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DISTRIBUTED GENERATION OF ELECTRICITY IN ISOLATED COMMUNITIES USING RENEWABLE ENERGY SOURCES IN THE CUBAN CONTEXT

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Abstract.
In this paper was performed an analysis of the technical and economic viability of a cogeneration system associated to biomass gasification system, designed to operate coupled to an internal combustion engine, in order to generate electricity and hot water in isolated areas. The proposed technology recover the heat of the hot engine exhaust gases (cogeneration). This fact would allow that this system configuration be more attractive than conventional systems. Was adapted a modified downdraft fixed bed gasifier, using biomass obtained in neighboring areas of the place of system installation as fuels, to feed a ZIL -130 engine,. Applying the First Law of Thermodynamics to the gasifier-cogeneration system, was calculated the main flows of energy) and the associated costs for the production of syngas. This cost was 0.139 USD/kWh for the producer gas obtained and the 0.017 USD/kWh for electricity, with an amortization period of 10 years and an interest rate of 7%. Mass and energy balances were performed, the thermal and electric efficiencies was 32.4% and 23.4% respectively, indicating an overall efficiency of 33.3%.

Keywords: *gasification, cogeneration, biomass, internal combustion engine, cost.*

Nomenclature

$\dot{m}$ – mass flow rate [kg/s or m^3/h]
T – temperature [K]
N – power [kW]
C_1,C_2,C_3– coefficients of the engine
ge – specific fuel consumption[g/kWh]
Tr – torque [kgf.m]
Cp – average specific heat [kJ/kgK]
E – energy [kWh]
I – Investment [USD$]
C_M– maintenance cost [USD$/kWh]
C – cost [USD$/kWh]
Fp – adjustment factor
r- annual interest rate
q - factor
f- annuity factor
LHV- low heating value [kJ/kg or MJ/m^3]

Subscript
bio – biomass
i– each parameter of engine
$_N$– nominal parameter of engine
out – outlet
in – inlet
hw – hot water
$hw_{HE\ 1,2,4}$ – hot water in heat exchangers
air_{HE3} – hot air in heat exchanger 3
th – thermal
eng/ger – engine generator
n –r.p.m
cw – cool water
exh – flue gas
elec – electricity
e- electric
net - net
gas- syngas
csys- cogeneration systems

Superscripts
t- amortization periods

Greek symbols
η– efficiency

1. INTRODUCTION

Cuba's total installed electricity capacity was 5,913.9 MW in 2011 (ONE, 2013). From the total installed capacity, 88.59% correspond to fossil fuel and 10.5% to renewable energy (cogeneration from bagasse in sugarcane power plants, hydroelectric and wind power plants).

With respect to renewable energy generation, the greatest contribution comes from the sugarcane industry, with an installed capacity of 543.9 MW. In 2009, the country counted with 61 operating sugarcane plants, which cogenerate electricity and heat for sugar production processes requirements. The hydroelectric installed capacity, reaches 58 MW, of which 43 MW correspond to one hydroelectric power plant and the others 15 MW are installed in 179 small, mini and micro-hydroelectric power plants. There are also 3 wind farms totaling 7.7 MW of installed capacity, in addition to 15 small wind turbines and 6068 photovoltaic panels which are distributed throughout the country (Informe Final Cuba, 2013).

2. PROPOSED PLANT

Figure1 shows a layout of the proposed small-scale cogeneration system, consisting of a modified downdraft gasifier and a ZIL-130 four-stroke Otto-cycle spark-ignition engine (ICE). The ICE was adapted to run on syngas, obtaining a maximum power output of 45.04 kW and maximum torque of 19.0 kgf·m at 2500 rpm. An electric generator was coupled to the ICE via coupling rod-type caps, designed and calculated to the actual system's working conditions. The characteristics of the three-phase electric generator are: nominal power of 60 kVA, power factor of 0.8, frequency of 60 Hz, nominal voltage of 230 V, nominal current of 37.5 A, star type grounded connection, independent field excitation and synchronous speed of 1800 rpm.

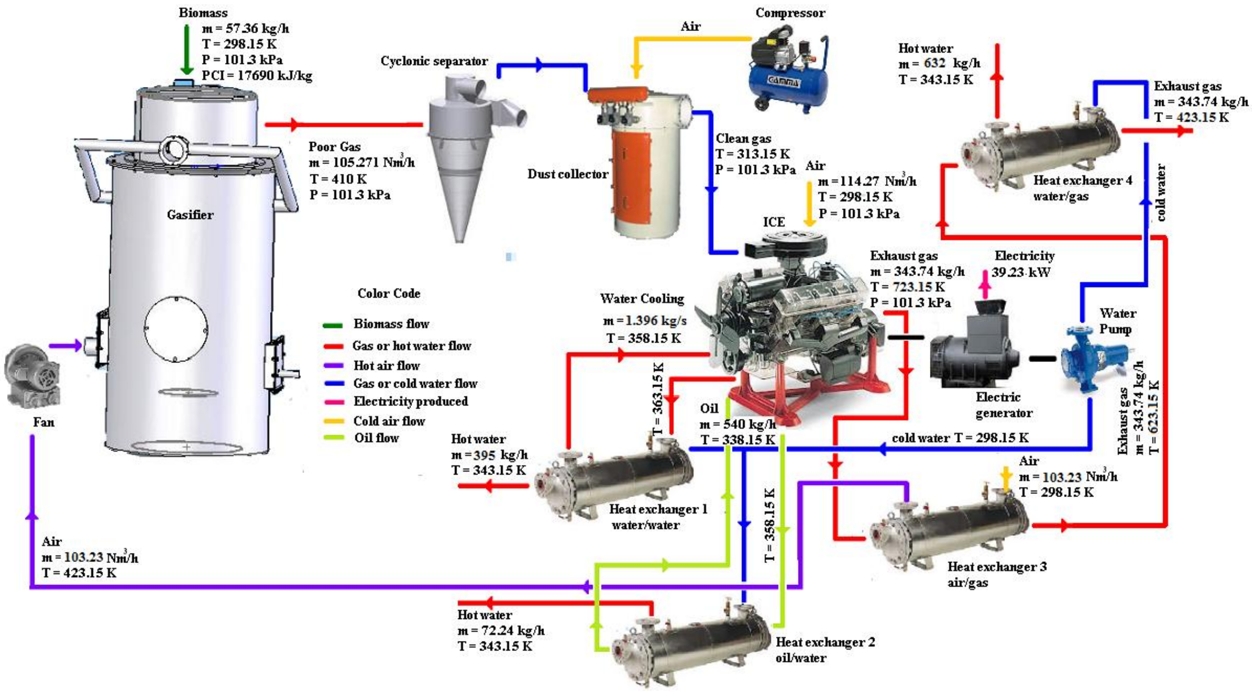

Figure1. Layout of the proposed biomass-fuelled CHP system.

Four shell and tube heat exchangers are used for heat recovery. The third air/gas heat exchanger (HE3), heats the gasifier air until a temperature of 150°C, with an effectiveness of 70%. The ICE exhaust gas circulating on the side of the tubes at a rate of 343.74 kg/h is cooled from 500°C to 400°C. The HE3 shell is made of steel 20, the tubes are made of stainless steel and the deflectors and caps are made of carbon steel. In this configuration, the heat transfer coefficient results in 15.7 $W/m^2 \cdot K$. The exhaust gas emerging from the HE3 goes through other heat exchanger type gas/water, the HE4, were it is cooled to 160°C with an effectiveness of 80%. The water enters to the HE4 at 25°C, experiencing a 45°C temperature increase. This HE4 heat exchanger is projected to be one pass shell-side, and two passes tube-side, seeking to increase the heat transfer efficiency. The HE4 tubes are copper made; the shell is constructed of steel 20, the deflectors of carbon steel and the caps of cast iron. The heat transfer coefficient in this case equals 40 $W/m^2 \cdot K$. The heat exchanger one (HE1), which acts as a radiator, is coupled to the ICE's cooling system, for hot water production. The ICE inlet and outlet water temperatures are 85°C and 90°C respectively, being the flow rate 1.396 kg/s. In the shell-side the water enters at 25°C and it is heated to 70°C with an effectiveness of 85%. The heat available in the ICE's lubricating oil is recovered through the heat exchanger two (HE2), which have similar characteristics to the HE1. In HE2, the oil temperature reaches a final temperature of 85°C, and with a flow rate of 540 kg/h is cooled to 65°C.

2.1 Downdraft gasifier

The gasifier used is an Imbert-type downdraft reactor, which was designed and built in the laboratory of fluid mechanics at the University of Camaguey following the methodology reported in (Estudio FAO, 1993), see Figure 2.

The gasifier consists of two coaxial metal structures. The external structure, marked with the reference number (1), is made of a carbon steel cylinder internally lined with refractory material (2) .The internal structure (3), made of stainless steel, is a cylinder ending in a cone reverse at the bottom for easy descent of the material and serve as a reservoir of biomass. The top of this structure is perforated to allow the exit of vapors and possible volatile substances derived from drying and pyrolysis of the biomass.

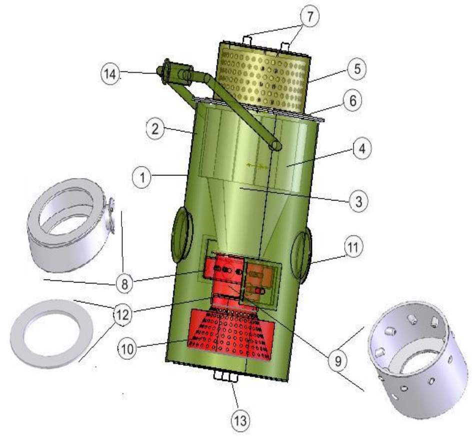

Figure 2. Modified downdraft gasifier.

This perforated structure is contained in a cylindrical cover (5) in this compartment occurs the cooling of the vapors that are condensed through the lateral tube (6), at the top of the cover are performed two semicircles to allow the entry of biomass (7). The two caps are mobile and linked by a security system against increase pressure inside the gasifier. On the outer of the tank, in the middle, are welded metallic half-tubes (4), in order to recover the heat carried by the hot gas from the gasification.

At the lower end of the cone of the internal structure of the reactor is located the combustion chamber (9), is made of stainless steel of high heat resistance and cylindrical shape, inside which were made nine orifices which form between them an angle of 72 °. Through these holes the air is admitted and distributed by a toroid (8) in the combustion zone.

The reactor have inside a perforated diaphragm (12) which is intended to support the biomass and allow gas exit. Complete the structure the conical metal grating (10), which has the task of sustain the coal entered through the door (11) made on the external metallic cylinder. Located below the grid there a hatch for discharging the ash (13). The Gas exit occurs by the top (14).

In the gasifier design proposed in the present work, three major changes reported by (Pedroso, 2006) were adopted with the aim of reducing the syngas tar concentration:

These modifications allowed obtaining less than 10 mg/Nm^3 of tar, quantity that was experimentally confirmed through information derived from a 15 kW gasifier prototype same as mentioned above, which was tested with different types of biomass, including Marabou, in the University of Sassari, Italy. The results are presented in Table 1.

Table 1. Experimental results from Dichrostachys Cinerea (Marabou) gasification (Pedroso, 2006).

Gas analysis	Unit	Composition		Unit	Value
CO	(% vol)	16.5	HHV	(MJ/Nm^3)	3.86
H_2	(% vol)	12.5	Tar	(mg/Nm^3)	8.73
CO_2	(% vol)	12.0	Water	(g/Nm^3)	102
CH_4	(% vol)	0.4	Char and ashes	(kg/Nm^3)	0.125
O_2	(% vol)	0.9	Density	(kg/Nm^3)	1.119
N_2	(% vol)	57.7			

The thermodynamic efficiency of the gasifier is calculated using equation (1).

$$\eta_{gasifier} = \frac{\dot{m}_{gas} \cdot LHV_{gas}}{\dot{m}_{bio} \cdot LHV_{bio}} \cdot 100 \quad (1)$$

2.2 Internal combustion engine

The ZIL-130 engine used in the system is a four-stroke Otto-cycle spark-ignition engine, fabricated in Russia. Table 2 presents its main specifications when working with gasoline. This engine was originally developed to run on gasoline, in which case it delivers a working power output of 103 kW at 2500 rpm. Since a lower rotation speed engine is more suitable for syngas applications, the engine's speed is fixed to 1800 rpm by a governor.

Table 2.ICE specifications.

Engine ZIL-130	
Number of cylinders	8 V
Nominal power (kW)	123
Maximum torque (kgf·m)	41
Nominal rotation speed rpm	3600
Rotation for maximum torque	1800
Compression ratio	6.5:1
bore (mm)	100
stroke (mm)	95
Displacement volume (cc)	5996

The operation of the ICE fueled with gasoline was simulated using the following equations (Arias Paz, 2008):

$$N_i = N_N \left[C_1 \left(\frac{n_i}{n_N}\right) + C_2 \left(\frac{n_i}{n_N}\right)^2 - C_3 \left(\frac{n_i}{n_N}\right)^3 \right] \quad (2)$$

$$ge_i = ge_N \left[1.2 - \frac{n_i}{n_N} + 0.8 \left(\frac{n_i}{n_N}\right)^2 \right] \quad (3)$$

$Tr_i = 716.2 \frac{N_i}{n_i}$ in this case Ni is express in CV. (4)

3. MATERIALS AND METHODS

In this section the equations used to determine the main parameters to the technical and economic study of the gasifier-cogeneration system are presented.
The Equations (5) to (11) are used for determining the parameters involved in the energy balance. Using Eq. (5) and (6) can be calculated efficiencies of power generation and hot water respectively. Thus, the overall cogeneration system efficiency would be the sum of these two efficiencies.

$$\eta_{elec} = \frac{E_p}{E_{fuel}} \quad (5)$$

$$\eta_{th} = \frac{E_{hwHE1} + E_{hwHE2} + E_{airHE3} + E_{hwHE4}}{E_{fuel}} \quad (6)$$

The efficiency for the overall integrated system, considering the gasifier efficiency, can be determine by the Eq. 6:

$$\boldsymbol{\eta_{global} = \eta_{gasifier} \cdot \eta_{csys}} \quad (7)$$

For know the energy supplied by the fuel Eq. (7) is used, and knowing the effectiveness of heat exchangers, can be determined the energy absorbed by the water in the exchangers one, two and four and the energy absorbed by the air in the exchanger 3 as well as the energy contained in the cooling water (E_{CW}), in the lubricating oil (Eoil) and exhaust gas (Eeg_{HE3} + Eeg_{HE4}) from the engine are determined with Eq. (8), taking into account the type of fluid and inlet and outlet temperatures.

$$E_{fuel} = \dot{m}_{gas} \cdot LHV_{gas} \tag{8}$$

$$E_{hw_i} = \dot{m}_{hw_i} \cdot C_{p_i} \cdot \left(T_{out_i} - T_{in_i}\right) \tag{9}$$

The energy dissipated or lost in the engine is calculated by the Eq. (10), in this case the calculated value was 13.36 kW (8%). Energy losses in the cogeneration system are 63.56 kW (37.86%) determined from the Eq. (11).

$$E_{lossICE} = E_{fuel} - N_{net} - E_{exh} - E_{cw} - E_{oil} \tag{10}$$

$$E_{losssys} = E_{fuel} - N_e - E_{hwHE1} - E_{hwHE2} - E_{airHE3} - E_{hwHE4} \tag{11}$$

For determining the cost of syngas, electricity generated and hot water produced, as well as investment, operation and maintenance costs of the involved equipments are used the Eq. (12-19). Subsequently the economic variable for decision-making are determined from Eq. (18), in this case the method of Discount Cash Flow (Horlock, 1997) is used.

$$C_{syngas} = \frac{I_{gasifier} \cdot f}{H \cdot E_{fuel}} + \frac{C_{bio} \cdot E_{bio}}{E_{fuel}} + C_{M_{gasifier}} \tag{12}$$

$$C_{elec} = \frac{I_{eng/ger} \cdot f}{H \cdot E_{fuel}} + \frac{C_{syngas} \cdot F_{P_{elec}}}{E_{fuel}} + C_{M_{eng/ger}} \tag{13}$$

$$C_{hw_i} = \frac{I_{HE_i} \cdot f}{H \cdot E_{hw_i}} + \frac{C_{syngas} \cdot F_{P_{HE_i}}}{E_{hw_i}} + C_{M_{HE_i}} \tag{14}$$

The cost for installing the necessary electromechanical instruments is considered as 10% of the total investment cost for the gasifier. The cost of civil works can be considered as 13% and the cost associated with project engineering as 30% of the total investment (CIRCE, 2005).The cost of electricity generation depends on the initial investment for installing the equipment ($I_{eng/ger}$), the fuel cost (C_{syngas}), the plant's working hours (H), and the operation and maintenance costs ($C_{Meng/ger}$, C_{Mgasif})

For calculating the syngas production cost using Eq. (17) it is assumed a cost for the woody biomass ready to be introduced into the reactor equal to 200.00 USD/m^3 (MINAGRI, 2006) or 0.25 USD/ kg.

$$C = C_r \left(\frac{S}{S_r}\right)^m \tag{15}$$

$$I_{gasif} = 180700 \cdot \left(\frac{P}{250}\right)^{0.7} \tag{16}$$

$$f = \frac{q^t \cdot (q-1)}{q^t - 1} \tag{17}$$

$$q = 1 + \frac{r}{100} \tag{18}$$

$$NPV = \sum_t^n \frac{ELC}{(1+j)^t} \tag{19}$$

The associated costs should be distributed in the two products of the plant, i.e. the two forms of energy delivered, electricity and heat. Thus, an adjustment factor (F) is used to allocate the energy costs of each flow, as follows:

$$F_{p_i} = \frac{E_i}{E_{elec} + E_{hw1} + E_{hw2} + E_{hw4} + E_{air}} \tag{20}$$

For the economic calculations it is assumed that the plant operates 2400 hours per year. To determine the cost of equipment, Boehm technique (Boehm, 1987), adapted from (Silveira, 1990) was selected. This technique is based on Eq. (15). In this study, incidence factor of 0.7, according to Robert, H.P and Don, W. G. (1984) was selected.

The values were obtained from actual data of manufacturers (Arauzo, 1998) and (UNIZAR, 2005), then following estimated cost technique can be obtained through the Eq. (16) the cost of a gasifier of 57 kg/h.

As an initial estimation, it is assume do cost of electricity of 0.15 − 0.35 USD/kWh which corresponds to the tariff charged to residential users that consume less than 300 kWh per month. The cost of hot water is considered 0.07 USD/kWh (ONE, 2013).

4. RESULTS AND DISCUSSION

The gasification efficiency determined by Eq. (1) resulted in 59.8%. This value is relatively low when compared with other values reported in the literature (Beenackers, 1999), (Warnecke, 2000) and (Bridgwater, 2003). This could be explained by the low caloric value of the produced gas, LHV_{gas}=3.557 MJ/Nm^3. The efficiencies for electricity and thermal generation and the overall cogeneration system's efficiency are presented in Table 3.

Table 3. Electricity, thermal and overall efficiencies for the proposed cogeneration system.

Efficiencies		
Electric generation efficiency	(η_{elec})	23.4%
Heat generation efficiency	(η_{th})	32.4%
Cogeneration system	(η_{csys})	55.8%
Global	(η_{global})	33.3%

In Figure 3 the theoretical operation of the ICE running with syngas and gasoline is presented. It can be observed that when using syngas, the power output is reduced in approximately 43%, with a compression ratio of 10:1. From previous studies, it is expected that in gaseous-fueled engines or dual-fuel engines running with syngas, the reduction of power output is in the order of 20−30% (Banapurmath & Tewari, 2009). Sridhar, G. and Yarasu, R.B. (Sridhar & Yarasu, 2010) report an engine operating with syngas the de-rating from the designed power rating was in the range of 40-50% when the compression ratio was 7:1 and 20% when was 11:1.

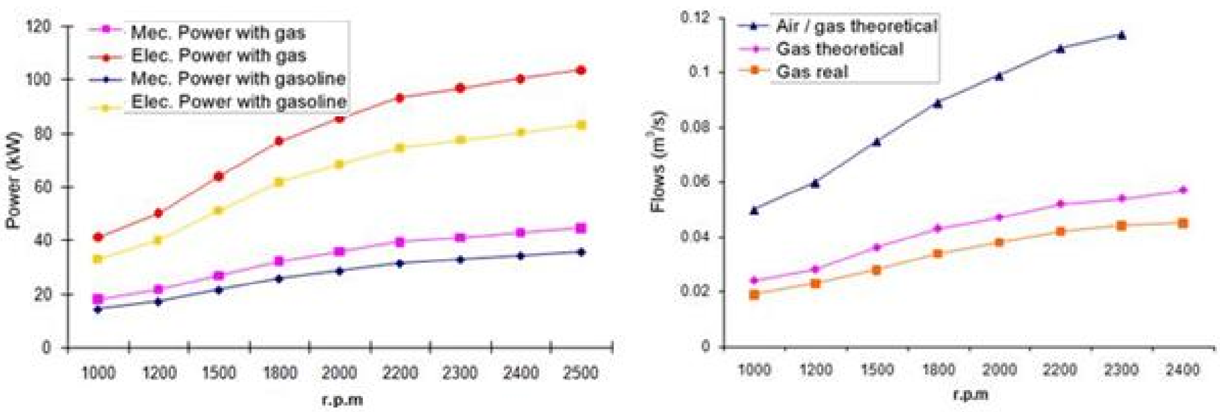

Figure 3. Fuel consumption and theoretical power output achieved by the ZIL−130 engine.

The cost of produced fuel (syngas) is shown in Fig. 4(a) obtained from the Eq. (12), and the cost of electricity generation will depend on the capital investment in the implementation and operation of the facility, Eq. (13), is shown in Fig. 4(b).

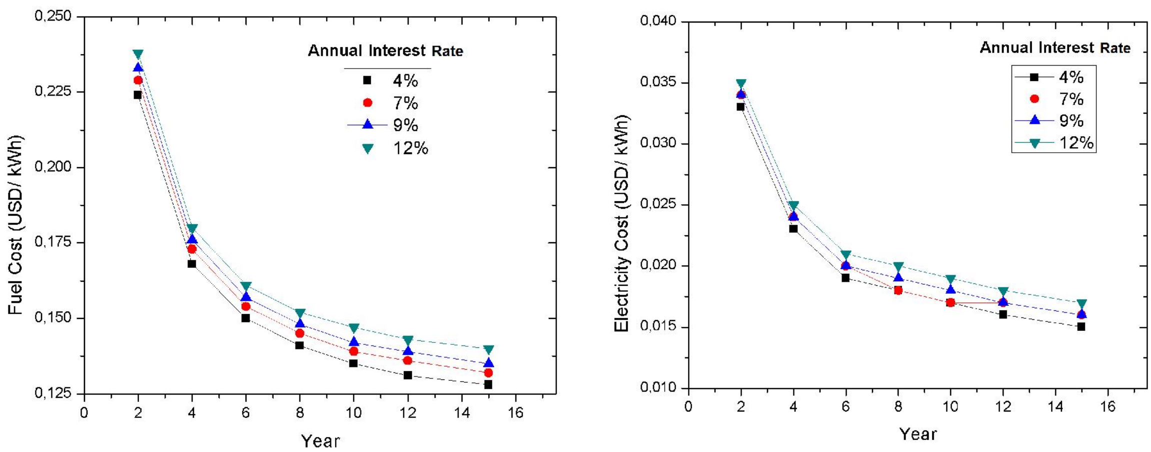

Figure 4. (a) Cost of the syngas (b) cost of generated electricity.

Considering an annual interest rate of 12% and a price of electricity of 0.30 USD/kWh the TRI resulted in approximately 5.3 years. In this scenario, the syngas fuel costs totaled 0.165 USD/kWh, the electricity cost was 0.022 USD/kWh and the costs of producing hot water in heat exchangers 1, 2 and 4 are 0.009738 USD/kWh, 0.014 USD/kWh and 0.00836 USD/kWh respectively, as can be observed in Fig. 4 and Fig. 5.

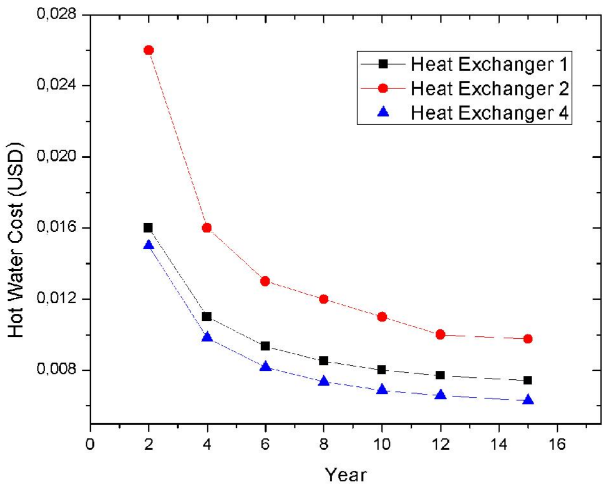

Figure 5. Comparison of the produced hot water in the system with a 12% annual interest rate.

In Figure 5 it is shown a comparison made between the three heat exchangers, about the price obtained for the hot water produced, noting that in heat exchanger four where is cheaper to obtain this product, it is mainly due to the high energy content in the exhaust gases, managing to produce a greater volume of hot water. The higher cost of hot water production is in the oil/water heat exchanger, this may be a consequence to the low productivity, being that their contribution can be disregarded for not being representative.

Finally in Figure 6 it is shown the expected annual revenues of the proposal made, where it can be seen that the most advantageous situation would be having a selling price of electricity of 0.3 USD/kWh, with a selling price of hot water 0.07 USD/kWh, and an annual interest rate of 5%. This would allow about three years approximately began to profit from the sale of these products. It is also noted that as the annual interest rate is increased there is an increase in the time of return on investment (TRI) and consequently, a decrease in Net Present Value (VPL) that accumulates over time.

It was determined that the selling price of electricity between 0.15 to 0.20 USD/kWh, gives an internal rate of return too large, doing unfeasible the project implementation, showing that they are not attractive price. Only from fixing a selling price of electricity between 0.25 to 0.30 USD/kWh, it is that this investment would become attractive with an IRR between 7 and 23% and VPL between 5,290 and 44,602 USD respectively, with a time of return on investment of 3 to 8 years for a 5% annual interest. If the annual interest rate it was 12%, only the investment would be feasible to have a selling price of 0.3 USD/kWh, with an IRR of 17%, an VPL 20,571 USD and time of return on investment (IRR) of approximately 5.3 years.

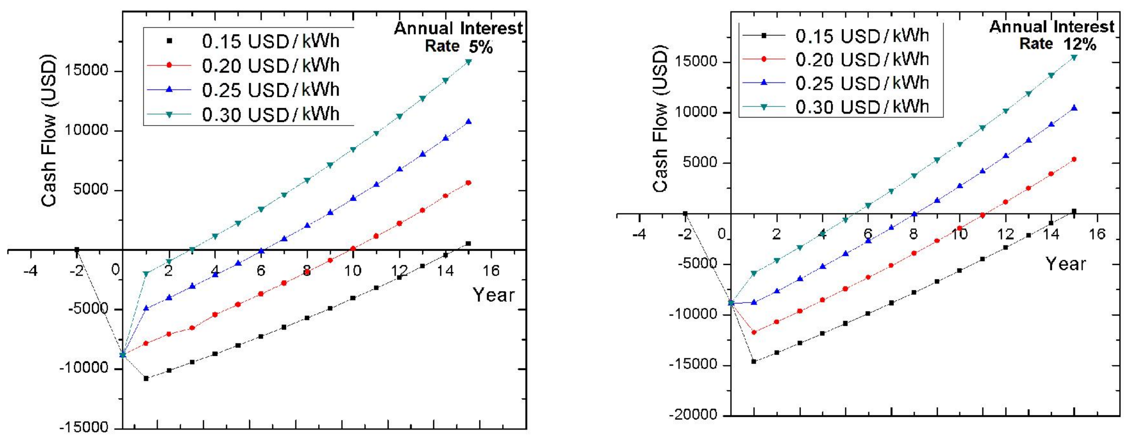

Figure 6: Payback time at an annual interest rate of 5% and 12%

5. CONCLUSIONS

This study present a theoretical study of a biomass-fuelled small-scale CHP system, with a downdraft gasifier and a spark ignition internal combustion engine. The authors propose an integrated approach for assessing the energetic and economic performance, of a biomass gasification cogeneration system, installed in isolated communities; where the access to fossil fuels is difficult but there are abundance of the residual biomasses. The heating value of the produced syngas was 3.557 MJ/Nm^3 based on the combustible gas components present in the syngas. The engine's power output efficiency using a 100% of syngas resulted in 23.4% at maximum load. Considering a mechanical-to-electric power conversion efficiency of 95%, the maximum efficiency of the syngas engine works out to be 24.6%.The heat efficiency of the proposed system was 38.8%, reaching an overall efficiency of 55.8%. Finally, the specific fuel consumption of *Dichrostachys cinerea* biomass, was 1.46 kg/kWh and the specific fuel consumption (syngas) was 2.68 Nm^3/kWh.

6. ACKNOWLEDGMENTS

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