements occur. The intersection of the curves with the horizontal axis (when the cash flow becomes positive) represents the time for return on investment (*Payback*).

Observing Tables 7 to 10 and Figures 14 to 17, it can be noted that Case 1 is presented as the least risky from the point of view of economics, since this case is the shortest return on investment and the highest values for the *IRR*. The payback time would be 6.5 years for a sale price of electricity from R$ 180.00/MWh (value claimed by the industry), and the *NPV* for this situation would exceed R$ 43,000,000.00 after a period of twenty years.

Cases involving biomass gasification reached for smaller values than in Case 1 and time of return from higher investment *IRR*. In the case of digestion of stillage (Case 2), there would be no return on investment for the selling price of electricity of R$ 150.00/MWh (value close to current values), and the *IRR* in this situation would not reach 11%. In the best situation analyzed (electricity sale price equal to R$ 180.00/MWh), the cash flow accumulated at the end of twenty years would be lower than that obtained by Case 1.

When considering the integration of gasification of straw to the plant of conventional power plant (Cases 3 and 4) the results are even worse. For these cases, there would be no return on investment for values lower electricity sales of R$ 170.00/MWh and the maximum *IRR* obtained were 16.3 % for Case 3 and 15.2 % for Case 4.

Table 6 Economic results for Case 1.

Sale Price (R$/MWh)	*NPV* (Million R$)	*IRR* (%)	*Payback* (years)
150.00	9.44	14.7	13.0
160.00	20.65	17.8	9.5
170.00	31.87	20.8	7.5
180.00	43.08	23.7	6.5

Table 7 Economic results for Case 2.

Sale Price (R$/MWh)	*NPV* (Million R$)	*IRR* (%)	*Payback* (years)
150.00	-4.36	10.9	-
160.00	9.57	14.2	14.0
170.00	23.51	17.4	9.5
180.00	37.45	20.4	7.5

Table 8 Economic results for Case 3.

Sale Price (R$/MWh)	*NPV* (Million R$)	*IRR* (%)	*Payback* (years)
150.00	-33.551	8.4	-
160.00	-7.85	11.2	-
170.00	17.85	13.8	14.5
180.00	43.55	16.3	11.0

Table 9 Economic results for Case 4.

Sale Price (R$/MWh)	*NPV* (Million R$)	*IRR* (%)	*Payback* (years)
150.00	-51.47	6.8	-
160.00	-22.75	9.8	-
170.00	5.98	12.6	18.0
180.00	34.71	15.2	12.0

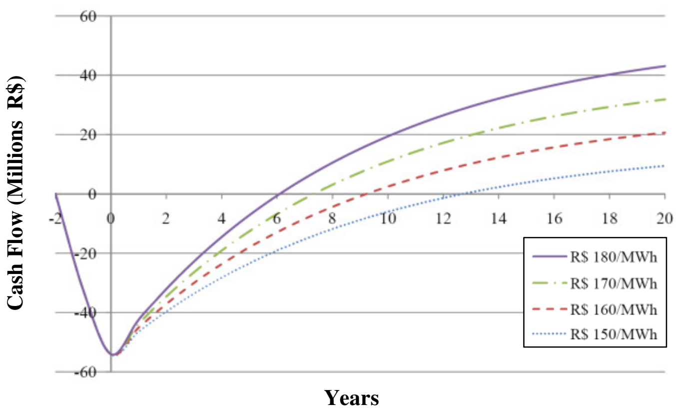

Figure 14 Cash flow during the plant life time (Case 1).

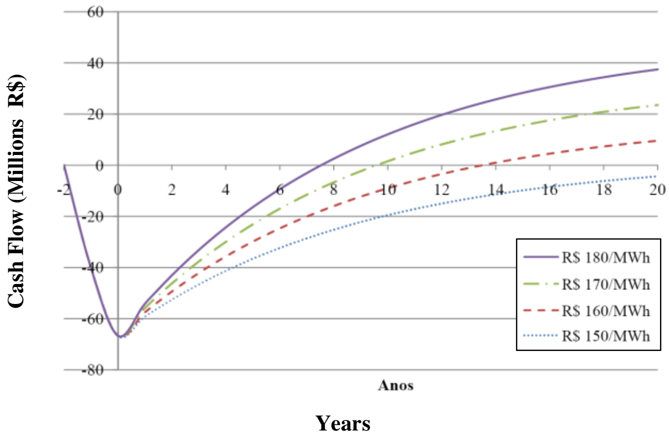

Figure 15 Cash flow during the plant life time (Case 2).

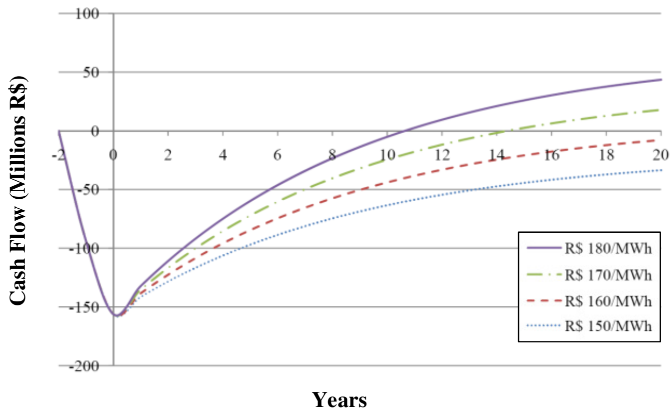

Figure 16 Cash flow during the plant life time (Case 3).

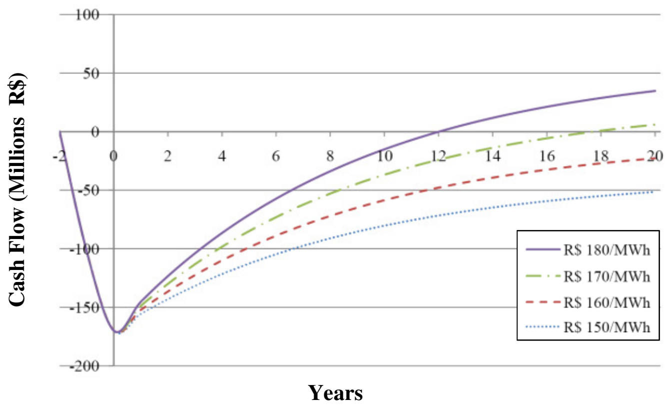

Figure 17 Cash flow during the plant life time (Case 4).

In Table 10 are presented the results of the thermoeconomic and economic analyses of the plants, including the initial investment for deployment of cogeneration systems, the average cost of generating electricity, the net present value (*NPV*), time of return on investment (*Payback*) and internal rate of return (*IRR*), for a desired sale price of electricity by the mill owners (R$ 180.00/MWh), and being considered the cost of R$ 15.00/t for bagasse, R$ 10.00/t for straw and R$ 5.00/m³ for stillage.

Table 10 Thermoeconomic and economic results obtained for a desired condition.

Parameter	Case 1	Case 2	Case 3	Case 4
Total Investment (Millions R$)	54.0	66.7	156.2	169.8
Electrical Energy Production (MW)	33.2	40.8	70.1	78.3
Electrical Energy Consumption (MW)	10.0	12.0*	17.0*	19.0*
Electrical Energy for Sale (MW)	23.2	28.8	53.1	59.3
Electricity Cost - Gas Turbine (R$/MWh)	-	284.9	93.9	100.1
Electricity Cost - Cond. Turbine (R$/MWh)	204.7	151.7	179.4	204.7
Electricity Cost - Ext.-Cond. Turbine (R$/MWh)	94.4	69.3	92.7	93.7
Electricity Cost - Back Pressure Turb. (R$/MWh)	89.2	60.7	81.8	82.8
Electricity Average Cost (R$/MWh)	93.4	105.3	102.3	108.8
Electrical Energy Cost / Power Installed (R$/MW)	1.63	1.63	2.23	2.17
Steam Production Cost (R$/t)	11.6	7.4	11.2	11.3
Payback (years)	6.5	7.5	11.0	12.0
NPV - Net Present Value (Million R$)	43.1	37.5	43.6	34.7
IRR - Internal Rate of Return (%)	23.7	20.4	16.3	15.2

* Value estimated according to some sugar cane mills data.

According to Table 10, it is verified that with the stillage digestion (Case 2) there is an increase of 25 % in the amount of electricity produced; with the straw gasification (Case 3) it is possible to double the amount of electricity produced; and with combination of straw gasification and stillage biodigestion (Case 4) it is allowed increase the generation of electricity in 155 %, in all cases if compared to the conventional steam power plant (Case 1).

The thermoeconomic results show that the Case 1 presents a better attractiveness, since this case presents the shorter return on investment and the highest values for *IRR*. The time for return on investment would be 6.5 years and the *NPV* for this situation would be approximately 43.1 million reais after a period of 20 years.

The cases which consider the biomass gasification and or biodigestion (Cases 2 to 4) have worse economic performance since the time of return of investment is higher than for Case 1. The initial investment in the plant of Case 4 is three times higher than in Case 1 and *NPV* of Case 4 at the end of 20 years is lower than that accumulated in the Case 1. In addition, Case 4 has the lowest value for the *IRR* among all the cases analysed.

CONCLUSIONS

In this work it was considerate the integration of straw gasification and stillage biodigestion in a conventional sugarcane mill, by means utilization of a combined cycle.

From the thermodynamic point of view, the incorporation of the straw gasification was the best technology experimented because it allows an increase of 105 kWh/t_{cane} in electricity generation. In relation to the biodigestion of stillage, there is also a gain in generation, although in lower scale (20 kWh/t_{cane}). In economic terms, Case 1 presents a better economic attractiveness, since it has the lowest payback time and the highest values for the Internal Rate of Return. However, for Cases 2, the investment return would be obtained before even half the life of plants.

It is important to remember that the BIG-GTCC technology used in the work applied to gasification of the straw is still far from becoming a commercial technology and its maturity cannot be expected in the coming years. But its development has been steadily increasing, so that, in the long term, this technology associated with a better remuneration for the electricity sale could become an interesting alternative to the sugarcane sector, contributing to avoid a possible crisis in the supply of electricity in the future.

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REFERENCES

[1] Website UNICA: http://www.unica.com.br.

[2] Salomon, K.R., Avaliação técnico-econômica e ambiental da utilização do biogás proveniente da biodigestão da vinhaça em tecnologias para geração de eletricidade, Tese de Doutorado, UNIFEI, Itajubá, 2007, 219 p.

[3] Seabra, J.E.A., Avaliações técnico-econômica para o aproveitamento integral da biomassa de cana no Brasil, Tese de Doutorado, Universidade Estadual de Campinas, 2008, Campinas.

[4] Romão Júnior, R.A., Análise da viabilidade do aproveitamento da palha da cana de açúcar para cogeração de energia numa usina sucroalcooleira, Dissertação de Mestrado, UNESP, Ilha Solteira, 2009, 164 p.

[5] Pellegrini, L.F., Oliveira Junior, S., Burbano, J.C., Supercritical steam cycles and biomass integrated gasification combined cycles for sugarcane mills, *Energy*, Vol. 35, 2010, pp. 1172-1180.

[6] Van Wylen, G.J.; Borgnakke; C.; Sonntag; R.E., Fundamentals of Thermodynamics, 6th edition, John Wiley & Sons, 794 p., 2003.

[7] Szargut, J.; Morris, D.R.; Steward, F.R., *Exergy analysis of thermal, chemical and metallurgical process*, New York: Hemisphere Publishing Corporation, 332 p., 1988.

[8] Bejan, A., Tsatsaronis, G., Moran, M., Thermal Design & Optmization, John Wiley & Sons, N.Y., 1996, 542 p.

[9] Sánchez Prieto, M.G.S., Alternativas de cogeração na indústria sucro-alcooleira, estudo de caso, Tese de Doutorado, Universidade Estadual de Campinas, 2003, Campinas.

[10] Gitman, L.J., Principles of Managerial Finance, 13rd edition, Prentice Hall, 944 p., 2013.

[11] SIMTECH IPSEPRO, Process Simulation Environment (PSE). Simtech, Austria, 2003.

[12] Klein, S.A.; Alvarado, F.L., EES - Engineering Equation Solver. Middleton: F-Chart Software, 1995.

[13] Hassuani, S.J., Leal, M.R.L.V., Macedo, I.C., Biomass power generation: Sugar cane bagasse and trash, PNUD-CTC, Piracicaba, 2005, 217 p.

[14] Garagatti Arriola, D.W., Sistema tri e tetra combinado de cogeração: avaliação exergética e termoeconômica, Dissertação de Mestrado, Universidade de São Paulo, São Paulo, 2000, 206 p.

[15] Larson, E.D., Williams, R.H., Leal, M.R.L.V., A review of biomass integrated-gasifier/gas turbine combined cycle technology and its application in sugarcane industries, with an analysis for Cuba, *Energy for Sustainable Development*, Vol. 5, n. 1, 2001, pp. 54-76.