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THE USE OF STRAW AS SUPPLEMENTARY FUEL FOR COGENERATION IN SUGARCANE MILLS

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Abstract. *This paper analyzes, from the thermodynamic, thermoeconomic and economic points of view, the integration of straw gasification in sugarcane mills, keeping the bagasse burning in the boiler to generate steam for the plant, being considered two cases. The first case considers the current steam power plant that uses modern and efficient equipment, including a boiler that produces steam at high temperature and pressure levels, that is used to generate electricity in a multistage extraction-condensation steam turbine and a backpressure turbine, being all drives of mills electrified. The second case involves the integration of straw gasification in the the current steam power plant. The results show that the gasification plant promotes a substantial increase in electricity generation and in the plant efficiency. However, from thermoeconomic and economic points of view, the plant that integrates gasification has a higher cost of electricity generation, making the project unfeasible for current values of electricity sales.*

Keywords: *Cogeneration, gasification, straw, sugarcane mills.*

1. INTRODUCTION

The straw burning has been a common practice in sugar cane mills to facilitate harvesting. However, the UNICA, representing the industry of the producing sugar, ethanol and bioelectricity, and the government of Sao Paulo state, signed on June 4th, 2007, the Environmental Protocol of the Sao Paulo Sugarcane Industry. This voluntary membership protocol established a series of policy principles and environmental techniques to be observed by the industries of sugar cane, until the straw burning be eliminated in 2017.

One possible use of straw for energy would be by recovering and utilization it in a gasification process, that is a technology for thermochemical conversion of a solid fuel in a fuel gas by partial oxidation of the biomass at high temperatures. Although the gas obtained presents a low calorific value, it is generated in large quantities allowing its use for energy purposes.

Several studies related to this subject are found in the literature. Corrêa Neto (2001) evaluated the technical and economic feasibility of projects for power generation using bagasse, straw and tips from sugar cane as fuel. The combined cycle technology integrated to cogeneration systems with the biomass gasification to produce combustible gas, with or without addition of natural gas, was considered. The economic analysis was performed through the modeling and construction of curves of economy of the project, based on prices of electricity, natural gas and biomass. Romão Júnior (2009) examined the possibility of using the straw as additional fuel for high pressure conventional boilers, thus allowing an increase of power generation for commercialization. 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 power generation, being financially beneficial to the company, greatly increasing the global efficiency of the plant, besides generating clean and renewable energy.

In this context, this paper has as objective analyze, under the point of view thermodynamic, thermoeconomic and economic, the gasification of sugar cane straw in sugarcane mills, considering the use of biomass gas in combined cycle.

2. METHOLOGY

The gasification of solid biomass can be defined as a chemical process for converting solid (fossil or biomass) in fuel gas with low calorific value by partial oxidation at high temperature. The mixture of hot gases that leaves the gasifier is called poor gas due to its low heat value (around 4.5 to 6.0 MJ/Nm^3), corresponding to approximately 10 % of the natural gas low heat value, although in most recent designs reaching a value of about 30%.

In the sugarcane sector, the main cogeneration system is one that employs steam turbines as thermal machines and appears linked to three basic configurations: backpressure turbines, backpressure turbines combined with condensation turbines, and extraction-condensation turbines. The condensation of a portion of the exhaust steam, or an extraction of steam from an extraction-condensation turbine, ensures the thermal energy requirements of the system. The technology of generating electricity from biomass gasification, which includes fuel and gas turbine combined cycle, is known as BIG-GTCC (Biomass Integrated Gasification – Combined Cycle Gas Turbine) being the same considered in this work.

2.1 Thermodynamic Analysis

Considering that the process occurs in steady state, ignoring all kinetic and potential energies, the conservation of mass and the laws of thermodynamics for a control volume are represented by Eq. (1) to (3):

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{1}$$

$$\dot{Q}_{c.v.} - \dot{W}_{c.v.} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \tag{2}$$

$$\dot{S}_{gen,c.v.} + \sum \left(\frac{\dot{Q}_{c.v.,j}}{T_j} \right) + \sum \dot{m}_{in} s_{in} - \sum \dot{m}_{out} s_{out} = 0 \tag{3}$$

where:

$\dot{m}$:	Mass flows in the control volume (kg/s);
h :	Specific enthalpy in the control volume (kJ/kg);
s :	Specific entropy in the control volume (kJ/kgK);
$\dot{Q}_{c.v.}$:	Heat transfer rate to the control volume (kW);
$\dot{W}_{c.v.}$:	Power relating to the control volume (kW);
$\dot{S}_{gen,c.v.}$:	Entropy rate generated in the control volume (kW/K);

The combination of the first and second laws of thermodynamic allows establishing the exergy balance as well as the irreversibility in the process. For a steady state process, the irreversibility generated is given by Eq. (4):

$$\dot{I}_{c.v.} = \sum \dot{Q}_j \left(1 - \frac{T_0}{T_j}\right) - \dot{W}_{c.v.} + \sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{out} ex_{out} \tag{4}$$

where:

ex :	Specific exergy in the control volume (kJ/kg);
T_j :	Superficial temperature of control volume (K);
T_0 :	Reference temperature (K);
$\dot{I}_{c.v.}$:	Irreversibility rate in the control volume (kW).

According to Szargut and Steward (1988), the total specific exergy is composed by physical and chemical exergy. Disregarding changes in kinetic energy and the specific physical exergy of a stream is calculated by Eq. (5):

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

where:

h_0 :	Enthalpy of the substance at T_0 and P_0;
s_0 :	Entropy of the substance at T_0 and P_0.

For an ideal solution for pure substances, the chemical exergy (ex_{ch}), according to Bejan and Moran (1996), is given by Eq. (6):

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

where:

x_i :	Molar fraction of each component of the mixture;
$\overline{ex}_{ch,k}$:	Molar standard chemical exergy of each component of the mixture (kJ/kmol);
$\bar{R}$:	Molar universal gas constant (kJ/mol K).

Some indexes are defined to evaluate the performance of the thermal power plants, being also utilized to compare products from different thermodynamic qualities, such as thermal energy and power produced, according to Sánchez Prieto (2003).

The Factor of Energy Utilization (FEU) is the ratio of thermal and electromechanical energy ($\dot{Q}_{useful}$ and $\dot{W}_{total}$) utilized in the cycle and the energy of the spent fuel for the generation of steam, show in Eq. (7):

$$FEU = \frac{\dot{W}_{total} + \dot{Q}_{useful}}{\dot{m}_f LHV_f} \tag{7}$$

where:

$\dot{m}_f$: Fuel mass flow (kg/s);

LHV_f : Fuel Low Heat Value (kJ/kg).

The Energy Saving Index (ESI) refers to energy saving achieved by cogeneration systems in comparison with conventional plants that produce electricity and heat separately and is defined by Eq. (8):

$$ESI = \frac{\dot{m}_f LHV_f}{\left(\frac{\dot{W}_{total}}{\eta_{ref\_thermal}}\right) + \left(\frac{\dot{Q}_{useful}}{\eta_{ref\_boiler}}\right)} \tag{8}$$

where:

$\eta_{ref\_thermal}$: Efficiency of a reference thermal plant (adopted as being 40%);

η_{ref_boiler}: Efficiency of a reference boiler (adopted as being 77%).

The amount of energy saving by using cogeneration (ESC) is given by Eq. (9):

$$ESC = 1 - ESI \tag{9}$$

The Power Generation Index (PGI) is a parameter to calculate separately the efficiency of power generation, discounting of the total energy input the energy utilized for heating, being represented by Eq. (10):

$$PGI = \frac{\dot{W}_{total}}{\dot{m}_f LHV_f - \left(\frac{\dot{Q}_{useful}}{\eta_{boiler}}\right)} \tag{10}$$

Another important index is the Power to Heat Ratio (PHR), which is the ratio between the total output power and heat energy used in the process, given by Eq. (11):

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

The overall efficiency of the plant ($\eta_{overall}$) is the ratio between the useful energy, either thermal or electromechanical, and the energy supplied to the system by the fuel, being given by Eq. (12):

$$\eta_{overall} = \frac{\dot{W}_{electric} + \dot{Q}_{useful} - \dot{W}_{compress} - \dot{W}_{pump}}{\dot{m}_f LHV_f} \tag{12}$$

Another important parameter is the ratio of the electrical power generated and the quantity of cane crushed ($R_{ele-cane}$), given in kWh/tc, by Eq. (13):

$$R_{ele-cane} = \frac{\dot{W}_{electric}}{\dot{m}_{cane}} \tag{13}$$

2.2 Thermoeconomic Analysis

After the thermodynamic analysis, a thermoeconomic analysis of plants for determining the production costs is carried out. The exergetic cost analysis involves cost balance for each of the components of a system.

Thus, for a given component (k) that receives heat and generates power, the balance of cost must take into account cost rates (R$/s) associated with exergy input ($\dot{C}_{in}$) and output ($\dot{C}_{out}$) and the work rates ($\dot{C}_w$) and heat transfer ($\dot{C}_q$), plus the rate cost of equipment ($\dot{C}_e$), considering the cost of it (C_e) and factors related to the amortization (f_a), fixed costs (f_{omf}) and variables (f_{omv}) with the operation and maintenance, according to the load factor (FC) and the number of operating hours (T_{oper}). These cost rates are related by Eq. (14), according to Bejan and Moran (1996):

$$\Sigma\left(\dot{C}_{in}\right)_k + \left(\dot{C}_w\right)_k = \left(\dot{C}_q\right)_k + \Sigma\left(\dot{C}_{out}\right)_k + \left(\dot{C}_e\right)_k \tag{14}$$

where:

$$\dot{C}_{in} = c_{in}\dot{E}x_{in} = c_{in}(\dot{m}_{in}ex_{in}) \tag{15}$$

$$\dot{C}_{out} = c_{out}\dot{E}x_{out} = c_{out}(\dot{m}_{out}ex_{out}) \tag{16}$$

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

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

$$\dot{C}_e = C_e\left(f_a + f_{omf} + FCf_{omv}\right)/(3600\, t_{oper}) \tag{19}$$

where:

c: Average cost per unit of exergy (R$/kJ);
C: Monetary cost (R$);
$\dot{C}$: Cost exergetic rate (R$/s);
$\dot{E}x$: Exergy rate (kJ/s);
$\dot{Q}$: Heat rate (kJ/s);
$\dot{W}$: Power (kJ/s).

The amortization factor (f_a) can be calculated using the annual interest percentage rate (j) and the number of years of equipment life (N), according to Bejan and Moran (1996), by Eq. (20):

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

The average cost per unit of exergy of the fuel (c_{fuel}) is given by:

$$c_{fuel} = \frac{C_{fuel}}{ex_{fuel}} \tag{21}$$

where:

C_{fuel} : Average cost per unit mass of fuel (R$/kg);
ex_{fuel}: Exergy of the fuel (kJ/kg).

2.3 Economic Analysis

The sophisticated techniques of analysis of capital investment, according to Gitman (1984), consider the time factor in the value of money and involve the concepts of supposedly known cash flows over the life of the project.

Techniques based on cash flows are most often used to describe the interaction between capital expenditures with the benefits obtained annually with the implementation of a project. These benefits are obtained through the use of fuel in a more rational. The method consist in upgrade to the zero year of operation the benefits over the life of the project at a discount rate, then these values are summed and discounted the initial capital expense, and the resulting value is called as the Net Present Value (NPV). The NPV method shows explicitly the liquid taxable income that the investor should receive over the lifetime of the project, and is defined by Eq. (22):

$$NPV = \left[\sum_{k=1}^{N} \frac{ABO}{(1+j)^k}\right] - TIC \tag{22}$$

where:

ABO : Annual benefit obtained;

j : Discount rate adopted;
N : Number of years analyzed;
TIC : Total invested capital at the beginning of operation.

The criterion when NPV is used to make decisions to accept or refuse the project is the following: if NPV is greater than or equal to zero must accept the project because the company will get a return equal to or greater that the cost of capital invested and the project will retain or increase their assets, otherwise, if NPV is less than zero, it must refuse the project.

2.4 Case Studies

2.4.1 Case 1

The first case considered is a thermal power plant of a conventional sugarcane mill shown in Fig 1. This plant has efficient and modern equipments, including boiler which produces 160 t/h of steam at 68.6 bar and 530 ºC, and 125 t/h of steam feeds an extraction steam turbine coupled to a 32 MW electric generator. There is an extraction of 97 t/h of steam at a pressure of 2.45 bar for evaporation of the broth, and the rest of the steam continues to expand until the pressure reach 0.07 bar, and then is condensed. The remaining steam (35 t/h) is directed to a backpressure turbine, which is coupled to a 12 MW electric generator. The steam is discharged at 2.45 bar, also intended to meet the demand of the industrial process steam.

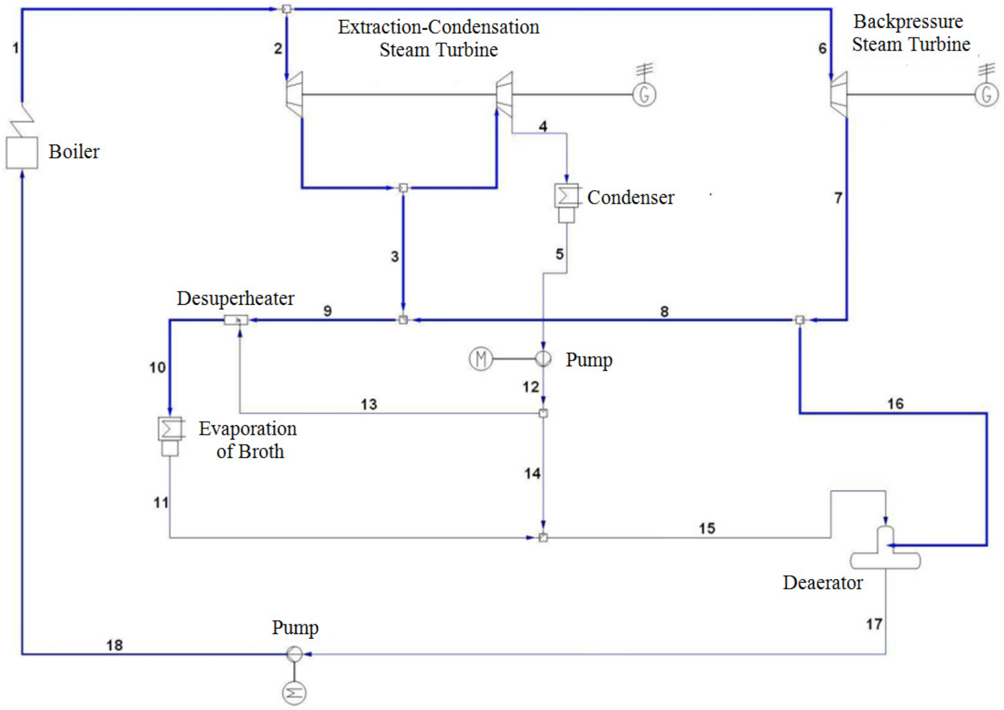


Figure 1. Conventional thermal power plant of a sugarcane mill.

2.4.2 Case 2

The second case considered is a hypothetical configuration in which is incorporated a straw gasification system in the conventional plant considered in Case 1. The system incorporated consists of a straw gasifier, a gas turbine coupled to an electrical generator, a heat recovery boiler and a steam system, comprising a condensation turbine, a condenser and a feed pump of the recovery boiler.

According to Romão Júnior (2009), the percentage of straw in sugarcane is about 12 %. Considering a harveste without ventilation, is possible to use 94 % of straw. In this paper, it is assumed that 12 % of total straw should stay in the land for the purpose of fertilization, so that, for a throughput of 286 t/h of sugarcane, the flow of straw gasification is approximately 30 t/h.

The scheme of the plant is shown in Fig. 2. The gasifier considered is the circulating fluidized bed, working at atmospheric pressure. As the gas is produced at a temperature range of 700 ºC, it is necessary to perform this cooling before being compressed.

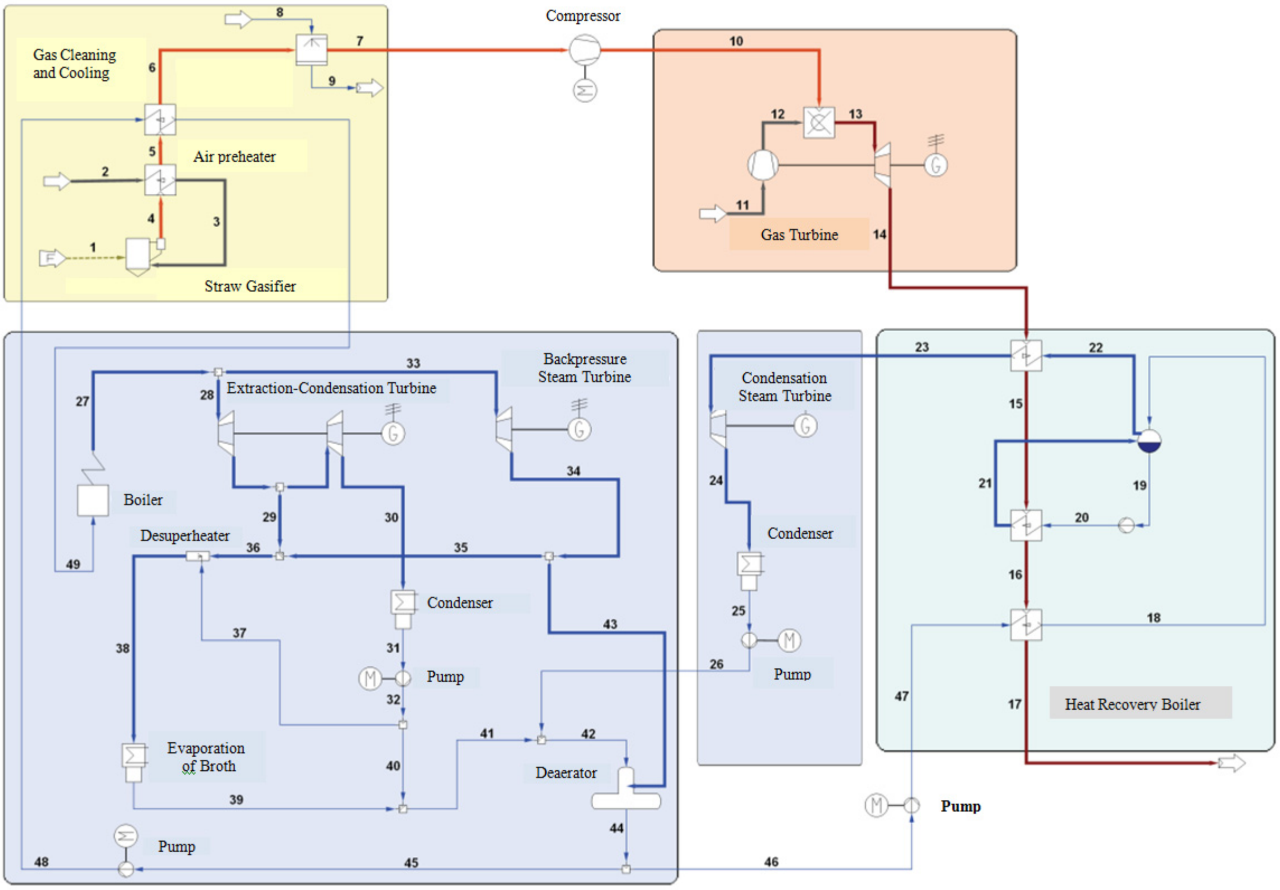


Figure 2. Modified thermal power plant of a sugarcane mill with integration of straw gasification system.

3. RESULTS

3.1 Thermodynamic Results

In this work, it was adopted for the reference state $T_0 = 298.15$ K and $P_0 = 101.3$ kPa. The Low Heat Value of straw and bagasse were considered as being, respectively, 13151 kJ/kg and 7736 kJ/kg. The exergy of straw and bagasse were defined as 15121 kJ/kg and 10170 kJ/kg, respectively. The solution of equations resulting from the thermodynamic analysis was obtained by the software IPSEpro®, according to Simtech (2003). Table 1 shows the power generated by the various plant equipments, in kW. Table 2 shows the power demanded by the thermal evaporation process of the broth and the power thermal condensation. Table 3 shows the indexes of plant performance for each case studied.

Table 1. Power generated/consumed by equipment, in kW, for each case considered.

Equipment	Case 1	Case 2
Compressors	0	- 10180
Pumps	- 504	-637
Gas turbine	0	31046
Extraction-Condensation turbine	26775	24852
Backpressure turbine	6527	7460
Condensation turbine	0	14317
Total	32798	66858

Table 2. Thermal power, in kW, for each case considered.

Local	Case 1	Case 2
Evaporation of the broth	79791	79791
Condenser	16760	45660

Table 3. Indexes of plant performance for each case considered.

Index	Case 1	Case 2
FEU	0.675	0.582
ESI	0.897	0.909
ESC	0.103	0.091
PGI	0.510	0.286
PHR	0.417	0.967
$\eta_{overall}$ (%)	67.2	54.2
$R_{ele\text{-}cane}$ (kWh/tc)	114	234

3.2 Thermoeconomic Results

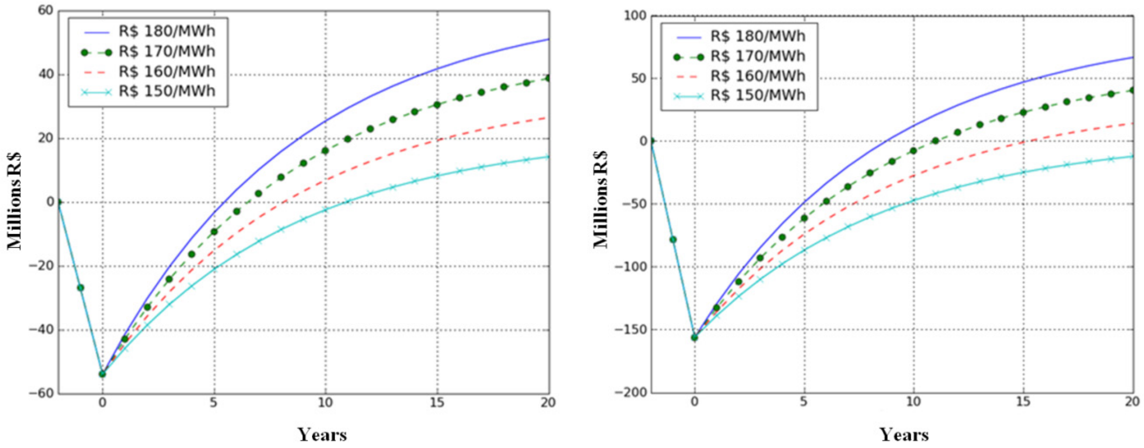
The solution of the equations resulting from the thermoeconomic analysis was performed using the program EES® (Engineering Equation Solver), which allows performing calculations in a simple and efficient way. The annual cost of equipment, with depreciation was calculated taking into account a depreciation period of 20 years. The interest rate was considered as 12 %. It was considered a cost of R$ 15.00/t for bagasse and R$ 32.00/t for the straw. Table 4 shows the production costs of electricity and steam for processes. It is observed that the gasification does not alter significantly these costs.

Table 4. Production costs of electricity and steam for processes, for each case considered.

Parameters	Case 1	Case 2
Gas turbine (R$/MWh)	-	75.02
Extraction-Condensing turbine (R$/MWh)	95.69	97.99
Backpressure turbine (R$/MWh)	89.29	87.82
Condensing turbine (R$/MWh)	-	137.50
Electricity average cost (R$/MWh)	94.44	95.12
Steam for processes cost (R$/t)	11.60	11.71

3.3 Economic Results

For the economic analysis, it was considered a useful life of 20 years, and the interest rate was maintained at 12 % per year. Cases 1 and 2 show an internal consumption of electricity of 10 and 18 MW, respectively, resulting in surplus of electricity for sale of 22.8 and 48.8 MW, respectively. Thus, there is an annual benefit of R$ 8208000.00 in Case 1 and R$ 17354000.00 in Case 2. Figures 3-a and 3-b show the cash flow over the life of the plant for multiple sales prices of electricity, considering a deployment period of the plant two years, in which the investment (R$ 54050000.00 for Case 1 and R$ 156150000.00 for Case 2) is realized. The intersection of curves with the horizontal axis indicates the time of return on investment.



a) Case 1

b) Case 2

Figure 3. Cash flow for each case considered.

Table 5 presents the Net Present Value (NPV) and Time of Return on Investment (TRI) for different values of electricity sales. It is observed that for a electricity sale price of R$ 150.00/MWh, the value actual liquid for Case 1 is only R$ 14 million, while sales value for this there is no return on investment. Thus, Case 2 shows only the financial viability of electricity sales values above R$ 155.00/MWh.

Table 5. Net Present Value (NPV) and Time of Return on Investment (TRI), for each case considered.

Sale Price	Case 1		Case 2	
(R$/MWh)	NPV (Millions R$)	TRI (years)	NPV (Millions R$)	TRI (years)
150	14.077	11	-12.119	-
160	26.338	9	14.125	16
170	38.600	7	40.370	11
180	50.862	6	66.614	9

4. CONCLUSION

In this paper it was analyzed numerically the integration of the straw gasification in a conventional thermal power plant of a sugarcane mill, by means of the BIG-GTCC technology.

The thermodynamic analysis shows that in the plant with straw gasification it is possible to double the amount of electricity produced with respect to the conventional plant. However, there is a reduction in the overall efficiency of the plant, since an additional fuel quantity is only used for generating electricity, of way that any part of this energy is used as useful heat.

The thermoeconomic and economic analyzes show that the implementation of straw gasification technology do not change significantly the production costs of electricity and steam for processes. Furthermore, the initial investment in gasification system of the straw is three times greater than for a conventional cogeneration system.

The investment in a cogeneration system becomes more attractive when the time for return on investment occurs before of half useful lifetime of the equipments. For values of electricity sales lower than R$ 155.00/MWh, the gasification project becomes unfeasible, according to the methodology adopted in this study, since results in no return on investment. Thus, the gasification of straw becomes an attractive investment only for values of electricity sales over than R$ 180.00/MWh.

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