TECHNICAL AND ECONOMIC ANALYSIS OF THE BAGASSE GASIFICATION PROCESS APPLIED IN SUGARCANE INDUSTRY

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Abstract. *The Brazilian sugarcane sector has great electric energy generation potential by the gasification of sugar cane bagasse and use in combined cycle cogeneration system. This paper aims to incorporate the gasification process in a conventional sugarcane industry to increase electricity surplus and also then sell the electricity to the concessionaires. To verify this process potential, a technical analysis is performed to estimate the electric energy production surplus, and an economic analysis is conducted to determine the annual savings from the sale of the electricity surplus. It is concluded that the plant with a gasification process can increase by 8.56 times the electricity production of the plant considered, indicating a positive annual saving when the sales price of the supply electricity is greater than 0.070 US$/kWh. Finally it can be concluded that the incorporation of gasification process allow greater economical feasibility and operational flexibility of Brazilian sugarcane industry.*

Keywords: *gasification, combined cycle, technical analysis, economic analysis*

1. INTRODUCTION

The Brazilian sugarcane industry has been developed based in the traditional processes that use a steam turbine operating in cogeneration systems. Many scientists have proposed new technologies and small modifications for better energy production applied in this important industrial sector. In this way, new processes to generate clean energy have a promising future (Silveira et al., 2014).

According to Diniz et al. (2013), the gasification has become one of the best alternatives for recovery of energy from biomass. The reason for this is due to this technology being easily inserted in the production process of the mill, without a large investment. Furthermore syngas could be produced by bagasse gasification.

This paper aims to study the technical and economic analysis of the incorporation of bagasse gasification in the sugarcane industry.

2. THERMODYNAMICS ANALYSIS

2.1. THERMODYNAMICS ANALYSIS IN THE SUGAR CANE CONVENTIONAL PLANT

The conventional plant, before the modification proposed by this paper, consists of a steam generator able to produce 150 ton/h of live steam at 6468 kPa and 530 °C (Fiomari, 2004). The steam turbine with nominal capacity of 40 MW has two extractions and also designed flow steam to the condenser in order to produce electricity and process heat. In the case of surplus of electricity, it may be sold. The configuration of the plant is also composed of other machines (backpressure steam turbines) producing mechanical power and useful heat for the process. This paper considers that the turbine of the water feed pump and steam turbine generator T does not operate.

The Fig. 1 shows the cogeneration plant and Tab. 1 exhibit the plant operating parameters.

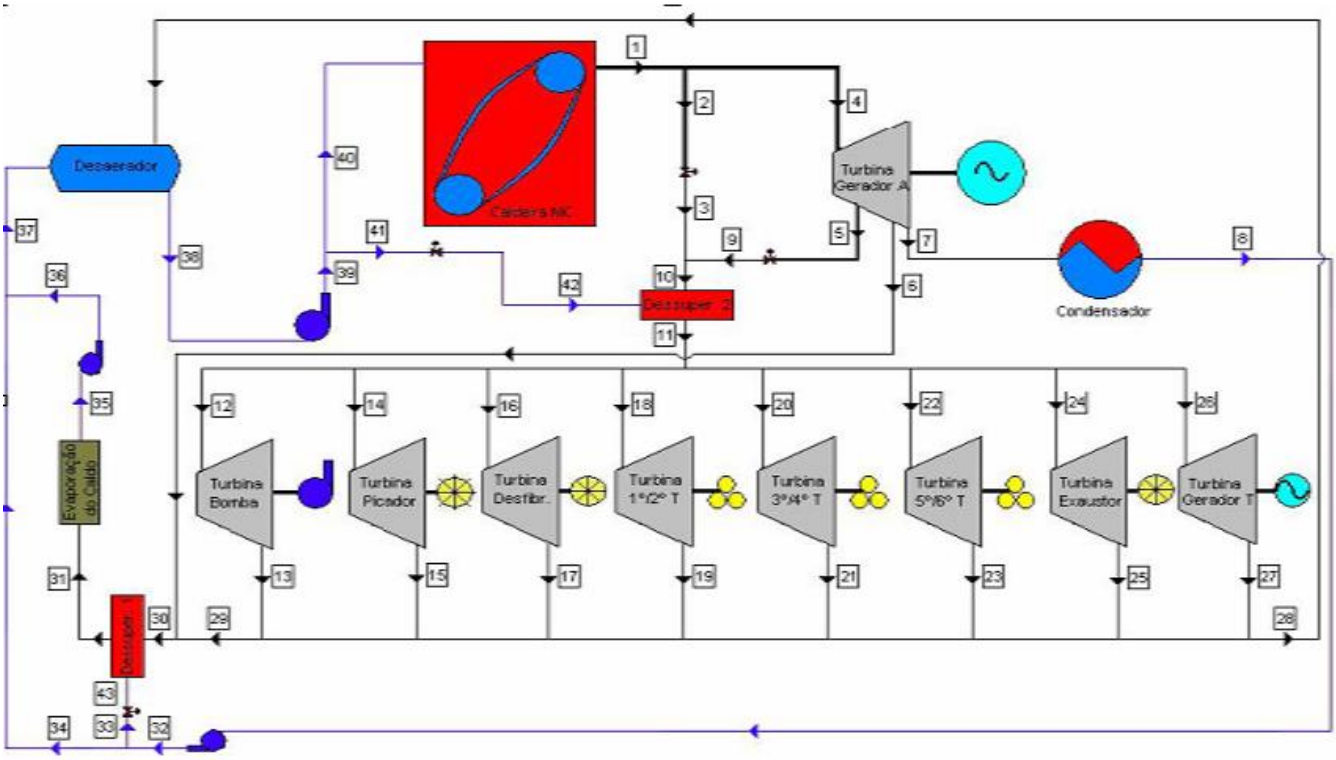

Figure 1. Conventional Condensing Plant, Steam Turbine with 2 Extractions (Fiomari, 2004)

Table 1. Plant Operating Parameters (Fiomari, 2004)

Pontos	$\dot{m}$ (kg/s)	P (kPa)	T (°C)	h (kJ/kg)	s (kJ/kg.K)
1	41,667	6468	530,0	3488,5	6,931
2	8,139	6468	530,0	3488,5	6,931
3	8,139	2156	510,2	3488,5	7,424
4	33,528	6468	530,0	3488,5	6,931
5	10,000	2650	426,0	3295,1	7,070
6	17,778	245	147,2	2759,3	7,165
7	5,750	8,5	42,7	2578,2	8,205
8	5,750	8,5	42,6	178,4	0,607
9	10,000	2156	422,7	3295,1	7,163
10	180,556	2156	462,0	3381,9	7,284
11	20,333	2156	320,0	3064,8	6,804
12	-	-	-	-	-
13	-	-	-	-	-
14	4,083	2156	310,0	3041,6	6,765
15	4,083	245.	185,0	2837,3	7,343
16	4,083	2156	310,0	3041,6	6,765
17	4,083	245	185,0	2837,3	7,343
18	4,167	2156	310,0	3041,6	6,765
19	4,167	245	194,5	2856,6	7,385
20	4,000	2156	310,0	3041,6	6,765

Pontos	$\dot{m}$ (kg/s)	P (kPa)	T (°C)	h (kJ/kg)	s (kJ/kg.K)
21	4,000	245	194,5	2856,6	7,385
22	4,000	2156	310,0	3041,6	6,765
23	4,000	245	194,5	2856,6	7,385
28	0,833	245	190,7	2848,8	7,368
29	19,500	245	190,7	2848,8	7,368
30	37,278	245	169,8	2806,1	7,274
31	38,333	245	135,0	2733,5	7,103
32	5,750	490	42,7	179,3	0,608
33	1,056	490	42,7	179,3	0,608
34	4,694	490	42,7	179,3	1,307
35	38,333	245	100,0	419,2	1,307
36	38,333	490	100,1	419,6	1,307
37	43,028	490	93,8	393,4	1,237
38	43,86111	245	105,0	440,3	1,363
39	43,86111	8820	106,8	454,1	1,376
40	41,66667	8820	106,8	454,1	1,376
41	2,194444	8820	106,8	454,1	1,376
42	2,194444	2156	107,8	454,1	1,394
43	1,055556	245	42,8	179,3	0,609

The electrical efficiency of the plant was calculated using Eq. (1):

$$\eta_e = \frac{E_{pST} - \dot{W}_P}{E_b} \tag{1}$$

The mass flow of bagasse used was 19.58 kg/s (Fiomari, 2004) and lower heating value of bagasse power as 7320 kJ/kg (Silva, 2010).

The global efficiency of the conventional cogeneration plant is calculated using the Eq. (2):

$$\eta_g = \frac{E_{pST} + E_M + H_p - \dot{W}_P}{E_b} \tag{2}$$

Where:

$$E_b = \dot{m}_b . LHV_b \tag{3}$$

Nomenclature:

E_b: power supplied by bagasse [kW];
E_M: Mechanical Power [kW]
E_{pST}: electrical power – steam turbine [kW];
LHV_b: Lower heat value of bagasse [kJ/kg];
$\dot{m}_b$: Bagasse mass flow [kg/s];
H_p: Useful heat in the process [kW];
$\dot{W}_P$: electrical power supplied to pump [kW];
η_e: electrical efficiency conventional plant [%];
η_g: global efficiency of the conventional cogeneration plant [%]

2.2. THERMODYNAMICS ANALYSIS OF THE GASIFICATION PROCESS

For the incorporation of the gasification process, a combined cycle utilizing a conventional gas turbine was proposed. The system also considers a bagasse dryer, gasifier, cyclone and filter. In this case, the gas turbine selected is made by Hitachi, model PG7241, suitable to operate with syngas. The Fig. 2 shows the combined cycle proposed and the operational parameters of this turbine are shown in Tab. 2.

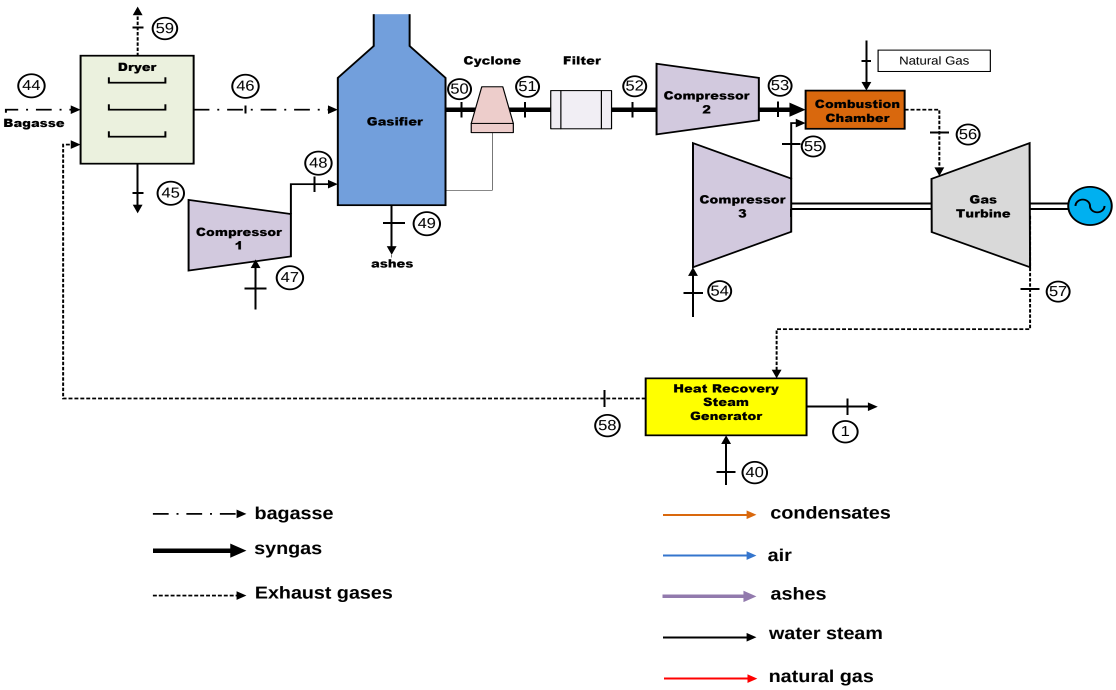

Figure 2: Combined Cycle Proposed

Table 2. Properties used in the turbine gas cycle, ISO Conditions (HANDBOOK, 2008)

Turbine	Power [MW]	Heat Hate [Btu/kWh]	Efficiency [%]	Pressure Ratio [-]	Flow of syngas [kg/s]	Exhaust temperature [ºC]
Hitachi PG 7241(E)	171700	9360	36,46	15,5	431,81	603,89

The total electrical efficiency of the combined cycle (gas turbine) system is calculated using Eq. (4).

$$\eta_{e_{gasif.}} = \frac{E_{p_{ST}} + E_{p_{GT}} - W_P}{E_{fuel_{total}}} \quad (4)$$

Where:

$$E_{fuel_{total}} = E_{syngas} + E_{NG} \quad (5)$$

$$E_{syngas} = \dot{m}_{syngas} * LHV_{syngas} \quad (6)$$

$$E_{NG} = \dot{m}_{NG} * LHV_{NG} \quad (7)$$

The global efficiency for the incorporation of the gasification process plant is calculated using the Eq. (8):

$$\eta_{g_{gasif.}} = \frac{E_{p_{ST}} + E_{p_{GT}} + E_M + H_p - W_P}{E_{fuel_{total}}} \quad (8)$$

When the amount of syngas produced is not sufficient to generate the maximum capacity of the gas turbine selected, supplementary fuel must be used. For this it was used natural gas as supplementary fuel.

According Paulino (2014), the lower heating value of syngas power as 4,755.47 [kJ/kg].

Nomenclature:

E_M: Mechanical Power [kW];
E_{NG}: power supplied by natural gas [kW];
$E_{p_{GT}}$: electrical power – gas turbine [kW];
$E_{p_{ST}}$: electrical power – steam turbine [kW];
$E_{fuel_{total}}$: power supplied by total fuel [kW];
E_{syngas}: power supplied by syngas [kW];
H_p: Useful heat in the process [kW];
LHV_{NG}: Lower heat value of natural gas [kJ/ kg];
LHV_{syngas}: Lower heat value of syngas [kJ/ kg];
$\dot{m}_{NG}$: natural gas mass flow [kg/s];
$\dot{m}_{syngas}$: syngas mass flow [kg/s];
$\dot{W}_P$: electrical power supplied to pump [kW];
$\eta_{e_{gasif.}}$: Electricity generation efficiency with incorporation gasification process [%];
$\eta_{g_{gasif.}}$: Global efficiency of cogeneration plant with incorporation gasification process [%];

2.3. RESULTS OF THE THERMODYNAMIC ANALYSIS

The Tab. 3 shows the results of thermodynamic analysis of the conventional cogeneration plant.

Table 3: Results of the thermodynamic analysis of convenvional cogeneration plant

Results	**Values**
Power supplied by bagasse (E_b) [kW]	151,496.66
Electrical Power – Steam Turbine ($E_{p_{ST}}$) [kW]	19,125.19
Mechanical Power (E_M) [kW]	3919,28
Heat process (H_p) [kW]	88714,83
Electricity generation efficiency (η_e) [%]	15,24
Global efficiency of cogeneration plant (η_g) [%]	77,54

In the process of the gasification it is possible to obtain 32.19 [kg/s] of syngas with the available bagasse. Therefore, in order to obtain maximum electrical power production incorporating the gasification, it is necessary 6.13 [kg/s] of natural gas as supplementary fuel in the combustion chamber or the gasification of 42.14 [kg/s] of sugar cane bagasse.

Table 4: Results of the thermodynamic analysis of convenvional cogeneration plant

Results	**Values**
Power supplied by fuel total ($E_{fuel_{total}}$) [kW]	447,335.69
Electrical Power ($E_{p_{GT}}$) [kW]	163,115
Electricity generation efficiency with incorporation gasification process ($\eta_{e_{gasif.}}$) [%]	40,73
Global efficiency of cogeneration plant with incorporation gasification process ($\eta_{g_{gasif.}}$)[%]	61,31

Figure 3 shows a comparison of electricity production of the conventional plant and with the incorporation of the gasification process. It is observed that after the incorporation of gasification electricity supply was increased by up to 8.56 times compared to power generation of the conventional plant, indicating the possibility of greater surplus sale to the concessionaire.

The Fig. 4 shows the electricity generation efficiency and overall efficiency of cogeneration plant of the conventional plant and the incorporation of the gasification process. It is observed that the plant with gasification has a higher yield of electricity generation efficiency, because that process has the function to increase the supply of electricity from the plant. Also, presents smaller overall efficiency of the cogeneration plant when supplementary firing of natural gas in the combustion chamber is used. Natural gas has a lower heat value and when burned together with the syngas into the combustion chamber brings the power supplied by total fuel $(E_{fuel_{total}})$ compared with conventional plant.

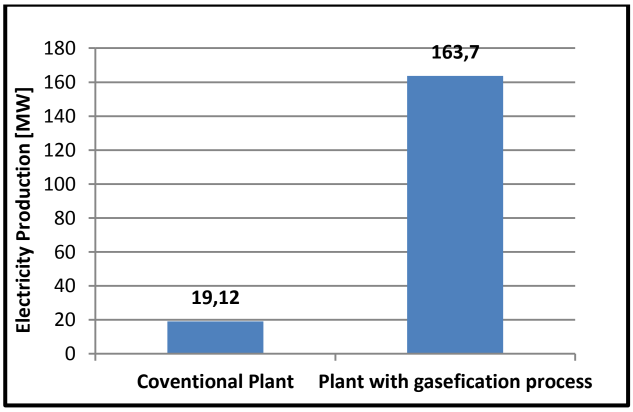

Figure 3: Electricity Production

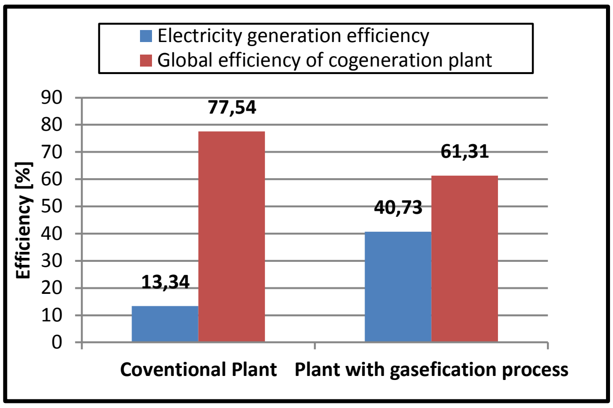

Figure 4: Efficiencies of Plants

3. ECONOMIC ANALYSIS OF THE GASIFICATION PROCESS

For economic analysis of the electricity production cost through the gasification process were taken into account the following factors: capital cost of equipment, operation and maintenance, interest rates, payback, cost of fuels and equipment lifespan.

Using Eq. (9) can determine the cost of production of syngas.

$$C_{syngas} = \frac{I_{GASIF.}*f}{H*E_{syngas}} + \frac{C_b*PCI_{b.s}}{E_{syngas}} + C_{M_{GASIF.}} + C_{O_{GASIF..}} \quad (9)$$

The investment cost of the gasifier ($I_{GASIF.}$) was estimated as 30% of the gas turbine set. According Sales (2006), the maintenance cost and the cost of the gasifier operation is 3 to 6% of the investment costs of the gasification system, respectively.

To determine the cost of electricity to the steam turbine (C_{elST}) and gas turbine (C_{elGT}), mechanical energy (C_{EM}) and process heat (C_{H_p}) in [US$/kWh] was used Eqs. (10), (11), (12) and (13) respectively.

$$C_{elST} = \frac{I_{ST}*f}{H*E_{pST}} + C_{M_{fuel}} * FP_{E_{pST}} + CM_{ST} + (Co * FP_{E_{pST}}) \quad (10)$$

$$C_{elGT} = \frac{I_{GT}*f}{H*E_{pGT}} + C_{M_{fuel}} * FP_{E_{pGT}} + CM_{GT} + (Co * FP_{E_{pGT}}) \quad (11)$$

$$C_{EM} = \frac{I_{TM}*f}{H*E_M} + C_{M_{fuel}} * FP_{E_M} + CM_{TM} + (Co * FP_{E_M}) \quad (12)$$

$$C_{H_p} = \frac{I_{HRSG}*f}{H*H_p} + C_{M_{fuel}} * FP_{H_p} + CM_{HRSG} + (Co * FP_{H_p}) \quad (13)$$

To plant study was need in the supplementary firing of natural gas, so it is necessary to calculate the medium cost of fuel (Eq. (14)) used in the combustion chamber.

$$C_{M_{fuel}} = (C_{syngas} * P_{syngas}) + (C_{NG} * P_{NG}) \quad (14)$$

The cost of electricity produced (C_{el}) by the plant is calculated by the Eq. (15):

$$C_{el} = \frac{(C_{elGT}*E_{pGT})+(C_{elST}*E_{pST})}{E_{pGT}+E_{pST}} \quad (15)$$

Using Eq. (17) to determine the annual revenue, considering the sale of surplus electricity:

$$R_{annual} = (E_{ptotal} - E_r) * H * (P_{s.surplus} - C_{el}) \quad (17)$$

Onde:

$$E_{ptotal} = E_{pST} + E_{pGT} \quad (18)$$

Nomenclature:

$C_{M_{fuel}}$: average cost of fuel [US$/kWh];
C_{NG}: natural gas cost [US$/kWh];
C_{syngas}: syngas cost [US$/kWh];
CM_{GT}: maintenance cost gas turbine [US$/kWh];
CM_{HRSG}: maintenance cost Heat Recovery Steam Generation [US$/kWh];
CM_{TM}: : maintenance cost mechanical turbine [US$/kWh];
CM_{ST}: maintenance cost steam turbine [US$/kWh];
Co: cost of operating staff [US$/kWh];
C_{syngas}: syngas cost [US$/kWh];
E_M: Mechanical Power [kW];
E_{pGT}: electrical power – gas turbine [kW];
E_{pST}: electrical power – steam turbine [kW];
E_{ptotal}: total electrical power in the plant [kW];
E_r: required electrical power by the plant [16,081.14 kW, Paulino(2014)];
E_{syngas}: power supplied by syngas [kW];
f: annual factor [1/ano];
$FP_{E_{pGT}}$: electricity production weighting factor in gas turbine [-];
$FP_{E_{pST}}$: electricity production weighting factor in steam turbine [-];
FP_{E_M}: mechanical energy production weighting factor [-];
FP_{H_p}: heat process production weighting factor [-];
H_p: Useful heat in the process [kW];
$I_{GASIF.}$: investment cost of the gasifier [US$];
I_{GT}: investment cost of the gas turbine [US$];
I_{HRSG}: : investment cost of the heat recovery steam generation [US$];
I_{TM}: investment cost of the mechanical turbine [US$];
H: equivalent period of use [h/ano];
$PCI_{b.s}$: Lower heat value of bagasse dry base [14,974.00 kJ/kg, Paulino(2014)];
P_{NG}: percentage of natural gas [%];
$P_{s.surplus}$: sale price of surplus electric power [US$/kWh];
P_{syngas}: percentage of syngas [%];
(R_{annual}) : annual revenue [US$/ano];

Table 5 presents the following amounts: initial investment for the gas turbine and heat recovery steam generation, the percentage of syngas produced by the gasification process and natural gas used as supplementary fuel in the combustion chamber and also the natural gas cost.

The Tab. 6 shows the equipment maintenance costs and Tab. 7 presents the weighting factor for each equipment, according to the amount of fuel spent to generate energy.

Table 05: Values used for economic analysis

Equipment	**Values**
Investment Gas Turbine [US$/kWh] (Paulino, 2014)	29,129,100
Investment Heat Recovery Steam Generation [US$/kWh] (Paulino, 2014)	6,058,688
Percentage Syngas [%] (Paulino, 2014)	80.23
Percentage Natural Gas [%] (Paulino, 2014)	19.77
Cost Natural Gas [US$/kWh] (FIRJAN ,2014)	0.06

Table 06: Equipment maintenance cost (Antunes, 1999)

Equipment	**Maintenance cost [US$/kWh]**
Steam Turbine	0.017
Gas Turbine	0.015
Mechanical Turbine	0.017
Heat Recovery Steam Generation	0.008

Table 07: Weighting factor according to the energy production (Paulino, 2014)

Energy	**Weighting factor [-]**
Electrical Energy (Steam Turbine)	0.517
Electrical Energy (Gas Turbine)	0.083
Mechanical Energy	0.017
Process Heat	0.383

3.1 RESULTS OF THE ECONOMIC ANALYSIS OF THE GASIFICATION PROCESS

Figure 5 and 6 shows the cost of the electricity produced by the gas turbine and the heat process cost generated by the Heat Recovery Steam Generation depending on the payback, respectively. Observe that it has higher production costs when compared to other power generation sources. This is presented in Fig. 7 and 8 and is due to the need to install a new gas turbine and Heat Recovery Steam Generation, requiring an investment. Also, the energy generated cost considering both steam and mechanical turbine has an almost constant curve since no investment was needed.

The Fig. 9 shows the annual revenue in function of the payback time for an operation period of 4000 h and 12 % interest rate and according to the possible sale price of surplus electricity. It is also possible to note on Fig. 9 that there is an increase in revenue as the amortization period increases and the best surplus electricity selling price is 0.070 US$/kWh.

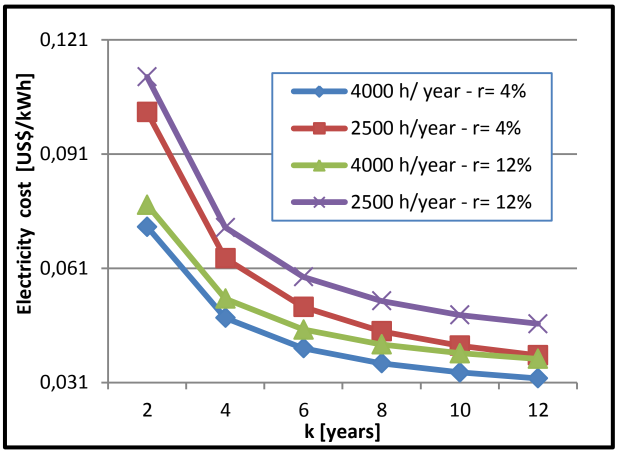

Figure 5: Electricity cost in gas turbine

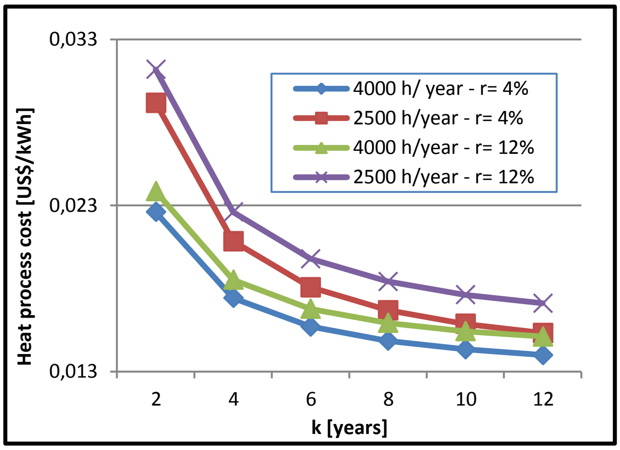

Figure 6: Heat process cost

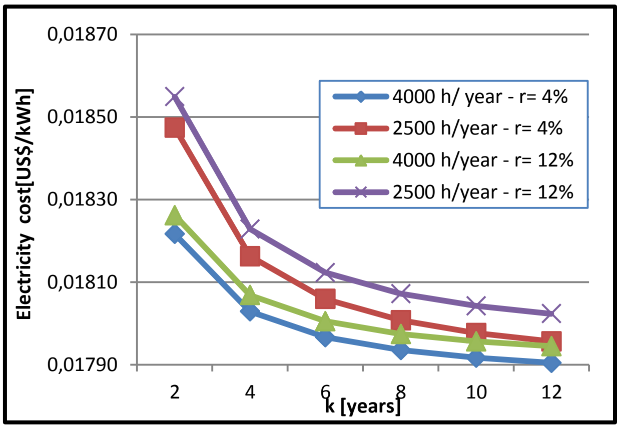

Figure 7: Electricity cost in steam turbine

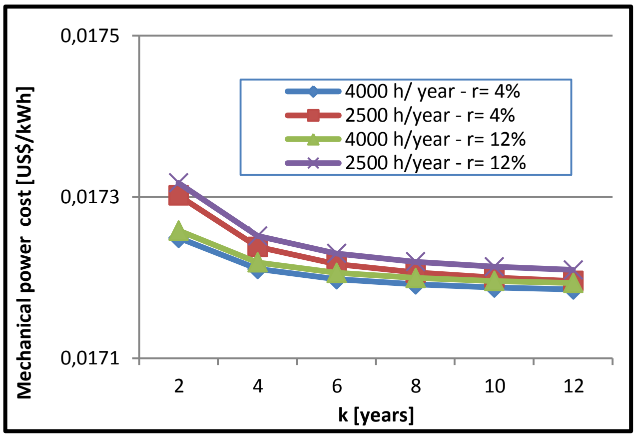

Figure 8: Mechanical power cost

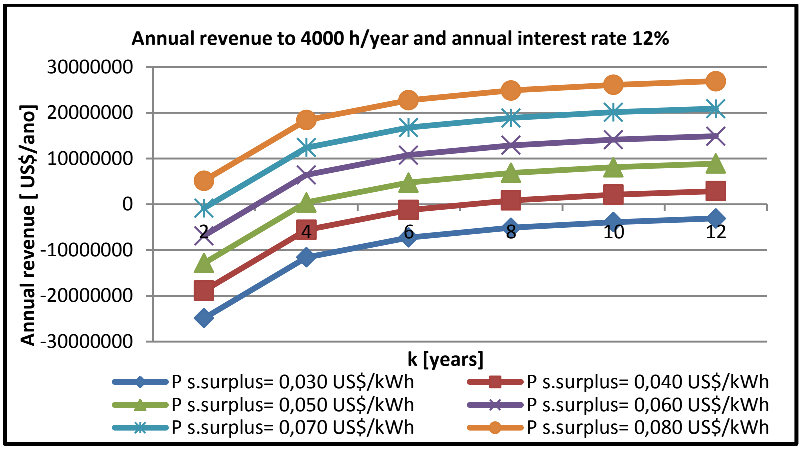

Figure 9: Annual revenue in function of payback

4. CONCLUSIONS

With the objective to incorporate new technology in the sugarcane sector, this paper shows relevant results in energy and economic analysis of bagasse gasification process associated with a combined cycle to increase the supply of electricity.

In terms of electrical efficiency, the plant incorporating the fluidized bed gasification operating with bagasse proves to be a good source of electricity production, with an electrical efficiency of 40.73%, while the plant without incorporation of the fluidized bed gasification has an electrical efficiency of 13.34%.

Through the economic analysis it turns out that the increase in electricity production allows higher expected annual revenue from the sale of surplus electricity and that the optimum sale price this electricity is 0,070 US$/kWh.

The incorporation of the gasification process allows an improvement in profitability and operational flexibility for sugarcane mills, corroborating to improve Brazil's position in the bioenergy ranking.

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