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THERMOECONOMICAL ANALYSIS OF AN INTERNAL COMBUSTION ENGINE FOR A COGENERATION SYSTEM USING SYNGAS FROM A DOWNDRAFT GASIFIER PERFORMING WITH DIFFERENT BIOMASS MATERIALS.

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Resumo: *This paper presents the results achieved in the evaluation of different alternatives of a cogeneration model consisting of a downdraft gasifier coupled to an internal combustion engine (ICE) and two heat exchangers water/gas. The methodology applied included an exergoeconomical analysis, available in the literature. The synthesis gas produced is cooled in a heat exchanger water/gas to generate hot water at 80 °C and then is used in the ICE to generate electric power, the heat of the exhaust gases is used in the second heat exchanger to produce hot water at 80 °C. This study considered three kind of biomass: sugarcane bagasse, rice husks and pine. From the point of view of the second law of thermodynamics, the overall efficiency of the system for bagasse is 13.5 %, for pine is 13 %, and for rice husk reached 13.8 %. The efficiency of power generation varies from 25.76 %; 22.04 % to 25.49 % for the bagasse, pine and rice husk respectively. The efficiency of generating hot water varies from 8.02 % to 12.82 % for the three types of biomasses studied. The cost of the synthesis gas varies from 0.043 to 0.16 US$/kWh, the electricity production cost varies from 0.048 to 0.22 US$/kWh and the cost of the hot water production fluctuates between 0.002 and 0.014 US$/kWh. The recovery time of the investment (payback), with an interest rate of 6%, is between 5 and 6 years.*

Palavras-chave: *Renewable energy, exergoeconomical analysis, gasification, cogeneration*

1. INTRODUCTION

Biomass can be converted to a wide variety of energy forms (electricity, process heat for industrial and domestic facilities, engine fuels, etc.) by means of a number of thermochemical and biochemical processes . (Coronado et al., 2011; Pedroso et al., 2013; Wang et al., 2008). Combustion, pyrolysis and gasification are the three main thermochemical processes. Gasification converts biomass in a combustible gas mixture (producer gas or syngas), mainly made of carbon monoxide, hydrogen and lower content of methane, which is able to provide a wide range of products, extending from clean fuel gas and electricity to bulk chemicals (Arena, 2012; Mastellone et al., 2013).

The gasification of the biomass presents itself as a sustainable alternative to energy generation, with low pollutant output which allows a little balance between consumption and the production of carbon gas in the global cycle of growth and consumption (burning) of vegetables. Gasification consists in a thermochemical process, by which the biomass is converted into fuel gas through the partial air oxidation, partial oxygen oxidation or partial water steam oxidation at high temperatures from approximately 750 0C to 850 0C. This fuel gas, which its low heat value (LHV) is from 4 to 6 MJ/Nm3, can be burned up directly or used as fuel for an internal combustion engine (ICE) or gas turbine (Coronado et al, 2011).

On the other hand, cogeneration has always demonstrated to be the best alternative regarding the lower energy consumption with the highest energy efficiency, as well as concerning the implantation of distributive generation of electrical energy. The alternative stationary engines have demonstrated to be an excellent choice about the generation of electric energy on a small scale; that is the reason that cogeneration with ICE presents itself as a viable alternative for residences and rural areas.

Several researcher groups in the past decade began studies for the optimization of energy systems, developing methods and models that combine principles from the thermal sciences (thermodynamics, heat transfer, and fluid mechanics) and economic engineering, with the aim of diminishing investment decisions, and energy systems develops

through a rationalization operation. These features resulted in a new thermal engineering area, the thermos -economics (Valero A, Torres C, 1989). Basically, thermos-economic combines the second law of thermodynamics, through the availability or exergy conception, with an economical approach of the system in study. In addition, the exergetic analysis is the qualitative and quantitative analysis of losses through the second law of thermodynamics. This kind of evaluation has assumed gradually a great importance in the thermal systems processes analysis, however, also the first law of thermodynamics (energy balance) is considered. The thermoeconomical optimization aims the energy systems analysis and design through the use of mathematical models involving thermodynamic parameters and economical costs (Silveira et al., 2010) with the exergetic analysis.
In order to evaluate different alternatives of the cogeneration system, and to determine the exergetic cost of hot water and electricity produced, it is employed the exergoeconomical method developed in accordance with the Silveira`s method, available in the literature by several papers (Silveira et al., 2010).

2. BIOMASS

Biomass includes all organic materials that come from photosynthesis process, as well as those that have evolved from it. (KAVALOV, B. 2005) The main features of pine, bagasse and rice husk, with a humidity of 20%, are shown in Table 1. It can be seen that the lower heat value LHV of Pine is the largest one with 18670 kJ/kg. Besides pine, this paper discusses the followed biomass: bagasse (14870 kJ/kg) and rice husk (16609 kJ/kg). (Yoon et al., 2012; Diniz Filho et al., 2013; Dogru et al., 2002)

Table 1. Elemental composition and LHV of the studied biomasses.

Biomasses	Weight percentages (%)							LHV (MJ/kg)
	C	H	O	N	S	Ash	W	
Bagasse (Diniz Filho et al., 2013)	35.934	4.28	31.64	0.304	0.01	7.832	20	16.462
Rice Husk (Yoon et al., 2012)	32.864	3.44	28.688	0.32	0.016	14.672	20	15.262
Pine (Dogru et al., 2002)	39.408	4.792	35.488	0.048	0.024	0.24	20	19.162

3. SYSTEM DESCRIPTION

The tested system shown in Fig. 1 is composed by a downdraft gasifier, two heat exchangers water/gas and a 15 kW ICE.

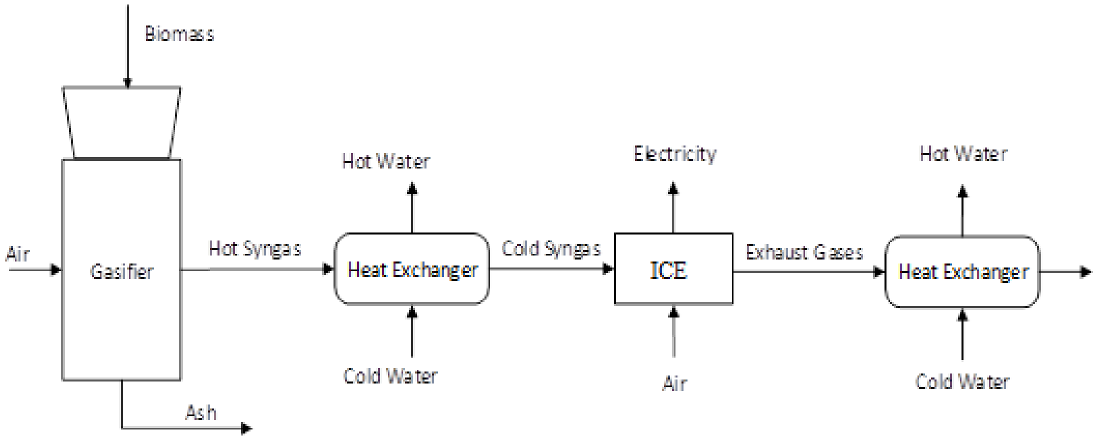

Figure 1. Physical diagram of the cogeneration system.

3.1. Gasifier system

The analyzed system in this paper is shown in Fig. 2.A) The biomass materials enter through the top of the downdraft gasifier. The atmospheric air enters through an intermediate point and descends in the same directio n of the biomass. Afterwards, it passes through the reduction process, the atmospheric air ascends without coming into direct contact with the incoming biomass, only exchanging heat to assist the pyrolysis process. The atmospheric air enters the pyrolysis region and produces a flame on account of the burning of most part of the volatiles. This flame is known as pyrolytic combustion by which the limited quantity of air produces fuel gases besides carbonic gas and water. When the residual volatiles are forced to pass through the combustion zone, they reach high temperatures converting them into non-condensable gases. After the combustion zone, the biomass is converted into vegetable coal, and the carbon dioxide and the water steam, coming from the combustion zone, reacts with the coal in order to generate more carbon monoxide and hydrogen. This process substantially cools down the gas, as the reduction reactions are endothermic.

For gasification thermal applications, when the gas is burned directly in a furnace, for example, it is more convenient to refer to "hot efficiency", because the thermal energy of exhaust gases is used. For power applications, such as the ICE and gas turbines, as presented in this paper, when the gas is cooled down during its conditioning (removal of particles and tar), it is valid to refer to "cold efficiency". The "hot efficiency" of the downdraft gasifier is 84.73% and the "cold efficiency" is 62.68%. (Coronado et al., 2011)

3.2. Compact cogeneration system

The name "cogeneration" is usually used to describe the joint production of electricity and thermal energy. These systems have a considerable decrease in the consumption of primary energy for heat and power production compared to conventional production. (Havelský, 1999)

A cogeneration cycle consists of an ICE to produce electricity and two heat recovery units, one that uses the engine exhaust gases and the other uses the syngas temperature at the outlet of the gasifier to produce hot water. (Tab. 2). (Coronado et al., 2011)

Table 2. Characteristics of the cogeneration compact system.

ICE	Alternator three-phase	Heat exchangers
• Model: GM Corsa Engine, 1.0 L "98"	• Frequency: 60 Hz	• Model: Shell & Tube gas/water
• 4 strokes	• Number of poles: 4	• Number of tubes: 76 (gas/water)
• Injection System: MPFI-Delphi	• 1800 rpm	• Diameter of tubes: 9.525 mm (both)
• Compression value: 9.4:1	Cos φ: 0.8	• Thickness of tubes: 0.79 mm (both)
• Max power: 44 kW	• Power:12.5kVA - 10 kW	• Weigh of tubes: 12.5 mm (both)
• Max power torque: 81 Nm.	• 220 V: 32.8 A	
• Max rotation: 6000 rpm		

The cogeneration system displayed in Fig. 2.B), is composed of: ICE model GM, 1.0 CORSA, coupled to a generator via belt and pulley to receive the mechanical energy produced by the engine. The motor used has a reducing "Rodogás" system pressure fuel supply that allows Liquefied Petroleum Gas (LPG) or Natural Gas Vehicles (CNG) operation and even with gasoline.

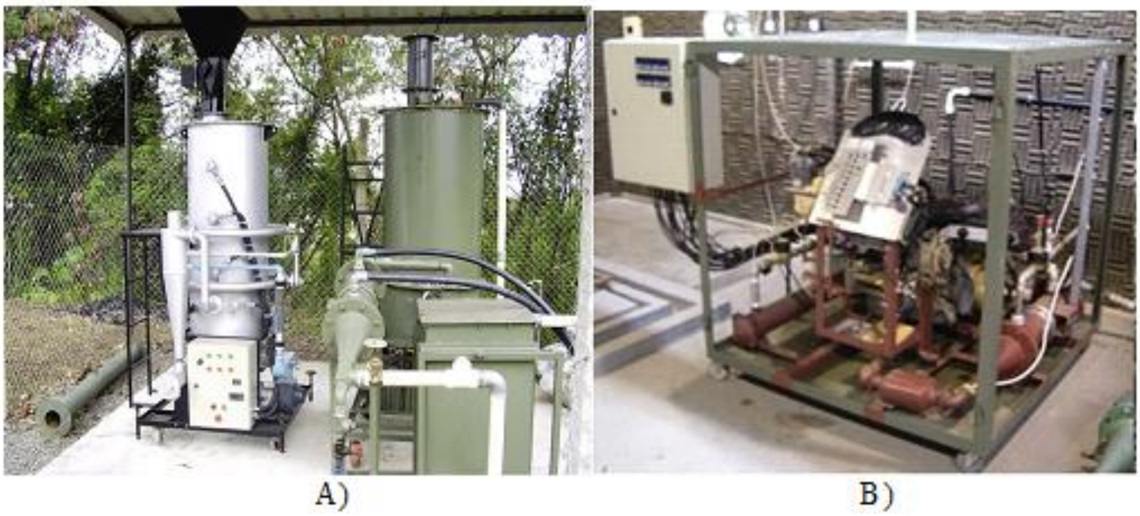

Figure 2. A) Prototype I and II. Downdraft wood gasifier [1]. B) Cogenerator compact system with alternative engine.

The Rodogás is an instrument, model TE-01, with a maximum capacity of 43 m^3/h of fuel, utilized in engines with power up to 89 kW. The maximum work pressure entrance is 250 bar and a minimum of 26 bar; It is operated by an electromagnetic valve, powered by 12 V voltage. Water flow through the heat exchanger water/gas is 120 kg/h, entering at 25 °C and is heated to 80 °C. The gas flows on the outside of the tubes at a rate of 56 kg/h, entering at a temperature of 541 °C and being cooled to 307 °C. The housing of the heat exchanger consists of DIN 2440 steel, and the remaining components are carbon steel. (Coronado et al., 2011)

4. METHODOLOGY

4.1. Syngas

The synthesis gas composition for pine, bagasse and rice husk are shown in Table 3 according to experimental results obtained by (Yoon et al., 2012; Abdoulmoumine et al., 2014; Proenza et al., 2014) for conditions similar study.

Table 3. Syngas composition % in volume

Gases	Biomass materials		
	Pine (ABDOULMOUMINE et al., 2014)	Rice Husk (YOON et al., 2012)	Bagasse (PROENZA, et al., 2014)
H2 [%]	10.36	13.6	16.43
CO [%]	14.18	14.9	22.61
CO2 [%]	16.35	12.9	10.5
CH4 [%]	2.94	2.3	0.67
N2 [%]	46.4	46.1	43.34
H2O [%]	9.8	10.2	9.8
LHV gas [MJ/kg] Dry bases	5.32	4.26	4.56

4.2. Thermoeconomical analysis of the gasifier-cogeneration system

The thermoeconomical analysis were based on exergy concepts and the construction of functional diagrams [10]. The exergetic functions were determined in an incremental base. The operation and maintenance costs for a downdraft gasifier, electricity, hot water, and the amortization investment period were determined.

The Fig. 3 presents the functional diagram based on exergetic increment, which represents the real cogeneration system (Downdraft Gasifier, Heat exchanger I and II, Internal Combustion Engine), and the exergetic flows entering and getting out of each subsystem.

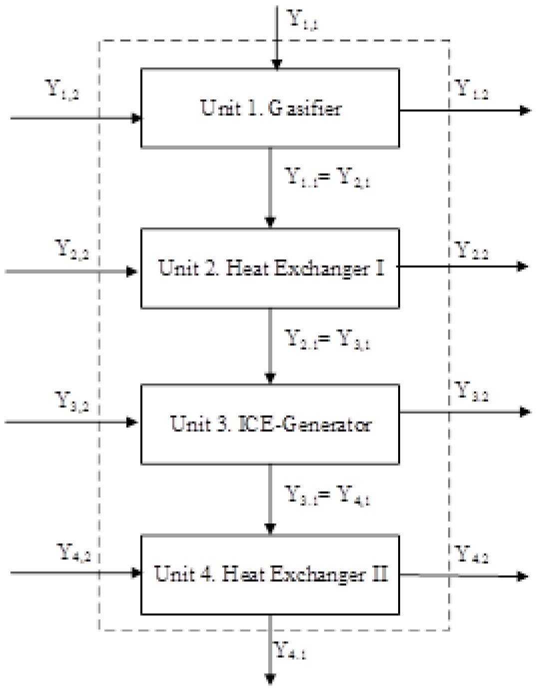

Figure 3. Functional diagram of cogeneration System.

4.3. Exergetic increment functions:

To determine the exergetic functions associated with the Cogeneration system, losses in the pipes will not be include. Considering the physical diagram and the thermodynamic properties values for each flow of the process steps, the values of exergy flows are determined in the associated incremental basis functional thermoeconomical diagram shown in Fig. 3.

Gasifier subsystem:

$$Y_{1,1}=E_b=m_b\cdot ex_b=m_b\cdot LHV_b \quad (1)$$
$$Y_{1,2}=m_{air}\cdot ex_{air} \quad (2)$$
$$Y_{1.1}=Y_{2,1}=m_g\cdot(ex_g^{PH}+ex_g^{CH}) \quad (3)$$
$$Y_{1.2}=m_{ash}\cdot ex_{ash} \quad (4)$$

Heat Exchanger subsystem I.

$$Y_{2,1}=Y_{1.1} \quad (5)$$
$$Y_{2,2}=m_w\cdot ex_{C.w}=0 \quad (6)$$
$$Y_{2.1}=m_g\cdot(ex_g^{PH}+ex_g^{CH}) \quad (7)$$
$$Y_{2.2}=m_w\cdot\{(h_{H.w}-h_0)-T_0(S_{H.w}-S_0)\} \quad (8)$$
$$\eta_{ex,HE}=\frac{Y_{2.2}-Y_{2,2}}{Y_{2,1}-Y_{2.1}} \quad (9)$$

ICE subsystem.
The ICE uses the both thermal and chemical exergy of syntheses gas.

$$Y_{3,1}=Y_{2.1} \quad (10)$$
$$Y_{3,2}=m_{air}\cdot ex_{air} \quad (11)$$
$$Y_{3.1}=Ep \quad (12)$$
$$Y_{3.2}=m_{ge}\cdot(ex_{ge}^{CH}+ex_{ge}^{PH}) \quad (13)$$
$$ex_{ge}^{CH}=\sum X_w\cdot ex_w^{CH}+\bar{R}\cdot T_0\sum X_w\cdot \ln X_w \quad (14)$$

where:
X_w is the gas molar fraction,
ex_w^{CH} is the chemical exergy of each gas compounding the exhaustion gases (SILVEIRA; TUNA, 2003)

$$Ep=\frac{E_{Cg}}{\eta_{ICE}} \quad (13)$$
$$E_{Cg}=m_g\cdot LHV_g \quad (14)$$
$$m_w=\frac{(E_{Hg}-E_{Cg}+m_{steam}\cdot hfg)\cdot\eta_{HE}}{C_{p,w}\cdot(T_o-T_i)} \quad (15)$$

Heat Exchanger subsystem II.

$$Y_{4,1}=Y_{3.2} \quad (16)$$
$$Y_{4,2}=m_W\cdot ex_{CW}=0 \quad (17)$$
$$Y_{4.1}=m_g\cdot(ex_g^{PH}+ex_g^{CH}) \quad (18)$$
$$Y_{4.2}=m_{HW}\cdot\{(h_{HW}-h_0)-T_0(S_{HW}-S_0)\} \quad (19)$$
$$\eta_{ex,HE}=\frac{Y_{4.2}-Y_{4,2}}{Y_{4,1}-Y_{4.1}} \quad (20)$$

The energy efficiency of the system is calculated by the Eq. (21)

$$\eta_{EX.Eff.\ System}=\frac{(Y_{3.2}+Y_{2.2}+Y_{4.2})}{Y_{1,1}} \quad (21)$$

4.4. Thermoeconomical analysis

This section studies the thermoeconomical feasibility of the Gasifier/ICE system, based on the allocation cost methodology developed by Silveira (Silveira et al., 2010). The equations used in this analysis are cited below:

$$C_{gas}=\left(\frac{Inv_{gasif}\cdot f\cdot\varphi}{H^*Y_{1.1}}\right)+\left(\frac{C_{Bio}\cdot Y_{1,1}}{Y_{1.1}}\right) \quad (22)$$
$$C_{EE}=\left(\frac{Inv_{ICE}\cdot f\cdot\varphi}{H^*Y_{3.2}}\right)+\left(\frac{P_{gas}\cdot FP_{Ep}}{Y_{3.2}}\right) \quad (23)$$
$$C_{HW}=\left(\frac{(Inv_{TC1}+Inv_{TC2})\cdot f\cdot\varphi}{H\cdot(Y_{2.2}+Y_{4.2})}\right)+\left(\frac{P_{gas}\cdot FP_{HW}}{(Y_{2.2}+Y_{4.2})}\right) \quad (24)$$

$$FP_{Ep}=\frac{Y_{3.1}}{(Y_{3.1}+Y_{2.1}+Y_{4.1})} \quad (25)$$

$$FP_{Ep}=\frac{(Y_{2.1}+Y_{4.1})}{(Y_{3.1}+Y_{2.1}+Y_{4.1})} \quad (26)$$

$$f=\left(\frac{q^{k}\cdot(q-1)}{q^{k}-1}\right) \quad (27)$$

$$q=1+\frac{i}{100} \quad (28)$$

$$G_{PEL}=Y_{3.1}\cdot H\cdot(PV_{EL}-C_{EL}) \quad (29)$$

$$G_{HW}=(Y_{2.2}+Y_{4.2})\cdot H\cdot(C_{Full}-C_{HW}) \quad (30)$$

$$G_{TOT}=G_{PEL}+G_{HW} \quad (31)$$

To calculate the exergetic cost of syngas, electricity generation and hot water Eq. (22) to (26) are applied, Eq. (27) and (28) reflect the annuity factor, the gain from the sale of electricity and hot water are obtained by Eq. (29) and (30), and Eq. (31) reflects the payback time installation. The parameters employed in the economical analysis of the proposed plant are shown in Tab. 4.

Table 4. Fixed parameters

Item	Value	Item	Value
Hours of operation per year	3000	$C_{Biomass}$ Bagasse [US$] (Diniz et al., 2013)	0.016
T° of syngas into TC1 [°C]	600	$C_{Biomass}$ Pine [US$/kg] (Rural, 2015)	0.02
T° of syngas from TC2 [°C]	35	$C_{Biomass}$ Rice Husk [US$/kg] (Rural, 2015)	0,022
T° of exhaust gases into TC2 [°C]	600	I_{TC1} [US$] (Coronado et al, 2011)	631.58
T° of exhaust gases from TC2 [°C]	149	I_{TC2} [US$] (Coronado et al., 2011)	421.05
T° Inlet of water from TC1 and TC2 [°C]	25 °C	I_{ICE} [US$] (Coronado et al, 2011)	15790
T° Output of water from TC 1 and TC2 [°C]	80 °C	$I_{Gasifier}$ [US$] (Coronado et al., 2011)	88421
Maintenance factor (φ) (Silveira et al, 2003)	1,09	Interest rate [%] (Boloy et al., 2011)	6

In order to calculate the specific heat of the exhaust gases, the composition of the gases for each biomass reported in Table 3 are utilized as well as the general equation for the combustion of synthesis gas with air excess α. (Proenza et al., 2015)

$$X_{H_2}H_2+X_{CO_2}CO_2+X_{CO}CO+X_{CH_4}CH_4+X_{N_2}N_2+X_{O_2}O_2+\alpha n_{stq}\ (O_2+3.76N_2)\rightarrow n_{CO_2}CO_2+n_{H_2O}H_2O+n_{N_2}N_2+n_{O_2}O_2 \quad (13)$$

Adopting a combustion with a typically excess air of 40 % (α = 1.4) in the ICE, after stoichiometric balance, the mass percentage of each component was determined, as shown in Table 5 for 1 mole of syngas.

Table 5. Mass percentage of each component in the exhaust gas.

Exhaust gases	% mass		
	Pine	Rice Husk	Bagasse
CO2	13.08	15.31	13.39
H2O	21.72	22.24	20.06
N2at	39.35	45.80	40.11
O2	25.84	16.63	26.44
MM (Molar Mass)	28.89	29.09	28.91

Afterward, the specific heat of the exhaust gases can be calculated by the empirical Eq. (14) according to the outlet temperature of the exhaust gas in Kelvin. (Silveira et al., 2003)

$$C_p(T)=0.11908\cdot Cp_{CO_2}(T)+0.04496\cdot Cp_{H_2O}(T)+0.71351\cdot Cp_{N_2atm}+0.12245\cdot Cp_{O_2} \quad (14)$$

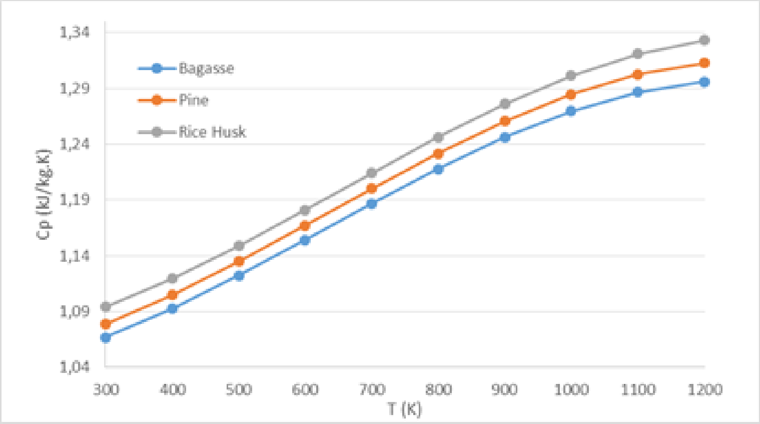

Fig. 3. Specific heat (Cp) of the exhaust gases depending on temperature variation.

5. RESULTS AND DISCUSSIONS

The calculated values of exergoeconomic analysis associated to the Gasifier/ICE system using the first and second law of thermodynamics are listed below:

The power supplied by biomass (Y1,1), the exergy of hot syngas (Y1.1), the exergy of cold syngas (Y2.1), the exergy of hot water HE1 (Y2.2), the electric power supplied by ICE (Y3.2), the increment of exergy of exhausted gas (Y3.1), the exergy of hot water HE2 (Y4.2), the gasifier exergetic efficiency (ηEX,Gasifier), the exergetic efficiency of heat exchanger (ηEX,HWI I and II), the exergetic efficiency of ICE (ηEX,ICE), and the exergetic efficiency of the System are displayed in Tab. 6.

The exhausted gas mass flow is equal to 135.95 kg/h, 176.84 kg/h and 210 kg/h, the air fuel ra tio for ICE are: 1.4 kg air/kg syngas, 1.2 kg air/kg syngas, and 1 kg air/kg syngas, using pine, sugar cane bagasse, and rice husk, respectively as fuel in gasification process.

Table 6. The increment of exergy value obtained from each biomass.

Symbol	Bagasse	Pine	Rice Husk	Description
$Y_{1,1}$ [kW]	140.66	140.66	140.66	Power supplied by biomass
$Y_{1.1}$ [kW]	94.40	93.97	94.43	Exergy of hot syngas
$Y_{2.1}$ [kW]	88.24	88.23	88.24	Exergy of cold syngas
$Y_{2.2}$ [kW]	0.78	0.73	0.79	Exergy of hot water HE1
$Y_{3.1}$ [kW]	15.00	15.00	15.00	Electric power supplied by ICE
$Y_{3.2}$ [kW]	30.83	31.85	31.75	Increment of exergy of exhausted gas
$Y_{4.2}$ [kW]	1.27	1.04	1.15	Exergy of hot water HE2
$\eta_{EX,Gasifier}$ [%]	62.730	62.726	62.728	Gasifier exergetic efficiency
$\eta_{EX,HWI}$ [%]	12.742	12.660	12.802	Exergetic efficiency of HE1
$\eta_{EX,ICE}$ [%]	26.130	26.605	26.556	Exergetic efficiency of ICE
$\eta_{EX,HW\ II}$ [%]	13.222	10.501	10.161	Exergetic efficiency of HE 2
$\eta_{EX,System}$ [%]	12.127	11.917	12.048	Exergetic efficiency of the System

Figure 6 presents the exergetic efficiency of the different components that form the system studied, as well as, the global exergetic efficiency of the system. The exergetic efficiency of the gasifier is approximately (62%) for the three biomass, The exergetic efficiency for Heat Exchanger I and II is (12%) for the three biomass and the ICE is (26.13 %) to the bagasse; (26.7 %) for pine and (29.07 %) to rice husk, the exergetic efficiency of the system for the bagasse is 12.13 %; 11.91 % for pine and 12.04 % for rice husk. This variation is directly related to the production of hot water, similar results are shown in (Proenza et al., 2015) (Datta et al., 2010) and (Sala et al., 2006).

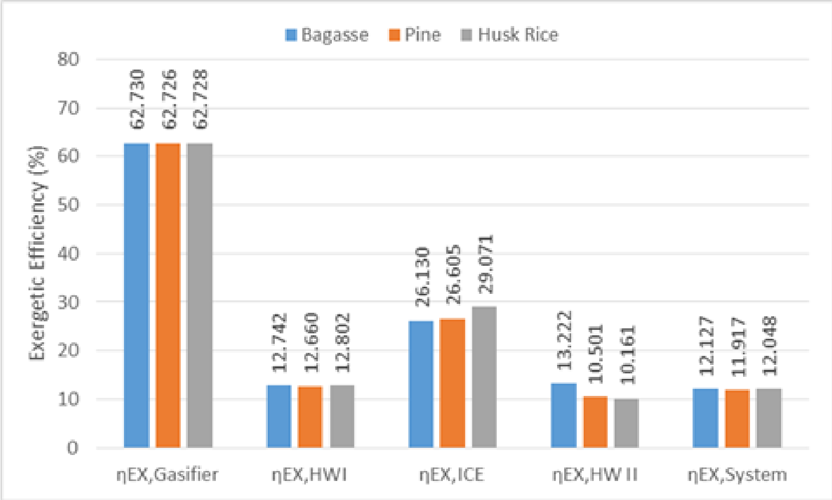

Figure 4. Exergetic efficiency for each component

The exergetic cost of syngas, hot water and electricity were calculated considering the investment in the gasification system, heat exchangers, as well as biomass prices, interest rates, maintenance and operation expenses. Production costs of syngas, hot water and electricity, for pine, bagasse and rice husk, for the annuity factor of 6%, are shown in Tab. 7, 8 and 9.

Table 7. Exergetic Cost of synthesis gas, electricity and hot water for bagasse.

Year	CSyngas [US$/kWh]	CEE [US$/kWh]	CHW TCI [US$/kWh]	CHW TCII [US$/kWh]
2	0.157	0.218	0.159	0.068
3	0.112	0.150	0.109	0.047
4	0.089	0.116	0.085	0.036
5	0.075	0.095	0.070	0.030
6	0.066	0.082	0.060	0.026
7	0.060	0.072	0.053	0.023
8	0.055	0.065	0.048	0.020
9	0.051	0.059	0.043	0.019
10	0.048	0.055	0.040	0.017
11	0.046	0.051	0.038	0.016
12	0.044	0.048	0.035	0.015

The exergetic cost of syngas, electricity and hot water for bagasse, at an annual interest rate of 6%, varies from 0.044 to 0.157 US$/kWh for syngas, 0.048 to 0.218 US$/kWh for electricity and for cost the hot water in TCI varies from 0.035 to 0.159 US$/kWh and TCII varies from 0.015 to 0.068 US$/kWh which represents the lowest cost.

Table 8. Cost of synthesis gas, electricity and hot water for Pine.

Year	CSyngas [US$/kWh]	CEE [US$/kWh]	CHW TCI [US$/kWh]	CHW TCII [US$/kWh]
2	0.206	0.221	0.089	0.060
3	0.150	0.152	0.061	0.100
4	0.122	0.118	0.047	0.068
5	0.105	0.097	0.039	0.053
6	0.093	0.083	0.033	0.043
7	0.085	0.074	0.029	0.037
8	0.079	0.066	0.026	0.033
9	0.075	0.061	0.024	0.029
10	0.071	0.056	0.022	0.027
11	0.068	0.053	0.021	0.025
12	0.066	0.050	0.020	0.023

The exergetic cost of syngas, electricity and hot water for Pine, at an annual interest rate of 6%, varies from 0.066 to 0.206 US$/kWh for syngas, 0.050 to 0.221 US$/kWh for electricity and for cost the hot water in TCI varies from 0.02 to 0.089 US$/kWh and TCII varies from 0.023 to 0.06 US$/kWh.

Table 9. Cost of synthesis gas, electricity and hot water for Rice Husk.

Year	C_{Syngas} [US$/kWh]	C_{EE} [US$/kWh]	$C_{HW\ TCI}$ [US$/kWh]	$C_{HW\ TCII}$ [US$/kWh]
2	0.201	0.220	0.129	0.049
3	0.147	0.151	0.089	0.034
4	0.120	0.117	0.069	0.027
5	0.103	0.097	0.057	0.022
6	0.093	0.083	0.049	0.019
7	0.085	0.073	0.044	0.017
8	0.079	0.066	0.039	0.016
9	0.075	0.060	0.036	0.014
10	0.071	0.056	0.033	0.013
11	0.068	0.052	0.031	0.013
12	0.066	0.049	0.029	0.012

The exergetic cost of syngas, electricity and hot water for Rice Husk, at an annual interest rate of 6%, varies from 0.066 to 0.201 US$/kWh for syngas, 0.049 to 0.220 US$/kWh for electricity and for cost the hot water in TCI varies from 0.029 to 0.129 US$/kWh and TCII varies from 0.012 to 0.049 US$/kWh. Results are consistent with those obtained (BORELLO et al., 2015) by for similar study conditions.

Figure 7 shows the payback period considering an annual interest rate of 6%, an electricity selling price of 0.07 US$/kWh according to (MME, 2015), and the price of hot water equal to the diesel fuel cost burned in the generation of it, which is 0.038 US$/kWh (Machin, 2015). It is observed that the investment recovery time is approximately 8 years for three biomasses.

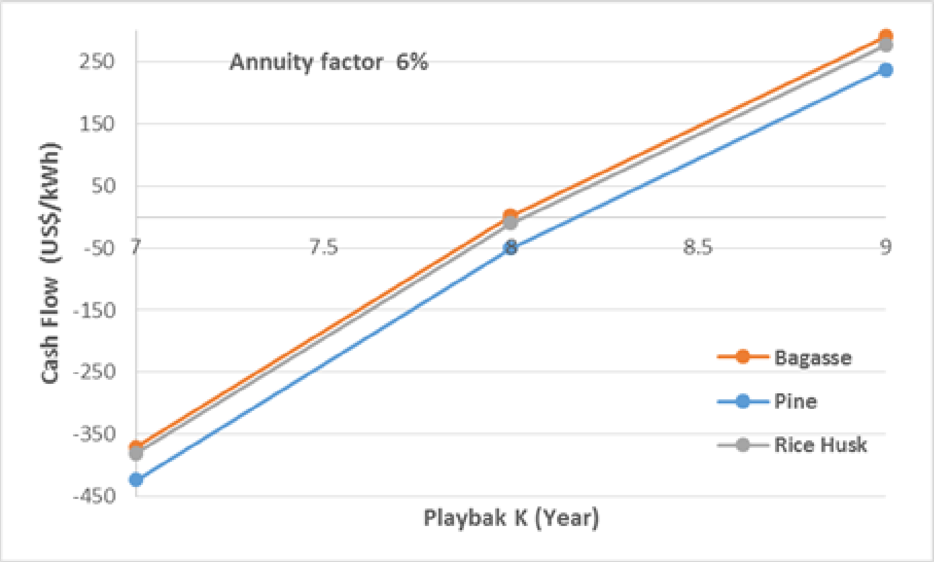

Figure 5. Cogeneration system payback period (in years) for each biomass.

6. CONCLUSIONS

In this paper were considered the thermoeconomical analysis of a compact cogeneration system composed by a downdraft gasifier, 2 water/gas heat exchangers and an ICE. Three different biomasses were evaluated (bagasse, pine and rice husk), for the production of 15 kW of electric power and hot water (80 °C) from heat recovery of exhaust gas and syngas.

The system was evaluated through the application of the second law of thermodynamics and economical tools. From the point of view of the second law of thermodynamics, the overall efficiency of the system for b agasse was 13.5 %, for pine 13 %, and for rice husk reached 13.8 %, the efficiency of power generation varied from 25.76 %; 22.04 % to 25.49 % for the bagasse, pine and rice husk respectively and the efficiency of generating hot water varied from 8.02% to 12.82 % for the three biomasses studied. The cost of the synthesis gas fluctuated from 0,043 to 0.16 US$/kWh, the electricity production cost varied from 0.048 to 0.22 US$/kWh and the cost of the production of hot water was between 0.002 to 0.014 US$/kWh. The recovery time of the investment (payback), with an interest rate of 6%, was between 5 and 6 years.

The study showed the feasibility of using compact cogeneration systems coupled with downdraft gasifiers in rural communities.

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