THERMODYNAMIC, THERMOECONOMIC AND ECONOMIC EVALUATION OF THE BIOMASS GASIFICATION IN THE COGENERATION SYSTEM OF A SUGAR-ALCOHOL FACTORY

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Abstract. *This work presents thermodynamic, thermoeconomic and economic analyses of biomass gasification systems integration in a sugar-ethanol factory. Five configurations, combining the actual cogeneration plant with straw and vinasse 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 vinasse 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 vinasse. Finally, Case 5 considers the gasification of straw and vinasse in a idealized plant with doubling cane crushing capacity and reduction of the process steam consumption with respect to Case 4. Thermodynamic analysis takes into account the application of mass balance and of the first and second thermodynamic´s laws for each element of the plant. Thermoeconomic analysis is based on exergy cost theory, which involves the balance of costs for each component of the system. For the economic analysis is adopted a technique that considers the influence of time on the investment value and involves the concepts of cash flow, being considered the Net Present Value (NPV) and Internal Rate of Return (IRR) to assess the financial performance of the projects. The results show that plants with gasification promote a substantial increase in electricity generation and in the efficiency of the plant. However, from the thermoeconomic and economic viewpoints, the plants that consider gasification present a higher cost of the electricity and a longer payback period.*

Keywords*: Gasification; cogeneration; straw; vinasse; economic analysis.*

1. INTRODUCTION

According to 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 areas with steepness smaller than 12 % and completely abolished in all areas by 2017.

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 biogas.

There is also a great potential for utilization of vinasse, which is a byproduct of the alcohol production process, through the process of bio-digestion. The vinasse is generated in large quantities and currently it is only used as fertilizer. The biodigestion process of the organic load of vinasse generates biogas, which can be used for power generation, and the vinasse digested retains its fertilizer power yet.

The literature contains several studies related to the subject, some of which will be outlined in the sequence.

Salomon (2007) conducted an economic and environmental evaluation of technologies for energy recovery from vinasse 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 vinasse, showing that an internal combustion engine presents themselves as the best option for electricity generation from biogas.

Seabra (2008) 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/tc, 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 (> US$ 75.00/MWh).

Romão Júnior (2009) examined the possibility of utilization of straw as a supplementary fuel in sugar-alcohol factories. It was found that the use of straw as a supplementary fuel to bagasse in conventional high pressure boilers is a good option to increase the power generation to be exported, greatly increasing the final revenue.

Pellegrini and Oliveira Jr. Burbano (2010) presented thermodynamic and thermoeconomic comparative studies of new technologies applied in sugar-alcohol 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/tc, whereas with pressurized gasification could reach up to 202 kWh/tc 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.

The objectives of this work are performing thermodynamic, thermoeconomic and economic analyses of straw, bagasse and vinasse gasification in a sugarcane mill. For this, five case studies are defined. The first case considers a steam plant of a modern conventional power plant (base case). The second case considers the anaerobic digestion of vinasse, the third case considers the straw gasification in a combined cycle, the fourth case considers the gasification of straw and vinasse, and the fifth case is the concept of a new plant with the double of the crushing mill and reduction of process steam consumption, over there gasification of straw and vinasse biodigestion.

2. METHODOLOGY

2.1. Thermodynamic Analysis

The problem solution involves the basic principles of thermodynamics: the mass conservation, the first law of thermodynamics (energy conservation) and the second law of thermodynamics.

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 Eqs. (1) to (3):

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

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

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

where:

$\dot{m}$: Mass flow rate crossing the control volumes (kg/s);
$\sum \dot{m}\, h$: Enthalpy flow rate crossing the control volumes (kW);
$\dot{Q}_{c.v.}$: Heat transfer rate to the control volumes (kW);
$\dot{W}_{c.v.}$: Power produced in the control volumes (kW);
$\dot{S}_{gen,c.v.}$: Irreversible entropy rate generated in the control volumes (kW/K);
$\sum \left(\dot{Q}_{c.v} / T \right)$: Entropy flow rate associated to $\dot{Q}_{c.v.}$ (kW/K);
$\sum \dot{m}\, s$: Entropy flow rate crossing the control volumes (kW/K).

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.

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 usual.

According to Szargut *et al.* (1988), Kotas (1985) and others, total specific exergy is composed by physical and chemical exergies. 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:

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

For an ideal solution of pure substances, the chemical exergy is given by (Bejan *et al.*, 1996):

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

where:

x_i : Molar fraction of the component in the mixture;

$\overline{ex}_{ch;k}$: Chemical standard molar exergy of the component in the mixture (kJ/kmol).

The specific chemical exergy of the bagasse and straw are evaluated with the help of the expression presented by Szargut *et al.* (1988) 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:

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

being:

$$\beta = \left\{1.0412 + 0.2160\left(Z_{H_2}/Z_C\right) - 0.2499\left(Z_{O_2}/Z_C\right)\left[1 + 0.7884\left(Z_{H_2}/Z_C\right)\right] - 0.0450\left(Z_{N_2}/Z_C\right)\right\} \Big/ \left[1 - 0.3035\left(Z_{O_2}/Z_C\right)\right] \tag{8}$$

where:

β : Function of the mass fraction of biomass chemical components (%);

Z_i: Fraction in mass of the chemical components (%);

Z_{water}: Fraction in mass of the water in the biomass (%);

L_{water}: Water vaporization enthalpy (2,442 kJ/kg);

ex_{water}: Chemical exergy of water liquid (50 kJ/kg).

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 (Sánchez Prieto, 2003).

The overall efficiency of the plant ($\eta_{overall}$) is the ratio of useful energy, either thermal ($\dot{Q}_{usefull}$) or electrical power available to exportation ($\dot{W}_{electr} - \dot{W}_{compr} - \dot{W}_{pump} - \dot{W}_{consumption}$), and the power supplied to the system by the fuel ($\dot{m}_{fuel}\,LHV_{fuel}$) that is being utilized in the plant (bagasse, straw and/or vinasse or association between them), according to:

$$\eta_{overall} = \frac{\dot{W}_{electr} + \dot{Q}_{usefull} - \dot{W}_{compr} - \dot{W}_{pump} - \dot{W}_{consumption}}{\dot{m}_{fuel}\,LHV_{fuel}} \tag{9}$$

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 use, regardless of whether or not it is being used in the plant (straw, bagasse, and biogas of vinasse), being defined by:

$$\eta_{utiliz,biom} = \frac{\dot{W}_{electr} + \dot{Q}_{usefull} - \dot{W}_{compr} - \dot{W}_{pump} - \dot{W}_{consumption}}{\dot{m}_{bagasse}\,LHV_{bagasse} + \dot{m}_{straw}\,LHV_{straw} + \dot{m}_{biogas}\,LHV_{biogas}} \tag{10}$$

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

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

With respect to the thermal demand for the sugar-alcohol production, the relation vapor-sugarcane ($R_{steam,cane}$) represents the heat that is being used in the process, expressed by kilograms of steam per ton of sugarcane. It is recommendable to reduce this number, so that the plant is able to process the cane with the lowest possible steam demands. Equation (12) illustrates the calculation of this relationship for a certain amount of cane milled.

$$R_{steam,cane} = \frac{\dot{m}_{steam}}{\dot{m}_{cane}} 1000 \tag{12}$$

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

$$R_{power,cane} = \frac{\dot{W}_{export}}{\dot{m}_{cane}} \tag{13}$$

2.2. 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 (US$/s) associated with the exergy input ($\dot{C}_i$) and exit ($\dot{C}_o$), and the rates associated with power ($\dot{C}_w$) and heat transfer ($\dot{C}_q$), beyond the rate of cost of equipment ($\dot{C}_e$), considering the equipment cost (C_e) and factors related to amortization (f_a), fixed expenses (f_{fom}) and variable (f_{vom}) with operation and maintenance, according to the load factor (*LF*) and the number of hours of operation (T_{oper}). These cost rates are related by (Bejan *et al.*, 1996):

$$\sum\left(\dot{C}_i\right)_k + \left(\dot{C}_w\right)_k = \left(\dot{C}_q\right)_k + \sum\left(\dot{C}_o\right)_k + \left(\dot{C}_e\right)_k \tag{14}$$

being:

$$\dot{C}_i = c_i \dot{E}x_i = c_i \left(\dot{m}_i ex_i\right) \tag{15}$$

$$\dot{C}_o = c_o \dot{E}x_o = c_o \left(\dot{m}_o ex_o\right) \tag{16}$$

$$\dot{C}_w = c_w \dot{W} \tag{17}$$

$$\dot{C}_q = c_q \dot{Q} \tag{18}$$

$$\dot{C}_e = \frac{\left[C_e \left(f_a + f_{fom} + LF\ f_{vom}\right)\right]}{t_{oper}\ 3600} \tag{19}$$

where:

c: Average cost per unit of exergy (US$/kJ);

C: Monetary cost (US$);

$\dot{C}$: Cost rate of exergy (US$/s);

$\dot{E}x$: Exergy rate (kJ/s);

$\dot{Q}$: Heat rate (kJ/s);

$\dot{W}$: Power (kJ/s).

The depreciation factor (f_a) can be calculated using the annual percentage rate of interest (j) and number of years of useful life of equipment (N), according to the following equation (Bejan *et al.*, 1996):

$$f_a = \frac{\left[j(1+j)^N \right]}{\left[(1+j)^N - 1 \right]} \tag{20}$$

2.3. 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 Gitman (2004), 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:

$$NPV = \sum_{k=1}^{N} \frac{BEN}{(1+j)^k} - I \tag{21}$$

where:

BEN: Annual benefit obtained (US$);
j: Discount rate adopted;
N: Number of years analyzed;
I: Total invested capital at the start of project operation (US$).

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.

Gitman (1984) says that probably the most used technical analysis to evaluate investment alternatives is the Internal Rate of Return (*IRR*), determined iteratively according to the expression:

$$\sum_{k=1}^{N} \frac{BEN}{(1+j^*)^k} - I = 0 \tag{22}$$

where:
j^*: Internal rate of return on investment (*IRR*).

The internal rate of return of an investment is the rate j^* 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.

2.4. Cases Studied

The first case studied is a conventional steam plant of a sugarcane mill (base Case), shown in Fig. 1. 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 rest of 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. The Tab. 1 presents some data from harvest of the plant.

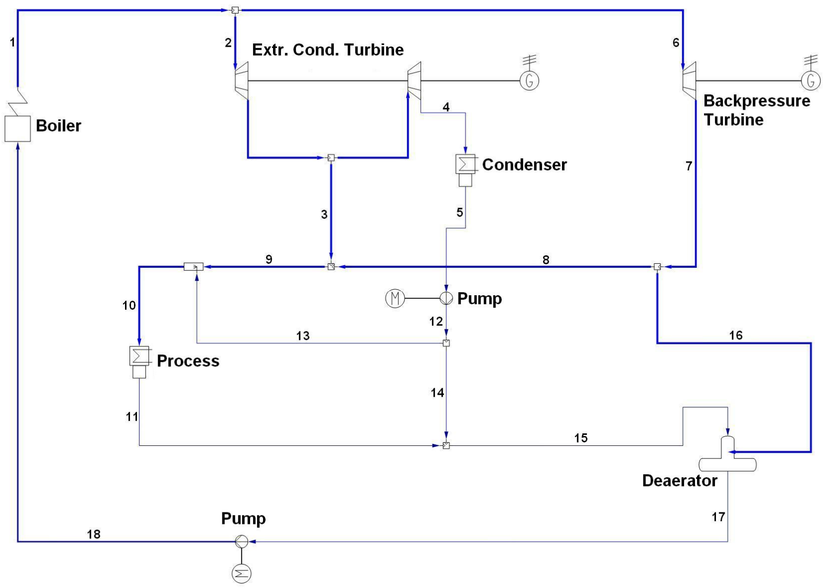

Figure 1. Conventional steam power plant (Case 1).

Table 1. Data harvest of the plant of 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 straw for the industry	30.0	t/h
Flow of vinasse produced	180.0	m^3/h
Flow of steam in the boiler	160.0	t/h
Steam consumption in the process	130.0	t/h

Figure 2 shows the steam power plants of Cases 2, 3 and 4. Case 2 presents the incorporation of a system for biodigestion of vinasse. 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.

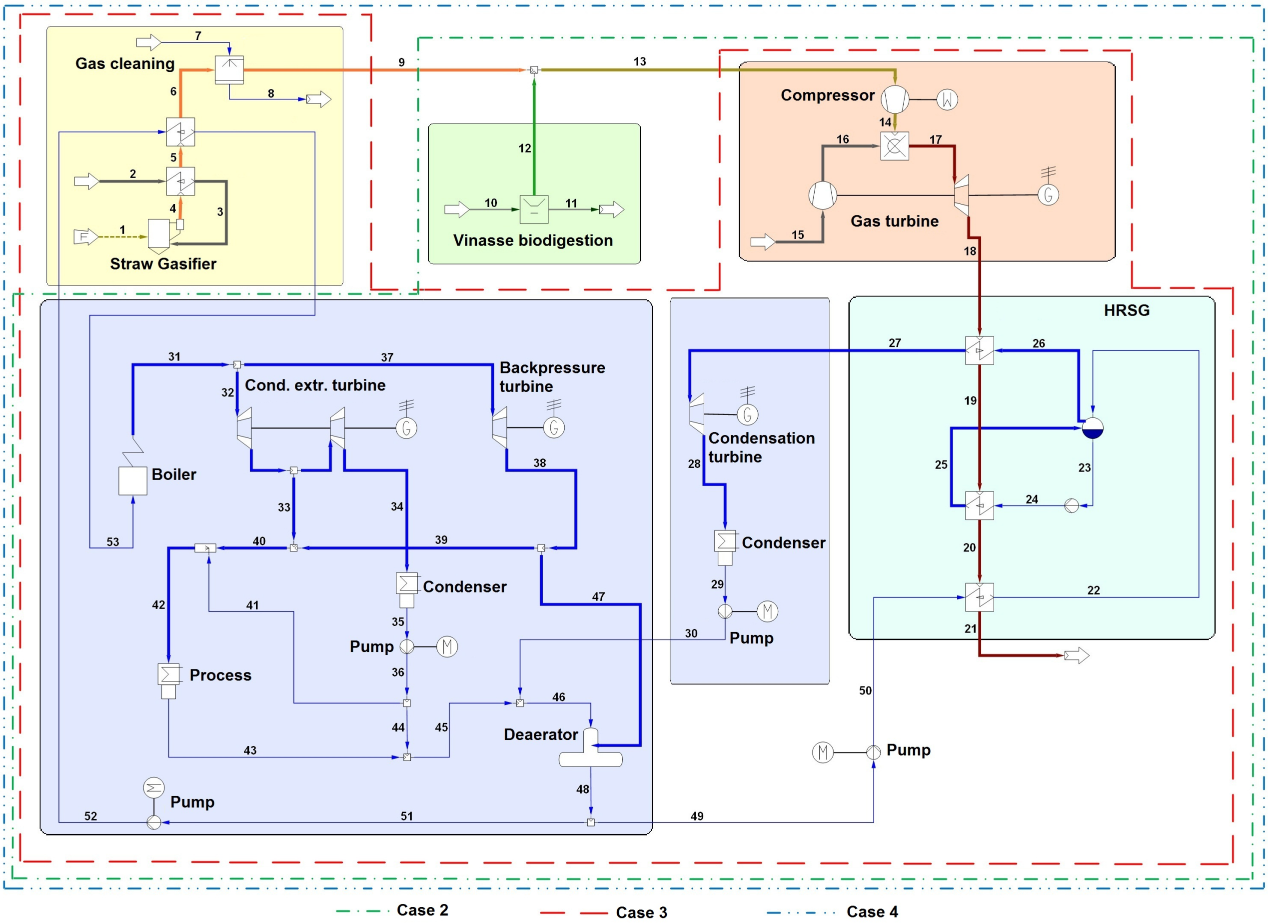

Figure 2. Modified steam power plants (Cases 2, 3 and 4).

In Case 3 is studied a hypothetical configuration in which is inserted a system for straw gasification. This system consists of a straw gasifier (atmospheric circulating fluidized bed type), a gas turbine coupled to an electric generator, a heat recovery steam generator and a steam system, comprising a condensation turbine, a condenser and pump power of the recovery boiler, and steam plant at the mill.

Case 4 considers a plant for gasification of straw and vinasse. The biogases from the straw and vinasse are compressed and mixed for use in a single gas turbine. This system is also composed of a recovery boiler that generates steam to a condensation steam turbine and to the steam plant.

Case 5, shown in Figure 3, was designed for an idealized plant gasification of straw and vinasse in a plant with twice the capacity of milling and high pressure steam produced by the boiler. The steam generated by the boiler is used only in an extraction-condensation turbine of high efficiency, and is also considered a reduction of steam consumption of the process (at least 10 %) to reach the levels of consumption required for new projects of sugar-alcohol mills and allow a greater production of electricity. Table 2 shows the operating parameters of Case 5.

Table 2. Data harvest of the plant of Case 5.

Parameter	**Value**	**Units**
Sugarcane milled at harvest	3,000,000	t
Sugarcane milled per hour	572.3	t/h
Flow of bagasse produced	163.0	t/h
Flow of bagasse in the boiler	150.0	t/h
Flow of surplus bagasse	13.0	t/h
Flow of straw for the industry	60.0	t/h
Flow of vinasse produced	360.0	m^3/h
Flow of steam in the boiler	340.0	t/h
Steam consumption in the process	231.0	t/h

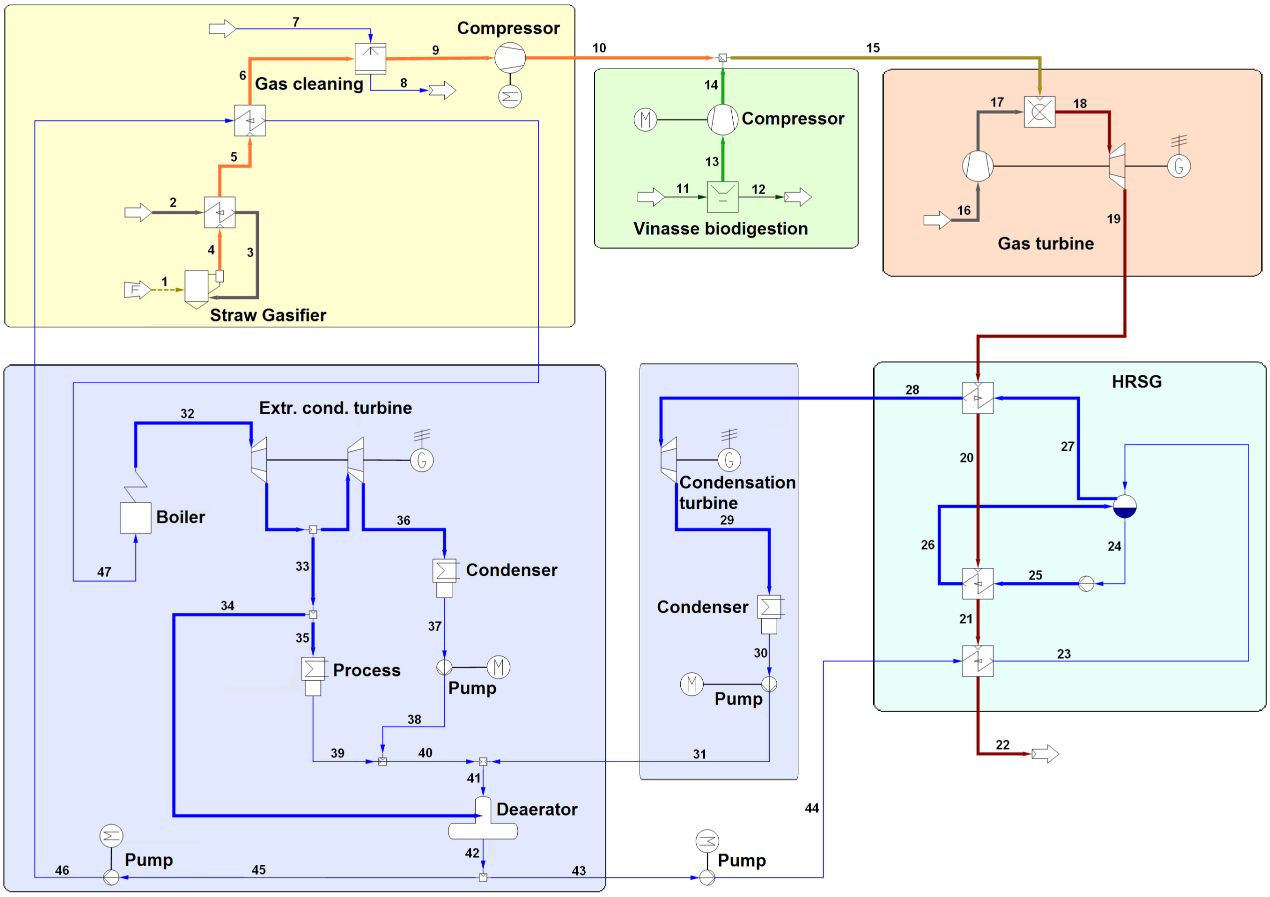

Figure 3. Proposed steam power plant with straw and vinasse gasification (Case 5).

3. RESULTS

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 (Hassuani, 2005). In the cases with digestion of vinasse, calculations were made based on the *LHV* of the biogas, which is 26,022 kJ/kg. The solution of the equations system that results from the thermodynamic analysis is achieved through the use of the software IPSEpro (SimTech, 2003).

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 Tab. 5 are presented the indexes of performance for the cases studied.

Table 3. Power generated/consumed by equipment of the plant, in kW, for each case studied.

Equipment	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Compressors	0	- 373	- 10,180	- 11,563	-20,931
Pumps	- 504	- 529	- 670	- 651	-1,870
Gas Turbine	0	5,512	31,046	40,838	72,350
Steam Turbine (Extraction-Condensation)	27,147	25,930	26,262	26,274	75,800
Steam Turbine (Backpressure)	6,527	7,460	9,325	9,325	0
Steam Turbine (Condensation)	0	2,796	14,317	14,128	39,682
Power Consumed by the Plant	- 10,000	- 12,000	- 17,000	- 19,000	-35,000
Total	**23,170**	**28,798**	**53,100**	**59,351**	**130,571**

Table 4. Thermal power, in kW, for each case studied.

Local	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Evaporation of the Sugarcane Juice (Process)	79,791	79,791	79,791	79,791	142,042
Condenser	16,372	21,740	50,452	50,067	124,562

Table 5. Indexes of performance, for each case studied.

Performance index	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
$\eta_{overall}$ (%)	61.4	58.7	48.1	47.3	47.1
$\eta_{utiliz,biom}$ (%)	34.9	36.1	44.2	46.3	47.1
PHR	0.290	0.359	0.662	0.740	0.915
$R_{steam,cane}$ (kg_{steam}/t_{cane})	454	454	454	454	403
$R_{power,cane}$ (kWh/t_{cane})	81	101	186	207	227

Table 3 shows that the vinasse digestion, in turn, allows an increase of 25 % in the amount of electricity produced in the plant. In addition, with the straw gasification it is possible to double the amount of electricity produced in the plant. Case 4, with the combined gasification of straw and vinasse, allow increasing the generation of electricity in 155 % in relation to the conventional steam power plant (Case 1).

According to Tab. 5, from the point of view of the overall efficiency of the plant, the gasification of straw and vinasse show less efficient than in Case 1, since the amount of additional fuel is used only for purposes of electricity generation, not being utilized for heating process. 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.

The annual cost of equipment with amortization was calculated taking into account a depreciation period of 20 years and an interest rate of 12 % per year. It was still considered a percentage of 9 % and 1 % for the annual cost related to fixed and variable costs, respectively, for operation and maintenance, with a load factor of 0.75. It was considered the cost of US$ 8.30/t for bagasse, US$ 18.00/t for straw and US$ 2.80/m³ for vinasse. For the economic analysis of the plant, it was considered a useful life of 20 years and the interest rate was maintained at 12 % per year.

The equipment costs of cogeneration systems were estimated from information available in the literature (Gas Turbine World Handbook, 2001-2002 and Garagatti Arriola, 2000), and are presented in Tab. 6. The costs of the vinasse digestion systems were estimated according to Salomon (2007), and the costs of equipment of BIG-GTCC systems were estimated according to Larson, Williams and Leal (2001).

In Tab. 6 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 sale price of electricity of US$ 100.00/MWh, that is close to the price currently practiced and represents a medium price in a more complete analysis conducted by Passolongo (2011) where was considered a variation between 85 to 115 US$/MWh.

Table 6. Thermoeconomic and economic results, for each case studied.

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Total Investment (Millions US$)	30.03	37.03	86.75	94.35	186.78
Cost of the Generated Electricity (US$/MWh)	51.88	58.50	56.83	60.44	57.89
Payback (years)	6.5	7.5	11.0	12.0	9.0
Net Present Value (Millions US$)	23.93	20.80	24.20	19.28	78.26
Internal Rate of Return (%)	23.7	20.4	16.3	15.2	18.3

According to Table 6, Case 1 presents a better attractiveness, since this case presents the shorter return on investment and the highest values for the Internal Rate of Return (*IRR*). The time for return on investment would be 6.5 years and the Net Present Value (*NPV*) for this situation would be approximately 24 million dollars after a period of 20 years.

The cases which consider the gasification of biomass had worse economic performance when compared to Case 1, since the time of return of investment was higher in all of them. The initial investment in the plant of Case 4 is three times higher than in Case 1 and Net Present Value of Case 4 at the end of 20 years is lower than that accumulated in the first case. In addition, Case 4 has the lowest value for the Internal Rate of Return (*IRR*) among the cases analyzed.

Furthermore, note that the Case 5, in which is considered an idealized plant with a modern and efficient equipment and with biomass gasification, would allow an *IRR* of 18.3% with an *NPV* of 140 million dollars after 20 years and return on investment happen before the middle of the useful life of the plant, according to the one shown in Tab. 6, which could make the project more interesting.

4. CONCLUSIONS

In this work it was considerate the integration of straw and vinasse gasification in a conventional sugarcane mill and in the design of a modern plant with biomass gasification in 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/tc in electricity generation. In relation to the digestion of vinasse, there is also a gain in generation, although in lower scale (20 kWh/tc). 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 and 5, 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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