ENERGETIC EFFICIENCY IN COGENERATION SYSTEM APPLIED TO SUGAR AND ALCOHOL PLANT

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Abstract. *The sugar cane culture had been introduced in Brazil to consolidate the Portuguese colonization and to guarantee great profits.The sugar cane became one of the most important products of Brazilian agro business. Currently, 15% of Brazilian's automotive fleet has engines working with ethanol, which is characterized as a not-pollutant fuel, interesting each time the nations pledged in reducing the emission of harmful gases to the health human. In this paper, energeticand economical analysiss of an expansion cogeneration system at Pioneiros Industry is done. This plant consists of high pressure steam generator with an extraction-condensation steam turbine. Performance indexes had been obtained based on First Law of Thermodynamics, beyond common indicators of sugar-alcohol plants, specific steam consume in turbines and specific steam consume in processes. As conslusion of these evaluations are shown actual values for energetic efficiencies and economicfeasibility for the expansion proposed of cogeneration system in thesugar cane industry studied.*

Keywords: *cogeneration system, energy exploitation, sugar-alcohol industry, sugar cane bagasse.*

NOMENCLATURE

η_e – electrical efficiency of the cogeneration system (-)
η_g – global efficiency (-)
η_{sg} – steam generator thermal efficiency – adopted 0.77 (-)
η_{st} – steam turbines thermal efficiency – adopted 0.40 (-)
η_t – useful heat efficiency of the cogeneration system (-)
AIR – annual interest rate (R$/year)
AS – annual saving (R$/year)
BPR – bagasse and power rate (kg/kWh)
c_{co} – tariff of electricity (R$/kWh)
c_{csg} – cost of steam production in conventional steam generator (R$/kWh)
c_e – electricity production cost (R$/kWh)
c_f – energetic cost of bagasse (R$/kWh)
c_{ii} – capital cost (R$)
c_m – maintenance cost (R$/kWh)
c_s – steam production cost (R$/kWh)
$\dot{E}_f$ – power supplied by the bagasse (kW)
f – annuity factor (1/year)
F_e – electricity production rate factor (-)
F_t – useful heat rate factor (-)
G_e – electricity generation saving (R$)
G_t – thermal energy saving (R$)
H – equivalent period of utilization (h/year)
I_{pl} – investment cost in the plant (R$)
LHV_b – Low Heat Value of bagasse (kJ/kg)

$\dot{m}_b$ – mass flow of bagasse (kg/s or kg/h)
P_{cr} – losses of energy by unit of time (kW)
P_e – surplus electricity price (R$/kWh)
$\dot{Q}_c$ – thermal energy lost in the condenser (kW)
$\dot{Q}_e$ – thermal energy for broth evaporation (kW)
$\dot{Q}_u$ – useful heat energy (kW)
$\dot{W}_e$ – electrical power (kW)
$\dot{W}_m$ – mechanical power (kW)
$\dot{W}_p$ – pumping power (kW)
$\dot{W}_t$ – mechanical and electrical power (kW)
$\dot{W}_r$ –electrical power required in industry (kW)

1. INTRODUCTION

According to Ensinas et al. (2007), the sugar cane production is one of the great economic activities of Brazil, face to its high efficiency and competitiveness. In this segment, sugar plants, alcohol distilleries and integrated plants of sugar and alcohol are found. In recent years, electricity also has been an aggregate product to this segment, being the sugar cane bagasse is used as combustible in cogeneration systems.

In 2006, there were 300 sugar cane plants in operation in Brazil (UNICA, 2006). A total of 394.4 Mt of sugar cane had been processed in the last harvest (2005/2006) for the production of sugar and ethanol (CONAB, 2006). In the Brazilian's case, the equivalent 1% of its total area (3.6 million hectares) is dedicated to the sugar cane culture (Grunwald, 2008). This production, approximately provides the production of ethanol at the cost of 0.22 US$/liter (Grunwald, 2008).

2. THERMODYNAMICS ANALYSIS OF A SUGAR-ALCOHOL PLANT

The most common way to determine the performance of thermal systems is the use of First Law of Thermodynamics (Horlock, 1997). This analysis allows defining, under the energy point of view, the performance of each equipment and also the global performance of the system. Although much used, this methodology has its limitations, therefore it is not worried about the inherent irreversibilities to all processes, and however, it provides a good evaluation of the performance in study.

Another important concept is the definition of adiabatic process. When no heat transference does not occur to or from the control volume, the process is known as adiabatic (Wylen et al., 2003).

2.1. Performance indexes based on First Law of Thermodynamics

The use of performance indexes has as objective to evaluate the cogeneration systems as a whole, clarifying the differences between them. This evaluation applied to a cogeneration plant, based on the First Law of Thermodynamics is a procedure that implies in the comparison of energetic products, such as, thermal energy and electric power. In the cogeneration systems that use water as fluid of work, some aspects exist that must be detached. In the sugar-alcohol plants case, the bagasse combustion in the steam generator liberates the energy responsible to transform water into steam that is expanded in a steam turbine, generating shaft work, that can be transform in electric power, being the escape of steam turbine, useful heat to satisfy the thermal demand of the industry plant.

2.1.1. Factor of energy use (FEU)

The factor of energy use is a common practice to evaluate cogeneration systems efficiency through the called efficiency of First Law, assigned as FEU. This parameter is the relation between thermal and electromechanical energies used in the cycle with fuel energy expensed in the steam generation. In resume, the factor of energy use represents the efficiency of first law of the system as a whole, such as represented in Eq. (1).

$$FEU = \frac{\dot{W}_t + \dot{Q}_u}{\dot{m}_b \cdot LHV_b} \tag{1}$$

2.1.2. Index of energy savings (IES)

The index of energy savings refers to the fuel energy saving obtained in the cogeneration system in comparison with conventional plants that produce electricity and thermal energy separately and is defined as presented in Eq. (2).

$$IES = \frac{\dot{m}_b \cdot LHV_b}{\frac{\dot{W}_t}{\eta_{st}} + \frac{\dot{Q}_u}{\eta_{sg}}} \tag{2}$$

2.1.3. Energy to save with cogeneration (ESC)

Eq. (2) shows that the system performance will be better as much as lesser the index of energy savings of fuel is with efficiencies adopted. Hence, the energy amount to save with cogeneration is showed by Eq. (3).

$$ESC = 1 - IES \tag{3}$$

2.1.4. Index of power generation (IPG)

IPG is a parameter defined to evaluate power generation efficiency separately, deducing from fuel energy the thermal energy showed by Eq. (4).

$$IPG = \frac{\dot{W}_t}{\dot{m}_b \cdot LHV_b - \frac{\dot{Q}_u}{\eta_{sg}}} \tag{4}$$

2.1.5. Power and heat rate (PHR)

This index shows the rate between total power generated (mechanical power and electric power) and thermal energy used in this process, Eq. (5).

$$PHR = \frac{\dot{W}_t}{\dot{Q}_u} \tag{5}$$

2.2. Important parameters in sugar-alcohol plants

Sugar cane bagasse is the main energy source of steam generators in the sugar-alcohol plant. This feature means that thermal systems are directly dependent of available amount and characteristics of this bagasse, consequently the steam generated in those steam generators varies.

Humidity is the main parameter to evaluate bagasse quality, normally around 51%, because low heat value decrease as a function of bagasse humidity.

There is a manner to evaluate efficiency of boilers and turbines sets, being with electrical or mechanical driving, through Eq. (6), in which bagasse and power rate is related to bagasse consumed with electrical and mechanical powers, showing how boilers use fuel energy (sugar cane bagasse) and how turbines use steam generated with bagasse utile energy.

$$BPR = \frac{\dot{m}_b}{\left(\dot{W}_e + \dot{W}_m\right)} \tag{6}$$

The evaluation through First Law of Thermodynamics provides to calculate shaft power generated for mechanical equipments (pricking, shredding, grinding, exhausting, and hydraulic pumps) and electrical generators, in addition pumping powers demanded by plant. Also is possible to evaluate useful thermal power in process, such broth water evaporation system and condenser losses.

Any power generated is considered to obtain a general evaluation of cogeneration system, electrical or mechanical, any useful and lost thermal energy, which is provided by bagasse. Thus, the global efficiency based in the First Law of Thermodynamic is defined for the cogeneration system, such Eq. (7).

$$\eta_g = \frac{\dot{W}_e + \dot{W}_m + \dot{Q}_e - \dot{W}_p - \dot{Q}_c}{LHV_b \cdot \dot{m}_b} \tag{7}$$

2.3. Description of cogeneration system of Destilaria Pioneiros

The cogeneration system focused on this case-study is showed on Fig. 1. It is composed by a high pressure steam generator (Caldeira MC), designed to produce 150 t of steam with a pressure of 6.468kPa and with 530ºC of temperature. The great consumers for steam generated in steam generators are the steam turbines used in mechanical driving of grinding machines and exhauster (points 17, 19, 21, 23, 25 and 27) and electric power generators (points 4, 6, 8 and 10). The turbo generator (Turbina Gerador T) has 4.0MW; other ones (Turbina Gerador 1, Turbina Gerador 2 e Turbina Gerador 3), are capable to generate 1.2MW each one.

There are two turbines in sugar cane preparation, one in pricker driving (Turbina Picador) and other in sugar cane shredding (Turbina Desfibrador), which are equipments to prepare raw materials before crushing. The broth extraction is done with other three turbines (Turbina 1°/2°T, Turbina 2°/3°T, Turbina 5°/6°T) through double driving, that is, each turbine drives two grinding machines with four coils each one.

Also there is a turbine responsible to drive a pump that feeds water to steam generator. There is another pump, which an electric motor drives it, with the same function of that first, but is allowed in stand by status. There is a second exhauster that is driven by an electric motor. Is important to note that turbo generator is a multiple stage engine while other steam turbines are simple stage. Because that, turbo generator is more efficient that other ones.

A minor part of escape steam from steam turbines returns directly to thermal desaerator (point 13), which pre-heater water and eliminates air that exist there. A major part of escape steam is used in sugar and alcohol manufacturer process, in heating, evaporating and boiling stages. However, before its uses in those processes, steam pass through desuperheater, where water is injected in it (point 31), deriving from water treatment station, to reduce its temperature near 135 ºC. This temperature, near steam saturation, enhances thermal change coefficient.

The steam used in sugar producing (point 30) condenses in broth evaporation system and returns to thermal desaerator (point 32). From then, water is pumped to boiler (point 36) and the cycle restarts.

Water used in this manufacturer process, mainly boilers, is collected from reservoir of Barragem de Tres Irmaos (Rio Tiete), with hydraulic pumps. Water collected is transferred to water treatment station, where is treated with flocculation, induced by sulfate of aluminum ($Al_2(SO_4)_3$), then is reserved for decantation and filtering through sand filter and its mitigation is accomplished through passing of cationic resins to capture some cations (Ca^{2+}eMg^{2+}). After this treatment, water is called “mitigated water” and is ready to be used in boilers.

Table 1 shows data from crushing, harvest time and bagasse production at Destilaria Pioneiros.

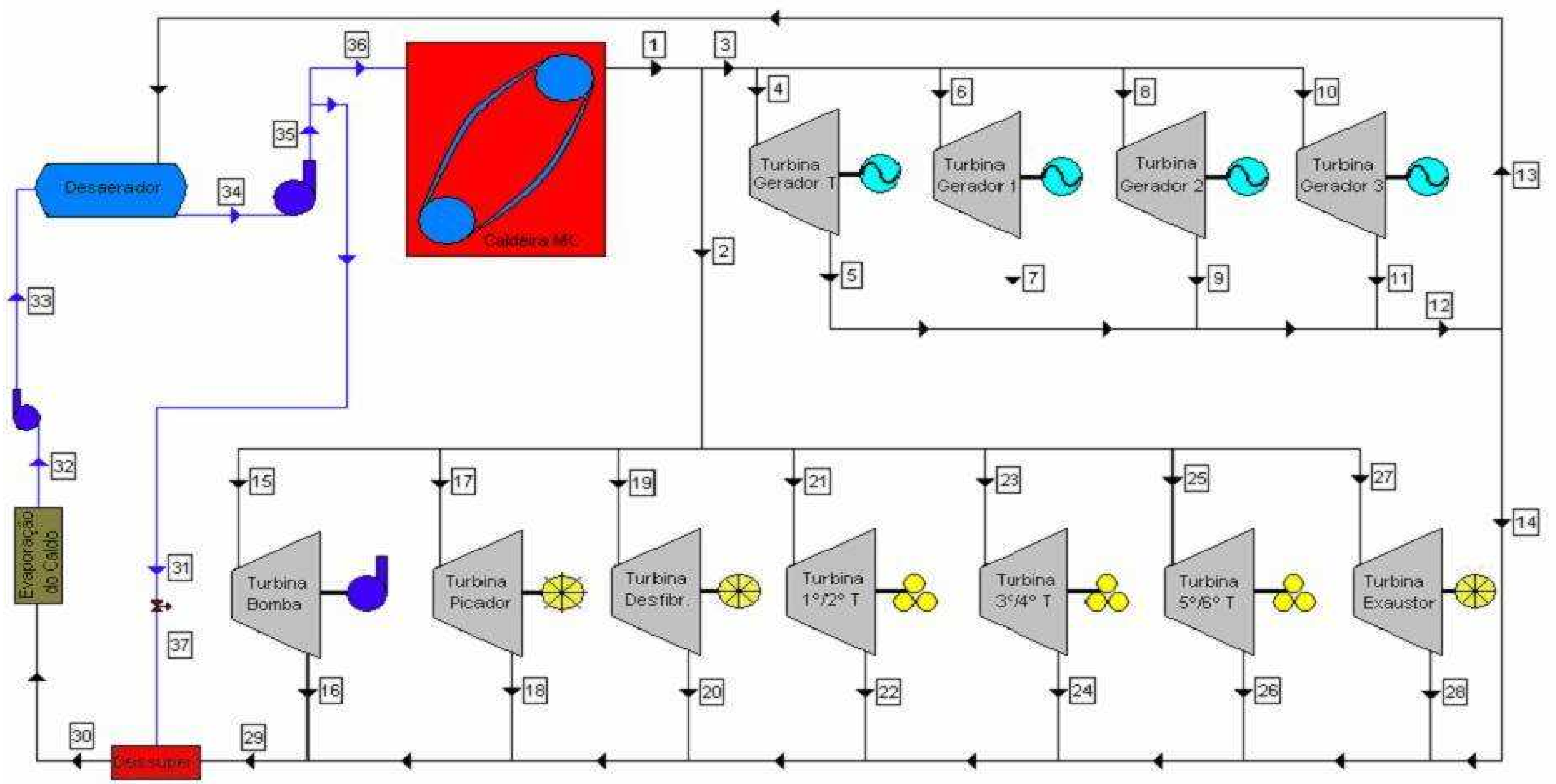

Figure 1. Diagram of Destilaria Pioneiros (Fiomari, 2004)

Table 1. Crushing, harvest time, bagasse production and consume at Destilaria Pioneiros.

Parameters	Values	Units
Total sugar cane crushed	1,160,000	t
Harvest days	215	days
Agriculture efficiency	94.3	%
Industrial efficiency	89.6	%
Effective crushing hours	4,329.2	hours
Crushing per hour	267.9	t/h
Bagasse-steam rate	0.47	kg/kg
Sugar cane fiber tenor	12.4	%
Bagasse fiber tenor	46.5	%
Bagasse flow in boiler MC	63.0	t/h
Total produced bagasse flow	71.5	t/h
Residual bagasse flow	8.5	t/h
Harvest residual total bagasse	36,678	t
Bagasse LHV	7,736	kJ/kg

Table 2 shows characteristics parameters of operation according to points viewed on Fig. 1, such as mass flow (m), temperature (T), pressure (P), specific enthalpy (h) and specific entropy (s).

Table 2. Operating parameters of Destilaria Pioneiros plant.

Points	m (t/h)	P (kPa)	T (°C)	h (kJ/kg)	s (kJ/kg.K)
1	134.00	2.156	300.0	3,018.2	6.724
2	78.70	2.156	300.0	3,018.2	6.724
3	55.30	2.156	300.0	3,018.2	6.724
4	25.00	2.156	300.0	3,018.2	6.724
5	25.00	245	138.0	2,739.9	7.119
6	15.20	2.156	300.0	3,018.2	6.724
7	15.20	245	180.2	2,827.5	7.322
8	15.10	2.156	300.0	3,018.2	6.724
9	15.10	245	180.2	2,827.5	7.322
10	0.00	2.156	300.0	3,018.2	6.724
11	0.00	245	180.2	2,827.5	7.322
12	55.30	245	160.9	2,787.9	7.232
13	1.20	245	160.9	2,787.9	7.232
14	54.10	245	160.9	2,787.9	7.232
15	7.10	2.156	300.0	3,018.2	6.724
16	7.10	245	215.0	2,898.2	7.472
17	13.40	2.156	290.0	2,994.4	6.683
18	13.40	245	165.0	2,796.3	7.252
19	13.40	2.156	290.0	2,994.4	6.683
20	13.40	245	165.0	2,796.3	7.252
21	13.70	2.156	290.0	2,994.4	6.683
22	13.70	245	174.3	2,815.4	7.295
23	13.20	2.156	290.0	2,994.4	6.683
24	13.20	245	174.3	2,815.4	7.295
25	13.20	2.156	290.0	2,994.4	6.683
26	13.20	245	174.3	2,815.4	7.295

27	4.70	2.156	300.0	3,018.2	6.724
28	4.70	245	185.0	2,837.3	7.343
29	132.80	245	169.5	2,805.5	7.273
30	137.00	245	135.0	2,733.5	7.103
31	4.20	3.920	105.8	446.4	1.369
32	137.00	245	100.0	419.2	1.307
33	137.00	490	100.1	419.6	1.307
34	138.20	245	105.0	440.3	1.363
35	138.20	3.920	105.8	446.4	1.369
36	134.00	3.920	105.8	446.4	1.369
37	4.20	245	106.5	446.4	1.379

Temperature in points 17, 19, 21, 23 and 25 are 10ºC less than steam temperature in boiler exit (point 1), because heat transfer along of steam pipes.

3. TECHNICAL ANALYSIS

Results of energy analysis through First Law of Thermodynamics are presented in this section.

The efficiency for each turbine, Tab. 3, where major efficiency is observed in turbo generator, because this is a double stage turbine and others are single stage turbines.

Table 3. Thermodynamic efficiency of turbines.

Turbines	η (%)
Pricker	46.1
Shredder	46.1
1st and 2nd Crusher	41.7
3rd and 4th Crusher	41.7
5th and 6th Crusher	41.7
Hydraulic pump	27.5
Exhauster	41.4
Generator 1	43.7
Generator 2	43.7
Generator 3	43.7
Turbo generator	63.8

Table 4 shows shaft powers obtained for each steam turbine (engine), using Eq. (7).

Table 4. Power generated in each engine.

Turbines	$\dot{W}(kW)$
Pricker	738
Shredder	738
1st and 2nd Crusher	681
3rd and 4th Crusher	656
5th and 6th Crusher	656

Hydraulic pump	237
Exhauster	236
Total Electromechanical	**3,942**
Generator 1	805
Generator 2	800
Generator 3	-
Turbo generator	1,933
Total Electrical	**3,538**

Sugar-alcohol plants work with thermal parity, at once process thermal energy is priority in facilities. Therefore, thermal power used in process ($\dot{Q}_c$) is that lost in condenser of extraction-condensation turbine. Its amount is 88,058 kW.

Considering all elements in this plant, with results of steam expansion in turbines, condensing in process and pumping, the efficiency (**η**) evaluated with first law for steam generator in plant (MC150/70) is 70.7%.

A global efficiency of 70.4% is determinate for thermodynamic evaluation of this cogeneration plant, and it relates any liquid energy exploited in this plant, such as power or thermal energy.

In this case-study there is a thermodynamic cycle that involves high pressure steam generator, mechanical drive through single and double stage turbines, and steam turbines drive through electric motors. Therefore, some criteria based on First Law of Thermodynamics are used to evaluate the plant performance, which provides a better analysis of all system. Table 5 shows indexes evaluation for this plant.

Table 5. Performance indexes based on first law of thermodynamics.

Performance index	
FUE	0.706
IPE	1.017
EEC	0.017
IGP	0.056
RPC	0.085

4. ECONOMICAL ANALYSIS

The economical analysis is done to verify economical feasibility of this cogeneration plant. For that, some parameters are used, such as electricity production cost, evaluated by Eq. (8).

$$c_e = \frac{\left(I_{pl} \cdot f\right)}{H \cdot \dot{W}_e} \cdot F_e + \frac{c_f \cdot \left(E_f - \dot{W}_e - \dot{Q}_u - \frac{P_{cr}}{2}\right)}{\dot{W}_e} + \frac{C_m \cdot F_e}{\dot{W}_e} \tag{8}$$

Cogeneration system investment (I_{pl}) is obtained with system initial investment summed to 30% that corresponds to carriage, insurance, logistics, constructions, installation etc. (Silveira, 1994), showed in Eq. (9).

$$I_{pl} = \left(C_{ii}\right) \cdot 1.3 \tag{9}$$

Electricity production rate factor (F_e) is evaluated with Eq. (10).

$$F_e = \frac{\dot{W}_e}{\dot{W}_e + \dot{Q}_u} \tag{10}$$

The losses of energy by unit of time is evaluated with Eq. (11).

$$P_{cr} = E_f - \dot{W}_e - \dot{Q}_u \quad (11)$$

Fuel price is evaluated with Eq. (12), relating based in Low Heat Value of bagasse with its price, that is R$ 25.00 per ton according to Romao Junior (2007).

$$c_f = \frac{0.025 \cdot 3,600}{7,736} = 0.012 \text{ R\$/kWh} \quad (12)$$

Equation (13) is used to evaluate electrical efficiency of the cogeneration system.

$$\eta_e = \frac{\dot{W}_e}{\dot{E}_f} \quad (13)$$

The power supplied by the bagasse can be evaluated with Eq. (14).

$$\dot{E}_f = \dot{m}_b \cdot LHV_b \quad (14)$$

Maintenance cost is considered 3 % of the plant investment, depending of annuity factor and the equivalent period of utilization, such as Eq. (15).

$$c_m = \left(\frac{I_{pl} \cdot f}{H} \right) \cdot 1.03 \quad (15)$$

Steam production cost in cogeneration system is evaluated such as electric power energy cost with Eq. (16).

$$c_s = \frac{\left(I_{pl} \cdot f\right)}{H \cdot \dot{Q}_u} \cdot F_t + \frac{c_f \cdot \left(\dot{W}_e + \dot{Q}_u + \frac{P_{cr}}{2} \right) \cdot c_m \cdot F_t}{\dot{Q}_u} \quad (16)$$

The useful heat Rate factor is obtained with Eq. (17).

$$F_t = \frac{\dot{Q}_u}{\dot{W}_e + \dot{Q}_u} \quad (17)$$

The useful heat efficiency of the cogeneration system is evaluated with Eq. (18).

$$\eta_t = \frac{\dot{Q}_u}{\dot{E}_f} \quad (18)$$

Electric power and steam production costs are dependant of investment, design costs, installation and maintenance, also cost of fuel used, related to electric and thermal efficiencies in plant.

4.1. Annual saving evaluation

Annual saving expected is obtained with electricity generation saving (G_e) and thermal energy saving (G_t). Both factors are directly dependant of thermal energy production (steam production) and electric power generation costs, electric power generated and required in the process, operating time and local company electric power price - tariff, such as Eq. (19) and (20). According to Coronado (2007), the cost of steam production in conventional steam generator is 0.010 R$/kWh. The electricity tariff adopted is 0.1096 R$/kWh, according to local company of electric power distribution.

$$G_e = \dot{W}_r \cdot H \cdot (c_{co} - c_e) + \left(\dot{W}_e - \dot{W}_r \right) \cdot H \cdot \left(P_e - c_e \right) \quad (19)$$

$$G_t = \dot{Q}_u \cdot H \cdot \left(c_{csg} - c_s \right) \tag{20}$$

Annual saving expected is obtained with Eq. (21), where both savings are added.

$$AS = G_e + G_t \tag{21}$$

5. RESULTS AND DISCUSSION

Figure 2 shows the behavior of electricity production cost in cogeneration system, as a function of annual interest rate and payback. It is observed that a major annual interest rate improves electricity production cost, considering same payback periods.

The same observation can be viewed in steam production cost in cogeneration system, as a function of annual interest rate and payback period, Fig. 3.

In the Fig. 4 and 5 are showed the values for the payback period as a function of the surplus electricity price range of 0.080 to 0.120 R$/kWh. Because annual investment costs are sum of savings obtained with electric power generation and thermal energy production. When this value is negative means that costs associated to this plant with cogeneration system improved are bigger than costs of a conventional system (Tuna, 1999).

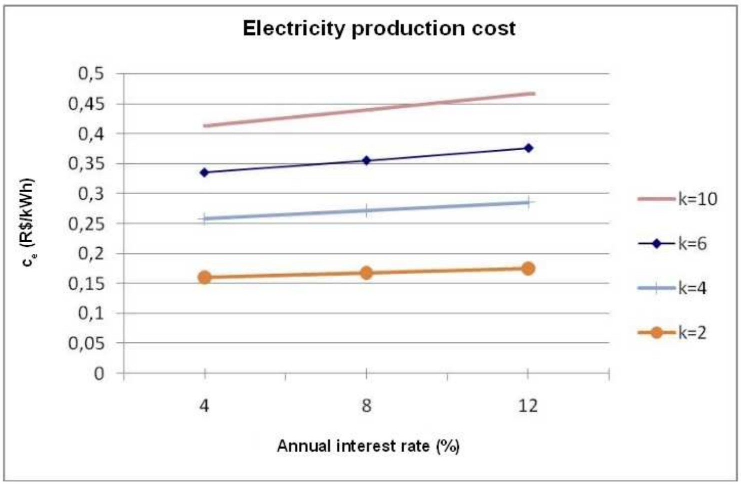

Figure 2. Electricity production cost (R$/kWh)

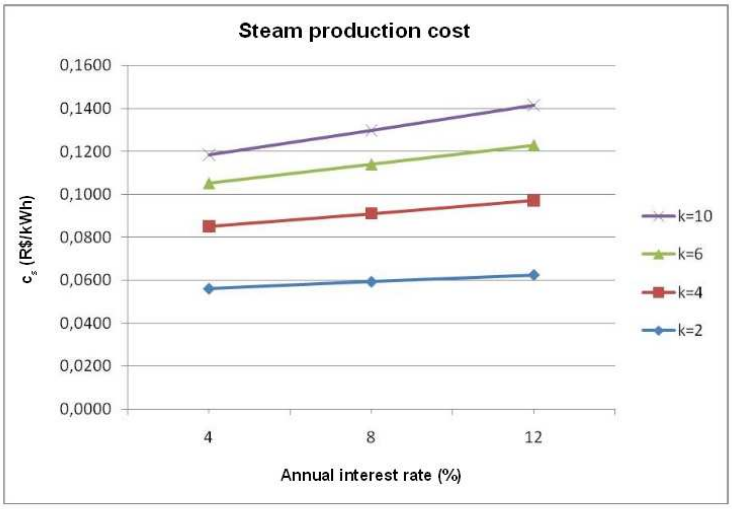

Figure 3. Steam production cost (R$/kWh)

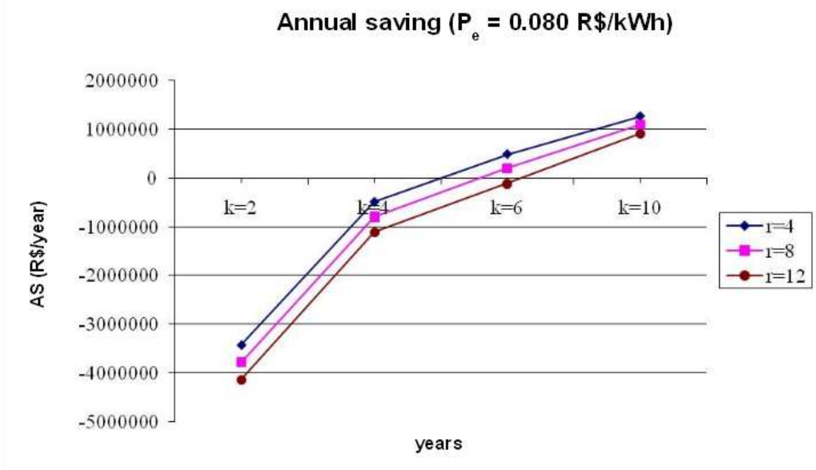

Figure 4. Annual saving considering P_e = 0.080 R$/kWh

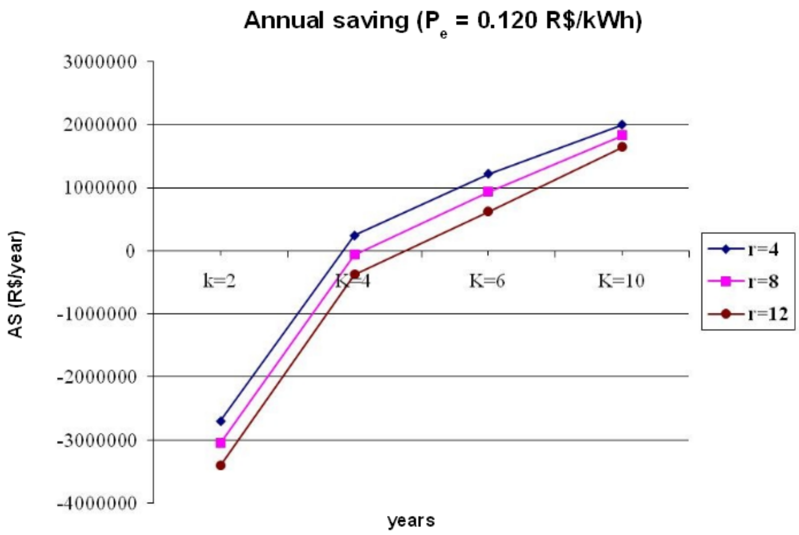

Figure 5. Annual saving considering P_e = 0.120 R$/kWh

6. CONCLUSIONS

This case-study showed applied in cogeneration system at Destilaria Pioneiros, presented the global efficiency of 70.4%, which is satisfactory when compared to literature. The electrical efficiency of the cogeneration system is 13.1% and the useful heat efficiency of the cogeneration system is 57.30%.

Also was possible to observe through cogeneration indexes, such as factor of energy use, the same energetic exploitation obtained with global performance evaluation. A short difference is demanded by power lost in pumping and into condenser. This last lost is considered for global performance evaluation, but is not for factor of energy use evaluation.

For Power and heat rate index is obtained a very low value what means that almost all electric power generated is used to produce thermal energy for the process, therefore surplus electric power is too short.

In economic analysis was possible to observe that electric power generation and steam production had a major cost of their production for major annual interest taxes with minor paybacks.

Although the electric energy generation surplus should be short, it is possible to sale it with the less price of 0.080R$/kWh and an interest rate of 12% per year, like this a six years payback is obtained.

A payback between 3.8 and 6 years can be obtained with the same interest rate for 0.080 R$/kWh and 0.120R$/kWh, respectively.

Is possible to confirm that cogeneration system proposed is technical and economical feasible to provide electricity and useful heat for Destilaria Pioneiros.

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