NATURAL GAS AND SUGAR CANE BAGASSE BASED COGENERATION SYSTEMS

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Abstract. *In the industry of sugar and alcohol the combined use of natural gas and sugar cane bagasse in cogeneration plants can generate steam and electricity for processes, as well as to allow the commercialization of surpluses. The yearly increase of electricity consumption in Brazil, the annual availability of sugar cane bagasse, and also the fact that the most important pipeline facility in Brazil crosses some regions of intense sugar cane production are the motivations to develop this study. The implementation of these cogeneration plants requests a detailed study that involves a discerning evaluation for the establishment of the best system option considering the fuels that will be used. This paper presents the comparative thermoeconomic analysis of four cogeneration systems designed for a sugar and alcohol mill that use natural gas and sugar cane bagasse as fuels. The thermoeconomic analysis developed for the cogeneration systems evaluates the exergy efficiency and the production costs of steam and electricity for each one of the cogeneration plants. It was verified that the choice of the best cogeneration plant considering the criterion of the minimum cost for kWh of energy produced is strongly influenced by the sugar cane bagasse price.*

Keywords*. cogeneration in sugar and alcohol mills; cofiring; thermoeconomic analysis.*

1. Introduction

According to the Ministry of the Mines and Energy, the brazilian installed capacity of electricity generation should increase 21.53% up to 2007, arriving to 109.3 thousand MW, and the sugar cane bagasse and the natural gas will have more and more strategic importance in the change of the brazilian energetic matrix. In agreement with the decennial plan of the ministry (2002/2011), the energy of the biomass - which has in the sugar cane bagasse its main generation source - will increase 56.13% up to 2007, corresponding to an installed power of 3,032 MW. Although relatively small, the biomass energy will start to have larger participation in the electricity generation in comparison to the one of the petroleum (diesel and fuel oil added), of the coal and of the nuclear and aeolic energy being lower than the hydroelectric generation and for the thermal ones by gas (Gazeta Mercantil, 2003 apud www.cenbio.org.br).

In the end of the last century the reality of the offer of the natural gas changed completely in Brazil due to the construction of the gas duct between Bolivia and Brazil, which crosses areas where sugar cane is produced. In the industry of sugar and alcohol, the combined use of natural gas and sugar cane bagasse in cogeneration plants can generate steam and electricity for processes, as well as to allow the commercialization of surpluses.

In this paper, configurations of cogeneration plants using natural gas and sugar cane bagasse are studied. The work consists of the evaluation of the exergetic efficiency and of the determination of the best option considering the minimum-cost criterion per kWh of energy produced. For this, a thermoeconomic analysis was accomplished with an evaluation of the costs of steam production and of electricity on an exergetic basis.

2. Natural gas and sugar cane bagasse

The intensification of the emissions of gases, mainly of carbon dioxide (CO_2), resulting from the burn of fossil fuels is provoking the excessive heating of the earth. It is considered that the use of fossil energy is responsible for 57% of the total of the emissions of gases that generate the greenhouse effect.

In substitution to the fossil fuels, the natural gas provokes a reduction in the emissions of CO_2, from 20 to 23% unless the fuel oil, and from 40 to 50% unless the solid fuels, as coal. In the current technological development of the use of fossil fuels, the natural gas is the least pollutant. The use of natural gas in appropriate gas burning equipments, also eliminates the emission of oxide of sulfur, soot and particulate materials, while the carbon monoxide emissions

(CO) and oxide of nitrogen (NO_X) can be well controlled (Cenbio, 2000).

In Tab. (1), the emission factors of greenhouse effect gases are presented for the main fuels, including natural gas and sugar cane bagasse. It is verified that the factors of emission of carbon (C), carbon monoxide (CO) and nitrogen oxide (NO_X) of the fossil fuels are larger than those for natural gas, and significantly larger than sugar cane bagasse.

Table 1. Emission factors of greenhouse effect gases for the main fuels (Cenbio, 2000).

	Emission factors (t/TJ)			
	C	**CO**	**CH_4**	**NO_x**
Fuel oil	21.10	0.015	0.003	0.161
Diesel oil	21.81	0.990	0.220	0.990
Natural gas	15.30	0.017	0.002	0.067
Firewood	0.00	0.002	0.015	0.115
Coal	26.80	0.093	0.002	0.329
Sugar cane bagasse	0.00	0.002	-	0.088

The natural gas presents other advantages in relation to the most traditional fuels as the fuel oil, coal and other. The use of natural gas makes possible high thermal income and it allows the control and simple tuning of the combustion, in means of an appropriate mixture between fuel and oxygen.

Alternatives of natural gas offer are growing in Brazil. Particularly, the gas duct Bolivia - Brazil, that begins in Campo Grande (Bolivia) and finishes in Canoas (RS) in Brazil, transports Bolivian gas for the South, Southeast and Center - West of Brazil. The construction of the gas duct was planned in two stages: the first stage (1970 km), initiated in 1998, is the north line of the gas duct, that begins in Bolivia, arrives in Paulínia (SP) and proceeds for an extension to Guararema (SP), in Brazil; the second stage (1180 km), begins in Paulínia (SP) and proceeds for Canoas (RS).

The natural gas of Bolivia presents high tenor of methane and ethane, reaching 97% of the total mass, what results in a gas of high heating value. In Tab. (2) the characteristics of this gas, supplied by the Bolivian company of petroleum YPFB - Yacimientos Petrolíferos Fiscales Bolivianos, are presented.

Table 2. Composition and lower heating value of the bolivian natural gas.

Componente	**Fórmula**	**% Molecular**
Methane	CH4	91.80
Ethane	C2H6	5.58
Propane	C3H8	0.97
I – Butane	C4H10	0.03
N – Butane	C4H10	0.02
Pentane	C5H12	0.10
Nitrogen	N2	1.42
Carbonic gas	CO2	0.08
TOTAL		100.00
Lower heating value		48,400 kJ/kg

Since July of 1999, Bolivia exports about 2.2 million cubic meters a day of natural gas to the market of the Southeast region of Brazil. In 2002, Brazil should be mattering about 12 million cubic meters a day of Bolivian gas. Starting from 2003, other 18 million cubic meters a day (of Bolivia or Argentina) should be added to complete the 30 million cubic meters a day that constitute the maximum capacity of transport negotiated for the gas duct (Santos, 1999).

According to the Ministry of the Mines and Energy, today to 2007 the participation of the natural gas in the national energy matrix will increase from 5.83% to 7.93%, and the one of the biomass, of 2.16% for 2.77%. Nowadays, the energy of the sugar cane bagasse is of 1,105 MW, and more of the half of this power is used internally to move the sugar and alcohol mills. According to entrepreneurs of the sector, less than 500 MW are marketed indeed during the harvest to the dealerships of electricity. The energetic potential of the sugar cane is 1.125 times superior that of the one of petroleum. That means that 320 million tons of sugar cane - annual volume foreseen for the next harvests -, including the broth, the bagasse and the straw, are equal to 360 million barrels of petroleum, in other words, to the Brazilian production of 225 days. The ministry studies a tariff for the biomass energy, in the extent of the Program of Incentive to Alternative Sources for Electric Power (Proinfa), that still was not regulated (Gazeta Mercantil, 2003 apud www.cenbio.org.br).

The sugar cane after the crop is prepared and put in mills, being extracted the juice that will be used in the sugar and alcohol production. The bagasse resulting from the grinding process, in the proportion of 30% in weight, has 50% of humidity and lower heating value of 10,470 kJ/kg as shown in Tab. (3).

Table 3. Sugar cane bagasse chemical composition (Kilicaslan, 1997)

Component	Formula	%
Water	H_2O	50.00
Carbon	C	25.40
Oxygen	O	20.00
Hydrogen	H	2.80
Ash	-	1.80
TOTAL		100.00
Lower heating value		10,460 kJ/kg

In the State of São Paulo (and, in smaller scale in the remaining of the country) practically all of the industries in the sector of sugar and alcohol are self-sufficient, in relation of the enormous amount of sugar cane bagasse generated in the cane processing (approximately 96 million tons produced at the country in 1998 and 1999). As the sugar cane bagasse represents a problem for the industry, there is no interest in investing in more efficient processes, what would result in still more useless bagasse (Cenbio, 2000).

3. Cogeneration systems

In cogeneration plants the simultaneous production of electricity or mechanical power and steam for process, can be done starting from a single source of energy that can be natural gas, fuel oil, biomass, etc. Because of the use of an effluent flow of energy, the cogeneration systems can operate with larger efficiencies than those found when the heat and the work are produced in separate processes.

The great industrial consumers of natural gas were the ones that began the installation of units of cogeneration, constituted of gas combined cycle units, with partial extraction of the steam for their industrial needs. In combined cycles the natural gas can be used as a fuel of gas turbine in order to generate electricity and its exhaust gas used as the energy input of a Rankine Cycle. In sugar cane mills the production of electricity can also be obtained by means of burning sugar cane bagasse in the boilers.

For the simultaneous production of electricity and steam it can be used a condensation and extraction turbine, in the process CEST - Condensing Extraction Steam Turbine. Part of the steam is extracted of the turbine in an intermediate pressure for use in processes. The remaining part of the steam expands in the turbine until the pressure of the condenser, it condenses and it returns to the boiler together with the condensed of the process. This process presents the best results in the electric power production (Coelho, 1992).

4. Selecting cogeneration systems

In the industry of sugar and alcohol the combined use of natural gas and sugar cane bagasse in cogeneration plants can generate steam and electricity for processes, as well as to allow the commercialization of surpluses. The implantation of these cogeneration systems requests a detailed study that involves a discerning evaluation for the establishment of the best system option in function of the fuels that will be used.

In this paper cogeneration systems were studied for the verification of the best option considering criterion of minimum cost for kWh of produced energy, using natural gas and sugar cane bagasse. Thermoeconomic analysis was accomplished starting from the results of plants simulation and field data. Finally, it was accomplished evaluation of the cost of the electric power and steam in function of the price of the sugar cane bagasse.

The cogeneration plants proposed and studied in this work are:

- **System A**: composed by a combined cycle based system with cogeneration using only natural gas as fuel of the gas turbine and a heat recovery steam generator operated only with the turbine exhaust gas, presented in Fig. (1);
- **System B:** is based on system A with another steam generator that uses sugar cane bagasse as fuel and generates steam to increase the power of the steam turbine, presented in Fig. (2).
- **System C:** is based on system B, with boiler air preheater, presented in Fig. (3).
- **System D:** is based on system A with a heat recovery steam generator that burns sugar cane bagasse with the exhaust gases of the gas turbine, presented in Fig. (4).
- **System E**: is based on system B, with the steam generator disabled during the time between sugar cane harvests (six months), presented in Fig. (2).

System A is used as a comparison reference for the other systems.

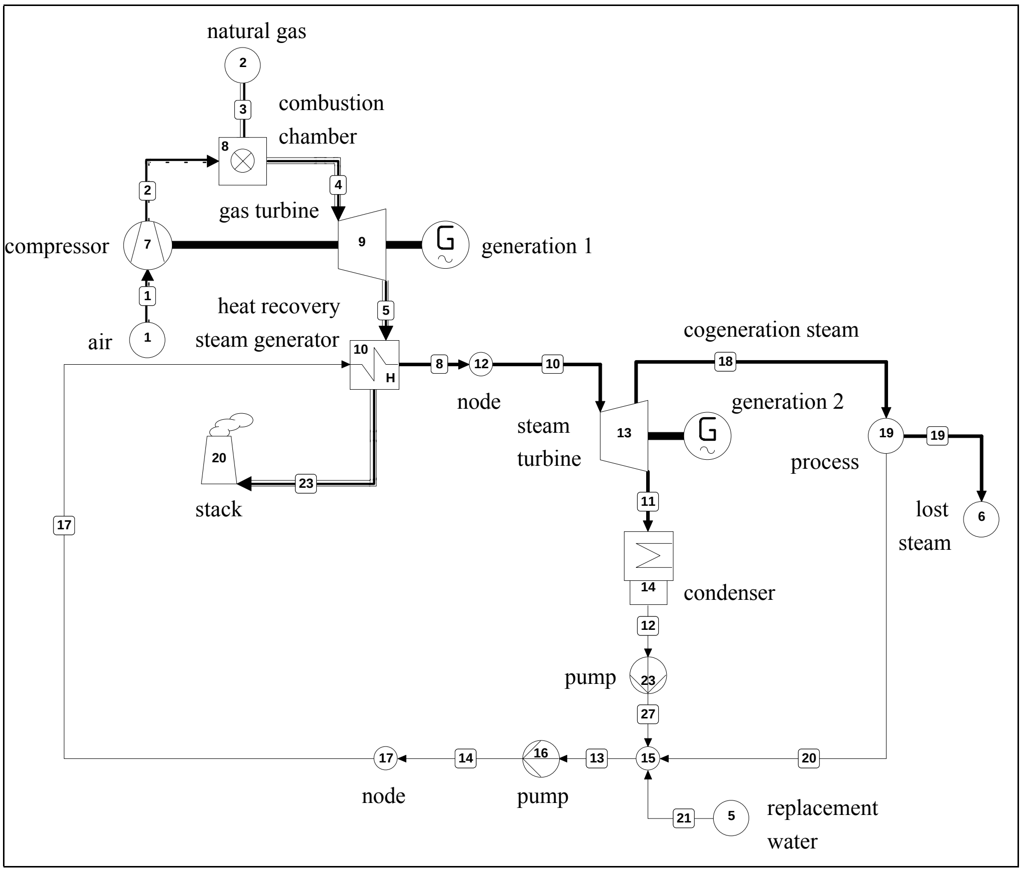

Figure 1. Combined cycle based system with cogeneration using only natural gas **(System A)**.

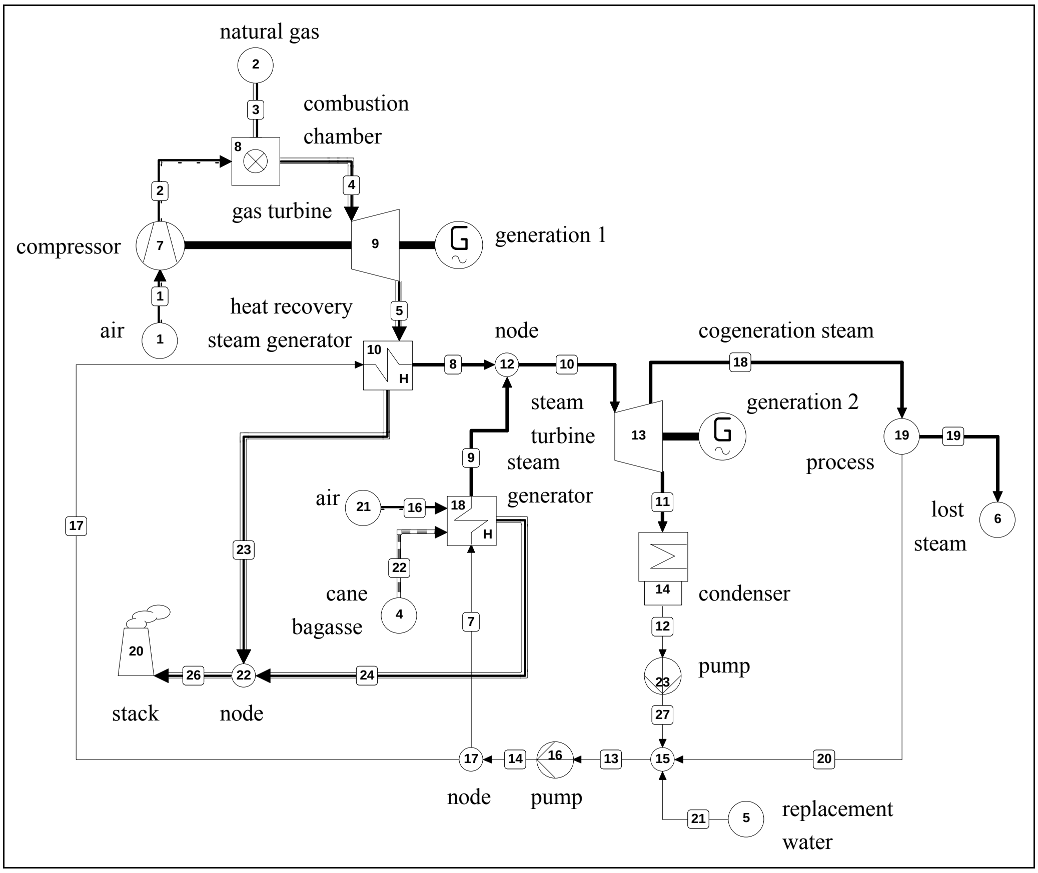

Figure 2. System A with another steam generator that uses sugar cane bagasse **(System B)**.

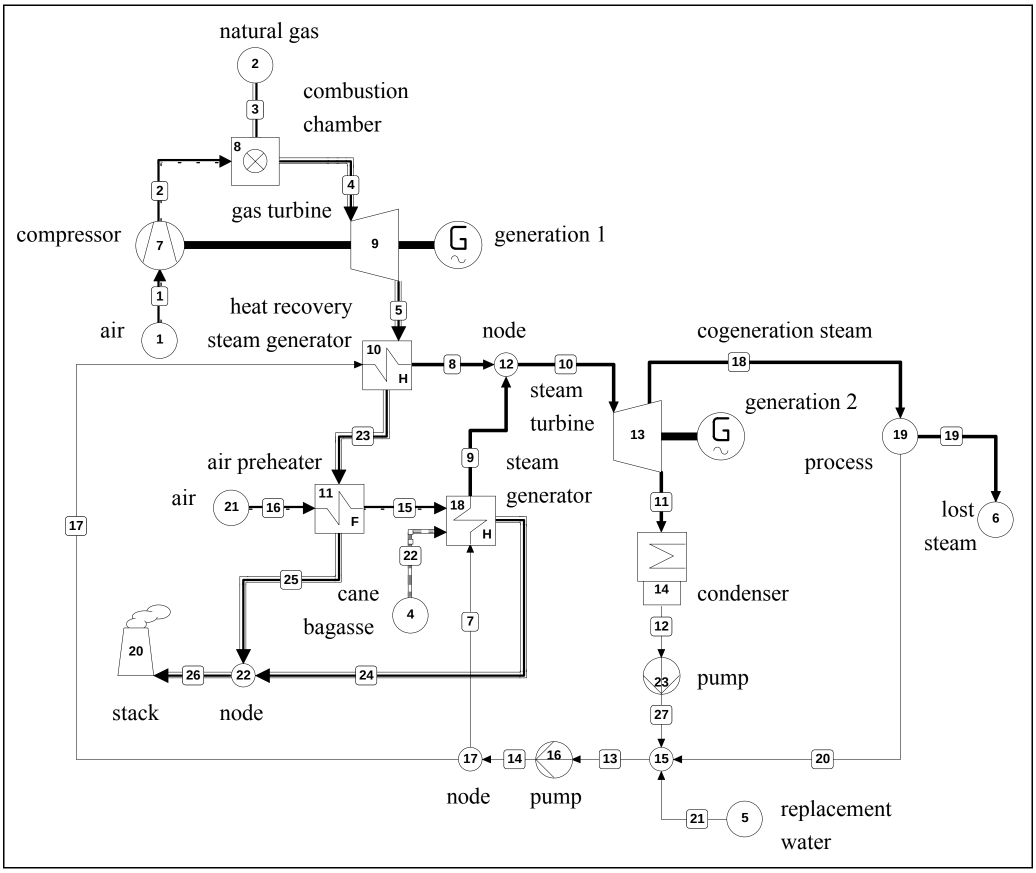

Figure 3. System B, with boiler air preheater **(System C)**.

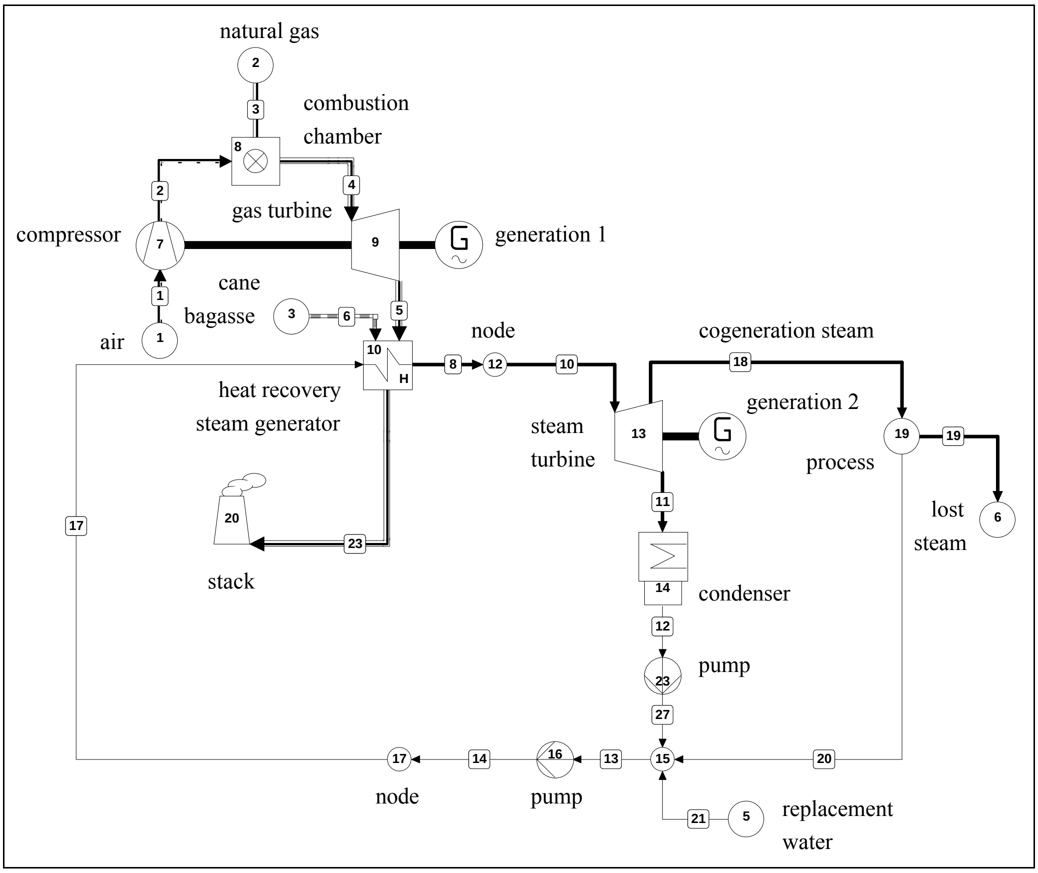

Figure 4. System A with a heat recovery steam generator that burns sugar cane bagasse with the exhaust gases of the gas turbine **(System D)**.

4.1. Operational conditions

The operational conditions presented in Tab. (4) were adopted for the simulation of the cogeneration plants, using the computational program Cycle Tempo (Cycle tempo, 1999).

Table 4. Operational conditions.

Air mass flow (kg/s)	277.78 kg/s
Sugar cane bagasse mass flow	15.86 kg/s
Environment temperature	25ºC
Temperature in tube 4	1,200ºC
Temperature in tubes 8, 9 e 10	520ºC
Environment pressure	100 kPa
Pressure in tubes 2, 3 e 4	1,600 kPa
Pressure in tubes 5, 15, 16, 23, 24 e 26	100 kPa
Pressure in tubes 7, 8, 9, 10, 14 e 17	7,000 kPa
Pressure in tubes 11 e 12	10 kPa
Compressor efficiency	83%
Combustion chamber efficiency	94%
Heat recovery steam generator efficiency	68%
Steam turbine efficiency	90%
Gas turbine efficiency	87%
Generator efficiency	90%

The operational conditions regarding the steam extraction for process were based on real plant with the following characteristics (Vertiola and Oliveira Jr., 1996):

- 77% of the turbine entrance steam mass flow is extracted for the cogeneration process at a pressure of 0.25 MPa;
- 35% of the process flow is lost in the steam form and condensed contaminated;
- mass flow replacement comes from an external source with environment temperature;
- the cost of the replacement water is 0.40 US$/t.

4.2. Thermoeconomic analysis

In the cogeneration plants two products exist whose generation costs should be calculated. In this case there is the need of thermoeconomic analysis. That consists of the balance of costs in exergetic basis application (Bejan; Tsatsaronis and Moran, 1998).

The cost balance can be made for any equipment and component of the system in cost terms (US$/s), as presented by the equation below (Garagatti, 2000):

$$\sum c_{prod} \cdot Ex_{prod} = \sum c_{inp} \cdot Ex_{inp} + C_{equip} \tag{1}$$

where c_{prod} is the product cost (US$/MWh), Ex_{prod} is the product exergy rate (kW), c_{inp} is the input cost (US$/MWh), Ex_{inp} (kW) is the input exergy rate and C_{equip} (US$/ano) is the equipment cost.

The extraction method was used for the determination of the specific production costs of the utilities. This method applied to the gas turbine and to the steam turbine supplies the relationships:

$$c_3 = c_5 \tag{2}$$

where c_3 is the natural gas cost and c_5 is the turbine exhaust gas cost;

$$c_{10} = c_{11} = c_{18} \tag{3}$$

where c_{10} is the inlet turbine steam cost, c_{11} is the outlet turbine steam cost and c_{18} is the steam cost for process..

The cost of the natural gas to the consumer was adopted in agreement with the market values, varying around 140.0 US$/t ($2.90 \cdot 10^{-3}$ US$/MJ). The cost of the sugar cane bagasse adopted was 7.0 US$/t ($0.67 \cdot 10^{-3}$ US$/MJ).

The gas turbine cost adopted was 400 US$/kW, the pump cost was 30,000 US$ and the condenser cost was 340,000 US$ (Teixeira and Oliveira Jr., 2001). The other equipment costs can be given by the following equations (Garagatti, 2000):

$$I_{boiler} = 768 \cdot Q^{0.78} \quad (4)$$

where, I_{Boiler} is the boiler cost (US$) and Q is the boiler heat capacity (kW).

$$I_{ST} = 17{,}082 \cdot W_{ST}^{0,68} \quad (5)$$

where I_{ST} (US$) is the steam turbine cost and W_{ST} is the steam turbine power (kW).

Set of equations

Applying the cost balance to system C (figure 3), as example, the following set of equations will be obtained:

$$C_{GT} + c_3 \cdot Ex_3 = c_{e1} \cdot W_{e1} + c_3 \cdot Ex_5 \quad (6)$$

where, C_{GT} (US$/s) is the cost of the gas turbine, c_{e1} (US$/MWh) is the cost of the electricity generated by the gas turbine and $\dot{W}_{e1}$ (kW) is the electricity generated by the gas turbine.

$$C_{HR} + c_3 \cdot Ex_5 + c_{17} \cdot Ex_{17} = c_8 \cdot Ex_8 + c_8 \cdot Ex_{23} \quad (7)$$

where, C_{HR} (US$/s) is the cost of heat recovery steam generator.

$$C_{SG} + c_{15} \cdot Ex_{15} + c_6 \cdot Ex_6 + c_7 \cdot Ex_7 = c_9 \cdot Ex_9 \quad (8)$$

where C_{SG} (US$/s) is the cost of steam generator.

$$C_{ST} + c_{10} \cdot Ex_{10} = c_{10} \cdot Ex_{11} + c_{10} \cdot Ex_{18} + c_{e2} \cdot W_{e2} \quad (9)$$

where, C_{ST} (US$/s) is the cost of steam turbine, c_{e2} (US$/MWh) is the cost of electricity generated by the steam turbine and $\dot{W}_{e2}$ is the electricity generated by the steam turbine (kW).

$$C_{CD} + (2 \cdot c_P) + c_{10} \cdot Ex_{11} + c_{20} \cdot Ex_{20} + c_{21} \cdot Ex_{21} = c_{14} \cdot Ex_{14} \quad (10)$$

where, C_{CD} (US$/s) is the cost of condenser and c_P (US$/s) is the cost of pump.

$$C_{AP} + c_8 \cdot Ex_{23} = c_{15} \cdot Ex_{15} \quad (11)$$

where, C_{AP} (US$/s) is the cost of air preheater.

Steam for the process:

$$c_{10} \cdot Ex_{18} = c_{20} \cdot Ex_{20} + c_{20} \cdot Ex_{19} + c_{PS} \quad (12)$$

The costs of equipment, C_{equip} are function of the amortized costs (Ca_{equip}):

$$C_{equip} = \frac{Ca_{equip}}{T_0} \quad (13)$$

where T_0 are the annual operation hours. In this paper 7.000 h were adopted.

$$Ca_{equip} = I_{equip}\left(f_a + f_{omf} + FC \cdot f_{omv}\right) \quad (14)$$

where f_a is the amortization factor, which is function of the amortization time (20 years) and the annual interests (12%), f_{omf} is the fixed annual operation and maintenance cost (1%), f_{omv} is the variable annual operation and maintenance cost (9%) and FC is the load factor (75%).

4.3. Exergetic efficiency

The exergetic efficiency of the cogeneration plants is given by:

$$\eta_{ex,cl} = \frac{\dot{W}_{e1} + \dot{W}_{e2} - \dot{W}_p + \dot{m}_{18} \cdot ex_{18} - \dot{m}_{20} \cdot ex_{20}}{\dot{m}_{NG} \cdot ex_{NG} + \dot{m}_B \cdot ex_B + \dot{m}_{21} \cdot ex_{21}} \tag{15}$$

where $\dot{W}_{e1}$ is the electricity generated by the gas turbine (kW), $\dot{W}_{e2}$ is the electricity generated by the steam turbine (kW), $\dot{W}_p$ is the power consumed by the pumps (kW), $\dot{m}$ is the mass flow, ex is the especific exergy (kg/s), the subscript 18 is the steam for process, 20 is the steam from process and 21 is the replacement water, NG and B refers to natural gas and sugar cane bagasse, respectively.

4.4. Results

The electricty and the steam flow generated by each system are presented in Tab. (6), where $\dot{W}_{e1}$ is the electricity generated by the gas turbine (kW), $\dot{W}_{e2}$ is the electricity generated by the steam turbine (kW) and $\dot{m}_s$ is the steam for process (kg/s).

Table 6. Power and mass flow generated by each system.

Mass flow and power \ Systems		A	B	C	D	E
$\dot{m}_s$	kg/s	30.3	62.1	65.0	63.1	46.2
$\dot{W}_{e1}$	kW	71,118	71,118	71,118	71,118	71,118
$\dot{W}_{e2}$	kW	29,078	59,538	62,365	60,547	44,308

The costs of electricity and steam generation, as well as the exergetic efficiency of the cogeneration plants, are presented in Tab. (7), where c_{steam} is the cost of steam for process, c_{e1} e c_{e2} are the electricity generation costs refer to generators 1 and 2 (gas turbine and steam turbine), c_m is the weighted medium cost between c_{e1} and c_{e2}, and η_{ex} is the exergetic efficiency.

Table 7. Exergetic efficiency and costs of electricity and steam generation.

Costs and efficiency \ Systems		A	B	C	D	E
c_{steam}	US$/t	3.49	2.97	2.90	2.36	3.98
c_{e1}	US$/MWh	33.39	33.39	33.39	33.39	33.39
c_{e2}	US$/MWh	45.61	34.13	33.42	33.37	49.61
c_m	US$/MWh	36.94	33.72	33.40	33.38	39.62
η_{ex}	%	54	43	44	44	55

More details of some results presented in the table 7 can be found in Leite (2003).

4.5. Results analysis

The cost of the electricity generated by the gas turbine was equal for all the plants, as it is demonstrated in Tab(7). The smallest cost of electricity generated by the steam turbine was of the cogeneration plant with natural gas and addition of sugar cane bagasse in the heat recovery steam generator (system D) with value around 33.37 US$/MWh.

5. Evaluation of the electricity and steam cost generation as a function of the price of the sugar cane bagasse

In Fig. (5) results of the electricity cost generation as a function of the price of the sugar cane bagasse are presented. The results presented in the Fig(5) show that:

a) $c_B < 7{,}6$ US$/t, the use of **system D** is recommended;

b) $7{,}6$ US$/t $< c_B < 25{,}6$ US$/t, the use of **system C** is recommended;

c) $c_B > 25{,}6$ US$/t, the use of **system A** is recommended (without the use of sugar cane bagasse).

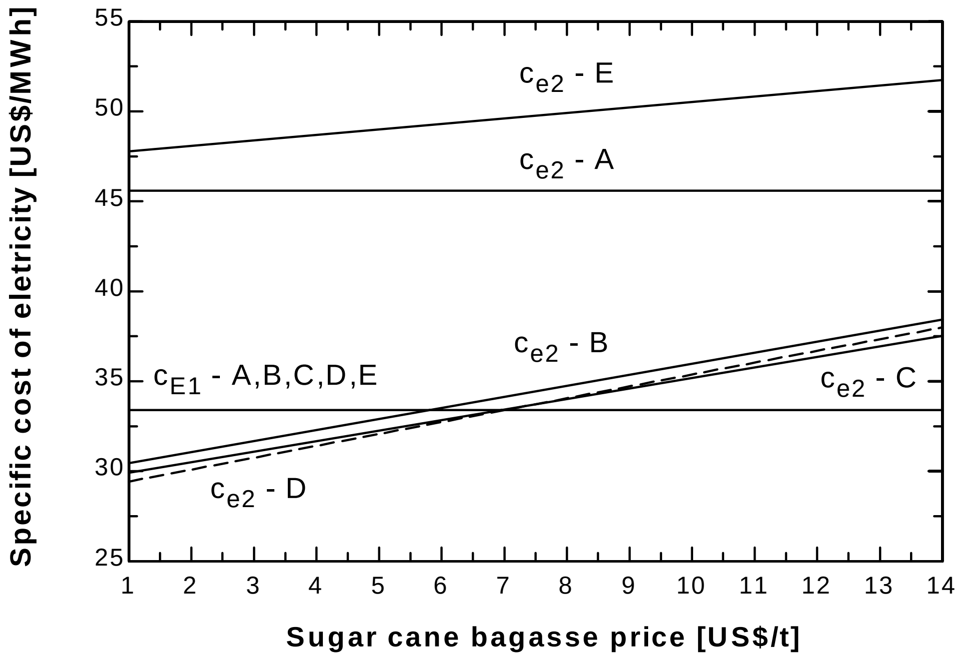

Figure 5. Sugar cane bagasse price vs. electricity generation cost

In Fig. (6) results of the cost of steam generation for process as a function of the price of the sugar cane bagasse are presented.

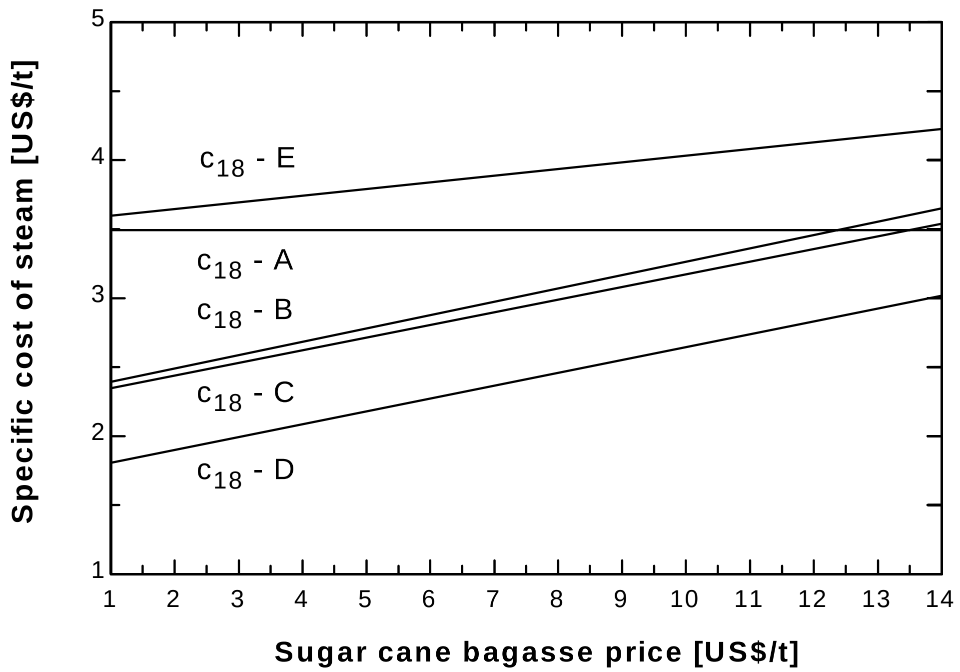

Figure 6. Sugar cane bagasse price vs. steam generation cost

The results presented in Fig. (6) show that the use of sugar cane bagasse is justified for:

a) $c_B < 19.1$ US$/t (system D);

b) $c_B < 13.5$ US$/t (system C);

c) $c_B < 12.4$ US$/t (system B);

For the results presented in Fig. (5) and (6) it is verified that in all of the analysed systems the price of the sugar cane bagasse can be above the reference value (7.00 US$/t) and, even so, the costs of electricity and of the steam will be lower than those produced in the plant that uses only natural gas.

6. Concluding remarks

The results show that the cogeração plants that use natural gas and sugar cane bagasse are much more economical than the ones that just use natural gas, with 32% in the cost of the steam and 27% in the cost of electricity generated by the steam turbine, for prices of the natural gas and sugar cane bagasse 140,0 US$/t and 7,0 US$/t, respectively.

The cogeneration plant that presents the best result is composed of a gas turbine that uses natural gas as fuel, a heat recovery steam generator that burns sugar cane bagasse with the gas turbine exhaustion gases and a condensation-extraction steam turbine (system D).

The results show that the use of natural gas and sugar cane bagasse in cogeneration plants is a viable alternative and it can be quite attractive.

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