ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

THERMODYNAMIC, THERMOECONOMIC AND ECONOMICS ANALYSES OF A SUGARCANE MILL WITH DIFFERENT PRODUCTION MIXES OF SUGAR-ALCOHOL

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Abstract. *In this paper different settings for operation of a sugarcane mill that produces sugar, ethanol and electricity are presented. Some changes were made to different grindings, production mix and plant condensing capacity. A global analysis on a modern cogeneration plant that has undergone a recent expansion, with addition of a boiler and an extraction-condensation turbogenerator that operate at high pressure and high temperature is carried out. In this new configuration it is necessary purchase bagasse to meet the energy sale contracts. Through some tools and thermodynamic and economic concepts are made some comments regarding the viability and attractiveness of the investments.*

Keywords: *Energy, Cogeneration, Bagasse, Sugarcane Mill.*

1. INTRODUCTION AND OBJECTIVES

Currently there are 438 sugarcane factories in Brazil (182 in São Paulo state) but little more than 100 of these industries supply electricity to the electrical system (half of them in São Paulo state). This is due to the uncertainties in the sugarcane sector and the lack of a dedicated sectorial policy to stimulate investment needed to increase this participation in the energetic matrix. So, many projects are still waiting for more favorable conditions to be implemented (UNICA, 2012).

These investments not only involve the replacement of electrical generation systems, but also the upgrading of the industrial process of manufacturing sugar and ethanol to enable minimize the energy consumption to result in higher surplus electricity to the Brazilian electric system.

In São Paulo state, the recovery of part of the straw that is ceasing to be burned as a result of the Environmental Protocol established between the sugarcane mills and the government in 2007, presents a great opportunity to use this biomass for increase the energy generation. But, as the straw gathering, cleaning, preparation and burning also results in operational costs and need new technologies and investments, these initiatives are not much utilized yet.

Nowadays many studies show new opportunities to generate additional power for the sugarcane mills through reform and modernization of existing plants and/or through the use of straw and also the stillage to generate bioelectricity. Among them may be mentioned: Walter (1994); Carpio *et al.* (1999); Corrêa Neto (2001); Sánchez Prieto (2003); Fiomari (2004); Hassuani *et al.* (2005); Ensinas *et al.* (2007); Seabra (2008); Dantas (2010); Pellegrini and Oliveira Junior (2010); and Passolongo (2011).

It is estimated that Brazil's ability to produce energy through biomass of sugarcane can reach up to 13,000 MW, equivalent to 3 plants of Belo Monte (UNICA, 2012). For reaching this energy potential it is necessary not only investment in new plants but mainly in existing plants. Thus, this work can help some analysis for expansion of existing cogeneration projects in sugarcane sector.

2. CASES DESCRIPTION

All cases considered were defined based on a sugarcane mill in expansion in the western region of Sao Paulo state. The initial plant, before the expansion, was constituted basically by a boiler which produced 150 t/h of steam at 70 bar and 530 °C; an extraction-condensation turbogenerator (32 MW); a backpressure turbogenerator (10 MW) that was utilized only for backup of the system; and a desuperheater for reduction of the exhaust steam temperature (175 °C) to a point close the saturation by injecting water, allowing the heat exchange maximization on evaporators.

In this configuration the plant had a satisfactory global efficiency but the mix of sugar-alcohol production was limited to 40 % due to steam process demands, restricting the possibility for sale greater amounts of energy. So, for a mix of 40 % and considering the crush of 1,500,000 tons of sugarcane in 240 days of harvest, with an effective grinding of 306 tons of cane per hour (tc/h), were produced per day 8,120 sugar bags of 50 kg (or 1,948,800 bags per harvest), 370 m³ of ethanol (or 88,800 m³ per harvest) and 736.8 MWh of electrical energy (or 176,832 MWh per harvest), being 508.8 MWh commercialized (or 121,536 MWh per harvest).

Operating under these conditions, the time to recover the investment would be very long (about 13 years) and the rate of return would be very low (less than 5 %). This is due to high costs involved on the reform of this plant, in which were the replacement of the boilers and the modifications of facilities for the operation of the plant with higher levels of pressure and temperature, besides the electrification of the grinding, with no increase of generation capacity of steam; and also due to the high costs involved in electrical installations for energy exportation.

In order to increase the capacity for production of sugar and power, as originally planned in the project, the plant was modified with inclusion of a new boiler that produces 120 t/h of steam at 70 bar and 530 °C and an extraction-condensation turbine (25 MW). In this new configuration, presented in Figure 1, the plant will operate with two boilers and three turbines, varying the tracks grinding and the mix of sugar-alcohol production.

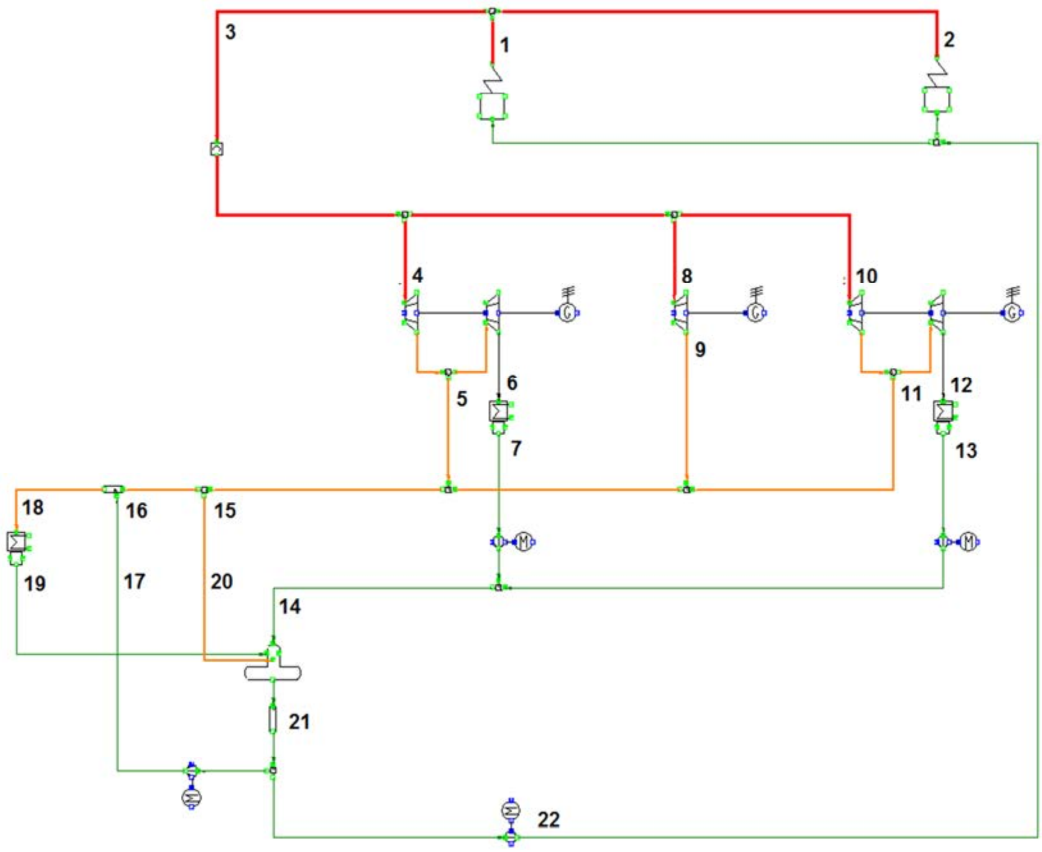

Figure 1. Thermal power plant of sugarcane mill after expansion.

It is important to say that in all cases after the expansion it is necessary to purchase bagasse to ensure the energy production for selling due to the limitation of crushing capacity, which is one of the factors that can result in the non-acceptance of the project through an economic analysis considering the point of view of energy generation. Before expansion there was an energy exportation contract of 84,000 MWh and after expansion was defined an additional contract of 88,000 MWh, resulting in a global production of 172,000 MWh of energy for selling.

3. METHODOLOGY

3.1 Thermodynamic analysis

Considering a steady-state process and assuming overall negligible kinetic and potential energy, the mass conservation as well as First and Second Laws of Thermodynamics for a control volume are represented in a simplified form by (Van Wylen *et al.*, 2003):

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

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

ISSN 2176-5480

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

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).

The energy analysis is incapable of taking into account the energy quality and irreversibility sources in the processes, being necessary the utilization of the exergy analysis for this purpose.

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

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

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

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

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 is evaluated by an expression presented by Szargut *et al.* (1988) that takes into account the correlation between the chemical exergy and Lower Heat Value of the fuel (LHV_{fuel}), considering its elementary composition, the ash content and the humidity, as follows:

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

being:

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

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 sugar plant based on the first Law of Thermodynamics ($\eta_{overall}$) is the ratio of useful energy, either thermal ($\dot{Q}_{useful}$) or electrical power available to exportation ($\dot{W}_{elec} - \dot{W}_{comp} - \dot{W}_{pump} - \dot{W}_{cons}$), and the power supplied to the system by the fuel ($\dot{m}_{fuel}\ LHV_{fuel}$) that is being utilized in the plant, according to:

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

where:

$\dot{W}_{cons}$: Electrical power consumed by the plant, milling, lighting and other equipment (kW);

$\dot{W}_{comp}$: Power consumed by the compressor system (kW);

$\dot{W}_{pump}$: Power consumed by the pumping system (kW);

$\dot{W}_{elec}$: Electrical power produced by the plant (kW).

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:

$$PHR = \frac{\dot{W}_{export}}{\dot{Q}_{useful}} \tag{10}$$

With respect to the thermal demand for the sugar-alcohol production, the relation vapor-sugarcane ($R_{steam,cane}$) represents the heat that is being utilized in the process, expressed by kilograms of steam per ton of sugarcane (kg_{steam}/tc):

$$R_{steam,cane} = \frac{\dot{m}_{steam}}{\dot{m}_{cane}} 1000 \tag{11}$$

It is recommendable to reduce this relation, so that the plant to be able to process the sugarcane with reduced steam demands.

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:

$$R_{power,cane} = \frac{\dot{W}_{export}}{\dot{m}_{cane}} \tag{12}$$

3.2 Thermoeconomic analysis

The thermoeconomic evaluation of the plant is based on Exergetic Costs Theory, 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):

$$\sum\left(\dot{C}_i\right)_k + \left(\dot{C}_w\right)_k = \left(\dot{C}_q\right)_k + \sum\left(\dot{C}_o\right)_k + \left(\dot{C}_e\right)_k \tag{13}$$

being:

$$\dot{C}_i = c_i\,\dot{E}x_i = c_i\left(\dot{m}_i\,ex_i\right) \tag{14}$$

$$\dot{C}_o = c_o\,\dot{E}x_o = c_o\left(\dot{m}_o\,ex_o\right) \tag{15}$$

$$\dot{C}_w = c_w \dot{W} \tag{16}$$

ISSN 2176-5480

$$\dot{C}_q = c_q \dot{Q} \tag{17}$$

$$\dot{C}_e = \frac{\left[C_e \left(f_a + f_{fom} + LF\ f_{vom} \right) \right]}{t_{oper}\ 3600} \tag{18}$$

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 (kW);
- $\dot{Q}$: Heat rate (kW);
- $\dot{W}$: Power (kW).

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):

$$f_a = \frac{\left[j\left(1+j\right)^N \right]}{\left[\left(1+j\right)^N - 1 \right]} \tag{19}$$

3.3 Economic analysis

Usually, the financial analysis of projects is based on estimative 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 deterministic indicators. However, these variables cannot be predicted with accuracy, indicating the importance of considering the risks associated with expected financial return for the project.

The more sophisticated technique 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 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 (Gitman, 2004):

$$NPV = \sum_{k=1}^{N} \frac{BEN}{\left(1+j\right)^k} - I \tag{20}$$

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 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 than 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:

$$\sum_{k=1}^{N} \frac{BEN}{\left(1+j^*\right)^k} - I = 0 \tag{21}$$

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.

3.4 Numerical solution

The solution of the equation system resulting from the thermodynamic analysis of each of the cases is obtained by employing the software IPSEpro® (SIMTECH IPSEPRO, 2003), whereas for the thermoeconomic and economic analyses was employed the software EES - Engineering Equation Solver (Klein and Alvarado, 1995).

4. RESULTS

4.1 Preliminary considerations

After the expansion, and removing some restrictions of the process, the harvest period considered was 260 days to be possible to increase the amount of sugarcane taking into consideration the design limit of milling (340 tc/h), which is corresponding to a grinding of 1,800,000 tc/harvest. The use of global time (the effective period of milling considering the charts for several factors) was 85 % and the recovery time of the generation sector and steam distribution was 98 %.

With operation of the new generator set, a new amount of energy was sold at market, which required a minimum generation of 39.3 MW during the harvest period for fulfillment of the energy contracts. The electricity consumed before the expansion was set at 31 kW per ton of cane milled and after the expansion it was fixed at 33 kW per ton of sugarcane. The averaged fiber contents in the sugarcane and in the bagasse were set, respectively, as 13.3 % and 48 %, resulting, in average, 277 kg per ton of sugarcane bagasse.

The cost of bagasse produced by grinding in the sugarcane mill was considered as US$ 2.50/t. After expansion of the plant, the bagasse produced is not enough to supply the consumption and it was necessary purchased bagasse externally by US$ 30.00/t.

The values of investment and the operation and maintenance costs were estimated through the historic of the unit, and the discount rate (*j*) utilized was 12 % per year. The annual cost of equipment with amortization was calculated taking into account a depreciation period (useful life) of 20 years and an interest rate of 12 % per year. It was considerate a sale price of electricity of US$ 75.00/MWh, that is close to the price currently practiced in the market.

The lower heating value (*LHV*) of bagasse was considerate as being 7,121 kJ/kg according to the analysis realized in the milling exit by CTC (Centro de Tecnologia Canavieira). The bagasse exergy was calculated taking into account its chemical composition, resulting 8,100 kJ/kg.

In the simulations performed, besides variations in the amount of sugarcane milled (1,500,000 to 1,800,000 tc/harvest), was considered the variation of *TRS* (Total Reduced Sugar) for the sugar production (product mix) from 40 to 80 % for each milling. It is also presented the result for the condition of maximum power generation, where the turbines operate with the maximum condensation rate (70 t/h).

In this work the reference temperature and pressure are considered, respectively, as T_0 = 298.15 K and P_0 = 101.3 kPa.

4.2 Thermodynamic results

Initially are presented in Table 1 the results for a power set at 39.3 MW, which is the minimum generation to meet the energy contracts, considering the variation of the milling per harvest (from 1,500,000 to 1,800,000 tons of cane) and mix production (from 40 to 80%). In such situations the total steam production ranged from 183 to 210 t/h at 70 bar and 530 °C, with the smallest flow position corresponding to the lower milling (1,500,000 tc/harvest) and mix of 40 % (40 % of *TRS* can be transformed into sugar or ethanol is converted into sugar and the remainder is used for ethanol production) and increased flow, corresponding to the situation of increased milling (1,800,000 tc/harvest) and mix of 80 %. In these situations the extraction-condensation turbines were operating so as to keep the steam required for the process with a fixed power of 39.3 MW, with a condensation rate ranging from 53 t/h to 19 t/h at 0.08 bar and 42 °C, being the highest condensation rate for milling of 1,500,000 tc/harvest with mix of 40 % and lowest for milling 1,800,000 tc/harvest with mix of 80 %. Steam extracted from turbines for utilization in the processes of heating, evaporation and crystallization ranged from 121 t/h to 189 t/h at 2.5 bar and 140 °C, being growing when milling and mix production increase. The electrical power sold ranged from 29.9 MW for milling 1,500,000 tc/harvest and 28.1 MW for milling of 1,800,000 tc/harvest.

Table 2 shows some thermodynamic parameters for generation of 39.3 MW as a function of mix production and

ISSN 2176-5480

milling. It is found that the overall efficiency of the plant tends to increase when the steam demand for processes increases. This is because for its calculation, besides the generated power, it is considered in the process the heat utilized for the juice evaporation. Thus, increasing the milling and/or the production mix, it is increased the power generated and steam flow to the process, and the overall efficiency of the plant will increase, if maintained the same rate of condensation. The overall efficiency is directly influenced by the condensation rate, although increasing the condensation rate allows a gain in power output, the performance is reduced because should take into account the heat required for steam condensation and the additional fuel used to raising the temperature of the condensate again to the boiler supply temperature.

Table 1. Operational conditions for generation of 39.3 MW as a function of mix production and milling.

Parameter	**Milling (tc/harvest)**	**Mix**				
		40 %	**50 %**	**60 %**	**70 %**	**80 %**
Bagasse Produced (t/h)	1,500,000	78.36	78.36	78.36	78.36	78.36
	1,600,000	83.58	83.58	83.58	83.58	83.58
	1,700,000	88.81	88.81	88.81	88.81	88.81
	1,800,000	94.03	94.03	94.03	94.03	94.03
Bagasse Consumed (t/h)	1,500,000	86.73	88.39	90.28	91.94	93.60
	1,600,000	88.39	90.19	92.04	93.84	95.73
	1,700,000	89.91	91.85	93.79	95.73	97.72
	1,800,000	91.42	93.51	95.64	97.63	99.76
Steam Produced (t/h)	1,500,000	183.00	186.50	190.50	194.00	197.50
	1,600,000	186.50	190.30	194.20	198.00	202.00
	1,700,000	189.70	193.80	197.90	202.00	206.20
	1,800,000	192.90	197.30	201.80	206.00	210.50
Steam Consumed (t/h)	1,500,000	121.67	130.68	139.68	148.68	157.68
	1,600,000	129.79	139.39	148.99	158.59	168.20
	1,700,000	137.90	148.10	158.30	168.50	178.71
	1,800,000	146.01	156.81	167.61	178.42	189.22
Steam Condensed (t/h)	1,500,000	53.00	49.00	44.00	40.00	35.00
	1,600,000	49.00	44.50	39.50	34.70	30.00
	1,700,000	45.20	40.00	34.90	29.80	24.60
	1,800,000	41.10	35.60	30.10	24.80	19.30
	1,800,000	28.1	28.1	28.1	28.1	28.1

Table 2. Thermodynamic parameters for generation of 39.3 MW as a function of mix production and milling.

Parameter	**Milling (tc/harvest)**	**Mix**				
		40 %	**50 %**	**60 %**	**70 %**	**80 %**
Heat Transfer Rate Process (MW)	1,500,000	76.7	81.9	88.1	93.3	99.2
	1,600,000	138.82	138.99	138.97	139.14	138.81
	1,700,000	86.7	93.2	99.5	105.9	112.4
	1,800,000	91.8	98.6	105.6	112.2	119.1
Heat Transfer Rate Condensation (MW)	1,500,000	31.4	29.1	26.1	23.7	20.8
	1,600,000	29.1	26.4	23.4	20.6	17.8
	1,700,000	26.8	23.7	20.7	17.7	14.6
	1,800,000	24.4	21.1	17.9	14.7	11.4
Overall Efficiency 1^{rst} Law (%)	1,500,000	43.81	47.34	51.50	54.75	58.54
	1,600,000	46.98	50.78	54.77	58.46	61.98
	1,700,000	49.85	54.04	57.98	61.77	65.48
	1,800,000	52.82	57.11	61.23	65.02	68.80
Specific Consume of Steam (kg_{steam}/kW)	1,500,000	4.66	4.74	4.85	4.93	5.03
	1,600,000	4.74	4.84	4.94	5.04	5.13
	1,700,000	4.82	4.93	5.03	5.14	5.25
	1,800,000	4.66	4.74	4.85	4.93	5.03
Power-Heat Rate *PHR*	1,500,000	0.39	0.37	0.34	0.32	0.30
	1,600,000	0.36	0.33	0.31	0.29	0.28
	1,700,000	0.33	0.31	0.29	0.27	0.26
	1,800,000	0.31	0.28	0.27	0.25	0.24
Steam-Cane Rate $R_{steam,cane}$ (t_{vapor}/tc)	1,500,000	0.65	0.67	0.67	0.69	0.70
	1,600,000	0.65	0.63	0.64	0.66	0.67
	1,700,000	0.59	0.60	0.62	0.63	0.64
	1,800,000	0.65	0.66	0.67	0.69	0.70
Electric Power-Cane Rate $R_{power,cane}$ (kW/tc)	1,500,000	138.82	138.99	138.97	139.14	138.81
	1,600,000	130.30	130.40	130.32	130.29	130.41
	1,700,000	122.71	122.66	122.65	122.65	122.65
	1,800,000	138.82	138.99	138.97	139.14	138.81

Table 3 shows the increase in the production of VHP Sugar, which is of interest to the plant because it is the most valued product, after installing the new boiler and new turbogenerator and with the possibility of the milling up to 1,800,000 tc/harvest and mix up to 80 % compared with the baseline situation where there were limitation of mix and milling (40 % and 1,500,000 tc/harvest, respectively). Just for comparison, for this minimum milling the sugar production which was 8.121 bags/day can reach 14,992 bags/day for a mix of 80 %. For this same mix and considering the maximum milling, it is possible to get a maximum output of 17,991 bags/day.

Table 3. Maximum production of sugar and etanol as a function of mix production and milling.

Mix	40 %		50 %		60 %		70 %		80 %	
Milling (tc/harvest)	**Sugar (bags/day)**	**Ethanol (m³/day)**	**Sugar (bags/day)**	**Ethanol (m³/day)**	**Sugar (bags/day)**	**Ethanol (m³/day)**	**Sugar (bags/day)**	**Ethanol (m³/day)**	**Sugar (bags/day)**	**Ethanol (m³/day)**
1,500,000	8,121	370	-	-	-	-	-	-	-	-
1,500,000	7,496	341	9,370	285	11,244	228	13,118	171	14,992	114
1,600,000	7,996	364	9,995	303	11,994	243	13,993	182	15,992	121
1,700,000	8,495	387	10,619	322	12,743	258	14,867	193	16,991	129
1,800,000	8,995	410	11,244	341	13,493	273	15,742	205	17,991	137

To increase electric power production and thereby increase the sale of the surpluses, keeping the same milling parameters, it should increase the steam flow rate for condensation, observing the limit of 40 t/h in the higher capacity turbine and 30 t/h in the other turbine. Keeping the bagasse production, according to the milling, there is a need to buy bagasse to meet the consumption, which may vary from 96.21 to 127.96 t/h, according to the milling and mix production.

Table 4 shows a comparison between the situation that the power was fixed at 39.3 MW to meet the amount of energy contracted (172,000 MWh), varying the grinding, and the maximum power produced and sold when the plant operates with maximum condensation rate (70 t/h) to different situations and mixes, without restriction in the power generated. It is noted that the exported energy, in the case of fixed output 39.3 MW, decreases with increasing milling, since it was determined the internal consumption of the plant in 33 kW/tc. In this way, the exported energy will have its lower value (172,000 MWh) for milling 1,800,000 tc/harvest and its highest value (183,000 MWh) for milling 1,500,000 tc/harvest, regardless of the mix adopted. When there is no restriction on the power generated, the exportation can go to 219,000 MWh, for milling 1,500,000 tc/harvest and mix of 40 %, and can reach up to 279,000 MWh for milling 1,800,000 tc/harvest and mix of 80 %.

Table 4. Maximum generation and selling of electric energy per harvest as a function of mix production and milling.

Mix	40 %		50 %		60 %		70 %		80 %	
Milling (tc/harvest)	**Prod. (MWh)**	**Sold (MWh)**	**Prod. (MWh)**	**Sold (MWh)**	**Prod. (MWh)**	**Sold (MWh)**	**Prod. (MWh)**	**Sold (MWh)**	**Prod. (MWh)**	**Sold (MWh)**
1,500,000	241,000	183,000	Energy produced and consumed fixed regardless of the production mix							
1,500,000	276,000	219,000	286,000	229,000	295,000	238,000	303,000	246,000	313,000	256,000
1,600,000	241,000	180,000	Energy produced and consumed fixed regardless of the production mix							
1,600,000	284,000	224,000	296,000	234,000	305,000	244,000	316,000	254,000	325,000	264,000
1,700,000	241,000	176,000	Energy produced and consumed fixed regardless of the production mix							
1,700,000	293,000	228,000	303,000	239,000	314,000	249,000	325,000	260,000	336,000	271,000
1,800,000	241,000	172,000	Energy produced and consumed fixed regardless of the production mix							
1,800,000	301,000	233,000	312,000	243,000	323,000	255,000	335,000	267,000	347,000	279,000

4.3 Thermoeconomic and economic results

The investments for expansion of the sugarcane mill were raised in about 50 million dollars, being realized in two stages of 55 million each, for a total installed capacity of 67 MW of generation and production of 270 t/h of steam at 70 bar and 530 °C.

The cost of electricity was calculated by Eq. (13), considering the flow of steam in the turbine, and the cost of steam, also calculated by flow of inlet of fuel, inlet of feed water and steam produced in the boiler, the specific cost of the flows of inlet and outlet gases of the boiler are considered null, and the specific cost of high and low vapor pressure were considered equal.

Table 5 shows the average cost of electricity production (*cw*), electric power sold and internal rate of return on investment (*IRR*) as a function of mix production and milling for generation of 39.3 MW. Observing the extremes, the energy cost will be US$ 28.78/MWh for milling 1,500,000 tc/harvest and mix of 40% or US$ 29.30/MWh for the same milling and mix of 80 %, since the bagasse consumption would increase from 86.7 to 93.6 t/h, increasing the need to purchase it, causing a reduction in the *IRR* from 10.83 to 10.36 %.

Table 6 shows the average cost of electricity production (*cw*), electric power sold and internal rate of return on

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investment (*IRR*) as a function of mix production and milling for condensation rate of 70 t/h. It is found that the energy cost will be US$ 30.27/MWh for milling 1,500,000 tc/harvest and mix of 40 % or US$ 31.77/MWh for the same milling and mix of 80 %, since the consumption of bagasse rise from 96.21 to 112.80 t/h. By the other side, the *IRR* would increase from 15.20 to 19.30 %.

Table 5. Average cost of electricity production, electric power sold and internal rate of return on investment as a function of mix production and milling, for generation of 39.3 MW.

Milling (tc/harvest)	Parameter	Mix				
		40 %	**50 %**	**60 %**	**70 %**	**80 %**
1,500,000	Average cost of electricity production (R$/MWh)	62.45	62.61	63.16	63.27	63.59
	Electric Power sold (MW)	29.9	30.0	30.0	30.0	29.9
	Internal rate of return on investment (%)	10.83	10.81	10.58	10.59	10.36
1,600,000	Average cost of electricity production (R$/MWh)	58.61	58.94	59.38	59.72	60.07
	Electric Power sold (MW)	29.4	29.4	29.4	29.3	29.4
	Internal rate of return on investment (%)	11.40	11.30	11.10	10.95	10.85
1,700,000	Average cost of electricity production (R$/MWh)	54.77	55.31	55.79	56.23	56.70
	Electric Power sold (MW)	28.8	28.7	28.7	28.7	28.7
	Internal rate of return on investment (%)	11.96	11.73	11.53	11.35	11.16
1,800,000	Average cost of electricity production (R$/MWh)	41.56	40.50	52.46	52.92	53.49
	Electric Power sold (MW)	28.1	28.1	28.1	28.1	28.1
	Internal rate of return on investment (%)	16.22	16.63	11.86	11.66	11.44

Table 6. Average cost of electricity production, electric power sold and internal rate of return on investment as a function of mix production and milling, for condensation rate of 70 t/h.

Milling (tc/harvest)	Parameter	Mix				
		40 %	**50 %**	**60 %**	**70 %**	**80 %**
1,500,000	Average cost of electricity production (R$/MWh)	65.69	66.70	67.61	68.16	68.95
	Electric Power sold (MW)	35.8	37.4	38.9	40.3	41.9
	Internal rate of return on investment (%)	15.20	16.20	17.20	18.30	19.30
1,600,000	Average cost of electricity production (R$/MWh)	62.82	64.10	64.97	66.05	66.77
	Electric Power sold (MW)	36.6	38.3	39.9	41.6	43.2
	Internal rate of return on investment (%)	16.90	17.90	19.00	20.10	21.20
1,700,000	Average cost of electricity production (R$/MWh)	60.16	61.40	62.53	63.56	64.51
	Electric Power sold (MW)	37.3	39.1	40.8	42.5	44.3
	Internal rate of return on investment (%)	18.50	19.60	20.80	21.90	23.10
1,800,000	Average cost of electricity production (R$/MWh)	57.70	58.90	60.28	61.53	62.68
	Electric Power sold (MW)	38.1	39.8	41.7	43.7	45.6
	Internal rate of return on investment (%)	20.10	21.30	22.50	23.70	24.90

Figures 2 and 3 show, respectively, the average cost of electricity production (*cw*) and internal rate of return on investment (*IRR*) and the Net Present Value (*NPV*) accumulated over the lifetime considered, as a function of mix production and milling, for generation of 39.3 MW.

Figures 4 an 5 show, respectively, the average cost of electricity production (*cw*) and internal rate of return on investment (*IRR*) and the cumulative cash flow actualized over the lifetime considered, as a function of mix production and milling, for the maximum condensation rate (70 t/h).

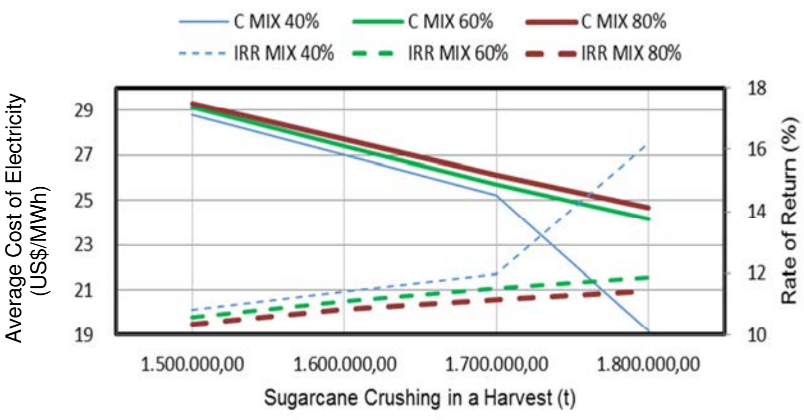

Figure 2. Average cost of electricity production and internal rate of return on investment as a function of mix production and milling, for generation of 39.3 MW.

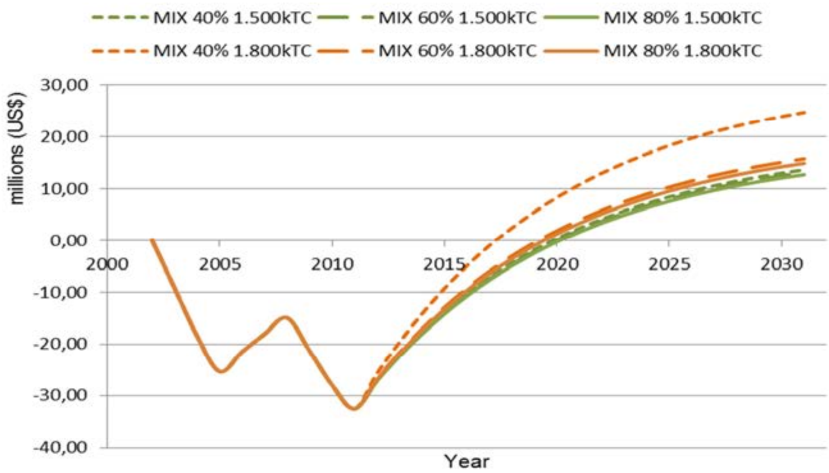

Figure 3. Cumulative cash flow actualized over the lifetime considered as a function of mix production and milling, for generation of 39.3 MW.

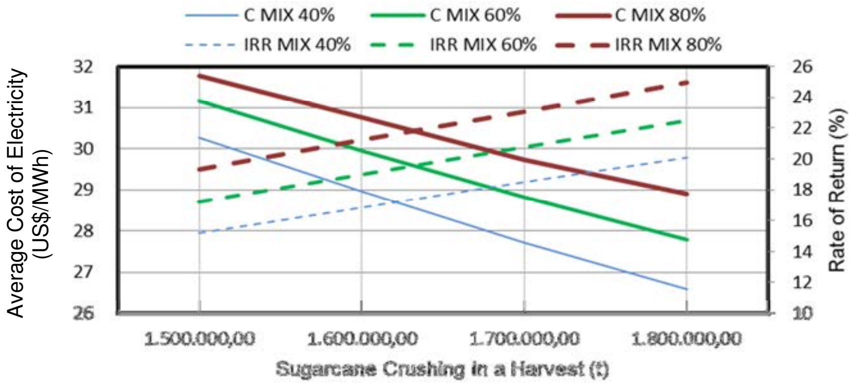

Figure 4. Average cost of electricity production and internal rate of return on investment as a function of mix production and milling, for the maximum condensation rate (70 t/h).

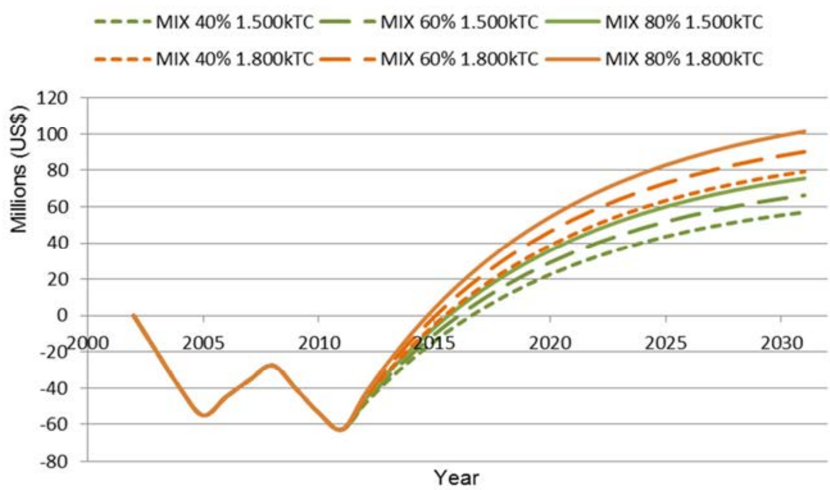

Figure 5. Cumulative cash flow actualized over the lifetime considered as a function of mix production and milling, for the maximum condensation rate (70 t/h).

For operation in a fixed power, from the economic point of view, it is more advantageous to seek a mix of low production, since the power generation can occur more efficiently with the possibility of higher flow for condensation and lower consumption of external bagasse.

ISSN 2176-5480

The increase of milling results in a large decrease in production cost, since the bagasse purchasing demand falls. It is interesting to note in Figure 3 that for a mix of 40 % and milling above 1,700,000 tc/harvest, there is a sharp drop in the cost of production, with a consequent sharp increase in the *IRR*. This is due to the fact that the production of bagasse is very close to its consumption, reducing the need to purchase (only 1 t/h for milling 1,700,000 tc/harvest) until it is no longer needed (there is a surplus of 2.6 t/h for milling 1,800,000 tc/harvest). In this case the return of the amount invested may occur between the years 2017 and 2020, depending on the available sugarcane and the production mix adopted.

5. CONCLUSIONS

Initially the sugar-alcohol factories worked with boilers at low pressure and temperature (around 22 bar and 290 °C), while enjoying the life of the equipment has reached the end to replace it by another. Now, with an additional investment, it was possible to work with high pressure and temperature, investing in cogeneration and initiate a process of electrification of mechanical drives and also the commercialization of surpluses.

With the installation of another boiler to supply steam enables increased mix of 40 to 80%. In practical terms, this gain, depending on the value of sugar on the market, may not be sufficient to implement the expansion of the entire thermoelectric but it is sufficient to install an additional boiler, that is the most expensive equipment of the expansion (40 % of the total cost), while the turbine is approximately 15 % of total cost. The economic analysis of this gain in sugar production was not taken into account in this work, being made only an economic analysis in relation to energy gains provided after the expansion for different situations mills, production mix, power output and condensation rate.

As the process increases the production mix for a given power generation specified, the efficiency of the plant increases slightly. On the other hand, there is a decrease in turbines efficiencies, because the generation of power decreases in the region of condensation, with an increase of the steam extracted. This increase in the mix also causes an increase in the consumption of bagasse, being necessary to purchase an additional amount, causing a small reduction in the internal rate of return on investment with an increase in the cost of energy produced, but in an overall analysis this facts should be compensated by the gain in the sugar production.

The need for additional external bagasse increase the cost of energy production for some values of purchasing and this prevents the generation of energy. In this situation should be purchased only the bagasse required to ensure the production of steam to meet the process. The cost of bagasse within reasonable values for generation enables the filling of condensation of turbo generators, enhancing the cost of energy because of the higher bagasse consumption for steam production, but increases the return for the surplus energy sold.

In general, the expansion of the plant is valid since it ensures operational flexibility in relation to the production mix, which provides additional gain to the possibility of further production of sugar and, together with the surplus energy produced, guarantees a return on invested capital.

6. ACKNOWLEDGEMENTS

The authors thank the sugar-alcohol factory Santa Adélia for supply the data needed for this work.

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