

## ENERGETIC AND ECONOMIC ANALYSIS OF AN INTERNAL COMBUSTION ENGINE COGENERATION SYSTEM USING SYNGAS FROM A DOWNDRAFT GASIFIER: INFLUENCE OF DIFFERENT BIOMASS MATERIALS

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**Abstract.** Gasification allows thermal conversion of biomass into a syngas which can be burned in internal combustion engines (ICE). This paper presents energetic and economic analysis of different alternatives of a cogeneration system comprising a downdraft gasifier connected to an internal combustion engine and water/gas exchangers. In this study were considered two kind of biomass: wood carob and wood eucalyptus. The syngas produced is cooled in a water/gas exchanger, which produces water at 80°C, and filtered before entering ICE to generate 15kW of electric power. Exhaust gases of ICE are utilized to heat water to 80°C in a second heat exchanger. The electrical system efficiency is 21.42%, and the global efficiency varies from 44,33 % to 49.77 % for the carob and the eucalyptus respectfully. The syngas production cost is between 0.01 and 0.35 US\$/kWh, the electricity production cost is among of 0.07 to 0.28 US\$/kWh and the hot water production cost is in the range of 0.04 to 0.17 US\$/kWh. The investment return period depends on the interest rates, for an interest rate of 8% it is between 8 to 9 years for the biomasses studied.

**Keywords:** Biomass Gasification; Internal Combustion Engine; Cogeneration; Energetic Efficiency; Economic Analysis.

### 1. INTRODUCTION

The biomass gasification systems have been utilized for some time and have proved to be a good energy alternative that allow power generation in isolated communities for replacing fossil fuels with renewables sources such as biomass, which are considered carbon neutral. These systems require management operation and simple maintenance, which permit high availability (CORONADO; YOSHIOKA; SILVEIRA, 2011). Gasification is a thermochemical process, where biomass is transformed into a combustible gas by partial oxidation at high temperatures (from 750-850 °C) in the presence of a gasification agent (BASU, 2012).

According to (CORONADO; YOSHIOKA; SILVEIRA, 2011), cogeneration has proven to be the best alternative with respect to the lower fuel consumption with highest energy efficiency, as well as in relation to the implementation of power generation in isolated rural areas. Alternative fixed engines are an excellent choice for the generation of electrical energy on a small scale; for this reason, the ICE cogeneration is presented as a viable alternative for residential in rural areas.

This work aims to present an energetic and economic analysis of a downdraft gasifier with a processing capacity of 20 to 30 kg/h of biomass connected to a compact cogeneration system to produce 15 kW of electric power and hot water. The purpose of this study is to evaluate the technical and economic feasibility of two biomasses: wood carob and the wood eucalyptus for power generation in places where electricity and hot water utilities are not accessible.

### 2. BIOMASS

Biomass includes all organic materials that come from photosynthesis, as well as those that have evolved from it. Therefore, it involves all organic matter that comes from trees, plants and animal waste that can be converted into energy; from agriculture (corn waste, coffee, rice, etc.), from sawmill (pruning, branches, sawdust, bark), from municipal waste (sewage, organic waste, and other) and energy crops.

The main features of wood carob and wood eucalyptus, with a moisture of 20%, are shown in Table 1. The LHV of carob is 17.61 MJ/Kg (BOLOY et al., 2011), and the eucalyptus is the (19.462 MJ/kg) (GALLIPOLITI, 2013).

Table 1. Analysis of the biomass materials used in weight percentage with humidity 20 %

Biomasses	Weight percentages [%]						LHV [MJ/kg]
	C	H	O	N	S	Ash	
Carob (GALLIPOLITI, 2013)	46.62	5.73	32.52	0.2	0.08	2.82	17.611
Eucalyptus (BOLOY et al., 2011)	49.00	5.87	43.97	0.3	0.01	0.72	19.457

### 3. System description

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

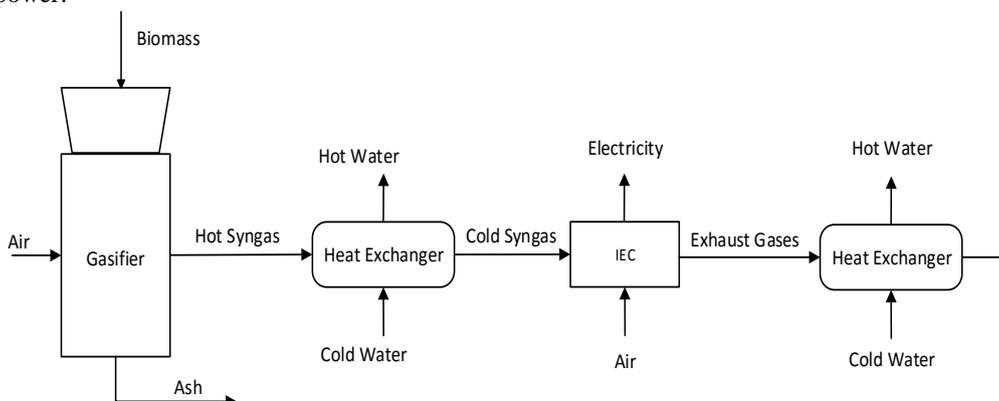


Fig. 1. Physical diagram of the cogeneration system

#### 3.1. Gasifier system

The Downdraft gasifier utilized in this study is installed in the Laboratory of Optimization of Energy Systems (LOSE) in School of engineering of Guaratingueta of the Sao Paulo State University (UNESP), and it is presented in Fig. 2. The gasifier consists of two cylindrical coaxial structures constructed using a mild steel sheet, with insulating material covering the outside, while the inner cylinder is provided with additional surfaces for heat recovery to improve the efficiency of the gasification process. The air is injected through a tube placed around the throat area. The throat area is  $0.0314 \text{ m}^2$  and its diameter is  $0.2 \text{ m}$ . The diameter of the pyrolysis region is twice as long as the throat region, which is  $0.4 \text{ m}$ . Regarding the throat, most authors consider it with an inclination of  $45^\circ$  (BOLOY et al., 2011).

It is recommended that the total height should be 2.5 larger than the pyrolysis region diameter. The volume reduction region is more than  $0.5 \text{ m}^3$  per  $\text{m}^2$  of the throat region. The region of reduction is  $0.04 \text{ m}^3$ . The internal capacity is  $0.452 \text{ m}^3$ , with a height of  $1.02 \text{ m}$ . The processing capacity is 20 to 30 kg/h. For applications in ICE, gas is cooled in order to remove particulate material and tar, in this study, the gasifier efficiency is considered equal to 62.68 % (CORONADO; YOSHIOKA; SILVEIRA, 2011).



Fig. 2. Prototype I and II. Downdraft wood gasifier

#### 3.2. Compact cogeneration system

The cogeneration cycle is composed by 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, Table 2 (CORONADO; YOSHIOKA; SILVEIRA, 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 shown in Fig. 3, is composed by: ICE model GM, 1.0 CORSA, coupled to a generator via belt and pulley to receive the mechanical energy produced by the engine. The engine employed has a reducing "Rodogás" system pressure fuel supply that allows Liquefied Petroleum Gas (LPG) or Natural Gas (NG) operation and even with gasoline.

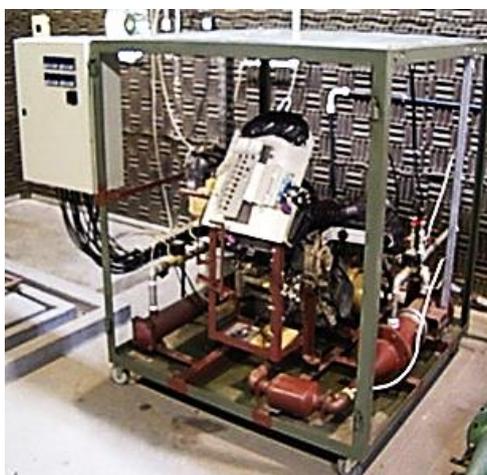


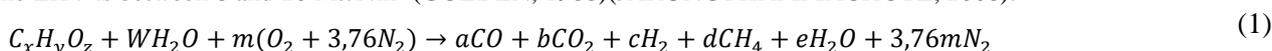
Fig. 3. Cogeneration compact system with alternative engine

The *Rodogás* implemented in the system have a maximum capacity of 43 m<sup>3</sup>/h of fuel and can be installed in engines with power up to 89 kW. The maximum working pressure inlet 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 water/gas exchanger supports until 150 kg/h, entering at 25°C and heated to 80°C. The housing of the heat exchanger consists of DIN 2440 steel, and the remaining components are carbon steel (CORONADO; YOSHIOKA; SILVEIRA, 2011).

## 4. METHODOLOGY

### 4.1. Syngas

Gasification is a thermochemical process in which a carbonaceous substrate (biomass) is transformed in a combustible gas, through of reactions with high temperature in presence of a gasifying agent such as air, oxygen, steam, CO<sub>2</sub> or a mixture of these, as shown in Eq. (1) (FLORIN; HARRIS, 2007)(GOPAUL; DUTTA; CLEMMER, 2014). The generated gas, known as syngas, is mainly composed of H<sub>2</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>, smaller carbon particles (solid carbonaceous residue), ashes, tars and oils, its low heat value (LHV) depends of the biomass and the gasifying agent applied. In the scenario of the gasification with air, the LHV is in the range of 4 to 8 MJ/Nm<sup>3</sup>. When it is utilized steam, oxygen and mixes of these, the LHV is between 8 and 20 MJ/Nm<sup>3</sup> (GOLDEN, 1988)(JARUNGTHAMMACHOTE, 2008).



The synthesis gas composition for Carob and Eucalyptus are displayed in Table 3 according to experimental results obtained by (GALLIPOLITI, 2013) (BOLOY et al., 2011) for similar study conditions.

Table 3. Syngas composition

Gases	Biomass materials	
	Carob (GALLIPOLITI, 2013)	Eucalyptus (BOLOY et al., 2011)
H <sub>2</sub> [%]	12.84	24.89
CO [%]	19.54	19.67
CO <sub>2</sub> [%]	13.5	10.14
CH <sub>4</sub> [%]	50.56	0.94
N <sub>2</sub> [%]	4.76	44.36
LHV gas [MJ/kg](dry bases)	4.23	5.50

#### 4.2. Energetic analysis of the set gasifier-cogeneration

This section presents the equations (2-9) applied for the development of the energetic analysis of the downdraft gasifier model, the ICE system and heat exchangers. Fixed values presented in Table 4 were taken into account for the energetic system analysis.

The required energy to generate 15 kW of electric power ( $E_p$ ), depends of the efficiency of the electricity generation ( $\eta_{GE}$ ) and the energy provided by the fuel ( $E_{syngas}$ ), which depends of the mass flow ( $\dot{m}_{syngas}$ ) and the low heat value of the syngas ( $LHV_{syngas}$ ), as is displayed in Eq. (2) and (3).

$$\eta_{GE} = \frac{E_p}{E_{syngas}} \quad (2)$$

$$E_{syngas} = \dot{m}_{syngas} * LHV_{syngas} \quad (3)$$

Biomass mass flow ( $\dot{m}_{Bio}$ ) is calculated according to Eq. (4), where is considered the syngas energy, the efficiency of the gasification system ( $\eta_{Gasifi}$ ), and the low heat value of the biomass ( $LHV_{Bio}$ ).

$$\dot{m}_{Bio} = \frac{E_{syngas}}{\eta_{Gasifi} * LHV_{Bio}} \quad (4)$$

The energy of the produced hot water in the heat exchanger ( $Ex_{HW1}$ ) and ( $Ex_{HW2}$ ) is obtained with Eq. (5) and (6), and depends of the water mass flow ( $\dot{m}_{HW}$ ) with the enthalpy variety ( $\Delta h_{Water}$ ). The hot water mass flows in the heat exchanger ( $Ex_{HW1}$ ) and ( $Ex_{HW2}$ ), is calculated with Eq. (7) and (8), which keep in mind the heat exchange efficiency ( $\eta_{TC}$ ), the mass flow of the syngas ( $\dot{m}_{syngas}$ ) and exhaust gases ( $\dot{m}_{exh.g}$ ), the temperature variation ( $\Delta t$ ) and the water enthalpy variety ( $\Delta h_{Water}$ ).

$$Ex_{HW1} = \dot{m}_{HW1} * \{(h_{HW} - h_0) - T_0(S_{HW} - S_0)\} \quad (5)$$

$$Ex_{HW2} = \dot{m}_{HW2} * \{(h_{HW} - h_0) - T_0(S_{HW} - S_0)\} \quad (6)$$

$$\dot{m}_{HW1} = \frac{\eta_{TC1} * \dot{m}_{syngas} * Cp_{syngas} * \Delta t}{\{(h_{HW} - h_0) - T_0(S_{HW} - S_0)\}} \quad (7)$$

$$\dot{m}_{HW2} = \frac{\eta_{TC2} * \dot{m}_{exh.g} * Cp_{exh.g} * \Delta t}{\{(h_{HW} - h_0) - T_0(S_{HW} - S_0)\}} \quad (8)$$

For the calculation of the global efficiency of the system ( $\eta_{Global}$ ), as is shown in Eq. (9), is considered the generated electric energy ( $E_p$ ), the energy of produced hot water in heat exchangers ( $E_{HW}$ ) and biomass energy ( $E_{Bio}$ ).

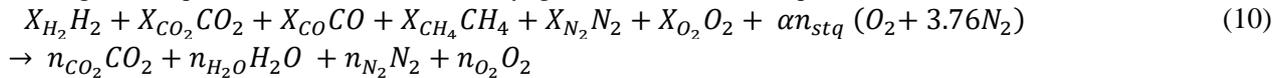
$$\eta_{XGlobal} = \frac{E_p + Ex_{HW1} + Ex_{HW2}}{E_{Bio}} \quad (9)$$

Table 4. Cogeneration system constant values

Item	Value	Item	Value
Electric energy produced, $E_p$	15 kW	T° inlet of water from TC1 and TC2	25 °C
T° syngas inlet TC1 (gas/water)	600 °C	T° output of water from TC1 and TC2	80 °C
T° syngas outlet TC1 (gas/water)	35 °C	Efficiency ICE (BOLOY et al., 2011)	17 %
T° of exhaust gases into TC2 (gas/water)	540 °C	Efficiency TC1 and TC2 (BOLOY et al., 2011)	70 %
T° of exhaust gases from TC2 (gas/water)	150 °C	Efficiency Gasifier	62,68%

#### 4.2.1. Calculating the specific heat of exhaust gases

To calculate the specific heat of the exhaust gases is used the gas composition for each biomass reported in Table 3 and the general equation for the combustion of syngas with air excess  $\alpha$ . Eq. 10 (PÉREZ et al., 2015a).



Where  $X$  and  $n$  represents the percentage in mass fraction of reaction compounds and the products of the combustion respectively.

Adopting a combustion with typically excess air of 40 % ( $\alpha = 1.4$ ) 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	
	Carob	Eucalyptus
CO <sub>2</sub>	13.09	13.39
H <sub>2</sub> O	21.72	20.05
N <sub>2</sub> (atmospheric)	39.35	40.10
O <sub>2</sub>	25.83	26.44
MM (Molar Mass)	29.10	29.61

Then, the specific heat of the exhaust gases can be calculated by the empirical equation (11) according to the outlet temperature of the exhaust gas in degrees Kelvin. (SILVEIRA; TUNA, 2003)

$$C_p(T) = X_{CO_2} \cdot C_{pCO_2}(T) + X_{H_2O} \cdot C_{pH_2O}(T) + X_{N_2} \cdot C_{pN_2atm}(T) + X_{O_2} \cdot C_{pO_2}(T) \quad (11)$$

#### 4.3. Economic analysis

The aim of economic analysis is to identify the costs of hot water, electricity and syngas produced [US\$/kWh]. Therefore, it is necessary to calculate the cost of syngas for each biomass, which depends on the investment in the gasification system and the cost of biomass.

The gasifier system cost includes the gases system cleaning and conditioning, such as cyclones, Venturi scrubber, heat exchangers, gas dryers and filters. The cost of ICE/generator adapted to work with syngas is calculated by the above methodology described and taking into account the actual equipment costs described by (CORONADO; YOSHIOKA; SILVEIRA, 2011).

Equations (12-21) are employed for economic evaluation; they take into account the production costs of fuel (syngas), the production cost of hot water, the cost of electricity generation and the annual income expected.

Eq. (12) to (18) are applied to calculate the cost of synthesis gas ( $C_{syngas}$ ), the cost of electricity generation ( $C_{EL}$ ) and the cost of hot water ( $C_{HW}$ ), considering the investment of the gasification system ( $I_{gasifier}$ ), engine ( $I_{ICE}$ ) and heat exchangers ( $I_{TC1} + I_{TC2}$ ), as well as, annuity factor ( $f$ ), the operation hours of the system ( $H$ ), the biomass price ( $C_{Bio}$ ), the syngas price ( $C_{syngas}$ ) and the diesel cost ( $C_{Fuel}$ ), the maintenance cost for each equipment ( $CM$ ), the electricity ponderation factor ( $FP_{Ep}$ ), the hot water ponderation factor ( $FP_{HW}$ ), annuity factor ( $f$ ), payback ( $k$ ), annual rate ( $q$ ) and interest rate ( $r$ ).

$$C_{syngas} = \frac{I_{gasifier} \cdot f}{H \cdot E_{syngas}} + \frac{C_{Bio} \cdot E_{bio}}{E_{syngas}} + CM_{Gaseif} \quad (12)$$

$$C_{EL} = \frac{I_{ICE} \cdot f}{H \cdot E_p} + \frac{C_{syngas} \cdot FP_{Ep}}{E_p} + CM_{ICE} \quad (13)$$

$$C_{HW} = \frac{(I_{TC1} + I_{TC2}) \cdot f}{H \cdot (Ex_{HW1} + Ex_{HW2})} + \frac{C_{syngas} \cdot FP_{HW}}{(Ex_{HW1} + Ex_{HW2})} + CM_{TC} \quad (14)$$

$$FP_{Ep} = \frac{E_p}{E_p + Ex_{HW1} + Ex_{HW2}} \quad (15)$$

$$FP_{HW1} = \frac{Ex_{HW1} + Ex_{HW2}}{E_p + Ex_{HW1} + Ex_{HW2}} \quad (16)$$

$$f = \left( \frac{q^{k \cdot (q-1)}}{q^{k-1}} \right) \quad (17)$$

$$q = 1 + \frac{r}{100} \quad (18)$$

The gain from the sale of electricity ( $GP_{el}$ ) and hot water ( $GP_{HW}$ ) are obtained by Eq. (19) and (20), which depends of electricity tariff ( $PV_{el}$ ) and diesel price ( $P_{HW}$ ).

$$GP_{el} = E_p \cdot H \cdot (PV_{el} - C_{EL}) \quad (19)$$

$$GP_{HW} = Ex_{HW} \cdot H \cdot (P_{HW} - C_{HW}) \quad (20)$$

The annual expected saving (AES) is the sum of the gain for selling electricity and the gain for selling hot water.

$$AES = GP_{el} + GP_{HW} \quad (21)$$

The parameters used in the economic analysis of the proposed plant are displayed in Table 6.

Table 6. Economic parameters for the proposed system

Item	Value	Item	Value
$C_{Bio}$ Carob [US\$/kg]	0.0045	$I_{TC2}$ [US\$]	444.45
$C_{Bio}$ Eucalyptus [US\$/kg]	0.0038	$I_{ICE}$ [US\$]	1660.6
Hours of operation per year	2400	$CM_{Gaseif}$ [US\$]	0.02
Interest rate [%]	8	$CM_{ICE}$ [US\$]	0.01
$I_{Gasifier}$ [US\$]	93340.5	$CM_{TC}$ [US\$]	0.005
$I_{TC1}$ [US\$]	666.67		

For economic calculations it is assumed that the plant operates 2400 h per year. This is because the selected motor is not designed to run on gaseous fuel, therefore is considered a total of 6.6 hours per day throughout the year, leaving the remaining time for repairs, maintenance and other contingencies during the operation of the facility.

## 5. Results and discussions

Starting from the electric nominal power production of 15 kW of the ICE, energy system analysis was performed, evaluating the biomass consumption per hour for each raw material. The analysis main results are shown in Table 7.

Table 7. Main results of de technical analysis.

Item	NG (PÉREZ et al., 2015b)	Carob	Eucalyptus
$\dot{m}_{Biomass}$ [kg/h]	-	22.84	20.67
$\dot{m}_{Gas}$ [kg/h]	3.798	59.60	44.46
$\dot{m}_{HW TC1}$ [l/h]	-	95.35	127.81
$\dot{m}_{HW TC2}$ [l/h]	151.2	155.51	182.39
$E_{HWT C1}$ [kW]	-	6.11	8.16
$E_{HWT C2}$ [kW]	9.69	9.93	11.69
$\eta_{GE}$ [%]	23.5	21.42	21.42
$\eta_{GHW}$ [%]	28.72	22.91	28.35
$\eta_{Global}$ [%]	52.22	44.33	49.77

The behavior of the electric, hot water and overall efficiency of the system is presented in Figure 4, electrical efficiency is 21.42 % for the biomasses studied, generating exergy efficiency of hot water is 22.91 % for carob and 28.35 % for eucalyptus, while the overall efficiency is 44.33 % for carob and 49.77 % for eucalyptus. This variation is directly related with the production of hot water.

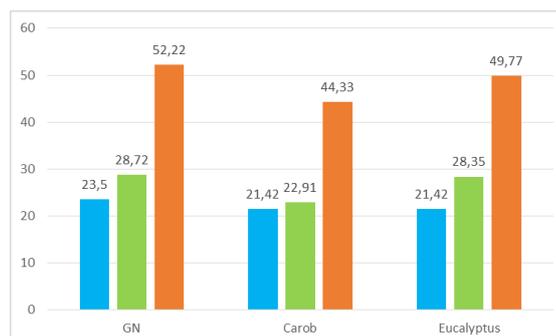
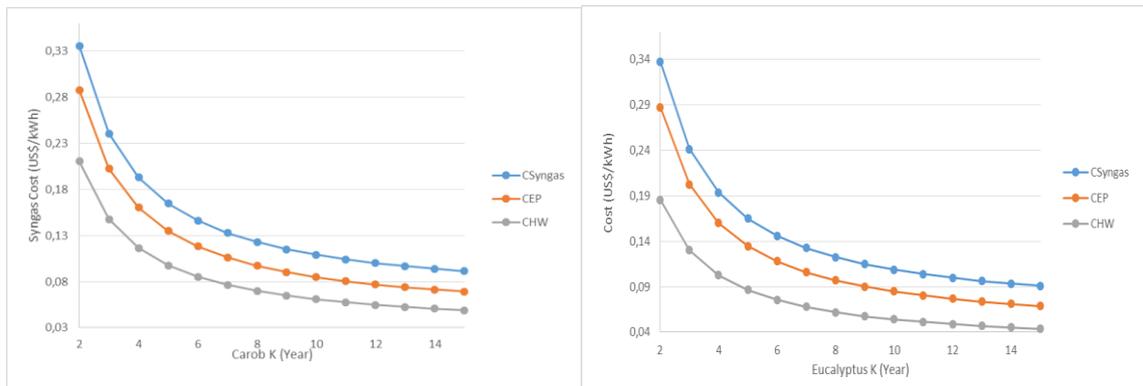


Fig. 4. Electrical and global system efficiency

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 carob and eucalyptus, for the annuity factor of 8 %, are presented in Fig. 5A and 5B.



A) B)  
Fig. 5. Cost of synthesis gas, electricity and hot water A) carob and B) Eucalyptus

The exergetic cost of syngas, electricity and hot water for carob Fig. 6A, at an annual interest rate of 8 %, varies from 0.091 to 0.34 US\$/kWh for syngas, 0.07 to 0.29 US\$/kWh for electricity and for cost the hot water varies from 0.049 to 0.21 US\$/kWh, which represents the lowest cost.

The exergetic cost of syngas, electricity and hot water for eucalyptus Fig. 6B, at an annual interest rate of 8 %, varies from 0.09 to 0.33 US\$/kWh for syngas, 0.07 to 0.29 US\$/kWh for electricity and for cost the hot water varies from 0.04 to 0.1 US\$/kWh.

Considering an annual interest rate of 8 %, an electricity tariff for isolated communities was 0.10 US\$/kWh (ANEEL, 2016) and a cost of hot water generation of 0.0022 US\$/kWh (BOLOY et al., 2011), for the two biomasses studied, the economic analysis results in a payback period of approximately 8.5 years (Fig. 6).

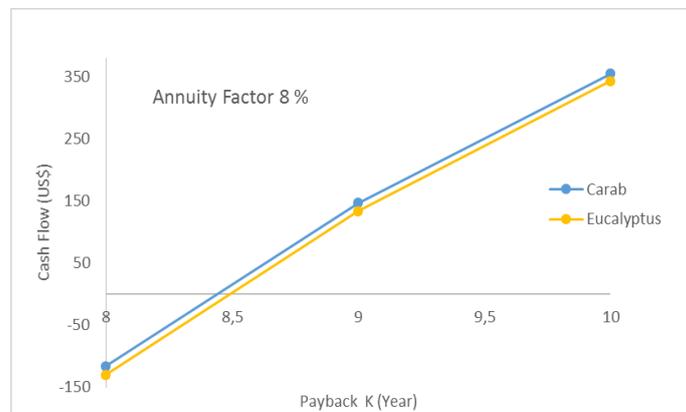


Fig. 6. Expected annual revenue based on the payback

Table 8. Cost synthesis gas, electricity, hot water and payback time, for an annual interest of 8%

Description	Eucalyptus	Carob
$C_{\text{syngas}}$ (US\$/kWh)	0.12	0.12
$C_{\text{HW}}$ (US\$/kWh)	0.06	0.07
$C_{\text{EL}}$ (US\$/kWh)	0.01	0.01
$P_{\text{HW}}$ (US\$/kWh)	0.10	0.10
$P_{\text{VEL}}$ (US\$/kWh)	0.022	0.022
Payback (year)	8.5	8.4

Table 8 presents all the results of economic analysis for an interest rate of 8 %, the recovery time of the investment, the syngas production cost, hot water production cost and the electricity production cost for the two biomasses studied are similar.

## 6. Conclusion

In this work were considered technical and economic aspects of a compact cogeneration system composed by a downdraft gasifier, two water/gas heat exchangers and an ICE. Two different biomasses were evaluated (carob and eucalyptus), 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 first law of thermodynamics and the application economic engineering. From a thermodynamic point, the global efficiency of the system for carob was 44.33 %, and for Eucalyptus reached to 49.77 %, the efficiency of electricity generation was about 21.42 %. The consumption of biomass to generate 15 kWh was approximately 22.83 kg/h for carob and rice husk with 20.67 kg/h.

The economic analysis evaluated that the cost synthesis gas varied from 0.09 to 0.33 US\$/kWh, the electricity production cost varied from 0.07 to 0.29 US\$/kWh and the hot water production price was between 0.04 and 0.21 US\$/kWh. Payback time, for interest rate of 8 %, is between 8 and 9 years.

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

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