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Short communication

Ecological impacts from syngas burning in internal combustion engine: Technical and economic aspects

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ABSTRACT

This paper evaluates and quantifies the environmental impact from the use of syngas in internal combustion engines associated with downdraft gasifier, considering technical, economical and ecological aspects. The ecological efficiency concept depends on the environmental impact caused by CO_2, SO_2, NO_x and particulate material (MP) emissions. The emission factors obtained from syngas burned in an internal combustion engines is compared to emission factors obtained from gasoline burn, biodiesel burn, natural gas burn and diesel burn, and were calculated separately. This paper considers technical and economic aspects such as: mass flow of syngas, exhaust gases, inlet air in gasifier and inlet air in ICE; heat capacity of syngas; thermal efficiency and electricity efficiency of ICE, gasifier cold efficiency, system efficiency; electricity costs production, syngas costs production, hot water costs production and expected annual saving. In an economical point view, considering the annual interest rates and the amortization periods, the costs of production of electrical energy and hot water were calculated, taking into account the investment, the operation and the maintenance cost of the equipments.

1. Introduction

To day, the worldwide preoccupation is not only focused on our energy source exhaustion, which is petroleum, but also on environmental problems and one may say this is the main focus. Recently, the pollutant indicators reduction of toxic substances in the environment produced by the industrial and the automotive transportation sectors is one of the most important targets that are being taken into account in the majority of the industrialized countries. Both sectors must adopt future strategies for the reduction of pollutants emission to the atmosphere, with the purpose of reducing the dangerous concentrations in the air. One factor that influences the feasibility analysis to apply technologies that use alternative fuels is the environmental impact that such technology could cause. Many researchers have devoted to lower the emissions of pollutant materials by these technologies, trying to reverse the current environmental situation. The control of emission factors such as: particulate matter (MP), CO_2, SO_2, NO_x represents a major concern worldwide. In the case of MP_{10}, it can easily get through the throat and settle down into the lungs, endangering human health. The CO_2 is considered as one of the main greenhouse effect agents, while SO_2 causes acid rain. NO_x is considered as the main culprit of the ecosystems' acidification.

Brazil has developed many sustainable energy programs in order to reduce carbonic gas emission. Those programs use technologies that must be respectful to environment and techno-economically competitive. For example: hydrogen production, biodiesel production, ethanol production and syngas production from biomass gasification, especially small-micro-scale systems gasifiers associated to an internal combustion engine. Some of these fuels could be used in a direct form, however, others need some kind of modification to replace the conventional diesel fuel – gasification when the subject is biomass, and transesterification when it is biodiesel [1]. Biomass gasification systems have been utilized for quite some time and have demonstrated to be a good sustainable technology, requiring simple management and maintenance that give them high availability. Gasification consists in a thermo chemical process through which the biomass is converted into fuel gas (synthesis gas) through the partial air oxidation, partial oxygen oxidation or partial water steam oxidation at high temperatures. Originally, two different types of fixed bed gasifiers were developed: updraft and downdraft gasifiers, in Table 1 are shown some aspects of these gasifiers. The main difference between updraft and downdraft gasifiers is that the gas flows co-currently downwards

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Nomenclature

AES	annual expected saving (US$/year)
b	biomass
C_b	biomass cost (US$/kWh)
C_{EL}	electricity cost (US$/kWh)
C_{HW}	hot water cost (US$/kWh)
CM_{ICE}	internal combustion engine maintenance cost (US$/kWh)
$CM_{Gasifier}$	gasifier maintenance cost (US$/kWh)
CM_{HE}	heat exchanger maintenance cost (US$/kWh)
$C_{Operation}$	operation cost (US$/kWh)
CO_{2e}	carbon dioxide equivalent per kilogram of fuel (kg/kg)
Cp	specific heat at constant pressure (kJ/kg K)
CP	parts cost
C_{Syngas}	syngas cost (US$/kWh)
dH_{H_2O}	heat of formation of water (kJ/kmol)
E_{HW}	thermal energy of hot water (kWt)
EP	power generated (kWe)
$EP_{gasifier}$	gasifier power generated (kWe)
$E_{SSyngas}$	power supplied by syngas (kW)
E_{Syngas}	thermal energy of syngas (kWt)
E_b	power supplied by the biomass (kW)
f	annuity factor (1/year)
FP_E	electricity production factor by consumed fuel
FP_{HW}	hot water production factor by consumed fuel
GP_{EL}	electricity gain (US$/year)
GP_{HW}	hot water gain (US$/year)
H	equivalent period of utilization (h/year)
H°f	formation enthalpy (kJ/kmol)
H_2O	steam water
h_b	biomass enthalpy (kJ/kg)
HE	heat exchanger
h_{fb}	biomass formation enthalpy (kJ/kg)
h_{syngas}	syngas enthalpy (kJ/kg)
I	inlet
ICE	internal combustion engine
I_{ICE}	internal combustion engine investment (US$)
$I_{Gasifier}$	downdraft gasifier investment (US$)
I_{HE}	heat exchanger investment (US$)
k	payback period (year)
LHV	lower heat value (kJ/Nm^3)
m_{air}	air mass flow (kg/h)
m_b	biomass mass flow (kg/h)
MC_o	maintenance cost
m_{H_2O}	water mass flow (kg/s)
MI	maintenance interval
m_{Syngas}	syngas mass flow (Nm^3 g/h)
MP	particulate matter per kilogram of fuel (kg/kg)
N_2	nitrogen per kilogram of fuel
NO_x	nitrogen oxide (kg/kg)
n_k	mole number (mol)
O	outlet
PEL	electricity tariff (US$/kWh)
PHW	hot water tariff (US$/kWh)
r	annual interest rate (%)
syngas	syngas
STP	standard temperature pressure
T	temperature (°C)
w	work base

Greek characters

ε	ecological efficiency
Π_p	pollutant indicator (kg_{CO2}/MJ)
η_{CG}	cold gas efficiency
η_S	system efficiency
η_{EP}	power generated efficiency
η_{HE}	heat exchanger efficiency
η_{HW}	hot water efficiency

with the biomass feed in the downdraft case. This leads to a different order of the reaction zones from top to bottom in this order: drying, pyrolysis, oxidation, and reduction zone with the result of a low tar content in the gas produced. The low-heat value of the syngas is in the range of 4–6 MJ/Nm^3 [2].

The methodology proposed in this paper analyzes the syngas burning in an internal combustion engine from the ecological, technical and economical point of view. The ecological efficiency parameter (ε) was considered for steam cycles which use coal as fuel [3]; it was extended for combined cycle plants that use natural gas, internal combustion engines and advanced cycles that use biomass as fuel [4].

2. System description

Fig. 1 shows the scheme considered for analysis in this paper. The biomass (eucalyptus), whose ultimate analysis appears in Table 2, enters through the top of the gasifier with 20% of moisture content, but the atmospheric air enters through an intermediary point and descends in the same direction of the biomass. After going 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, react 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.

The free energy minimization Gibbs's method for the C–H–O atom blend of the biomass fuel and oxidant mixture was applied for predicting the syngas composition obtained from the gasification process at 800 °C of temperature using equivalence ratio equals to 0.25, which is within the range for ideal and theoretical gasification (0.19–0.43) [5]. The syngas contain mainly CO_2 (10.14%), CO (19.67%), H_2 (24.89%), N_2 (44.36%) and CH_4 (0.94%) in dry basis [6], the lower heat value (LHV) is 5.50 MJ/Nm^3 [6] and density 1.03 kg/Nm^3 [6]. The syngas was cleaned in a cyclone to eliminate particulate material. In the next stage, the syngas at 600 °C [7] is cooled around 35 °C [8] in a gas–water heat exchanger producing hot water at 40 °C, 45 °C, 50 °C, 55 °C and 60 °C, heat exchanger contains a valve to purge the condensation of the syngas (tars), under these conditions, the syngas goes through a sleeve filter to remove the remaining particulate material, guaranteeing the syngas quality and that it is suitable to be used as fuel by an ICE. These conditions [9] appear in Table 3. Ultimately, an internal combustion engine, made by Honda EP 5500, model GX 340 as appears in Table 4 was used to produce electricity. A generator is coupled to the engine by a pulley and belt and, through these, receives the mechanical energy produced by the combustion engine. The electrical generator (three-phase) functions at 60 kHz, 4 poles (polarizations),

Table 1
Comparison between updraft gasifier and downdraft gasifier.

Gasifier	Temperature (°C) Reaction	Output	Gas flow	Biomass fed	Gasification agent	Tar contents
Updraft	700–1000	250	Upwards counter-current to the biomass fed	From the top	Bottom	High
Downdraft	700–1000	800	Downwards co-currently to the biomass fed	From the top	Top or at least at a certain height above the Bottom	Low

Table 2
Eucalyptus ultimate analysis (dry bases, weight percentages, molar fraction).

Weight percentages						
Biomass	C	H	N	S	O	Ash
Eucalyptus	49	5.87	0.3	0.01	43.97	0.72
				Molar fraction		
	4.08	5.87	0.02	0.0001	2.75	

Table 3
Quality of synthesis gas used in power systems [9].

Parameters	ICE
Particulate (mg/Nm^3)	50 (maximum)
Size of particle (μm)	10 (maximum)
Tar (mg/Nm^3)	100 (maximum)
Alkalines metals (mg/Nm^3)	–

20–10 kW power, and operating at a rated voltage of 220 V and a current of 32.8 A. The engine utilized in this study has a pressure reducer made by "Rodagás", which allows the operation both on GLP or GNV and even on gasoline. The pressure reducer used by this experiment is the model TE-01, which has a capacity for up to 43 m^3/h of fuel, good for engines with power up to 120 HP. Working pressures are: max input pressure 250 bar and minimum input pressure 26 bar; it is operated by an electro valve and is powered by a 12 V source.

3. Methodology

3.1. Simplifications and assumptions

In this study, an ICE Honda EP 5500 was selected; the consumption of gasoline of this engine is 2370 g/h operating at full load. The thermal efficiency of a spark ICE operating with gasoline is found between 15% and 20% [10]. In the case of the Honda engine, its thermal efficiency is in the order of 17%. This ICE operating with syngas achieves lower values of thermal efficiency than when operating with gasoline, due to the lower heat value of syngas is smaller than lower heat value of gasoline; for the calculation of syngas consumption by the ICE, the thermal efficiency of the ICE was considered in the range of 10–15%, considering an efficiency of 95% for the electric generator. The ratio between the syngas produced and the consumption of biomass by gasifier was considered as 1 kg of biomass producing 2.50 m^3 of syngas [10], the stoichiometric air/fuel ratio in a biomass gasification process is 5.22 m^3 air/kg of biomass [5]. In case of ICE the air/fuel ratio is in the range of 10–13 when is operated with syngas; for this study was considered 12.

For the economical analysis, the gasifier operation costs, the gasifier maintenance costs, the electricity cost, the syngas cost, the hot water cost, the thermal and electricity energy gain and the annual expected saving of the system were determined. In the case of biomass gasifier, the following costs were determined:

- Maintenance costs, considering 1250 h/year or 3.47 h/d of gasifier maintenance and eucalyptus cost equals to 0.0038 $/kWh [11].
- Syngas cost production can be calculated considering gasifier investment, operation time, power supplied by biomass and annuity factor.

In the case of heat exchanger, the hot water cost production was determined by the heat exchanger investment, hot water thermal energy, operation time, annuity factor and the hot water production factor by consumed fuel. Finally, on the engine/generator set, the electricity cost was determined, using the engine/generator investment, the electric power generated, operation time, annuity factor and the electricity production factor by consumed fuel. The AES was determined from thermal and electricity production gain. For the analysis, an electricity tariff for isolated communities considered was 0.10 $/kWh [6] and 0.0022 $/kWh [12] for hot water generation.

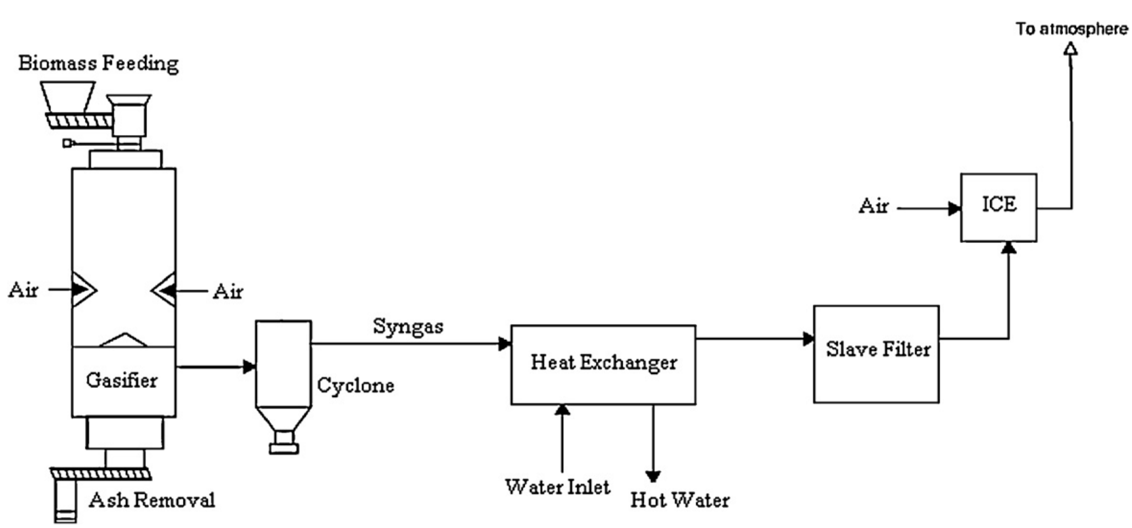

Fig. 1. Biomass air gasification/ICE system scheme.

Table 4
Assumptions for set Gasifier/ICE technical and economical analysis.

Item	Value	Item	Value
Air ISO conditions	P = 10,1325 Pa, T = 25 °C	Operation time (h/year)	2000, 3000, 4000, 5000, 6000
Hot water temperature (°C)	40, 45, 50, 55, 60	Heat exchanger investment (US$)	700
Heat exchanger efficiency (%)	80, 75, 70, 65	Gasifier investment (US$) [13]	10,000
Specific heat of water (kJ/kg K)	4.19	ICE maintenance cost (US$/kWhe) [14]	0.011
ICE investment (US$) [13]	1437.02	Heat exchanger maintenance cost (US$/kWh)	0.003
Annual interest rate (%)	12	Biomass lower heat value (kJ/kg)	19,457
Syngas enthalpy (kJ/kg) [6]	1543.63	Ash enthalpy (kJ/kg) [6]	538.28
dH_{H_2O} (kJ/kmol) [6]	−212,814.51	Air enthalpy (kJ/kg) [6]	398.81
Wage rate in US$/h for each operation time considered (2000, 3000, 4000, 5000, 6000) and 3 operators [6]	11.37, 7.58, 5.68, 4.55, 3.79	Maintenance Interval (h)	1250
Parts (US$) [6]	29.25	Labour maintenance in US$ for each wage rate considered and 5 h of maintenance [6]	56.84, 37.89, 28.42, 22.74, 18.95

Heat capacities (constants A, B, C and D) [15]

Chemical species	t_{max}	A	10^3B	10^6C	$10^{-5}D$	Cp (kJ/kmol K)	ΔH (kJ/kmol)
CH_4	1500	1.702	0.009081	−0.000002164		56.55	43,821.29
H_2	3000	3.249	0.000422	–	8300	29.63	22,961.31
CO	2500	3.376	0.000557	–	−3100	31.16	24,146.13
CO_2	2000	5.457	0.001047	–	−115,700	48.33	37,448.84
N_2	2000	3.28	0.000593	–	4000	30.75	23,829.66
H_2O	2000	3.47	0.00145	–	12,100	37.43	29,001.74
C	2000	1.771	0.000771	–	−86,700	16.87	13,068.25

3.2. Technical analysis of the Gasifier/ICE system

This section presents the equations used (Eqs. (1)–(12)) to develop the energy balance of a fixed bed gasifier downdraft type coupled with a ICE system. After listing the equations, the procedure which was calculated for each of them will be detailed. In Table 4, the fixed values of the system are presented. These values have been mentioned in the previous section and are presented in this part to development the energy balance.

The power supplied by biomass was calculated using Eq. (2), which allowed us to calculate the system efficiency using Eq. (3). The thermal energy of water was calculated by Eq. (4), which allowed us to calculate the hot water flow in heat exchanger at different temperatures (40 °C, 45 °C, 50 °C, 55 °C and 60 °C) using Eq. (6). Finally, the power supplied by syngas was determined by Eq. (7).

Using Eqs. (8) and (9), the syngas thermal energy and the specific heat of syngas were determined. The biomass formation enthalpy and biomass enthalpy were calculated by Eqs. (10) and (11). Finally, using Eq. (12), a gasifier cold efficiency was determined [2].

$$\eta_{EP} = \frac{EP}{E_{SSyngas}} \tag{1}$$

$$E_b = m_b \times LHV_b \tag{2}$$

$$\eta_S = \frac{EP + E_{HW}}{E_b} \tag{3}$$

$$E_{HW} = E_{Syngas} \times \eta_{HE} \tag{4}$$

$$\eta_{HW} = \frac{E_{HW}}{E_b} \tag{5}$$

$$m_{H_2O} = \frac{\eta_{HE} \times E_{Syngas}}{Cp_{H_2O} \times (T_O - T_I)} \tag{6}$$

$$E_{SSyngas} = \frac{EP}{0.95 \times 0.135} \tag{7}$$

$$E_{Syngas} = \frac{m_{Syngas} \times Cp_{Syngas} \times (T_{SO} - T_{SI})}{3600} \tag{8}$$

$$Cp_{Syngas} = \frac{\sum_{i=element}^{n} Cp_i}{6 \times 24.034} \tag{9}$$

$$h_{fb} = (LHV_b) + \left(\sum_{i=prod}^{n} n_k \times (h_f^{-0})_i \right) \tag{10}$$

$$h_b = ((1 - MC) \times h_{fb}) + \left(MC \times \left(\frac{dH_{H_2O}}{24.03} \right) \right) \tag{11}$$

$$\eta_{CG} = \frac{m_{Syngas} \times LHV_{Syngas}}{m_b \times LHV_b + m_{air} \times h_{air}} \tag{12}$$

3.3. Economical analysis of the Gasifier/ICE system

This section studies the economic feasibility of the Gasifier/ICE system, based on the allocation cost methodology developed by Silveira et al. [16–19].

The equations utilized in this analysis are cited below:

$$C_{Operation} = \frac{Wage\ Rate \times Hours}{EP_{Gasifier} \times H} \tag{13}$$

$$CM_{Gasifier} = \frac{MC + CP}{EP_{Gasifier} \times MI} \tag{14}$$

$$C_{Syngas} = \frac{I_{Gasifier} \times f}{H \times E_{SSyngas}} + \frac{C_b \times E_b}{E_{SSyngas}} + CM_{Gasifier} + C_{Operation} \tag{15}$$

$$C_{EL} = \frac{I_{ICE} \times f}{H \times EP} + \frac{C_{Syngas} \times FP_E}{EP} + CM_{ICE} + \left(C_{Operation} \times \frac{EP}{EP + E_{SSyngas} + E_{HW}} \right) \tag{16}$$

$$C_{HW} = \frac{I_{HE} \times f}{H \times E_{HW}} + \frac{C_{Syngas} \times FP_{HW}}{E_{HW}} + CM_{HE} + \left(C_{Operation} \times \frac{E_{HW}}{EP + E_{SSyngas} + E_{HW}} \right) \tag{17}$$

$$FP_E = \frac{EP}{EP + E_{HW}} \tag{18}$$

$$FP_{HW} = \frac{E_{HW}}{EP + E_{HW}} \tag{19}$$

Table 5
Reagents in the combustion process in an ICE at STP.

Syngas composition in dry basis	
H_2 (mol)	0.2489
CO (mol)	0.1967
CO_2 (mol)	0.1014
CH_4 (mol)	0.0094
N_2 (mol)	0.4436
MP (g/Nm^3)	10, 20, 30, 40
LHV (MJ/kg)	5.50
Air	
O_2 (mol)	0.2416
N_2 (mol)	0.9085
ICE synthesis gas intake temperature (K)	308
Combustion Flame temperature (K)	1960
ICE Air intake temp. (K)	298

$$f = \frac{q^k \times (q-1)}{(q^k - 1)} \tag{20}$$

$$q = 1 + \frac{r}{100} \tag{21}$$

$$\mathrm{GPEL} = \mathrm{EP} \times H \times (P_{\mathrm{EL}} - C_{\mathrm{EL}}) \tag{22}$$

$$\mathrm{GPHW} = \mathrm{EP}_{\mathrm{HW}} \times H \times (P_{\mathrm{HW}} - C_{\mathrm{HW}}) \tag{23}$$

$$\mathrm{AES} = \mathrm{GPEL} + \mathrm{GPHW} \tag{24}$$

3.4. Ecological analysis of the Gasifier/ICE system

3.4.1. Calculation of emissions produced by syngas combustion in an internal combustion engine

A Syngas, presents the following molecular composition on a dry basis: H_2 = 0.2489, CO = 0.1967, CO_2 = 0.1014, CH_4 = 0.0094, N_2 = 0.4436. The molecular weight is 23.04 kg/kmol and its density is 1.03 kg/Nm^3. Table 5 relates the initial conditions of reagents in the syngas combustion process in an ICE at STP. The combustion reaction for normalized air excess is as follows:

$$\begin{aligned} &0.2489\mathrm{H_2} + 0.1967\mathrm{CO} + 0.1014\mathrm{CO_2} + 0.0094\mathrm{CH_4} + 0.4436\mathrm{N_2} \\ &\quad + 0.2416\alpha\mathrm{O_2} + 0.9085\alpha\mathrm{N_2} \rightarrow 0.3075\mathrm{CO_2} \\ &\quad + 0.2677\mathrm{H_2O} + 0.2416(\alpha-1)\mathrm{O_2} + 0.9085\alpha\mathrm{N_2} \end{aligned} \tag{25}$$

3.4.2. Calculation the carbon dioxide equivalent

The carbon dioxide equivalent (CO_{2e}) is composed by a hypothetical pollutant concentration factors, which is shown by Eq. (26). For the calculation of this coefficient, the maximum allowed value for the CO_2 concentration is divided by the air quality standard in NO_x, SO_2 and MP in 1 h [1].

$$\mathrm{CO_{2e}} = \mathrm{CO_2} + 80\mathrm{SO_2} + 50\mathrm{NO}_x + 67\mathrm{MP} \tag{26}$$

The best fuel, from the ecological standpoint, is the one that presents a minimum amount of CO_{2e}, obtained from its burning. In order to quantify this environmental impact, the "pollutant indicator" (Π_p) is defined by [1]:

$$\Pi_p = \frac{\mathrm{CO_{2e}}}{\mathrm{LHV_{Syngas}}} \tag{27}$$

3.4.3. Ecological efficiency

Environmental problems span a continuously growing range of pollutants, hazards and ecosystem degradation over wide areas. Problems with energy supply and use are related not only to global warming, but also to environmental concerns such as air pollution, acid precipitation, ozone depletion, forest destruction, and emission of radioactive substances. These issues must be taken into consideration simultaneously if mankind is to achieve a bright energy future with minimal environmental impacts.

Table 6
Technical analysis associated to the heat exchanger.

Parameters	Heat exchanger efficiency (%)			
	80	75	70	65
System efficiency (%)	15.03	14.65	14.26	13.88
Hot water efficiency (%)	6.18	5.80	5.41	5.02
Thermal energy of water (kW)	3.68	3.45	3.22	2.99

The ecological efficiency is defined as an indicator which allows the evaluation of thermoelectric power plant performance, in respect to pollutant emission, by comparing the hypothetically integrated pollutant emission (CO_2 equivalent emissions) with the existing air quality standards. The conversion efficiency is also considered as a determining factor on the specific emissions, expressed by a fraction number. Eq. (28) can be used for determining the ecological efficiency [1,3,4]:

$$\varepsilon = \left[\frac{0.204 \times \eta_{\mathrm{system}} \times \ln(135 - \Pi_p)}{\eta_{\mathrm{system}} + \Pi_p}\right]^{0.5} \tag{28}$$

where "ε" comprises, in a single coefficient, the aspects that define the thermoelectric unit environment impact intensity, fuel composition, combustion technology, pollutant indicator and thermodynamic efficiency. "ε" is directly proportional to the thermoelectric power plant efficiency (η), inversely proportional to Π_p, the pollutant indicator value, and also is located between 0 and 1, similar to the thermoelectric efficiency. The situation is considered unsatisfactory from the ecological point of view when $\varepsilon = 0$; however, $\varepsilon = 1$ indicates an ideal situation from the point of view of energetic efficiency. According to the fuel classification, pure hydrogen would have 0% of impact in the environment, while sulphur would cause 100% of impact;

4. Results and discussion

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

The power supplied by biomass is equal to 59.45 kW, gasifier cold efficiency is equal to 69%, power supplied by syngas is equal to 38.99 kW, thermal energy of syngas is equal to 5.39 kW, air mass flow in ICE is equal to 314.75 Nm^3/h, exhaust gas specific heat is equal to 1.41 kJ/kg K, biomass enthalpy formation is equal to 5593.09 kJ/kg, biomass enthalpy is equal to 2461.84 kJ/kg, syngas specific heat is equal to 1.33 kJ/kg, exhaust gas mass flow is equal to 340.98 Nm^3/h, exhaust gas enthalpy is equal to 4533.71 kJ/kg. It can be noted that the value of gasifier cold efficiency is found in range of values reported in literature from 60% to 70% [10]. The ICE thermal efficiency is 13.50% and the electricity generation efficiency is 12.82%. Table 6 shows the technical analysis associated to the heat exchanger. It can be observed that the system efficiency, the hot water efficiency and the thermal energy of water decrease for different heat exchanger efficiencies (80–65%).

Fig. 2 shows the syngas production and biomass feeding in the gasifier, associated to ICE for different values of thermal efficiencies. It can be noted that for ICE thermal efficiency range of 13–14%, optimal values for biomass feeding and syngas production were obtained. The biomass feeding value in gasifier was approximately 10.5 kg/h producing 26 m^3/h of synthesis gas.

In an economical point of view, it can be noted that the total gasifier maintenance and operation cost ranged from 0.0012 $/kWh to 0.005 $/kWh during the operation time of the gasifier. This value is found in range value reported in the literature 0.00125–0.005 $/kWh [20] as shown in Table 7.

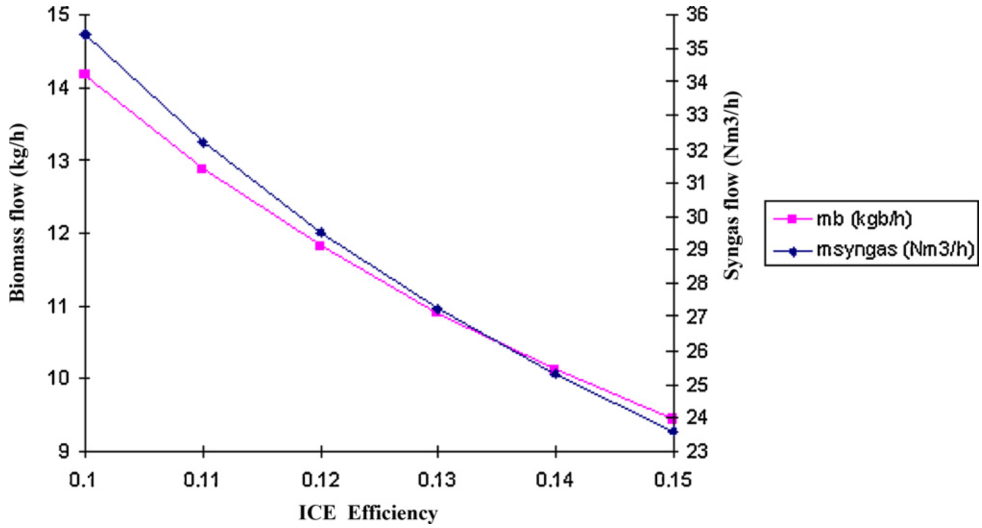

Fig. 2. Syngas production and biomass feeding in gasifier associated to internal combustion engine.

Table 7
Gasifier maintenance and operations costs.

Costs	2000 h/year	3000 h/year	4000 h/year	5000 h/year	6000 h/year
Maintenance	0.01377–0.00909	0.01074–0.00606	0.00923–0.00455	0.00832–0.00364	0.00771–0.00303
Operation	0.00057	0.000253	0.000142	0.000091	0.000063
Total	0.012	0.009	0.007	0.006	0.005

Table 8 relates all costs calculated in Gasifier/ICE system adopting the following conditions: eucalyptus price equals to 0.0038, interest rate equals to 12% yearly and the payback period was ranging from 1 to 8 years. In case of syngas cost, it can be noted that for each gasifier operation time, gradually decreases when the payback period increases. For the case of electricity cost, it can be seen that for each gasifier operation time, gradually decreases as payback period increases. From payback period equaling to 5 years, the electricity cost calculated for each gasifier operation time achieves lower values compared to the electricity tariff. In case of hot water cost considering thermal energy of water equaling to 3.68 kW, it can be noted that for each gasifier operation time evaluated, a hot water production cost for domestic use did not achieve lower values compared to hot water tariff, therefore the Gasifier/ICE system did not produce hot water with competitive prices.

Table 8
Electricity cost, hot water cost and syngas cost for different operation time in Gasifier/ICE system.

Payback	2000 h/year	3000 h/year	4000 h/year	5000 h/year	6000 h/year
Electricity cost (US$/kWh)					
1	0.368	0.251	0.193	0.158	0.135
2	0.203	0.140	0.109	0.090	0.078
3	0.150	0.105	0.082	0.069	0.060
4	0.123	0.087	0.069	0.058	0.051
5	0.107	0.076	0.061	0.052	0.046
6	0.097	0.069	0.056	0.047	0.042
7	0.089	0.064	0.052	0.045	0.040
Hot water cost (US$/kWh)					
1	0.264	0.178	0.135	0.110	0.093
2	0.143	0.097	0.074	0.061	0.051
3	0.104	0.071	0.055	0.045	0.038
4	0.084	0.058	0.045	0.037	0.032
5	0.072	0.050	0.039	0.032	0.028
6	0.064	0.045	0.035	0.029	0.025
7	0.059	0.041	0.032	0.027	0.023
Syngas cost (US$/kWh)					
1	0.286	0.194	0.148	0.121	0.102
2	0.156	0.106	0.081	0.066	0.056
3	0.115	0.078	0.060	0.049	0.042
4	0.094	0.064	0.050	0.041	0.035
5	0.082	0.056	0.044	0.036	0.031
6	0.073	0.051	0.040	0.033	0.028
7	0.068	0.047	0.037	0.031	0.026

Fig. 3 shows the annual expected saving variation with an increasing payback period for the analysis conditions established as: electricity gain, hot water gain, an interest rate of 12% per year, hot water production factor and payback period of 1–8 years. It can be seen that for payback period equaling to 2 years, a Gasifier/ICE system operating with 6000 h/year or 17 h/d is economically feasible. Under these conditions, it is not possible to operate a Gasifier/ICE system in isolated communities, thus, for isolated communities, an operation time equaling 8 h/d or 3000 h/year is considered fine. Under these conditions, for payback period equaling to 5 years, a Gasifier/ICE system is economically feasible, these results are according to values reported in literature, 4 years [21].

The combustion of any gaseous fuel in an internal combustion engine needs an air excess of approximately 40% [1]. The chemical composition in mole fraction of exhaust gas in the ICE is listed below:

$CO = 0.00418$, $CO_2 = 0.20251$, $H = 3.55E{-}05$, $H_2 = 8.38E{-}04$, $H_2O = 0.17872$, $N_2 = 0.61034$, $NO_x = 0.00063$, $O = 2.17E{-}05$, $O_2 = 2.01E{-}03$, $OH = 7.15E{-}04$. These values were determined using the GASEQ (chemical equilibrium for perfect gases) software ver. 0.54 developed by Morley [22]. Note that the combustion of 1 kg of syngas produces 29.43 g of exhaust gases. In the literature, it is difficult to find models that explain the numerical simulation of the synthesis gas combustion in an ICE, due to the fact that the synthesis gas is an unusual fuel, it has limited commercial value and possibly having various molecular compositions, since different types of biomass could be used to produce the syngas [23].

The results of the syngas combustion with air in an ICE using GASEQ software were validated by comparing the calculated results

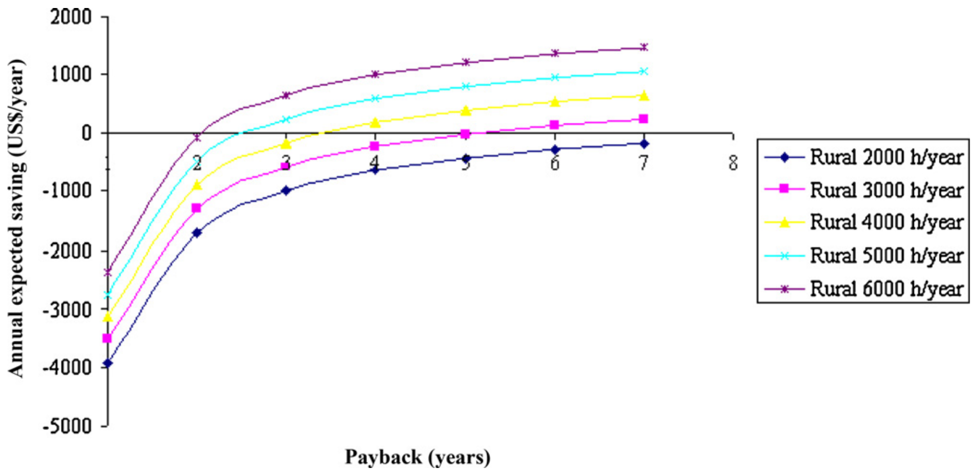

Fig. 3. Gasifier/ICE system annual expected saving for analyzes payback period.

Table 9
Comparison of results for each program used at the end of the combustion process.

Chemical species	TCW Mole fraction	GASEQ Mole fraction	Relative error %
H (g)	0.0000335	0.0000355	5.97014925
OH (g)	0.000720	0.000715	0.6944444
H_2 (g)	0.000837	0.000838	0.11947431
H_2O (g)	0.17868	0.17872	0.02238639
CO (g)	0.00416	0.00418	0.48076923
CO_2 (g)	0.20254	0.20251	0.0148119
NO_x (g)	0.000637	0.000630	1.0989011
N_2 (g)	0.61030	0.61034	0.00655415
O (g)	0.0000213	0.0000217	1.87793427
O_2 (g)	0.00199	0.00201	1.00502513
Total	1.000	1.000	

using Information and Thermochemical Equilibrium Calculations (TCW) software. In TCW, it can be simulated the reaction of gaseous fuels and synthesis gas using air as the oxidizing agent. The same conditions adopted for the modelling using GASEQ (see Table 5) were also used for analysis using TCW. Table 9 shows the comparison of results for each program used. It can be noted that the results obtained using GASEQ software are close to the results obtained with the TCW software, the relative error is small and is ranging from 0.0065% to 5.97%, good enough to apply these results in the field of engineering.

Table 10 presents the results of ecological efficiency for each value of emissions of particulate matter. Note that the increase in the pollution indicator affects the reduction of environmental efficiency, this means that lower values of particle emissions in the ICE determines the ecological feasibility of the syngas as a type of fuel.

Finally, we performed a comparison between the ecological efficiency achieved by burning the syngas in the ICE and ecological efficiencies obtained by burning fossil fuels (diesel, natural gas, gasoline, biodiesel B20, B100 biodiesel) in the ICE [1]. The result is shown in Fig. 4. Burning syngas has a better environmental sustainability than burning fuels such as diesel and B20 biodiesel. This is due to the burning of diesel and biodiesel B20 in the ICE that increases the emission of carbon dioxide and particulate matter in comparison burning the syngas in ICE.

Table 10
Results referred to the calculations of ecological efficiency, emission factors and pollution indicators.

	MP (kg/kg_{syngas})			
	0.000010	0.000019	0.000029	0.000039
MP (kg/kg_{syngas})	0.00065	0.00130	0.00195	0.00261
NO_{xe} (kg/kg_{syngas})	0.04089			
CO_{2e} (kg/kg_{syngas})	0.42831	0.42896	0.42961	0.43027
Πp (kg_{CO2}/MJ)	0.08004	0.08017	0.08029	0.08041
η_{system}	0.15035	0.14648	0.14262	0.13876
ε (%)	80.80445	80.78310	80.76177	80.74045

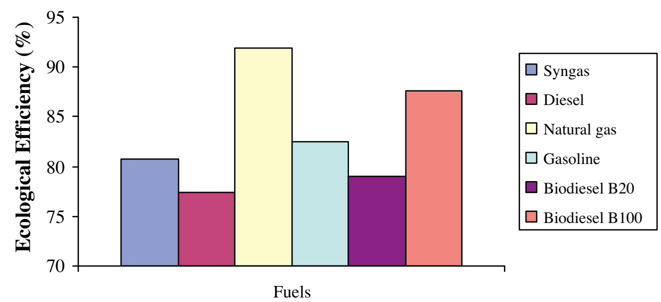

Fig. 4. Ecological efficiency variation in function of syngas, diesel, natural gas, gasoline with 20% anhydrous alcohol, biodiesel B20 and biodiesel B100.

5. Conclusions

This paper shows that it is possible to evaluate the ecological impact considering technical and economic aspects by syngas burning in an internal combustion engine using the ecological efficiency parameters, therefore, the following can be concluded.

The system was assessed by modelling the first law of thermodynamics and economics tools. Three forms of analysis were studied, technical analysis, economical analysis and ecological analysis. In the point of view of thermodynamic analysis, the system efficiency of the Gasifier/ICE achieved values from 13.88% to 15.03%, electrical generation efficiency was around 12.82% and cold gasifier efficiency was approximately 69%. These results turn Gasifier/ICE into an attractive technology and technically feasible, allowing a lower emission of pollutants compared to other combustion technologies. In the ecological analysis, we performed a comparison between the ecological efficiency achieved by burning the syngas in the ICE and ecological efficiencies obtained from burning fossil fuels in the ICE. The burning syngas has a better environmental sustainability than burning fuels such as diesel and B20 biodiesel. The economical analysis evaluated the syngas, electricity and hot water production cost and annual expected saving in the Gasifier/ICE system, the study shows the feasibility of system for payback period of 4 years adopting 12% of annual interest rate.

This study shows that the use of syngas as alternative fuel, from an ecological point of view, is better than the use of diesel fuel, presenting higher values of ecological efficiency.

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References

[1] Coronado CR, Carvalho JR, Yoshioka JT, Silveira JL. Determination of ecological efficiency in internal combustion engines: the use of biodiesel. Appl Therm Eng 2009;29:1887–92.
[2] Lora EES, Nogueira LAH, Dendroenergia:. Fundamentos e Aplicações. 2nd ed. Rio de Janeiro; 2003.
[3] Cardu M, Baica M. Regarding a global methodology to estimative the energy ecologic efficiency of thermo power plants. Energ Convers Manage 1999;40:71–87.
[4] Salomon KR. Quantitative evaluation of the gaseous emission environmental impact and of the cooling water use in thermoelectricity generation installations. Thesis (Master's Degree) EFEI, Itajubá, Brazil; 2003 [in Portuguese].
[5] Zainal ZA, Rifau A, Quadir GA, Seetharamu KN. Experimental investigation of a downdraft biomass gasifier. Biomass Bioenerg 2002;23:283–9.
[6] Boloy RAM. Computational simulation of a gasifier associated with an internal combustion engine. Thesis (Master's Degree) FEG-UNESP-Guaratinguetá, Brazil; 2010 [in Portuguese].
[7] Yong ML.International Conference on Bioenergy Utilization and Environment Protection – 6th LAMNET Project Workshop. 2003.
[8] Baratieri M, Baggio P, Bosio B, Grigiante M, Longo GA. The use of biomass syngas in IC engines and CCGT plants: a comparative analysis. Appl Therm Eng 2009;29:3309–18.
[9] Kaltschmitt M, Hartmann P. Energie aus biomass: grundlagen. Techniken und Verfahr: Springer-Verlag; 2001.
[10] Rajvanshi AK. Alternative energy in agriculture. India: E-Publishing Inc.; 1999. p. 83–102.
[11] Boloy RAM, Silveira JL, Tuna CE. Technical and economical analysis of biomass integrated gasifier/combined cycle power. In: ENCIT 2008, 12th Brazilian Congress of Thermal Sciences and Engineering, ABCM – UFMG, Proceedings of Encit 2008. Belo Horizonte – MG: E-Publishing Inc.; 2008. p. 121–31.
[12] Kong XQ, Wang RZ, Huang XH. Energy efficiency and economic feasibility of CCHP driven by stirling engine. Energ Convers Manage 2004;45: 1433–42.
[13] Projeto CTNERG, processo 555072/2006-1.
[14] Wu DW, Wang RZ. Combined cooling, heating and power: a review. Prog Energ Combust 2006;32:459–95.
[15] Robert HP, Don WG. Perry's chemical engineers handbook. 6th ed. New York: McGraw Hill; 1984.
[16] Silveira JL, Braga LB, Souza ACC, Antunes JS, Zanzi R. The benefits of ethanol use for hydrogen production in urban transportation. Renew Sust Energ Rev 2009;13:2525–34.
[17] Silveira JL, Carvalho Jr JA, Villela IAC. Combined cycle versus one thousand diesel power plants: pollutant emissions, ecological efficiency and economic analysis. Renew Sust Energ Rev 2007;11:524–35.
[18] Silveira JL, Leal EM, Ragonha Jr LF. Analysis of a molten carbonate fuel cell: cogeneration to produce electricity and cold water. Energy 2001;26:891–904.
[19] Silveira JL. Estudo de sistema de geração aplicado a fabricação de papel e celulose. M.Sc. Dissertation, Escola Federal de Engenharia de Itajubá – EFEI; 1990.
[20] Reed T, Dass A. Handbook of biomass downdraft gasifier engine systems. 3rd ed. U.S. Department of Energy Solar Technical Information Program: Solar Energy Research Institute (SERI); 1989.
[21] Coronado CR. Analise Técnica-Econômica de um Gaseificador de Biomassa de 100 kg/h para acionamento de um motor de combustão interna. M.Sc. Dissertation, Universidade Estadual Paulista de Guaratinguetá-FEG-UNESP, Guaratinguetá; 2006.
[22] Morley C. GASEQ. Chemical equilibria in perfect gases, 0.79; 2005, http://www.gaseq.co.uk.
[23] Gamiño B, Aguillón J. Numerical simulation of syngas combustion with a multi-spark ignition system in a diesel engine adapted to work at the Otto cycle. Fuel 2010;89:581–91.