THERMOECONOMIC ANALYSIS OF BIG GT CC COGENERATION PLANT

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Abstract. *Using Thermoeconomics as a tool to identify the location and magnitude of the real thermodynamics losses (energy waste, or exergy destruction and exergy losses) it is possible to assess the production costs of each product (electric power and heat) and the exergetic and exergoeconomic cost of each flow in a cogeneration plant and to assist in decision – marketing procedures concerning to plant design, investment, operation and allocations of research funds. Thermoeconomic analysis of Biomass Integrated Gasification Gas Turbine Combined cycle (BIG GT CC) cogeneration plant for its applications in sugar cane mills brings the following results: (i) the global exergetic efficiency is low; (ii) the highest irreversibilities occur in the following equipment, by order: scrubber (38 %), gas turbine (16 %), dryer (12 %), gasifier and HRSG (6 %); (iii), due to the adopted cost distribution methodology, the unit exergetic cost of the heat (4,11) is lower than electricity (4,71); (iv) the lower market price of biomass is one of the most sensible parameter in the possible implementation of BIG-GT technology in sugar cane industry; (v) the production costs are 31 US$/MWh and 32 US$/MWh for electricity and heat respectively. The electricity cost is, after all, competitive with the actual market price. The electricity and heat costs are lower or almost equal than other values reported for actual Rankine cycle cogeneration plants.*

Key words: *Thermoeconomic analysis, Exergy, BIG-GT, Gas turbine, Biomass*

1. INTRODUCTION

Classical thermodynamics provides, among others, the concepts of energy, energy transfer by heat and work, energy balance, entropy, and entropy balance, as well as relations for calculating thermodynamic properties at equilibrium. The second law of thermodynamics complements and enhances an energy balance by enabling the calculation of both the true thermodynamic value of an energy carrier, and the actual thermodynamic inefficiencies and losses from process systems. The concept of exergy is extremely useful for this purpose (Tsataronis, 1993).

Exergy is the maximum work attainable from an energy carrier under the conditions imposed by a given environment. The exergy of an energy carrier is a thermodynamic property that depends on both the state of the carrier being considered and the state of the environment. It expresses the maximum capability of the energy carrier to cause changes (Gaggioli, 1983). Thus, exergy is not only an objective measure of thermodynamic carrier; it is also very closely interrelated to the economic value of the carrier because users pay for the potential of energy to cause changes. When cost is assigned to energy carriers, exergy, rather than energy or mass, serves as a basis in the cost formation process.

Today, the term thermoeconomics is used to indicate an appropriate combination of exergetic and economic analysis. The most characteristic element of this analysis is the assignment of cost to the exergy (not the energy) content of an energy carrier (exergy costing). In parallel, however, the expressions *thermoeconomic analysis* has been used to report conventional thermodynamic analyses based only in the first law of thermodynamics and economic analyses conducted separately from the thermodynamic ones without consider the energy or exergy costing. In 1983 the term exergoeconomic was introduced to give more precise and unambiguous characterization of the combination of an exergy analysis with an economic one using exergy costing (Tsatsaronis, 1983). The thermodynamic and economic analyses do not have to be combined in the more general field of thermoeconomics, whereas in exergoeconomic they are integrated through exergy costing. Consequently, exergoeconomic is a part, the most significant one, of thermoeconomics.

Nowadays, several theories for thermoeconomics are known, and they are more used in depending on the specific applications. Thermoeconomic Functional Analysis (Frangopoulos, 1983) has the purpose of optimization thermal plants (or energy systems). A comprehensive system modeling is necessary for its use. The aim of the Exergetic Cost Theory (Valero and Lozano, 1993) is to perform a diagnostic of an actual plant, and only needs the thermodynamic data of the energetic fluxes, so it is easier to be applied. This is the key of the success of this theory.

The exergetic cost theory is applicable in many situations (energy process, in general, where exergy carrier can be computed). In our particular case it is applied to the thermoeconomic (unit exergetic cost) and exergoeconomic (exergetic cost) analyses of Biomass Integrated Gasifier / Gas Turbine / Combined Cycle cogeneration plant using bagasse as fuel with electric power and heat as products.

Wood, bagasse and other types of biomass have attracted attention of the world as fuel for generating electricity. The increasing availability and productivity of biomass fuels, and the development of innovative technologies to use them, promises to make the so-called biomass power an increasingly attractive option (Patterson, 1994).

By means of the scope of technological innovations, including gasification and gas turbines, biomass power can generate the most versatile energy carrier, electricity, cleanly and efficiently from a renewable fuel, which can be stored and used as desired. Biomass not only absorbs as much carbon from the atmosphere as it emits when burned, but may do so for years before it is used. Since biomass power is able to emit very low levels of nitrogen oxides and almost not sulphur, its impact on the atmosphere is very low, giving a major environmental advantage, especially compared with coal-fired power.

Fuel gas from biomass, like than from coal, can also be used to fuel a gas turbine. Until the 1980's, gas turbines were common in jet engines for aircraft. But, in stationary terrestrial applications were regarded as a specialized technology confined to certain special cases, for example, as stand-by generators, or as peaking plant to run only at infrequent intervals of high demand of an electricity system. This is because the gas turbine has traditionally been using what has been considered premium fuel, either light fuel oil or natural gas. However, natural gas is not any more a scarce and expensive premium fuel, it is now the fossil fuel for which demand is growing faster, as new reserves have come on the market around the world. Using the most advanced turbine design now available, a modern natural gas fired combined cycle station may have efficiency higher than 50 % (ISO basis).

A combined cycle based on biomass gasification may prove to have a high capital investment cost, partly because the gasifier complex and steam cycle will be high in the size range likely to be appropriate for biomass power plant. In these conditions the objective of using thermoeconomic and exergoeconomic analyses in the study of BIG-GT combined cycle cogeneration plants, using bagasse as fuel, with electric power and heat as products, are:

- To identify the location, magnitude of the real thermodynamical losses (energy waste, or exergy destruction and exergy losses);
- To assess the production costs of each product (electric power and heat) and the exergetic and exergoeconomic cost of each flow in the plant and
- To assist in decision – marketing procedures concerning plant design, investment, operation and allocations of research funds.

2. ENERGY MODEL AND ASSUMPTIONS

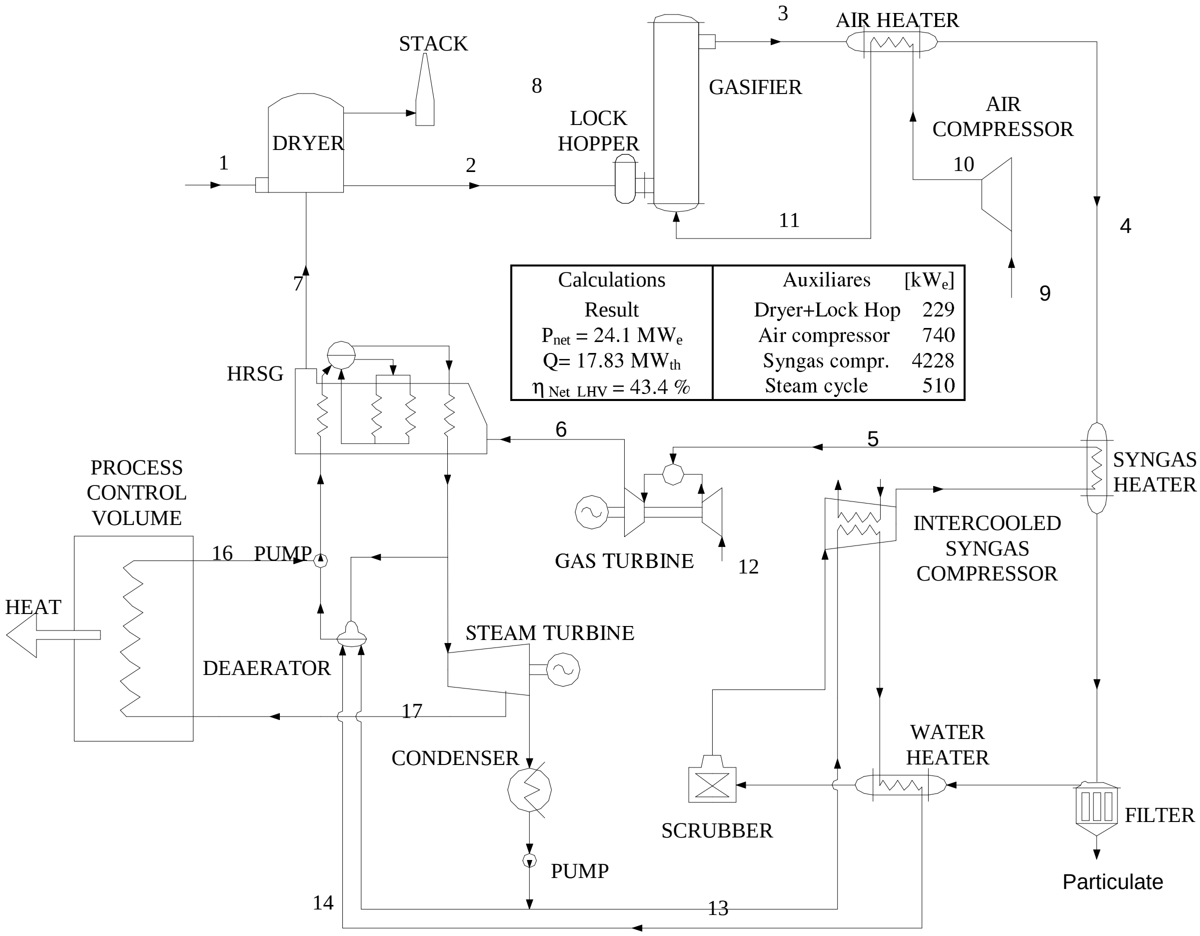
Here just BIG-GT systems based on atmospheric air-blown gasification are considered. The plant diagram could be seen in Consoni and Larson, (1994). Results of biomass gasification (raw gas composition and its temperature at the exit of the gasifier) are based on simulations performed by Souza-Santos (1997), considering sugar-cane bagasse as feedstock. A simulation program (Souza-Santos, 1987, 1989) has been developed for cases of boilers and gasifiers operating with coal. After improvements, it has been validated for cases of biomass gasification (Souza-Santos, 1994).

Assumed data of bagasse ultimate analysis and raw and clean syngas composition are presented in Fig. 1. One important simulation result is that syngas at the exit of the gasifier has a temperature of 635°C, so allowing the elimination of the very expensive syngas cooler. For syngas cleaning it was assumed a low temperature system with the use of fabric filter and wet scrubber. Before the scrubber a set of heat exchangers is used and the raw syngas energy is sequentially recovered to preheat the clean syngas (up to 450°C) before its injection at the gas turbine combustion chamber.

The power system is based on the ABB GT10 gas turbine, an industrial machine able to produce 24.6 MW when natural gas is burned at ISO basis. Predicting gas turbine operation with syngas at 27°C (average annual ambient in the majority sugar producing countries) and 1 bar of ambient pressure an off-design simulation procedure is required. A computational code was used for this purpose, using the solution correspondent to the GT operation with natural gas as reference. Details of the off-design simulation procedure are described in Walter et al. (1998).

Gas turbine exhaust gas is used to produce steam at the HRSG. Steam temperature is function of the GT exhaust temperature and the specified HRSG approach temperature as well. Steam generation is maximized according to the constraint imposed by the pinch point limit (15 °C).

Assumptions used to estimate auxiliary power consumption are the same as those described in Walter et al. (1998). In the Fig. 1, the overall mass and energy balances for the BIG-GT combined cycle cogeneration plant are given.



Biomass ultimate analysis and gas composition (% mole) by type.

Bagasse, % Weight – Dry basis		Element	Raw syngas	Clean syngas	Exit gas	Stack
	Point		(3; 4)	(5)	(6; 7)	(8)
Carbon	44.8	O_2	0.00	0.00	19.14	17.64
Oxygen	39.5	H_2	11.34	14.02	0.00	0.00
Hydrogen	5.4	CO	5.27	6.51	0.00	0.00
Nitrogen	0.4	CO_2	20.14	24.90	1.54	1.42
Sulfur	0.0	CH_X	8.81	10.89	0.00	0.00
Ash	9.8	H_2O	21.51	3.22	1.44	9.14
LHV_{dry} [MJ/kg]	17.7	N_2	32.72	40.46	77.87	71.79
		Others	0.21			
$LHV_{50\ \%\ Moisture\ contents}$ [MJ/kg]	9.45	LHV, [kJ/kg]		5615		

Figure 1- Diagram with: the control volumes considered, biomass and predicted gas composition in different points for thermoeconomic and exergoeconomic analyses of BIG-GT combined cycle, based on near - atmospheric pressure, directly heated gasification and ABB GT10 gas turbine; using bagasse as fuel with 50 % of moisture content.

2.1 Thermoeconomic and exergoeconomic models

Following the mass and energy balances as first step, the thermoeconomic and exergoeconomic model can be applied. In all cases thermodynamical properties are evaluated, as is show in Fig. 2. The specific bagasse exergy (*b*) is computed using the Lower Heating Value (*LHV*) in all cases, *h*, *s*, and *T* are the enthalpy, entropy and temperature respectively. The subscripts *ch*, *ph* and *0* are refer to the chemical exergy, physical exergy and environment respectively.

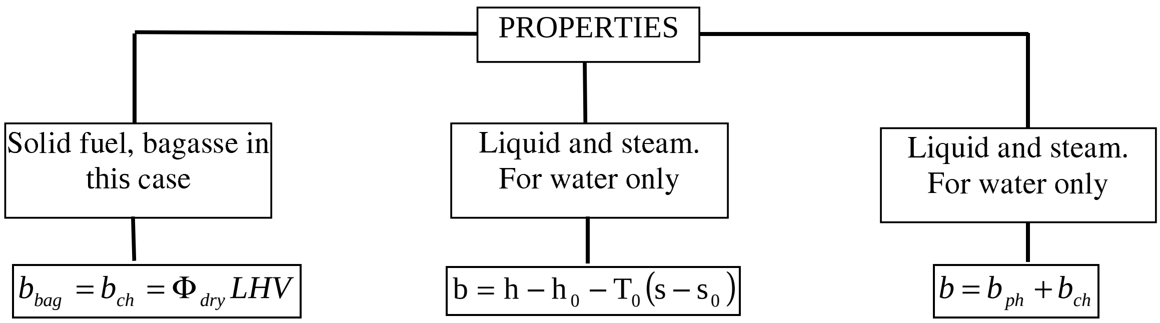


Figure -2. General concepts for thermodynamic, thermoeconomic and exergoeconomic modeling.

Bagasse is the only fuel for this study. Its specific exergy is calculated through chemical exergy concepts only. The Φ_{dry} coefficient is computed as proposed by Szargut, et al. (1988) using relations for wood and biomass fuels. Water flows, as liquid and steam phases in the BIG-GT are not involved in the chemical reaction process, so the specific exergy for those are computed considering the physical exergy concept only. For all gases, including air, two of the four components of exergy were considered: physical and chemical. Physical and chemical exergy in air is neglected because it is at the reference state, for other situations only physical exergy is considered and calculated using an ideal gas model. For syngas, raw and clean; gas combustion products and exit gas after drying both, physical (ideal gas model) and chemical exergy were considered. The model and data for computing specific exergy of ideal gas mixture were extracted from Kotas, (1985). In all cases the components of kinetic and potential energy were neglected.

In Fig. 3 the plant physical and productive structure used for thermoeconomic and exergoeconomic analyses is presented. The control volumes adopted are refereed to Fig. 1, but it was necessary to include some others, specifically, the process, electric plant and the three junctions and/or splitters; with the objective of representing the plant operation and performance as it is.

Fundamental equations, expressed in a matrix form for both, thermoeconomic and exergoeconomic modeling, are presented in Fig. 4. To make these models, solve the equations and compute the cost values, the four propositions of Theory of Exergetic Cost were used.

Proposition 1. The exergetic cost of the flow, fuel, and product is the quantity of exergy needed to produce it. Therefore, the exergetic cost is a conservative property. The matrices [A], [α_e] and [α_b] were the same for both models. For the exergoeconomic model, the external valorization vector [Z], which represents the economics components for each control volume associated in the incidence matrix [A], must be included into the formulation with [-] as signal, as shown in Fig. 4, because is a capital outlet.

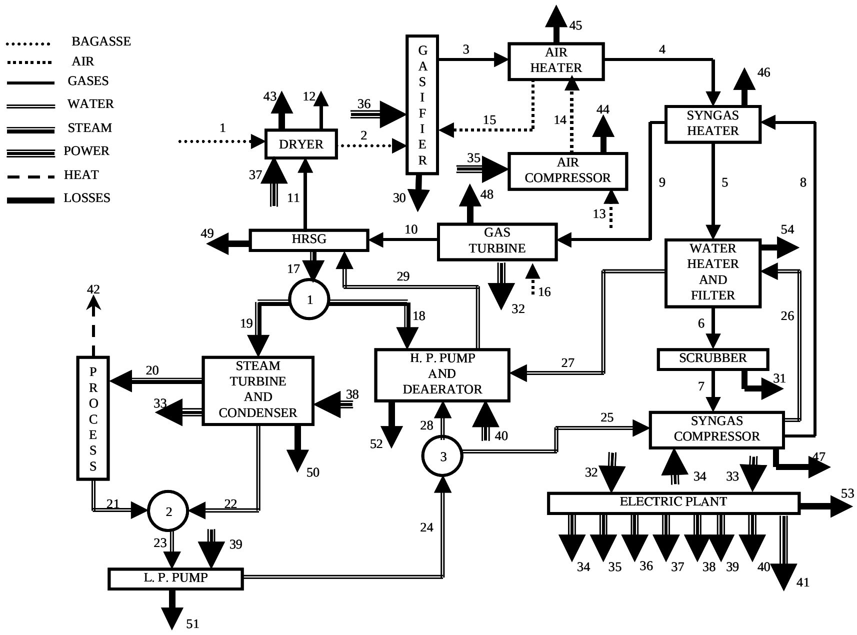


Figure 3- Productive and physical structure of the BIG-GT cogeneration plant.

Proposition 2. In absence of external assessment, the exergetic cost for all fuels used in the plant are equal to their exergy [B_e]. This permits to include the fuel carries equations in the external assessment matrix [α_e]. For the exergoeconomic model the external valorization vector for fuels [C_e], must be included into the formulation with [+] as signal because it is an income due to the exergy used in the plant to obtain the products.

roposition 3. All cost generated by the production process must be included in the cost of the final products. In absence of an external assessment we have to assign 'zero' value for the exergetic cost of the plant losses. This permits include the losses carries equations in the external assessment matrix [α_e].

Proposition 4 (a). If an output flow of a unit is a part of the fuel of this unit, then it is understood that its unit exergetic cost is the same as that of the input flow from which it comes. For example, turbines or heat transfer equipment.

Proposition 4 (b). If in a unit the product is composed for several flows, then the same unit exergetic cost will be assigned to all of them. For example, junctions, distributors and the electric plant in this case. The proposition 4 (a & b) determines the relation exergy matrix [α_b]. Not exergoeconomic vector is associated in these equations.

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$$\begin{bmatrix} \overleftrightarrow{A} \\ \overleftrightarrow{\alpha_e} \\ \overleftrightarrow{\alpha_b} \end{bmatrix} * \left[\overrightarrow{B^*} \right] = \begin{bmatrix} \vec{0} \\ \overrightarrow{B_e} \\ \vec{0} \end{bmatrix}$$

$$\begin{bmatrix} \overleftrightarrow{A} \\ \overleftrightarrow{\alpha_e} \\ \overleftrightarrow{\alpha_b} \end{bmatrix} * \left[\overrightarrow{C^*} \right] = \begin{bmatrix} \overrightarrow{-Z} \\ \overrightarrow{C_e} \\ \vec{0} \end{bmatrix}$$

Figure 4. Fundamental equations for both, thermoeconomic and exergoeconomic modeling.

Finally, the number of equations is completed and it is possible to compute the cost of each flow in the plant. The equations for all control volumes of physical and productive structure are given in matrix equations as is presented in Fig. 4. Symbols like *B** and *C** are the thermoeconomic and exergoeconomic costs respectively.

To complete the exergoeconomic model, economic information of the capital investment and operation and maintenance of the plant are necessary. The objective is to determine the external valorization vector [Z] for each control volume and the external assessment vector (C_e). In table 1 are given the Purchase Equipment Cost (PEC) (Faaij et al., 1997), the Total Investment Cost, and External Valorization Vectors (Z and C_f) for exergoeconomic analysis. The purchase equipment cost does not include the cost of heat transfer equipment at the gasifier outlet. Usually, this is proposed for BIG-GT scheme to reduce the syngas stream temperature. The gasifier exit temperature is at 635 °C in this case and the mentioned heat exchanger it is not necessary.

Table 1. Purchase Equipment Cost (PEC), Total Investment Cost, and External Valorization Vectors (*Z* and *C*) for exergoeconomic analysis.

I	Subsystem (PEC)	MUS$		US$/s
1	Dryer	4.8	Z_1	0.026748
2	Air compressor	0.2	Z_2	0.001114
3	Gasifier	2.6	Z_3	0.014488
4	Air heater	0.5	Z_4	0.002786
5	Syngas heater	0.6	Z_5	0.003343
6	Water heater & filter	1.5	Z_6	0.008359
7	Scrubber	0.9	Z_7	0.005015
8	Syngas compressor	0.9	Z_8	0.005015
9	Gas turbine	10.0	Z_9	0.055724
10	HRSG	2.4	Z_{10}	0.013374
11	Steam turbine & condenser	3.2	Z_{11}	0.017832
12	Low pressure pump	0.3	Z_{12}	0.001672
13	High pressure pump & deaerator	0.3	Z_{13}	0.001672
14	Electric plant	2.8	Z_{14}	0.015603
15	Process	1.1	Z_{15}	0.006130
16	Junction 1	0.0	Z_{16}	0.000000
17	Junction 2	0.0	Z_{17}	0.000000
18	Junction 3	0.0	Z_{18}	0.000000
Total PEC		32.1	C_f	0.060284
Purchase equipment installation		6.4		
Instrumentation and control		3.8		
Total onsite cost		10.2		
Land		0.0		
Civil structural & others		3.5		
Total offsite cost		3.5		
Engineering & supervision		1.2		
Contingency		5.1		
Total indirect cost		6.3		
Total investment cost		52.0	1753 US$/kW	

The dryer cost is added to the total cost of the fuel plant (storage, sizing, and others). Process capital cost also includes the investment necessary to reduce industrial steam consumption. The investment, for a sugar cane mill of 200 tc/h of capacity, is estimated as US$ 310 thousand to reduce steam demand from 450 to 380 kg/tc, US$ 320 thousand to reduce from 380 to 320 kg/tc, while more than US$ 440 thousand is required to reach 280 kg/tc.

The external valorization vectors in Table 1 are determined for mass balance of material consumption and handling (fuel, inert, ash, water and other) consider in the cash flow of cost in the plant operation (Table 2).

For cash flow calculations fixed costs of 3 % of total capital investment by year was adopted for 25 years of life cycle. Details about maintenance, staff, water, inert material and ash disposal could be consulted in Faaij et al. (1997). The fuel cost, as it is received, of 5 US$/t and 10 % of interest rate were adopted.

Table 2. Cost cash flow determining the external valorization vector for each control volume (Z and C_e) in the BIG–GT combined cycle cogeneration plant for exergoeconomic analysis. All values in 1997 US$.

Year	0	1	2	3	…	25
Load factor	0.00	0.30	0.85	0.85	…	0.85
Maintenance	0.000	0.347	1.042	1.042	…	1.042
Personnel	0.000	0.000	0.420	0.420	…	0.420
Water	0.000	0.001	0.003	0.003	…	0.003
Inert material	0.000	0.075	0.213	0.213	…	0.213
Ash disposal	0.000	0.120	0.340	0.340	…	0.340
Fixed costs	0.021	0.021	0.021	0.021	…	0.021
Working capital	0.000	0.140	0.000	0.000	…	0.000
Capital investment	13.025	39.075	0.000	0.000	…	0.000
Total cost	13.05	40.08	2.89	2.89	…	2.89
Interest rate	0.10	0.10	0.10	0.10	…	0.10
Capitalization factor	1.00	1.10	1.21	1.21	…	1.21
Actualized value, MUS$/year	13.05	44.09	3.50	3.50	…	3.50
Present value, US$/s	0.178874					
Fuel cost, 5 US$/t	0.00	0.57	1.62	1.62	…	1.62
Actualized value, MUS$/year	0.00	0.63	1.95	1.95	…	1.95
Present value, US$/s	0.060284					

3. DISCUSSION OF RESULTS AND CONCLUSIONS

In Table 3, thermoeconomic analysis is presented for some control volume including the whole plant. The exergetic cost of fuel (F*) and product (P*) are given. As can be seen, the exergetic efficiency (η) of BIG-GT is 22 %. The causes are the necessary implementation of divers systems to prepare the solid fuel to be consumed in a gas turbine plant. The highest irreversibilities (I, δ-relative irreversibility) are given in the following equipment by order: scrubber (38 %), gas turbine (16 %), dryer (12 %), gasifier and HRSG (12 %).

Using the thermoeconomic model, it is possible to explain the process of exergetic cost formation. The drying, gasification and cleaning system are responsible for a big amount of irreversibilities in the plant with the only purpose of conditioning the gas fuel for the gas turbine. The 56 % of exergetic cost of the electricity produced by the cogeneration plant is formed in these systems.

Table 3. Thermoeconomic analysis for some control volume and the whole plant.

Subsystem	F*	P*	I	η	k	δ
Dryer	155093	122571	14631	0.89	1.12	0.117
Gasifier	159962	116256	7383	0.94	1.06	0.059
Scrubber	157861	66103	47332	0.58	1.72	0.377
Gas turbine	110659	110658	19737	0.56	1.80	0.157
HRSG	38559	38559	6001	0.61	1.63	0.048
Total Plant	125549	125549	98333	0.22	4.61	0.780

In the thermoeconomic model, the electricity production was adopted as the main goal of the plant operation, and the vapor was treated as a working fluid. So, the unit exergetic cost (k) of the heat (4,11) is lower than electricity (4,71) (Table 4).

Table 4. Calculation results of thermoeconomic and exergoeconomic modeling for selected flows in the BIG-GT combined cycle cogeneration plant.

Flow Nº	Type	P bar	T °C	m kg/s	E MW	B MW	B* MW	k	C* US$/s	C* US$/MWh
2	Bagasse	1.01	70	12.1	104.9	122.6	155.1	1.27	0.119	3
3	Raw gas	2.00	639	7.5	80.9	116.3	160.0	1.38	0.146	5
9	Clean gas	21.75	450	11.4	65.9	71.4	177.6	2.49	0.188	9
17	Steam	80.00	465	11.3	24.0	10.1	41.5	4.11	0.077	27
32	Work			7.5	24.7	24.8	110.7	4.48	0.173	25
33	Work				4.2	4.2	24.7	5.91	0.064	55
41	Work				22.9	22.9	107.8	4.71	0.200	31
42	Heat				18.3	4.3	177.2	4.11	0.039	32

For the plant, 80 % of the capital investment is focused on the BIG-GT system. For the fuel price (5 US$/t) and other data adopted in the exergoeconomic model, the investment and operation costs are more representative than the fuel cost. A lower market price of biomass is one of the most sensible parameter in the possible implementation of BIG-GT technology in sugar cane industry.

The production cost of electricity (31 US$/MWh) and heat (32 US$/MWh) were obtained using an exergoeconomic model for several adopted conditions. The electricity cost is, after all, competitive with a market price. For heat cost, there are no sources of information to make a good comparison. The costs obtained depend on the fuel cost and the interest rate adopted. The interest rate value of 10 % and the 25 years of life cycle, used in the calculations, are due that the authors think that this type of system must receive a different economic treatment considering its high ecological and social profits. The cost of the fuel is high considering the market prices of 1999. The values here obtained can be compared with these reported by (Barreda and Nebra, 1999), who consider an actual industrial system with an interest rate of 12 % and a life cycle period of 15 years.

Acknowledgments

To the Brazilian National Petroleum Agency (ANP) by the financial support to develop this paper. To the professor Arnaldo Cesar da Silva Walter (UNICAMP) for several suggestions and important observations.

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