COB-2023-1738
SYNGAS PRODUCTION FROM MUNICIPAL SOLID WASTE FOR DUAL-FUEL ENGINE OPERATION WITH BIODIESEL: AN ECONOMIC ANALYSIS

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Abstract. *The world generates enormous amounts of municipal solid waste every day, leading to environmental pollution and the depletion of natural resources. Converting waste into an energy source is a promising solution to address this issue. This study explores the use of waste, specifically plastic and paper waste, as part of the feedstock mixture in a gasification unit for synthesis gas (syngas) production and presents an economic analysis of the use of an internal combustion engine associated with a generator for electricity supply. Based on experimental data, a technical analysis is performed for the use of the produced syngas in a dual-fuel blend with biodiesel, which was also obtained in laboratory from the process of transesterification of waste cooking oil. Thermodynamics calculations are performed for calculating the power delivered by the engine, the heat flux of energy gases and the electricity efficiency, among other parameters. The syngas used presented about 9% of hydrogen in its composition, and the electricity efficiency was of about 18% in the experiment with the syngas-biodiesel as fuel. The economic analysis considered cost of investment, cost of operation and cost of maintenance, also, three levels of interest rates were applied for a sensibility analysis. It is observed that for interest rates of 4% and low fuel production costs, the payback period of the plant is achieved in around 3 years considering residential electricity tariffs applied nowadays.*

Keywords: *gasification, municipal solid waste, syngas, biodiesel, waste-to-energy.*

1. INTRODUCTION

This paper aims to demonstrate economic studies of a waste-to-energy (WtE) technology application that uses biofuels such as synthesis gas (syngas) and biodiesel in a dual-fuel blend for electricity supply. Biomass pellets and municipal solid waste (MSW) materials were used as feedstock in a small-scale industrial gasifier, in which the syngas is obtained under controlled temperature and pressure conditions. The syngas is then used to enrich the fuel blend being admitted into an internal combustion engine (ICE) running with biodiesel. Syngas and biodiesel were produced in laboratory through the processes of gasification and transesterification, respectively.

There are several discussions being made about ways for stopping global warming. This climatic urgency has been on the highlights of government proposals around the globe, being the United Nations (UN) the organization responsible for developing the 17 Sustainable Development Goals (SDG), which are an urgent call for action by all countries - developed and developing - in a global partnership (UN, 2023). Several studies correlate factors regarding MSW management such as Gross Domestic Product (GDP), sustainability indicators, accounting behavior, and governmental strategies and policies (FERRAMOSCA, 2019) (ROMANO *et al.*, 2019). In a recent study, WtE technologies such as gasification, incineration, composting, among others, were strictly reviewed and analyzed in terms of technical and operational parameters, products obtained and their advantages (FERRAZ DE CAMPOS *et al.*, 2021). Figure 1 is elaborated for resuming some of the 17 SDG that are related to the topic of WtE.

Figure 1. Sustainable Development Goals related to Waste-to-Energy.

Currently, waste-to-energy is considered as a pathway for sustainable development, given its characteristic of supplying energy whilst properly destinating waste materials. This topic has been vastly studied since there are multiple ways for dealing with waste management and reducing the environmental and human being impacts related to its unproper disposal.

Gasification is one technology that converts solid materials or waste into a gas. This process occur at high temperatures of around 700ºC and several materials can be used as feedstock such as MSW(SALEH *et al.*, 2019), biomass, waste tires, plastics, Waste from Electrical and Electronic Equipment (WEEE) (CHAUDHARI *et al.*, 2003), as well as mixtures for making co-gasification such as MSW (Rubber, Plastic, Cardboard) + Coal + Biomass (BOUMANCHAR *et al.*, 2019). Syngas, the main product of gasification, may present various compositions, depending on the feedstock material utilized but it contains combustible gases such as hydrogen (H_2) and methane (CH_4).

Figure 2 shows a flowchart the resumes the options of waste management being practiced nowadays.
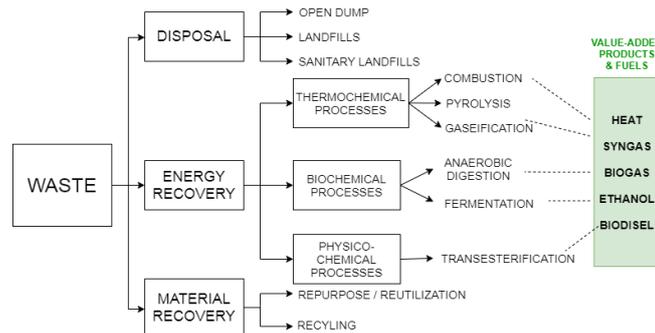

Figure 2. Flowchart of waste management pathways (FERRAZ DE CAMPOS *et al.*, 2021).

In the Section 2 of this paper, the authors present some technical and economic parameters (Section 2.1) that were considered for the calculation, while the experiment is explained, illustrated and the equations displayed in Section 2.2, and the results are presented in Section 2.3. Conclusions of this study are presented in Section 3.

2. WASTE-TO-ENERGY TECHNOLOGY APPLICATION

The results presented in this paper are based on experimental studies of co-gasification of mixtures between waste materials found on MSW such as paper and plastic with Pinus pellets that are available in the market. These materials were mixed in a proportion of mass of 85:15 of pellets and MSW, respectively. Figure 3.a shows the feedstock material used as feedstock in the gasification unit and the scheme of the gasification unit and its processes involved, and Figure 3.b shows the control volume of the ICE operating with syngas-biodiesel fuel blend. The diesel engine is fueled with biodiesel while in the admission of air there is also syngas added, which was produced in the gasification process.
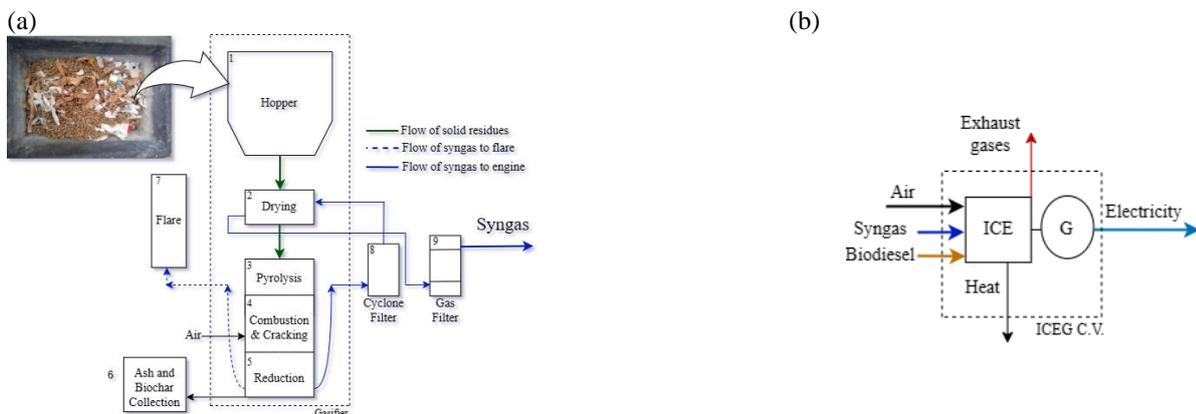

Figure 3. Cogasification schematics (a) and ICE operating with syngas-biodiesel schematics (b).

Additionally, the biodiesel used in the ICE was produced in laboratory through the process of transesterification of waste cooking oil (WCO) and methanol, using KOH as catalyst. The reaction will produce mostly biodiesel and glycerol (FEREIDOONI *et al.*, 2018), which decants in the funnel after some time left in resting. Figure 4 shows the result of trans-esterification process made in laboratory from WCO being the last quadrant the situation 24h after the experiment, in which is possible to see the glycerol on the bottom part of the funnel.

Figure 4. Biodiesel production and formation of glycerol.

2.1 Technical set-up and thermodynamics analysis

Two independent experiments were conducted. Firstly, the ICE was fueled with Biodiesel (produced in laboratory), and the bench test parameters were fixed with a torque of 4 N.m and rotation of 3000 RPM. The equipment consists of a 2-stroke Diesel engine with a power range of 2.2 to 7.5 kW, a maximum torque of 12 N.m, and a maximum speed of 6000 rpm. A fixed fuel volume of 16 mL was used for all tests, controlled by a graduated volumetric pipette. To determine fuel consumption for each fuel configuration, time was measured with a timer. This first case is considered as reference, in which the parameters collected during the experiment are time of consumption of 16 mL of fuel (T_c), temperature of exhaust gases ($T_{exhaust}$) and temperature variation of engine cooling water (ΔT (ºC)). Local temperature was 15ºC, measured by a thermometer installed in the building. The fuel consumption was obtained by dividing the volume by the time obtained with chronometers using proper conversion factors from minutes to seconds.

The second experiment consisted of the same engine fueled with Biodiesel whilst the air inlet was enriched with the syngas produced from the cogasification of wood pellets and MSW. Hence, the second experiment comprehends a dual-fuel configuration of the ICE using the mixture named Syngas-Biodiesel. Table 1 resumes the two experiments and their parameters obtained experimentally.

Table 1. Fuel configurations and parameters of operation of ICE bench test for 16 mL.

Fuel	$T_{exhaust}$ (ºC)	T_c (min)	ΔT (ºC)	Consumption (mL/s)
Biodiesel	175	2.33	10	0.11
Syngas-Biodiesel	375	2.75	10	0.08

The LHV of the produced Biodiesel was obtained using a bomb calorimeter IKA C200 model resulting in 38,200 kJ/kg, approximately. The syngas samples collected during the cogasification experiments were analyzed by gas chromatography using a Varian 450-GC Gas Chromatograph with a Ther-mal Conductivity Detector (TCD) (used for identification and quantification of the gaseous constituent's CO, CO_2, H_2, CH_4 and light hydrocarbons). The syngas LHV was the calculated based on its composition. According to the manufacturer, the efficiency of the generator is of around 80%, considering the model NPE32 4 poles and power of 7.5 KVA type 32-A/4.

Given the ICE and Generator (ICEG) control volume presented in Figure 3.b, it is possible to apply the first law of thermodynamics, or the law of conservation of energy. Eq. 1 is formulated to express this balance.

$$E_{Fuel} + \dot{m}_{air} . cp_{air}. T_{air} = E_p + \dot{m}_{eg}. cp_{eg}. T_{eg} + E_{jcw} + L, \tag{1}$$

where E_{Fuel} is the power available in the fuel mixture [kW], $\dot{m}_{air}$ is the mass flow [kg/s], cp_{air} is the calorific value of air [kJ/kg.K] at the temperature T_{air} [K], E_p is the power produced [kW], $\dot{m}_{eg}$ is the exhaust gases flow [kg/s], cp_{eg} is the calorific value of the exhaust gases [kJ/kg.K], T_{eg} is the temperature of exhaust gases [K], E_{jcw} is the power from the engine jacket cooling water system [kW] and L are loses due to friction and radiation [kW]. It is possible to calculate the power available in the fuel mixture E_{Fuel} [kW] considering Eq. 2.

$$E_{Fuel} = \dot{m}_{syngas} . LHV_{syngas} + \dot{m}_{biodiesel} . LHV_{biodiesel}, \tag{2}$$

where $\dot{m}_{syngas}$ and $\dot{m}_{biodiesel}$ are the mass flow rates [kg/s] and LHV_{syngas} and $LHV_{biodiesel}$ are the lower heating values [kJ/kg] of syngas and biodiesel, respectively. Considering the conservation of mass, it is possible to assert the following equality from Eq. 3.

$$\dot{m}_{syngas} + \dot{m}_{biodiesel} + \dot{m}_{air} = \dot{m}_{eg}, \tag{3}$$

where the sum of mass flows in the inlet of the ICE, i.e. $\dot{m}_{syngas}$ [kg/s] and $\dot{m}_{biodiesel}$ [kg/s] (fuel) added to $\dot{m}_{air}$ [kg/s] (air) results in the mass flow of exhaust gases $\dot{m}_{eg}$ [kg/s]. The mechanical power delivered by the ICE, i.e., mechanical energy from the axis $\dot{W}$[kW], is determined by Equation 4.

$$\dot{W} = \frac{T \cdot N \cdot \frac{2\pi}{60}}{1000}, \tag{4}$$

where T is the torque [N.m] and N is the engine's rotation in RPM (rotations per minute), which were controlled parameters available in the engine bench test. The power produced E_P[kW] can be than estimated using Eq. 5, considering the association of the ICE with a generator.

$$E_P = \dot{W} \cdot \eta, \tag{5}$$

where η is the generator efficiency, considered of 80% according to the manufacture's manual.

Finally, the electric efficiency of the ICE can be calculated according to Eq. 6.

$$\eta_{ele} = \frac{E_p}{E_{fuel}}, \tag{6}$$

2.2 Economic analysis

The methodology of economic engineering is applied for the calculation of electricity production cost c_{el} [US\$/kWh] of the proposed system, as it can be observed in Eq. 7.

$$c_{el} = \frac{I_{PL} \cdot f}{E_p \cdot H} + c_{fuel} \cdot \frac{E_{fuel}}{E_p \cdot H} + c_M, \tag{7}$$

where I_{PL} [US\$] is the investment of the plant, f [1/year] is the annuity factor (Given by Equation 8), H [h] is the hours of operation in the period of one year, E_p is the power produced (calculated using Eq. 5), c_{fuel} [US\$/kW] is the cost of the fuel mixture and C_M [US\$/kWh] is the cost of maintenance.

$$f = \frac{q^k \cdot (q-1)}{q^k - 1}, \tag{8}$$

where k [years] is the payback period and q is a parameter calculated according to the interest rate as expressed in Eq. 9.

$$q = 1 + \frac{i}{100}, \tag{9}$$

where i [%] is the interest rate, which will be assumed in this paper as 4%, 8% and 12% as a matter of sensibility analysis. The cost of fuel will be calculated in function of the total power of the fuel mixture (syngas + biodiesel) that is feeding the ICE. Therefore, the cost of fuel in the ICE is given by the Eq. 10.

$$c_{fuel} = \frac{\dot{m}_{syngas} \cdot LHV_{syngas} \cdot c_{syngas} + \dot{m}_{biodiesel} \cdot LHV_{biodiesel} \cdot c_{biodiesel}}{E_{fuel}}, \tag{10}$$

where c_{syngas} and $c_{biodiesel}$ are de costs of syngas and biodiesel, respectively, considering the total mass of Pinus pellets ($m_{pellets}$ [kg]) and MSW material (m_{MSW} [kg]) used in the gasification process (16 kg of pinus pellets and 3 kg of MSW plastic and paper resulting in the total of gasification feedstock m_{total} of 19 kg), and these parameters can be expressed as follows in Eq. 11 and Eq. 12.

$$c_{syngas} = \frac{m_{pellets}}{m_{total}} \cdot c_{pellets} + \frac{m_{MSW}}{m_{total}} \cdot c_{MSW}, \tag{11}$$

where $c_{pellets}$ [US\$/kg] is the purchase price of Pinus pellets and c_{MSW} [US\$/kg] is the cost of MSW materials such as plastic and paper, which are parameters that are properly referenced in the results section of this paper.

$$c_{biodiesel} = p_{bio} \cdot v_{bio}, \tag{12}$$

where p_{bio} [US\$/l] is the production cost of biodiesel and v_{bio} [l] is the volume of biodiesel consumed by the engine.
The cost of maintenance is calculated according to the Eq. 13.

$$c_M = \frac{0.05 \cdot I_{PL} \cdot f}{E_p \cdot H},$$ (13)

Finally, the expected annual revenue R [US$] is given in Eq. 14.

$$R = E_P \cdot H \left(c_{tariff} - c_{el} \right),$$ (14)

where c_{tariff} [US$/kWh] is the price of the electricity tariff for residential consumers and considered 0.20 US$/kWh.

2.3 Results and discussions

The results of the thermodynamic analysis rely on data from the cogasification of wood pellets and MSW material as paper and plastic. The main parameters of the gasification process, elements detected in the syngas composition, the LHV of syngas, feedstock consumption and experiment time are displayed in Table 2.

Table 2. Main gasification parameters and results of syngas composition.

Parameter	Unit	85% pellets + 15% MSW
Temperature of oxidation	°C	797
Temperature of reduction	°C	548
Volume of air	m³/h	7.00
CO_2	%	4.16
C_2H_4	%	0.25
C_2H_6	%	0.06
C_2H_2	%	0.01
H_2S	%	0.00
CH_4	%	1.41
N_2	%	77.73
H_2	%	8.52
LHV	MJ/m³	2.53
Feedstock consumption	kg/h	5.63
Experiment time	min	200

From the results of the gasification experiment, it is possible to apply Equation 1 for the energy balance and Table 3 is elaborated with all the results from the ICE operating with both fuel configurations.

Table 3. ICEG Energy analysis results for both fuel configurations.

Parameter	Unit	Biodiesel	Syngas-Biodiesel
E_{fuel}	kW	3.30	5.71
$\dot{m}_{syngas}$	kg/s	-	0.0011
$\dot{m}_{biodiesel}$	kg/s	1.10×10^{-4}	8.50×10^{-4}
$\dot{m}_{air}$	kg/s	0.0015	0.0013
$\dot{m}_{eg}$	kg/s	0.0016	0.0025
E_P	kW	1.00	1.00
E_{eg}	kW	0.77	1.74
E_{jcw}	kW	0.0075	0.0075
L	kW	1.51	2.96
η_{ele}	%	30.45	17.59

It is important to note that it was considered a calorific value of the air of 1.05 kJ/kg.K and air inlet temperature of 298 K, an exhaust gases calorific value of 1.10 kJ/kg.K and temperature of 648 K (obtained during the experiment), then the heat flux of the exhaust gases (E_{eg} [kW]) is obtained. Furthermore, the specific mass of syngas was calculated as 1.0327 g/L and and the specific mass of biodiesel of 0.88 g/ML. The LHV of syngas being added into the ICE was calculated based on its composition, resulting in 2,454.4 kJ/kg. Considering the 200 min of experiment from the gasification unit, the ICEG operating with syngas-biodiesel would have consumed 1.16 L of biodiesel and delivered around 3.35 kWh of electricity, while consuming the total mass of the gasifier feedstock.

Sankey diagrams from both fuel configurations, i.e., Biodiesel and Syngas-Biodiesel fuel-blend, were elaborated and the result is present in Figure 5. Considering the first experiment, the power from Biodiesel fuel (100%) is converted into the outputs: loses (45.93%), Power produced (30.45%), heat flux (HF) of exhaust gases (23.37%) and power from the jacket water cooling system E_{jcw} (0.23%), as it can be observed in Figure 5.a. Regarding the Sankey diagram of Syngas-Biodiesel dual-fuel, from Figure 5.b, it is possible to observe that the from the total power available in the fuel blend (5.71 kW), 42.95% comes from the syngas and 57.05% from the biodiesel and the outputs are divided as follows: power produced represents 17.59% (1.00 kW), HF of exhaust gases 30.43% (1.74 kW), loses are 51.82% (2.96 kW) and power from jacket water cooling system E_{jcw} 0.13% (0.0075 kW).

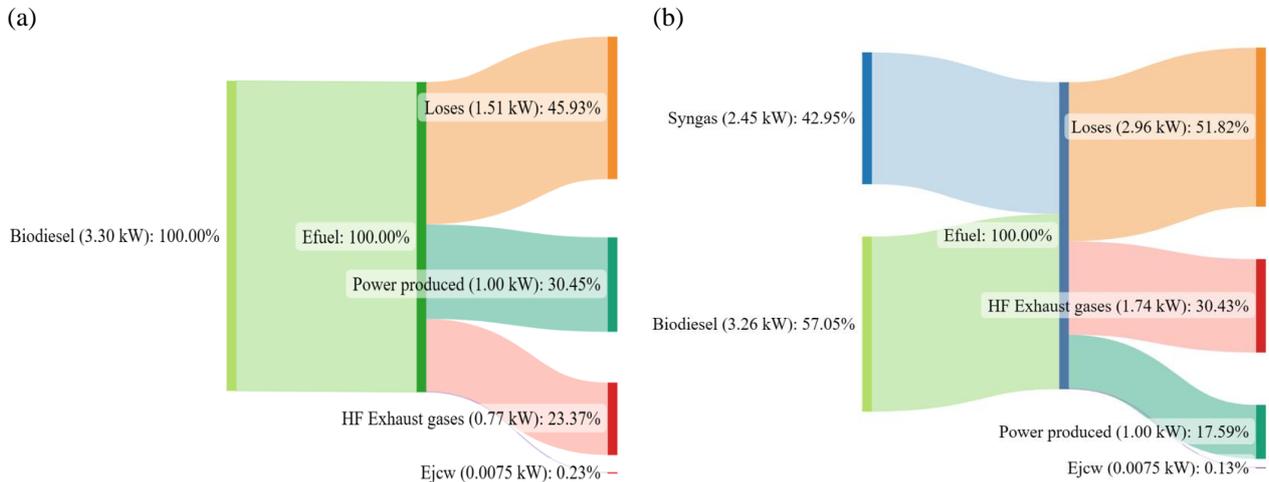(a)   (b)

Figure 5. Sankey diagrams of ICE operating with Biodiesel (a) and Syngas-Biodiesel (b).

From the energy results, an economic analysis can be performed considering an investment of U$ 2000,00 for the plant (engine and generator – this cost estimate was obtained through market research with similar engine specifications) and 12 hours of daily operation (resulting in 4380 hours in one year). According to Guabiroba *et al.*, (2017), almost 70% of biodiesel production cost comes from the price of WCO, which in Brazil values around 0.59 BRL/L. Thus, the cost of biodiesel production adopted in this paper is 0.84 BRL/L, which is equivalent to 0.167 USD/L with the currency rate of 5.03 BRL/USD. According to Henao *et al.* (2022), an actual price for wood pellets is 126.37 USD/ton, and, according to Klaimi *et al.* (2022), the price of MSW is 50 USD/ton. Figure 6.a shows the graphic of cost of electricity generation (US$/kWh), in which it is highlighted the cost of the electricity tariff (0.83 BRL/kWh, or 0.165 USD/kWh) which is equivalent to the intermediary residential tariff according to the online ANEEL (National Agency of Electrical Energy of Brazil) platform (ANEEL, 2023), and the payback period will be the point of intersection of the tariff curve with the cost curves depending on the interest rate (i=4%, i=8%, i=12%). Additionally, the annual expected revenue (R) is presented in the graph of Figure 6.b, in which the payback period is obtained with the intersection of the curves with the "x" axis, that is, the moment when the cost of electricity generation is lower than the cost of electricity tariff. This study obtained the payback period of around 3 years considering interest rates of 4% for the syngas-biodiesel fuel mixture, against around 5 years when compared to the biodiesel fuel.
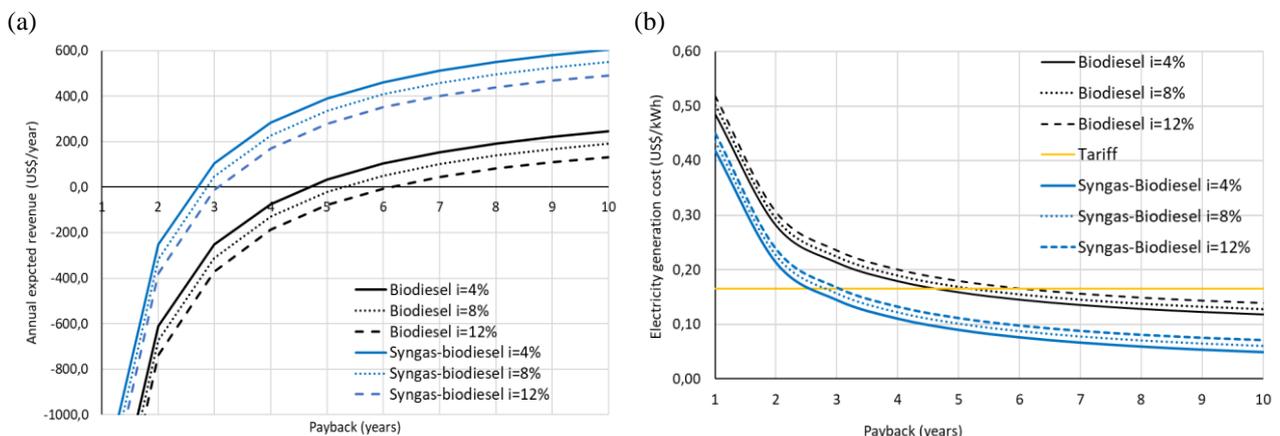
(a)   (b)

Figure 6. Electricity generation cost vs payback (a) and annual expected revenue (b).

3. CONCLUSIONS

This paper aimed in demonstrating the economic calculations of a practical experiment involving multiple processes. Starting with the co-gasification of Pinus pellets and MSW materials such as paper and plastic, the thermochemical processes resulted in a syngas with around 9% of hydrogen gas in its composition. The biodiesel, which was produced in the laboratory, was used as liquid fuel in an ICE, which was fed with syngas in the air inlet under atmospheric pressure, which resulted in a dual-fuel situation inside the combustion chamber of the engine made of a fuel mixture of syngas and biodiesel. It was verified that there are greater loses in the dual-fuel configuration since cogeneration is not considered, which could be an alternative considering the elevated temperatures of exhaust gases found in the experiment. The results of this paper indicate that the payback of the electricity generation from ICE running with a dual-fuel mixture of syngas and biodiesel is approximately 3 years considering an interest rate of 4%, against around 5.5 years for the same engine operating with biodiesel only. This payback period will be impacted by the biodiesel production cost, the MSW cost of purchase, or collection/transportation, and the cost of the main wood pellets used in the gasification unit.

4. ACKNOWLEDGEMENTS

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