EXERGOECONOMIC ANALYSIS OF SMALL-SCALE BIOMASS STEAM COGENERATION

César Adolfo Rodríguez Sotomonte, c.rodriguez32@unifei.edu.br[1]
Electo Eduardo Silva Lora, electo@unifei.edu.br[1]
[1]Universidad Federal de Itajubá, Av. BPS, 1303, bairro Pinheirinho, Itajubá – MG

Osvaldo José Venturini, osvaldo@unifei.edu,br[1]
José Carlos Escobar, jocescobar@hotmail.com[1]
[1]Universidad Federal de Itajubá, Av. BPS, 1303, bairro Pinheirinho, Itajubá – MG

Abstract. *The principal objetive of this work is to develop a calculation process, based on the second law of thermodinamics, for evaluating the thermoeconomic potential of a small steam cogeneration plant using waste from pulp processing and/or sawmills as fuel. Four different configurations are presented and assessed. The exergetic efficiency of the cycles that use condensing turbines is found to be around 11%, which has almost 3 percent higher efficiency than cycles with backpressure turbines. The thermoeconomic equations used in this paper estimated the production costs varying the fuel price. The main results show that present cost of technologies in a small-scale steam cycle cogeneration do not justify the implementation of more efficient systems for biomass prices less than 100 R$/t.*

Keywords*: Cogeneration, Exergoeconomic Analysis, Exergetic Analysis, Biomass, Rankine Cycle.*

1. INTRODUCTION

Energy and development are closely linked concepts, for that reason it is confirmed that the progress of society depends on a wide, economic and high quality energy supply. During recent years, Brazil has been studying the utilization of biomass as fuel for distributed generation systems, aiming to diversify the country's energetic matrix and also the supply of electricity to small communities in isolated regions. In these regions the lack of systems for electric power supply affects the economic activities resulting in a lower quality of life. For the improvement of these thermal systems, especially when they are related to efficiency gain, the reduction of losses in conversion process is mandatory. The Amazon rainforest is one of the biggest biomass reservoirs in the world, but disregarding the wood as a cooking fuel, the use of it biomass energy potential as fuel, is almost zero. Residues from agriculture, agroindustry and wood industry in this region can play an important role in power generation.

As such, power and cooling cogeneration systems can be useful; these systems are particularly interesting for tropical regions such as the Brazilian Amazon, where the main business activities - fruit harvest and fishing - are subject to high losses due to poor preservation by the nonexistence of cold stores in the state.

According to Silva and Haddad (2006) and Wu and Wang (2006), several prime movers such as: Micro-turbines, Internal Combustion Engines and Stirling Engines are used to cogenerate electricity and cooling for small scale applications.

Currently, most isolated systems in the Amazon region have small diesel engines, due to their lower initial investment costs and their high performance operating at part load that offers the user a flexible source of electricity. Nevertheless, the difficulty in supplying fuel, its high cost and frequent maintenance intervals increase the costs of operation substantially. Other technologies such as: Micro-turbines, Stirling engines and fuel cells that have high performance at partial loads and high electrical efficiencies are more well suited for cogeneration systems in the small scale.

However, the utilization of biomass with these technologies requires a previous stage of treatment for the conversion of the biomass into liquid or gaseous fuel via a chemical, thermochemical or biochemical process. Although feasible, most of these conversion technologies still do not have competitive cost, for this reason, the most used technology for energy conversion from biomass is direct combustion (Lian *et al.* 2010).

As a result, other electricity generation technologies, such as steam turbines, although having lower efficiencies, are more suitable due to their high level of development. Moreover, these systems are associated with a minimization of environmental impact, especially when the goal is the reduction of CO_2 emissions, as contemplated in the Kyoto protocol, since, biomass fuels are considered to emit a total of zero net CO_2 (EPA, 2007).

Nowadays, in some communities in the Amazonian region, electricity is produced by using backpressure steam turbine adapted from other industrial applications, with isentropic efficiencies around 60%, meanwhile, cooling power is produced through electric vapor compression chillers with a low coefficient of performance (*COP*) (Rendeiro and Nogueira, 2008).

Considering these scenarios, this paper presents a comparative study, based on exergoeconomic analysis, of several thermal cogeneration systems using steam turbines, in order to clarify which is the best cycle configuration, evaluate the exergy destruction, the exergetic efficiency in each component and calculate the monetary costs of the main products of the thermal cycle.

2. COGENERATION SYSTEM DESCRIPTION

The cycles proposed in this paper are three different configurations of the Rankine cycle associated with an absorption chiller and also a Rankine cycle producing electricity to power an electric chiller. The absorption unit is a NH_3-H_2O single effect, which is installed to increase the efficiency of the thermodynamic cycle by using part of the steam energy at the outlet of the turbine, which is generally rejected to the environment through the condenser, or using a steam extraction in the case of a condensing turbine.

These cycles were simulated to produce 300 kW of electric power and 210 kW of cooling power, the average consumption of a community of 200 - 300 inhabitants with a sawmill and a refrigeration unit to sell ice and to keep pulp and fish (Nogueira, 2010).

In the thermodynamic analysis the following general assumptions are made: 1) The kinetic and potential energy are neglected; 2) The reference state temperature (T_0) and pressure (P_0) are 298.15 K and 101.325 kPa; 3) The temperature and pressure of fuel and air inlets are 298.15 K and 101.325 kPa; 4) Steady state operation; 5) Load condition 100%. The main operating parameters are summarized in Tab. 1

Table 1. Operating conditions of the power plant

Turbine Inlet Steam Pressure (kPa)	2100	
Boiler efficiency (%)	70	
Turbine Inlet Steam Temperature (K)	623,15	
Isentropic efficiency of turbines (%)	60	
Efficiency Electric Generator (%)	98	
Chiller Heat Source Temperature (K)	408,15	
COP	0,5	
Isentropic Efficiency of Pumps (%)	85	
Excess Air (%)	30	
Lower Heating Value (kJ/kg)*	13800	
Biomass composition (% w/w)	Carbon	39,33
	Hydrogen	4,68
	Nitrogen	0,239
	Sulfur	0,002
	Oxygen	35,1
	Water	20
	Ash	0,63

*Wasted wood (moisture content 20%)

Main evaluated case studies are:

2.1. Simple Rankine Cycle with Back Pressure Turbine (*SRCB*)

The cycle ***SRCB*** (Fig. 1a) has a backpressure turbine where steam expands up to a pressure of 120 kPa. Part of the steam exhaust is used as a heat source of absorption chiller and the remaining flow is conducted to the condenser. The operating temperature of the absorption chiller is controlled using spray water in an attemperator. The condensate from the chiller together with the outflow from the condenser is pumped to the boiler to close the thermodynamic cycle.

2.2. Simple Rankine Cycle with Condensing Turbine (*SRCC*)

The cycle ***SRCB*** (Fig. 1b) uses a condensing turbine with a controlled steam extraction at 69 kPa which is used as a heat source for the absorption chiller. The steam turbine output is led to the condenser with the following conditions 20 kPa and saturated steam. The condensate at the chiller and condenser are sent back to the boiler to close the thermodynamic cycle.

2.3. Regenerative Rankine Cycle with Condensing Turbine (*RRCC*)

The cycle ***RRCC*** (Fig. 1c), as well as the cycle ***SRCC***, uses a condensing turbine that operates under the same conditions. However, this cycle has a feedwater heater that uses another steam extraction at 120 kPa in order to raise the boiler feedwater temperature up to 373 K.

2.4. Simple Rankine Cycle (*SRC*)

The cycle ***SRC*** **(**Fig. 1d), represents the thermal system currently used in some regions in the Brazilian Amazon to provide electricity and cooling power. In this cycle, the boiler produces superheated steam that drives a backpressure turbine; this steam expands up to a pressure at 120 kPa. The total electric power generated by the system is 384 kW, of which, the electric chiller consumes 84 kW to generate 210 kW of cooling power.

In Table 2 the main results of simulations of the analyzed cycles are summarized. The energy efficiency is quantified as the ratio of useful energy output and total input energy in the system (Eq.1), while electric efficiency doesn´t takes into account the cooling power generation.

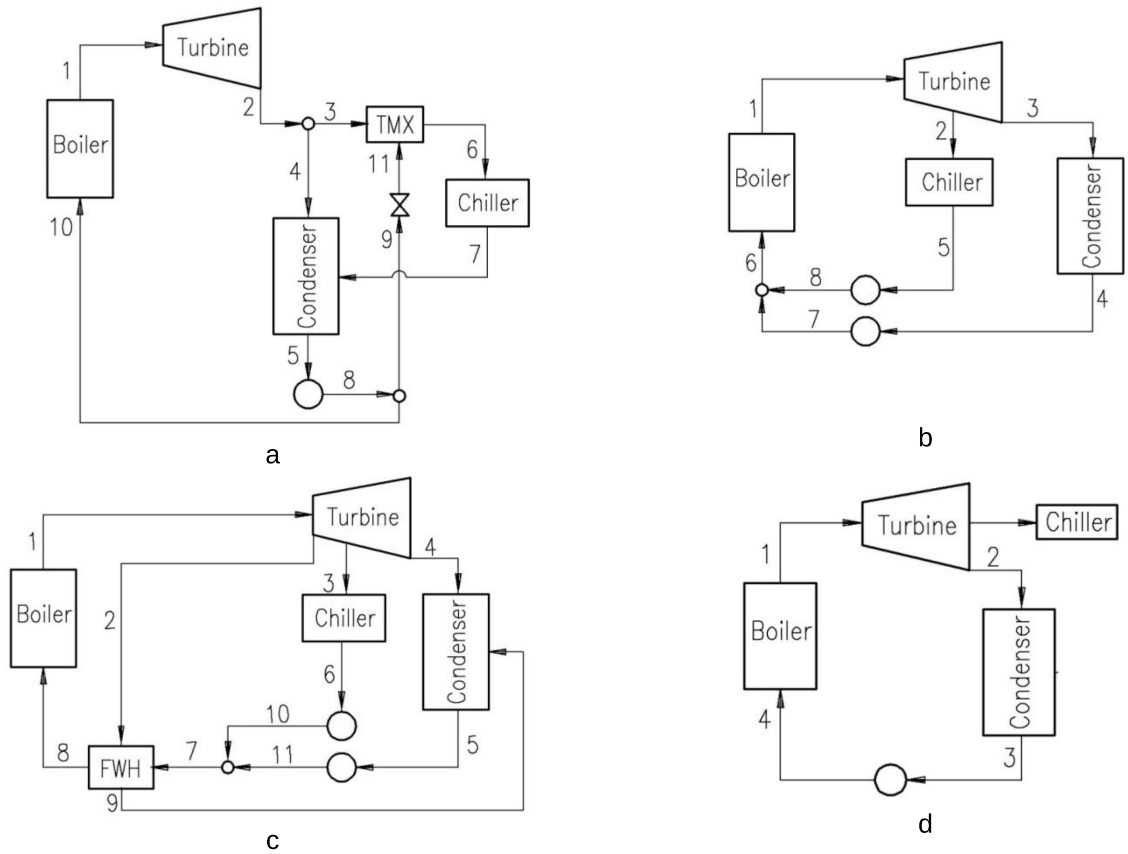

Figure 1. Physical structure of the biomass steam cogeneration cycle.
a) SRCB, b) SRCC, c) RRCC and d) SRC

Table 2. Results of the cogeneration cycle simulation

PARAMETERS	SRCB	SRCC	RRCC	SRC
Net Electrical Power (kW)	299,95	300	299,91	299,74
Cooling Power (kW)	213,55	210,14	209,96	210
Biomass Consumption (kg/h)	840,1	685,97	627,4	1124,2
Auxiliary Equipment Consumption (kW)	2,1	1,60	1,64	86,73*
Electric Efficiency	9,29	11,40	11,8	6,93
Energy Efficiency	15,90	19,40	20	11,8

* includes consumption for the compression chiller.

3. EXERGOECONOMIC ANALYSIS

According to Tsatsaronis (1993), the thermoeconomic analysis has the following steps:

1. Exergetic analysis, which would establish the exergy flows, identify the location and magnitude of the thermodynamic losses;

2. Economic Analysis that provides monetary costs which are related to capital investment and costs related to the operation and maintenance of the plant;
3. Exergoeconomic analysis of each flows of the system.

3.1. Exergetic analysis

To evaluate the efficiency of a cogeneration system that produces cold and electric power, the First Law of Thermodynamics states that, this is quantified as the ratio of useful energy output and total input energy in the system and is calculated by Eq. (1):

$$\boldsymbol{\eta} = \frac{\dot{W}_n + \dot{Q}_{evp}}{\dot{Q}_T} \tag{1}$$

Where $\dot{W}_n$ is the net electrical power generated in the cycle, $\dot{Q}_{evp}$ is the cooling capacity in the chiller's evaporator and $\dot{Q}_T$ is the total energy supplied to the thermodynamic cycle. However, this analysis is not sufficient to identify energy losses and efficiencies of these systems, as this principle only takes into account the quantity of energy, but not its quality, and the result is an overvaluation of the heat component.

Table 3. Resources, Products, irreversibilities and exergy efficiency of the plant components in the evaluated scenarios.

Simple Rankine cycle with back pressure turbine (*SRCB*)				
	F (kW)	P (kW)	I (kW)	ε
Boiler	3641,83	887,71	2754,12	24,38
Turbine	469,93	308,21	161,73	65,59
Chiller	88,83	32,97	55,85	37,12
Condenser	323,72	26,97	296,75	8,33
Pump	2,09	1,84	0,25	88,14
Cycle	3641,83	332,92	3269,26	9,14
Simple Rankine cycle with condensing turbine (*SRCC*)				
	F (kW)	P (kW)	I (kW)	ε
Boiler	2965,96	687,41	2278,55	23,18
Turbine	495,94	307,77	188,17	62,06
Chiller	75,98	32,44	43,54	42,70
Condenser	116,28	19,06	97,23	16,39
Pump1	1,17	1,01	0,16	86,02
Pump2	0,44	0,38	0,06	86,94
Cycle	2965,96	332,45	2607,70	11,21
Regenerative Rankine cycle with condensing turbine (*RRCC*)				
	F (kW)	P (kW)	I (kW)	ε
Boiler	2876,74	687,30	2189,45	23,89
Turbine	495,14	307,80	187,34	62,16
Chiller	75,80	32,40	43,40	42,74
Condenser	112,47	18,21	94,26	16,19
FWH	19,22	14,51	4,71	75,48
Pump1	1,20	1,04	0,17	86,07
Pump2	0,44	0,38	0,06	86,52
Cycle	2876,74	332,40	2519,39	11,55
Simple Rankine cycle with electrical chiller (*SRC*)				
	F (kW)	P (kW)	I (kW)	ε
Boiler	4873,70	1155,94	3717,76	23,72
Turbine	599,07	394,36	204,71	65,83
Chiller	84,00	32,42	51,58	38,60
Condenser	559,33	47,15	512,18	8,43
Pump	2,73	2,46	0,27	90,23
Cycle	4873,70	332,16	4541,54	6,82

To overcome this problem, the exergy ($\dot{E}$) can be used as a quality and quantity measure of energy which involves the first and second thermodynamic laws, so an exergetic analysis is useful to identify, locate and quantify the thermodynamic efficiencies of a thermal system. Thus, exergy efficiency (ε) of the cogeneration system is defined as follows:

$$\boldsymbol{\varepsilon} = \frac{\dot{W}_n + \dot{E}_{evp}}{\dot{E}_T} \tag{2}$$

Where $\dot{E}_{evp}$ is the exergy variation of the working fluid (NH_3) in the chiller evaporator and $\dot{E}_T$ the total exergy supplied to the thermal system.

According to Tsatsaronis (1993), resources (*F*) are flows that act as exergy sources, necessary for the manufacturing of a certain product (*P*). Consequently, the exergy efficiency of equipment (*n*) is given by:

$$\boldsymbol{\varepsilon_n} = \frac{\dot{E}_P}{\dot{E}_F} \tag{3}$$

Using the concept of resources (*F*) and products (*P*), if the system operates in steady state, neglecting the heat losses in equipment, the exergy balance for calculation of irreversibilities (*I*) in the equipment can be written as follows:

$$\dot{I} = \dot{E}_F - \dot{E}_P \tag{4}$$

The parameter presented by exergy analysis provides a clear criterion for evaluating the performance of each thermal system and its components. A good description of the concepts used to evaluate the exergy flows are reported in Kotas, (1985); Szargut *et al.* (1988) and Zaleta *et al.* (2007).

The exergetic analysis of the cycles presented in this paper introduces the exergetic efficiency as an evaluation parameter of the real performance from the thermodynamic point of view. Once the products (*P*) and the resources (*F*) in the thermal system are identified, the irreversibility and exergy efficiency (ε) for each subsystem are determined. Using the previous expressions Eq. (2-4), the plant was analyzed and the properties of each component were calculated and summarized in Tab. 3.

3.2. Economic Analysis

The economic analysis of each thermodynamic cycle was performed according to the purchased-equipment cost (*PEC*). These costs were obtained by the cost correlations proposed by Peters and Timmerhaus (1991), using data from equipment manufacturers. The Table 4 shows the estimated costs updated to the year 2009. It is important to remark that the uncertainty range for this estimate is approximately ± 40%

Table 4. Purchased Equipment Cost

Equipment	SRCB (R$)	SRCC (R$)	RRCC (R$)	SRC (R$)
Boiler	600000	600000	600000	600000
Turbine/Condenser	563288,31	1213983,44	1213983,44	669412,76
Pump1	28454,52	17307,04	17683,53	35563,39
Pump2	-	7537,02	7537,02	-
FWH	-	-	38786,63	-
Chiller	300000,00	300000,00	300000,00	140000,00
TOTAL	1491742,84	2138827,50	2177990,62	1444976,15

Based on the purchased-equipment cost, direct costs, indirect cost and maintenance costs can be estimated. Table 5 shows the distribution of fixed capital investment (*FCI*) and operation using the methodology proposed by Bejan *et al.* (1995).

For a useful life of 20 years (*N*) and annual interest rate (*i*) of 12%, the total cost of annuities (*A*) is obtained by Eq. (5). Thus, assuming a plant operation of 8040 h per year, the cogeneration cycles were assessed and the total cost of maintenance and investment (*Z*) in each equipment summarized in Tab 6.

$$A = FCI\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \tag{5}$$

Table 5. Distribution fixed capital investment and operation.

Installation	25% PEC
Piping	15% PEC
Instrumentation and control	10% PEC
Electric parts	13% PEC
Civil building	15% PEC
Total direct cost (TDC)	**78% PEC**
Total indirect cost (TIC)	**13% TDC**
Annual maintenance (M)	**5% PEC**

Table 6. Amortized costs for each equipment.

Equipment	**Z_{SRCB} (R$/s)**	**Z_{SRCC} (R$/s)**	**Z_{RRCC} (R$/s)**	**Z_{SRC} (R$/s)**
Boiler	0,00679	0,00572	0,00572	0,00777
Turbine/Condenser	0,00697	0,01503	0,01503	0,00829
Pump1	0,00035	0,00021	0,00022	0,00044
Pump2	-	0,00009	0,00009	-
FWH	-	-	0,00048	-
Chiller	0,00371	0,00371	0,00371	0,00173

The price of biomass varies significantly for different varieties, harvesting methods and treatments needed. In addition, distance and transportation also affect the cost. In this work, the fuel used is waste from pulp processing and/or sawmills; for that reason, the total cost of this resource is only associated with loading cost to the transportation vehicles and storage, assuming a total value of R$10/t. .

3.3. Exergoeconomic Analysis

As discussed previously, all production processes require an investment in the purchase, installation, operation and maintenance of the plant equipment, in addition to the cost of resources required by the process. Due to the fact that no real process is 100% efficient, or in other words, that not all resources are transformed into useful products, it is mandatory to ensure that, the final products cover the costs of all related expenditures. The Thermoeconomic analysis through appropriate mathematical relationships, based on the second law of thermodynamics and concepts of economics, can quantify the exergy losses (exergy cost) and how much these losses affect the cost of the products "monetary cost".

As such, an exergoeconomic analysis based on the structural theory of thermoeconomics was performed to evaluate the monetary costs of products generated by the cogeneration system.

Figure 2 shows the productive structure of the analyzed cycles using total exergy flows. The Productive structures are represented with fewer units, since the condenser joins the turbogenerator to form a single subsystem.

The structural theory proposed by Valero *et al.* (1993), is a practical method to determine the monetary costs (C) in a system with m flows (mass, heat or power) through a system resolution of (m x m) equations. The (m x m) equation system is achieved by some assumptions as show in Eq. 6-7:

$$\sum c_P \dot{E}_P - \sum c_F \dot{E}_F + Z_k = 0 \tag{6}$$

A multi-product of the same nature in a subsystem must have an equivalent unit cost, which means:

$$c_{Pa} = c_{Pb} = c_{Pc} \tag{7}$$

Where (c) the monetary cost per unit of a product (P), or a resource (F) and represents the amount of external monetary resources are spent to produce one unit of this exergy flow.

Solving the set of linear equations obtained by Eq. 6-7, the unit monetary costs of the resources (c_F) and the unit monetary costs of the product (c_P) are presented in Tab 7-8.

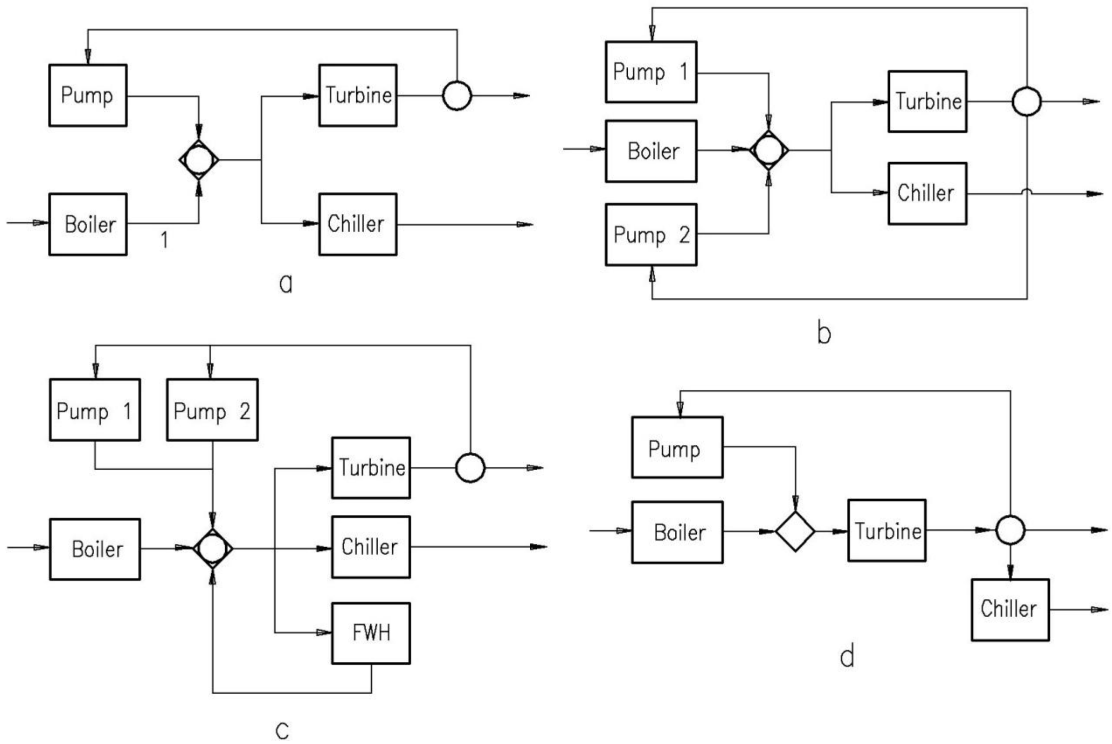

Figure 2 Productive structure a) SRCB, b) SRCC, c) RRCC and d) SRC

Table 7. Unit exergetic cost in the cycles with backpressure turbines

	SRCB		SRC	
Subsystem	c_F R$/MWh	c_P R$/MWh	c_F R$/MWh	c_P R$/MWh
Boiler	14,9E-5	36,99	20,5E-5	33,92
Turbogenerator	39,06	185,71	35,65	184,08
Chiller	39,06	510,99	184,08	669,02
Pump	185,71	894,16	184,08	848,28

Table 8. Unit exergetic cost in the cycles with condensing turbines

	RRCC		SRCC	
Subsystem	c_F R$/MWh	c_P R$/MWh	c_F R$/MWh	c_P R$/MWh
Boiler	11,2E-5	39,09	12,2E-5	39,93
Turbogenerator	40,45	260,89	42,07	264,80
Chiller	40,45	506,63	42,07	510,19
FWH	40,45	172,69	-	-
Pump1	260,89	1068,40	264,80	1059,27
Pump2	260,89	1156,70	264,80	1154,94

4. RESULTS AND DISCUSSION

The Exergetic analysis presented in this paper introduces the exergetic efficiency as an evaluation parameter of the real performance based on the thermodynamic point of view. This way, the irreversibility and exergetic efficiency are determined in each thermal system and their components. Figure 3 shows that systems that uses condensation turbines *RRCC* and *SRCC* transform more than 11% of the resources that enter in production systems (electricity and cold).

While cycles that use back pressure turbines have less exergetic efficiency, 9,14% and 6,82% for SRCB and SRC cycles respectively.

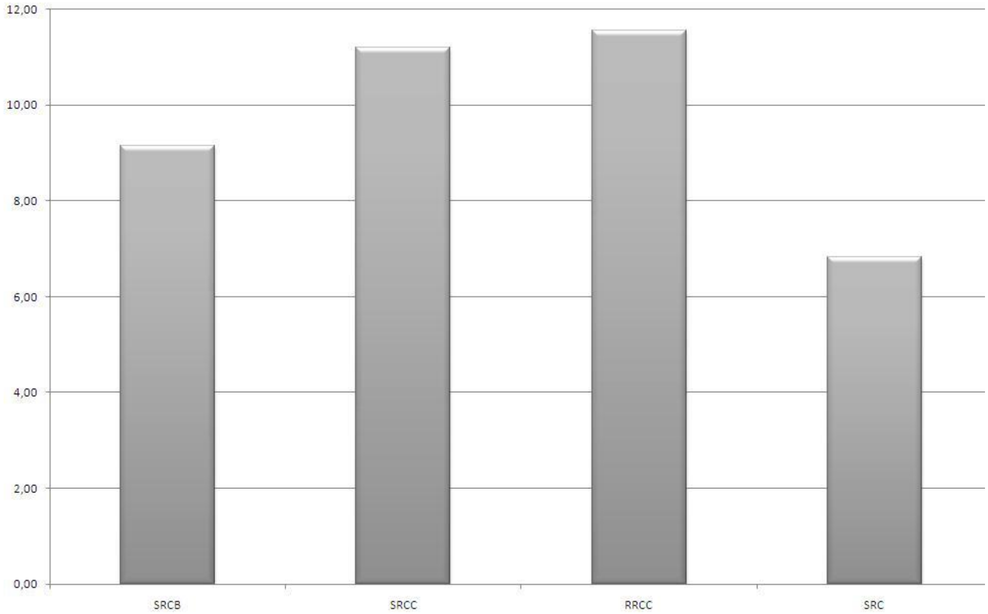

Figure 3. Exergy efficiency steam cogeneration cycles.

This difference in exergetic efficiencies is due to the bigger exergy destruction Fig. (4). In cycles that use back pressure turbines *SRCB* and *SRC* the irreversibility is 30% and 80% higher when compared to cycles that use condensation turbines; since the boiler and condenser are the main responsible for the irreversibility rise in the cycle Fig. (5), this due to high biomass consumption and more quantity of rejected heat in the condenser.

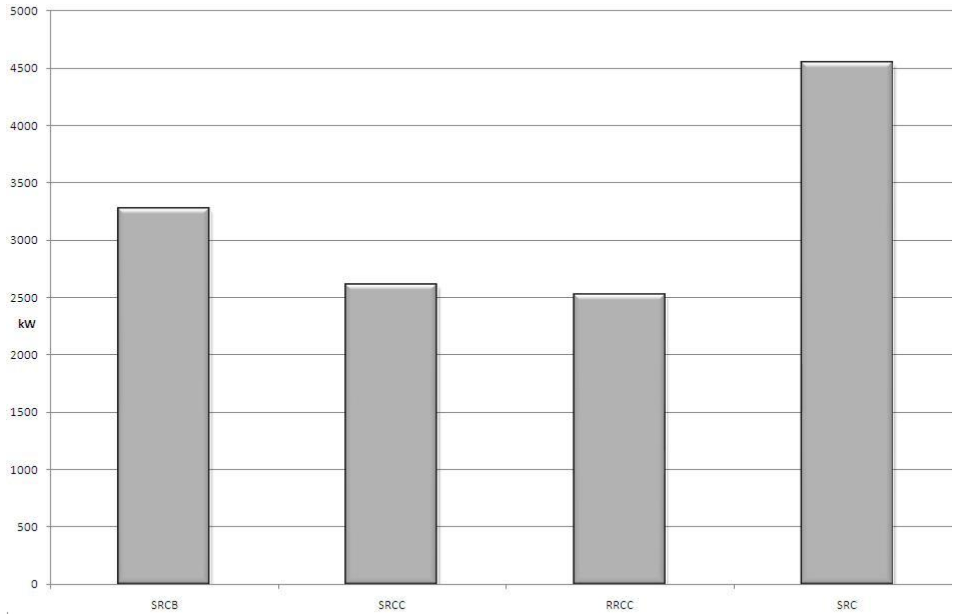

Figure 4. Exergy destruction steam cogeneration cycles.

As mentioned before, the boiler and the condenser are the main causes for exergy destruction. As it may be observed in Fig. (6), these equipments together are responsible for more than 93% of irreversibility in cycles that use back pressure turbines and 91% in cycles which use condensation turbines. This exergetic destruction is caused by low rates of heat transfer in steam generator and by exergetic destruction caused during combustion process.

The rest of exergetic loss is concentrated in steam expansion system ≅ 5% for *SRCB* and *SRC* cycles and ≅ 7%for *SRCC* and *RRCC* cycles. To reduce exergy loss in turbines, it is necessary to improve isentropic efficiency in this equipment by designing a customized steam turbine for this application.

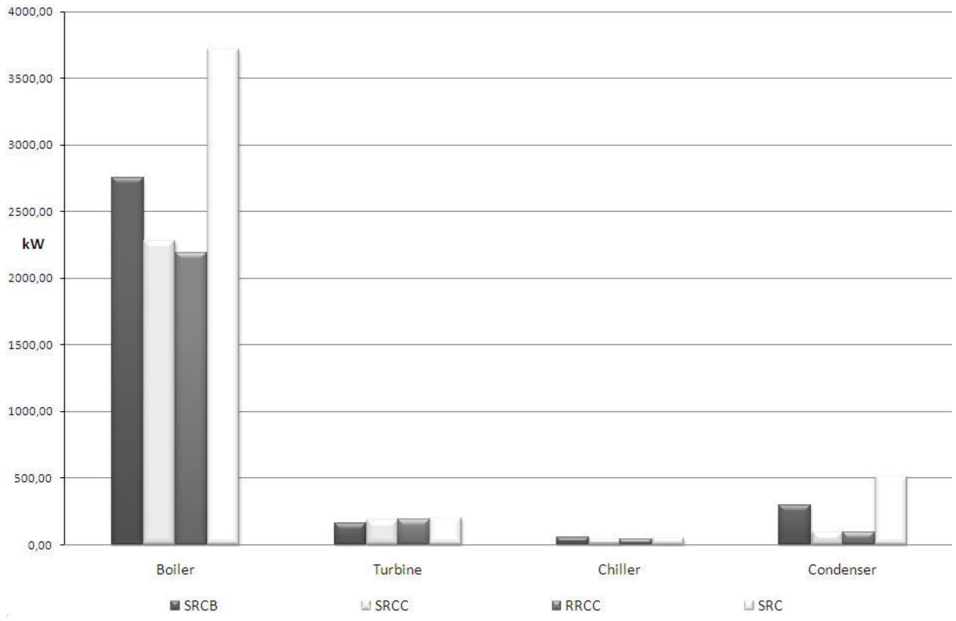

Figure 5. Exergy destruction of each equipment.

In all cycles, the chiller is the equipment which generates less irreversibility, less than 2% of the total destructed exergy.

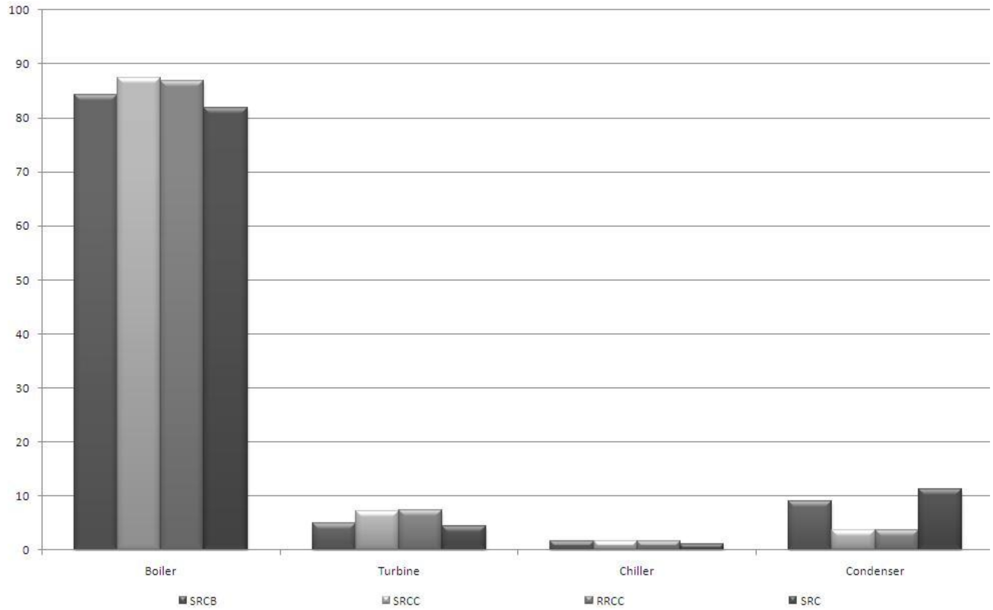

Figure 6. Exergy destruction of each equipment.

Results obtained by the exergoeconomic analysis allow for the estimation of the cost of each flow in the system. In Figure 7 the costs of the main product in each analyzed cycle are presented.

Results obtained by the exergoeconomic analysis allow estimating the necessary cost to produce each flow in the system. Figure 7 presents the costs of the main product in each analyzed cycle.

Results show that in cycles which use backpressure turbines, although having less exergetic efficiency, their production costs are lower than the cycles that use condensation turbines; mainly in electricity production prices. This is easily attributed to the purchase cost of the back pressure turbine, which is around 50% of the condensation turbine, and the low price of the used fuel, making the difference in thermal systems efficiency, as the backpressure turbine has less impact on production costs.

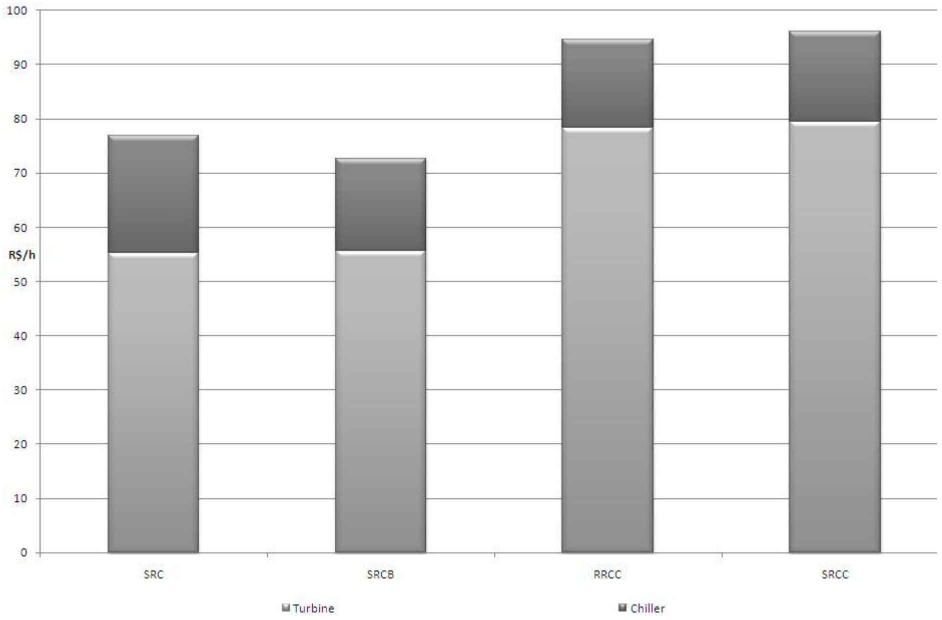

Figure 7. Cost Production of electricity a cooling power

Based on what was previously mentioned, and taking into account that biomass costs may significantly vary in different regions, Fig. (8) shows a sensitivity analysis of the global production cost. If the fuel is less than R$50/t, the cycles which use back pressure turbines have lower production costs; above this value, the *SRC* cycle starts to lose attractiveness.

Cycles that use condensation turbines, specifically the *RRCC* cycle, match their production costs to the *SRCB* cycle when the biomass price is around R$100/t. From that price, the use of condensation turbines were attractive considering the production cost point of view.

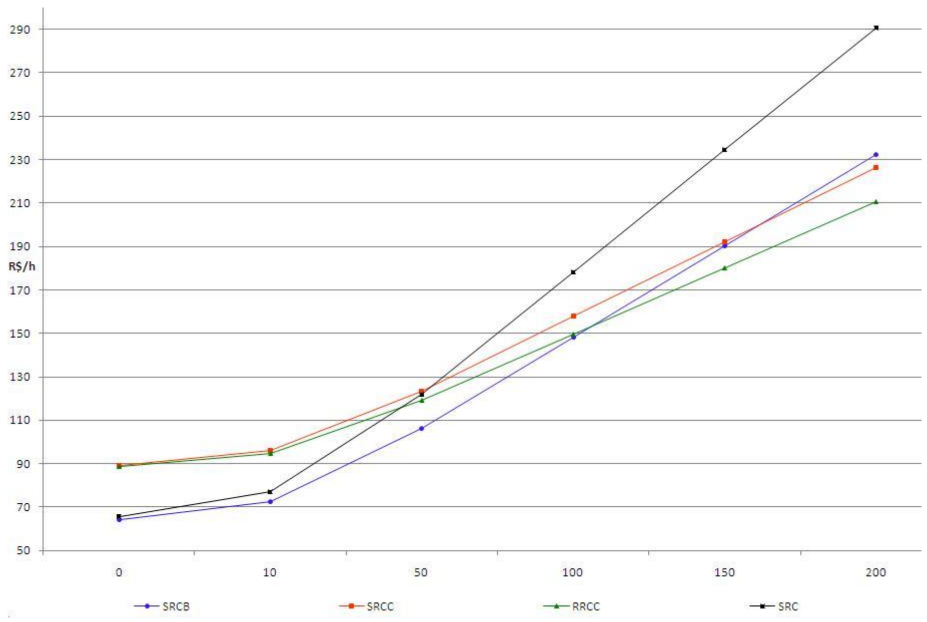

Figure 8. Variation of overall cost production with biomass price.

5. CONCLUSIONS

Based on the second law of thermodynamics, four different cogeneration plants configurations that use biomass as fuel were analyzed. The exergoeconomic analysis proved to be an efficient thermodynamic tool to evaluate the performance thermal systems. Once used, it makes the irreversibility determination easier, identifying the components that cause more exergy destruction in the plant; allowing for the evaluation of the efficiency in each equipment. For that reason, it provides a real view of the productive process and offers information related to production costs and interactions among different equipment in a thermal system. This information may be used to improve the system performance in order to have an effective use of resources.

Currently, the most widespread technology in the Brazilian Amazonia for electricity production and cooling power in small scale, the *SRC* one, is characterized by a small efficiency of the system and a higher consumption of resources when compared with cogeneration cycles which use absorption chiller.

The present cost of technologies in a small-scale steam cogeneration cycle does not justify the implementation of more efficient systems using condensation turbines, if biomass has prices lower than 100 R$/t.

An emphasis should be made in technologies which a bigger efficiency is inherent to a low cost project and where the different components irreversibility in a steam cycle is reduced. Some examples are as follows, the externally-fired gas-turbine (EFGT), Organic Rankine cycle (ORC) and Steam Engines.

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7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

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