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THERMOECONOMIC EVALUATION OF A PROPOSAL TO INTEGRATE A BIOMASS GASIFICATION SYSTEM TO THE PULP AND PAPER INDUSTRY

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Abstract. *Papermaking is a high consumption energy process, and most of the energy consumed in the processes is generated by burning of two fuels: black liquor and biomass. Thus, the largest mills use cogeneration systems that provide electricity and steam for the papermaking processes. Over the years, studies have been made for different types of configurations for these systems, but almost all are driven by the combustion of eucalyptus and its residues, which can emit a large amount of greenhouse gases. Regarding this, with the current scenario of growing electricity consumption, gasification from biomass is very interesting from the energetic point of view, becoming an alternative process for supplying energy for the papermaking process. In this work, an energy cogeneration system based on biomass gasification was analyzed, evaluating the viability of substituting the traditional process, which are usually steam turbine Rankine cycles, used for the generation of electric energy, studying the action of the composition of the gases obtained in the gasifier. In gasification, there is the possibility of introducing the combined cycle, using the gas in the turbine and the thermal waste in a heat recovery steam generator, thus increasing the overall efficiency of this cycle. Thermoeconomics combines concepts from two different areas, Thermodynamics, part of physics that studies the laws governing energy relations, and economics, which is the science that studies material production and consumption, allowing the costs of each one to be rigorously separated.*

Keywords: *Pulp and Paper Plant, Cogeneration, Thermoeconomics, Gasification, Cost Allocation for BIG/GTCC.*

1. INTRODUCTION

In the 20th century, the first Brazilian paper mill was opened in the district of Ipiranga, in São Paulo (SP). Brazil relied on imports of pulp to manufacture paper, but during World War II, when it could no longer maintain this incoming, the national manufacturing had a great impulse. In 1961, Suzano was the first industry to manufacture paper with 100% eucalyptus fiber (SUZANO, 2021). Since then, the world consumption of paper has been increasing significantly, being only 4 kg per inhabitant/year in Brazil and in developed countries it varies between 12 and 18 kg per inhabitant/year (SANQUETTA, 2020).

Pulp production in Brazil is known as the Kraft process, which uses a solution of sulfite and sodium hydroxide, known as white liquor, which separates the pulp from the fibrous part. In this stage, which is known as digestion, the wood solubilizes, coming out in the form of black liquor, which is burned in the recovery boiler to produce steam and electricity. As this material is not enough to supply the energy demand of the process, wood residues and husks in the boiler's initial processing, called biomass (SILVA, 2002).

The use of biomass as an energy source is a challenge because it has to be collected, where it is found, transported and stored so that it does not lose its qualities in energy conversion, to be used in conversion units that are economically viable. The papermaking process consumes a large amount of electricity and steam (SILVA, 2002). Gasification is one of the thermochemical processes that can be employed in the conversion of biomass into energy, and is considered to be one of the most effective ways of doing this. It produces the so-called synthesis gas from carbon-rich organic material. Through the production of synthesis gas resulting from gasification, we have a wide possibility of renewable energy products (BASU, 2010). However, this process powered by biomass that opens the doors to a wide range of possible energy routes and renewables products, including the synthesis of advanced liquid and gaseous fuels, hydrogen gas and electricity, through the production of synthesis gas resulting from gasification (SIKARWARA, et al., 2017). Biomass

gasification systems that convert energy from the gas produced into power basically includes the following equipments: gas cleaning system, biomass dryer, gasifier, gas turbine and recovery boiler.

This paper investigates the energy integration issues for cogeneration of electricity from biomass gasification. The focus of this paper is the thermoeconomic analysis of the plant and possible gains from the integration of the compressor, gas turbine and combustion chamber. Thus, evaluating how heat and power integration can improve the exergetic efficiency of the plant. For this, data from the Ferrarini (2016) work plant was used, where all the boilers were grouped in a single unit, in addition to the union of the turbines.

1.2 Cogeneration

The cogeneration method consists in the simultaneous generation, from a single fuel, of two energy forms, being thermal and mechanical (or electrical). Cogeneration consists in taking advantage of a large part of the heat generated in the other thermal processes. The efficiency of this system provides reliable and low-cost energy production, often making the production unit self-sufficient in electricity generation (BALESTIERI, 2020).

This study was based on data such as pressure, temperature and flow of the states from the previous study carried out by Ferrarini (2016), who analyzed the base of the pulp and paper plant, defined as Plant 1 (Figure 1). In this plant, gasification, defined as Plant 2 (Figure 2), was integrated, comparing them using the methodology explained in the following topics.
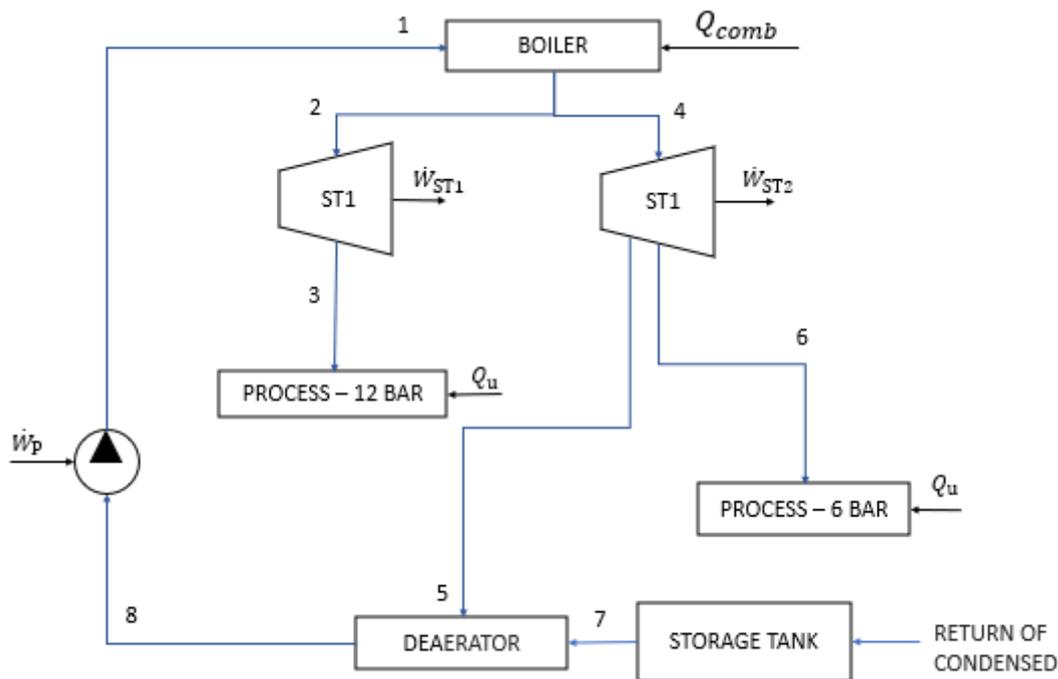

Figure 1. Pulp and paper thermal plant (Plant 1).

The boiler maintains the stability of the steam demand. The steam produced by the boilers is distributed to the processes and used in various equipment. Medium and low-pressure vapors are obtained from the extraction of the turbines, which are ST1 and ST2. The condensed water is pumped by a high pressure pump, returning to the boiler and thus closing the cycle.

With the description of the papermaking stages, it's clear the need for the use of steam. The boiler is of utmost importance.

1.3 Gasification

Gasification is a thermochemical conversion process of solid or liquid materials of organic origin, in an atmosphere of steam, air, carbon dioxide or pure oxygen in order to produce a gas of medium or low calorific value, generically called synthesis gas (PELLEGRINI, 2009). The materials used for gasification are associated with the calorific value produced, used to produce energy. Some of the materials used for gasification are wood, sugarcane bagasse, oils, straw, garbage, waste, among others.

The gasification process is mainly developed in four processes, which can occur in the same region of the equipment, depending on the technology applied (REED; GAUR, 2001). First, there is the drying region, in which excess moisture is removed through evaporation, a slower stage for more humid fuels. The pyrolysis region, which begins at at least 280°C, when vaporization of the volatile parts takes place, forming non-condensable gases. Combustion or oxidation zone is necessary to the process, where exothermic reactions combine the oxygen gas molecules with carbon molecules, resulting in carbon dioxide and carbon monoxide. The reduction zone is composed of endothermic reactions that use previous products to form hydrogen molecules, methane, and hydrocarbons. At the end of this step gasification is complete, which generally produces combustible gases at temperatures above 400 °C.

To begin the gasification procedure, the material is confined in a controlled atmosphere, where a small portion is burned, providing the heat required near the chemical reactions. Once the temperature is reached, the air supply is restricted, initiating the remaining chemical reactions. The result is the release of fuel gas accompanied by particulates, tars and carbon oxides. This gas is then cracked, cleaned, and cooled to be directed to the turbines.
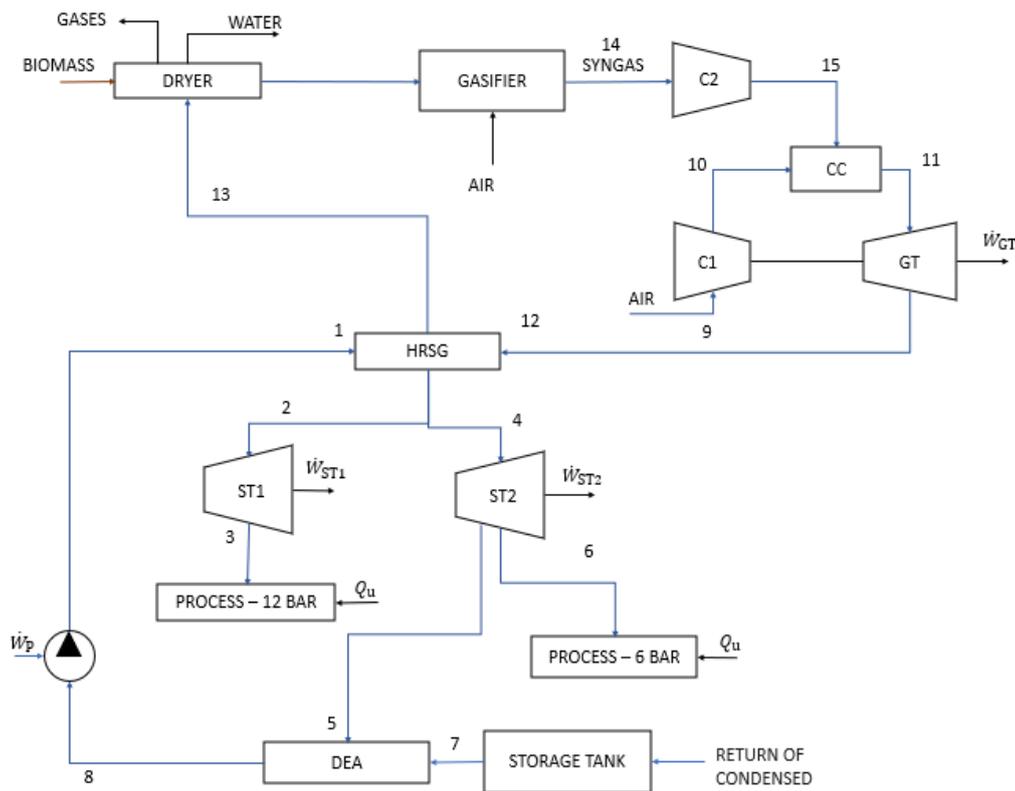

Figure 2. Pulp and paper thermal plant with integrated gasification (Plant 2).

In this process, the steam cycle remains the same, but the gas cycle will be included, where the gasification process will generate the fuel from this cycle, which will feed a combustion chamber (CC), in this combustion chamber the fuel will be mixed with air, which will be admitted and compressed by the compressor (C1), and in the gas turbine (GT), the exhaust gases will pass at high pressure and temperature to generate energy.

In the gas turbine the exhaust occurs at a very high temperature, so these exhaust gases from the turbine will go through a recovery boiler (HRSG), which will replace the traditional boiler, to generate steam to feed the steam cycle, and these gases are directed to a drying chamber to pre-treat the biomass before entering the gasifier.

With the definition of the physical plants, the simulations begin. Being made based on data from the work of Ferrarini (2016). The Engineering Equation Solver (EES) software, the temperatures, pressures and flows taken from the Ferrarini work (2016) were used to perform the mass and energy balance calculations and to define operating points such as pressure, temperature of all flows.

2. METHODOLOGY
2.1 Energy and exergetic analyses

The energy analysis was developed by applying the principle of conservation of mass and the first law of thermodynamics for the system working in steady state and neglecting the effects of potential and kinetic energies, according to Moran (2000):

$$\dot{Q}_{vc} - \dot{W}_{vc} + \sum \dot{m}_e h_e - \sum \dot{m}_s h_s = 0 \tag{1}$$

where $\dot{Q}_{vc}$ is the heat transfer rate generated (kW), $\dot{W}_{vc}$ the power rate generated or consumed (kW), $\dot{m}$ the mass flow rate (kg/s), and h specific enthalpy (kJ/kg).

The second Law of Thermodynamics establishes a possible direction of energy conversion. Here, the meaning of exergy is incorporated so that the potential work produced can be measured, knowing the quality of the energy employed. Energy conversion systems must be evaluated in terms of energy and exergy balance. Analyses must be performed to minimize unnecessary losses in the ability to perform work, improving the utilization of energy resources. For a flow of matter through a control volume in a permanent regime, the kinetic energy and potential energy are neglected, the variation of the exergy of the system, in kW, obtained in Moran (2000):

$$\Delta B = \sum \dot{m}_e (h_e - T_0 s_e) - \sum \dot{m}_s (h_s - T_0 s_s) \tag{2}$$

where ΔB is the change in physical exergy, s_e and s_s the specific entropy of input (kJ/kg.K) and output T_0 reference temperature (K).

The potential specific work (kJ/kg) of a stream in any state is defined as the physical exergy of the stream.

$$b = (h - h_0) - T_0(s - s_0) \tag{3}$$

where h_0, s_0 e T_0 are flow properties with temperature and pressure in equilibrium with the reference environment.

For the fuel studied, it is necessary to determine the chemical exergy to define its available energy quantity. Following the methodology of Szargut, Morris and Steward (1988), we have that the exergy of biomass can be calculated as:

$$e_{biomass} = B(PCI + h_a Y_a) + e_a Y_a \tag{4}$$

$$B = \frac{1.0412 + 0.2160 \left(\frac{Z_{H2}}{Z_C}\right) - 0.2499 \left(\frac{Z_{O2}}{Z_C}\right)\left(1 + 0.7884 \left(\frac{Z_{H2}}{Z_C}\right) - 0.045 \left(\frac{Z_{N2}}{Z_C}\right)\right)}{1 - 0.3035 \left(\frac{Z_{O2}}{Z_C}\right)} \tag{5}$$

where $e_{biomass}$ is the exergy of biomass, h_a the enthalpy of vaporization of water, e_a the chemical exergy of liquid water, Y_a the moisture of bagasse and Z_i the respective percentages of composition.

The properties below were taken from the work of Ferrarini (2016).

Table 1. Biomass characteristics and composition.

Description	Value
PCI (kJ/kg)	9169,60
Moisture (%)	35,00
Carbon (%)	31,12
Hydrogen (%)	3,38
Nitrogen (%)	0,12
Oxygen (%)	24,56

2.2 Thermoeconomics Analysis

Thermoeconomics is the application of energy for the allocation of economic costs, in order to generate a product the cost of this product has to compensate for the sum of the input costs to produce, acquisition, operation and maintenance costs (LAZZARETTO, 2002):

$$\dot{C}_p = \dot{C}_f + \dot{Z}^{AQ} + \dot{Z}^{OM} \tag{6}$$

where $\dot{Z}^{AQ}$ is the acquisition cost stream, $\dot{Z}^{OM}$ maintenance cost stream, $\dot{C}_p$ product cost stream, and $\dot{C}_f$ the input cost stream.

For each mass, labor, and heat flow, an exergy cost can be associated:

$$\dot{C}_i = c_i E_i \tag{7}$$

where c_i is the unit exergy cost at the input or output of the system.

For the unit exergy cost, thermoeconomics also defines it analogously to the unit monetary cost, where it disregards equipment costs and the unit fuel cost being equal to unity (FERRARINI, 2016).

The exergy destroyed internally in the system is calculated from the equations below:

$$\Sigma \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \Sigma \dot{m}_i e_i + \Sigma \dot{m}_e e_e - \dot{E}_d = 0 \tag{8}$$

where $\dot{E}_d$ is the flow of exergy destruction.

Valero and Lozano (1994), associated costs with the exergy destroyed in each component of a thermal power plant. Which is the theoretical basis of thermoeconomic analysis.

2.3 Thermoeconomic Modeling

Some of the points of thermoeconomics is to understand how an input is used by a production unit to provide a product and how the cost of obtaining this input is passed from the unit to the product.

Every production unit must have at least one product and one input. The product that arrives at a production unit has a cost that refers to its acquisition. The production unit uses this product, which consequently adds a new cost to that product. At this point, the equations used to assign costs take into account the inefficiencies that are present in the process. "E" Model is the methodology that uses exergy in total, without disaggregating it, by the definition of input and product (FARIA, 2014). For exergy flows not associated with the work fluid, the definition of input and output is simply made by observing the role played by exergy in the production unit. Therefore, the definition of input and product is similar to the "E" model, where the portion passing through a unit increases, then the portion is the product of the unit. If the parcel reduces, then it is the unit's input (COLOMBO, 2016).

Thermoeconomics has proven to be an interesting tool both for analysis of losses in energy conversion processes and for determining the costs of a plant using the laws of thermodynamics, thus making it possible to identify more clearly the components where measures will be applied to improve the performance of systems and equipment (VALERO, 1994).

To quantify the inputs and outputs, the following equation was used:

$$E_i = \dot{m}_i e_i \tag{9}$$

The inputs and products and their respective costs for each equipment are shown in Table 2.

Table 2. Definition of input and output of the systems following the Model E (Plant 1).

Systems	Fuel	Product
Boiler	$Q_{comb} + k_{pot}.\dot{W}_{boiler}$	$E_{1:2}$
ST1	$E_{2:3}$	$\dot{W}_{STG1}$
ST2	$E_{4:5}$	$\dot{W}_{STG2}$
DES	$E_{7:8}$	$E_{5:10}$
Pump	$\dot{W}_P$	$E_{1:8}$
Process	$E_{6:7} + E_{3:7}$	$k_u.Q_u$
J-B	$(E_{2:3} + E_{4:5} + E_{6:7} + E_{3:7})$	$E_{1:8} + E_{1:2} + E_{7:8}$
GE	$\dot{W}_{STG1} + \dot{W}_{STG2}$	$\dot{W}_{boiler} + \dot{W}_P + \dot{W}_{net}$

The productive diagrams of the plants following E Model are represented in Figures 3 and 4, where the equipment that contributes to the increase in fluid effort is on the left side, and the one that decreases it is on the right side.

Figure 3. Pulp and paper mill productive diagram according to E Model (Plant 1).

The inputs and products and their respective costs for each piece of equipment in Plant 2 are represented in the table below.

Table 3. Definition of input and output of the systems following the Model E (Plant 2).

Systems	Input	Product
HRSG	$\dot{W}_{boiler} + E_{11:2}$	$k_{boiler}.E_{1:2}$
ST1	$E_{2:3}$	$k_{pot1}.\dot{W}_{STG1}$
ST2	$E_{4:5}$	$k_{pot}.\dot{W}_{STG2}$
DES	$E_{7:8}$	$k_{es}.E_{5:10}$
Pump	$\dot{W}_P$	$k_{Pump}.E_{1:8}$
Process	$E_{6:7} + E_{3:7}$	$k_u.Q_u$
JS-BS	$(E_{2:3} + E_{4:5} + E_{6:7} + E_{3:7})$	$k_{Pump}.E_{1:8} + k_{boiler}.E_{1:2} + k_{DEA}.E_{7:8}$
GT	$W_{STG1} + W_{STG2}$	$k_{pot}.\dot{W}_{boiler} + k_{pot}.\dot{W}_P + k_{pot}.\dot{W}_{net} + k_{pot}.\dot{W}_{GT}$
Gasifier	$Q_{biomass}$	$k_{gasif}.E_{syngas}$
C1	$\dot{W}_{C1}$	$k_{c1}.E_{9:10}$
C2	$\dot{W}_{C2}$	$k_{c2}.E_{15:16}$
CC	$E_{10:15}$	$k_{cc}.E_{15:11}$
GT	$E_{11:12}$	$k_{pot}.\dot{W}_{GT}$
JG-BG	$k_{c1}.E_{9:10} + k_{c2}.E_{15:16} + k_{cc}.E_{15:11} + k_{gasif}.E_{syngas}$	$k_{eg}.(E_{11:12} + E_{11:2})$

Figure 4. Productive diagram of the pulp and paper mill according to Model E (Plant 2).

After the production structure and flows have been determined, the cost equation systems are assembled. To calculate the monetary costs, Equation 10 is used for each equipment.

$$c_f F - c_p P = \dot{Z}_{equip} \tag{10}$$

where c_f is the monetary cost of the equipment input, F the value of the input on an exergetic basis, c_p the monetary cost of the flow promoted by that equipment, P the value of the product on an exergetic basis, and $\dot{Z}_{equip}$ the hourly monetary cost of the equipment.

For this, using data from Passolongo (2011) we know that the costs of the production units are:

Table 4. Estimated Equipment Costs.

Equipment	Cost [R$]
Boiler	28,000,000.00
Turbine	17,000,000.00
Deaerator	2,000,000.00
Pump	1,800,000.00
Gasifier	39,000,000.00
GasTurbine	19,800,000.00
Gas Compressor	6,700,000.00
HRSG	3,510,000.00

To continue with the monetary costs, it is necessary to estimate the amortization costs of each piece of equipment, to make this assessment, Equation 11 determined equations, considering 20 years of service, an annual interest rate of 12.4%, and a maintenance factor of 7%, thus arriving at a more realistic final cost, from Passolongo (2011).

$$\xi = \frac{(i(1+i)^{n_a}}{3600 n_a n_h ((1+i)^{n_a} - 1)} \tag{11}$$

where ξ is amortization factor, i annual interest rate, n_a a number of years and n_h number of hours per year.

3. RESULTS

After performing the energy and exergy balances, obtaining the exegetical flows of each of the flows present in the cycle, with these flows we carry out the thermoeconomic balance, managing to survey the cost of each equipment, this cost will show how much is needed monetarily or in exergetic terms to generate exergy in each of the equipment. Based on the equations and definitions presented previously, the main results for Plant 1 are presented in Table 5.

Table 5. Unit exergy cost of the physical flows of Plant 1 according to the Model E.

Production Unit	Unit Exergetic Cost [kW/kW]	Unit Monetary Cost [R$/MWh]
Boiler	2.39	50.99
DEA	1.58	33.75
Pump	4.62	98.65
Exergy	2.45	52.28
Power	3.19	68.07
Heat	2.45	52.28

For the plant with integrated gasification, the main results are presented in table 6.

Table 6. Unit exergy cost of physical flows for Plant 2 according to the Model E.

Production Unit	Unit Exergetic Cost [kW/kW]	Unit Monetary Cost [R$/MWh]
HRSG	1.59	33.90
DEA	1.85	39.41
Pump	2.25	48.02
Steam Exergy	1.19	25.44
Gas Exergy	1.19	25.44
Power	1.55	33.13
Heat	1.19	25.44
Gasifier	1.17	25.08
CC	1.89	40.19
C1	1.94	41.41
C2	3.14	67.00

The biomass gasification process performed satisfactorily when compared to the process without it. When we compare the costs between the two, we see that the cost of Plant 2 decreases a lot in almost all units, even adding the value of the new configuration, where the equipment is considered new, therefore, besides the operation and maintenance costs, the costs of the invested capital must be added.

This increase is explained by the higher efficiency of the combined cycle when compared to a Rankine cycle, where we apply a HRSG, avoiding wasted work in the system. The exhaust gases from the gas turbine are recovered, heating and producing more steam, generating heat and power for the process.

The pump and boiler units have the highest unit exhaust costs due to lower efficiency. In addition, these values are very high because the cycle did not consider the irreversibilities of the processes, so they are ideal cycles.

With the implementation of the biomass gasification plant, there was an increase in deaerator unit cost (14.59%) and monetary cost (14.36%).

The unit exergetic costs are not equal to those of Ferrarini (2016), which is explained by the changes made in the plant studied. The modeling allows obtaining a system of equations that represents the entire cost formation process in the thermal plant. This system of equations takes into account all the internal flows of the system, and also the external flows of the system, this explains the difference in values. Nevertheless, obtaining the cost of each of these products with the cost of production of each separate one is of paramount importance for comparison purposes.

4. CONCLUSION

Initially, it is pointed out that this work aims at the development of Thermoeconomics science, which appeared around 1960 and is, therefore, a relatively new field, Thermoeconomics has made it possible to determine the costs of all plant flows, based on the values generated, the cost-forming structure can be analyzed, identifying the processes that make high-value production.

The proposal presented by this work refers to the analysis of two thermal plants, assembling the production diagram, observing the cost of power and useful heat in cogeneration systems with steam turbines when compared with a cogeneration system with gas turbines, in general exergetic and thermoeconomic analyzes have proven to be powerful tools in the task of optimizing thermal systems such as IGCC, which proves to be a profitable and very safe investment.

Throughout the work, exergy analyzes were carried out, identifying in which parts of the process exergy destruction occurred and its magnitude and making it possible to identify which components should be applied measures to improve the system performance. At this point, by taking the costs of the equipment into account, it is possible to compare those values between the cycles with and without the gasification processes.

Gasification is yet a growing technology process regarding its integration with the combined cycle and using biomass as fuel. But, it is clear that this technology has an immense potential to increase the efficiency of the power generation processes used nowadays. Knowing that, this paper aims to help spread the study of this integration of technologies.

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6. AUTHORIAL RESPONSIBILITY

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