



Biomass gasification for combined heat and power generation in the Cuban context: Energetic and economic analysis



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HIGHLIGHTS

- The performance of spark-ignition engine using producer gas was studied theoretically.
- The specific consumption of biomass per unit of energy produced was 1.46 kg/kWh.
- The electricity cost per kWh obtained was 0.022 USD/kWh with a payback of 5.3 year.

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ABSTRACT

In the present work is performed a technical and economic analysis of a combined heat and power generation system (CHP), designed to operate coupled to an internal combustion engine (ICE) fueled with biomass producer gas, in order to generate electricity and hot water for isolated communities of power distribution network. In the proposed system configuration, the energy of the engine's hot exhaust gases is recovered (cogeneration), making this system more attractive in relation to conventional configurations, which are normally used to produce solely mechanical and electrical energy. The proposed system is composed of a modified downdraft gasifier, Imbert technology; coupled to an internal combustion engine, model ZIL–130. The system is designed and built in the laboratory of fluid mechanics at the University of Camagüey. The feedstock studied for the gasifier was *Dichrostachys Cinerea*, collected in neighboring areas to the proposed place of installation. The main energy flows and the costs associated with the production of producer gas were determinate. From the mass and energy balances, the thermal and electric efficiencies of the cogeneration systems resulted in $\eta_{hw} = 32.4\%$ and $\eta_{ge} = 23.4\%$ respectively, whereas the overall efficiency led to $\eta_{global} = 33.3\%$. In the economic analysis were studied the Internal Rate of Return (IRR), the Net Present Value (NPV) and time of return on investment (TRI) or payback, considering a project lifespan of 15 years. For the annual interest rate of 12%, the electricity should be sold at 0.3 USD/kWh in order to the project be feasible. The IRR resulted in 12%, the NPV was 20,571 USD and payback period resulted in 5.3 years. In the proposed configuration, the system consumes 1.46 kg of biomass per kW_e produced, with a maximum cost of generated electricity of 0.022 USD/kWh.

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1. Introduction

The adequate provision of energy services has become especially important for economic development since the industrial revolution [1]. In recent decades, energy issues have been

fundamental components of the conceptual and strategic discussions on sustainable development worldwide.

Cuba experienced a major economic crisis during the 1990s as a result of the termination of its favorable trade relationships with the countries of the Council for Mutual Economic Assistance (CMEA). Consequently, Cuba was forced to severely reduce its energy imports, which affected capability to satisfy the country's energy requirements. The quest for energy solutions became the primary activity of national and territorial (State) institutions, specialists, technicians and workers [2].

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Nomenclature			
\dot{m}	mass flow rate [kg/s or m ³ /h]	i	each parameter of engine
T	temperature [K]	N	nominal parameter of engine
N	power [kW]	Out	outlet
C_1, C_2, C_3	coefficients of the engine	in	inlet
G_e	specific fuel consumption [g/kWh]	hw	hot water
Tr	torque [kgf.m]	$hw_{HE\ 1,2,4}$	hot water in heat exchangers
C_p	average specific heat [kJ/kgK]	air_{HE3}	hot air in heat exchanger 3
E	energy [kWh]	th	thermal
I	investment [USD\$]	eng/ger	engine generator
C_M	maintenance cost [USD\$/kWh]	cw	cool water
C	cost [USD\$/kWh]	exh	flue gas
F_p	adjustment factor	elec	electricity
r	annual interest rate	e	electric
q	factor	net	net
n	r.p.m	gas	producer gas
HHV	High heating value	csys	cogeneration systems
LHV	low heating value [kJ/kg or MJ/m ³]		
Subscript		Superscripts	
Bio	biomass	t	amortization periods
		Greek symbols	
		η	efficiency

A major priority for Cuba's government is the economic growth and satisfy the population's growing energy demand, by using domestic resources, while continuing to addressing environmental priorities.

Cuba's total installed capacity for electricity generation was 5913.9 MW in 2011 [3]. From the total installed capacity, 89.59% corresponds to fossil fuel technologies and 10.5% to renewable energy sources (cogeneration from bagasse in sugarcane power plants, hydroelectric and wind power plants) [3].

Concerning to renewable energy generation in 2012, the greatest contribution comes from the sugarcane industry, with an installed capacity of 543.9 MW, in the forty-nine sugarcane plants that operated that year. The hydroelectric installed capacity reaches 58 MW, of which 43 MW correspond to one hydroelectric power plant and the other 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. Additionally, 15 small wind turbines and 6068 photovoltaic panels are distributed throughout the country [4].

Regarding thermal power plants that use fossil fuels, 2488 MW correspond to thermal power plants fueled with domestic crude and fuel oil and 455 MW correspond to gas turbines and combined cycles burning gas oil. Also 2349.9 MW of diesel based power plants are used to provide energy mainly for distributed energy generation, and the nickel industry, with an installed capacity of 45 MW, that cogenerates electricity and steam for the process [4].

The total electricity generated in 2011 was 17,754.1 GWh. From which 5.2% was provided by renewable generation (809.6 GWh correspond to sugar mills, 99.2 GWh to hydroelectric power plants and 18.5 GWh to wind and photovoltaic power plants) and 94.7% derived from fossil fuel generation [3].

From the exposed figures, it can be observed that Cuba is betting for a decentralized and diversified energy matrix, showing a strong interest to introduce renewable energy sources in the national energy balance.

Biomass gasification represents one potential option for distributed electricity and heat generation, due to its intrinsic properties. Small-scale and micro-scale biomass CHP systems can

reduce biomass transportation costs and provide heat and power where needed, in contrast to larger CHP power plants where is more difficult to find an end-user for the amount of heat produced by them [5,6]. Further, cogeneration plants has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation [7]. In developing countries, such as Cuba, small-scale and micro-scale biomass-fueled CHP systems have a particular strong relevance in life quality improvement, especially in remote villages and rural communities, located in mountainous areas isolated from the national electric grid, and where the temperatures drop in the evening and the hot water generated in CHP systems can also be used for bath and cooking food, decreasing energy consumption. Hence it, there is a significant interest in small-scale biomass-fueled combined heat and power technologies (<100 kWe) [8,9].

Thus, the main purpose of this work is a technical and economic assessment of the feasibility of this alternative in isolated areas from the national electric grid where electricity services is not available. The analysis was performed in a biomass-based heat and power generation system located in Cuba, composed by a wood gasifier with a processing capacity of 50–60 kg/h of biomass coupled to an internal combustion engine.

2. Small scale CHP plants coupled with ICE

An interesting technological alternative for relatively small scale distributed generation plants is based on biomass gasification coupled with gaseous-fuel-fired electricity generation equipment. Typically this kind of plants consist of gasifier, gas cleaning devices, reciprocating ICE, heat exchangers and other auxiliary equipment.

The first attempt to use producer gas to operate an ICE was carried out in 1881 [10]. Other studies were conducted during 1896 with producer gas as fuel and using different types of engines [11]. Wang et al. [12], Bhattacharya et al. [13], Henriksen et al. [14], Ramadhas et al. [15,16] and Kalina [17] described the operation of engines using producer gas derived from biomass. These publications present experimental data related to the engine's brake power, torque, efficiency, power de-rating, emissions, exhaust

temperature, pressure drop, output gas composition and calorific value taking into account the influence of the air-fuel ratio, the compression ratios and the mass flow rate.

Shah et al. [18] focused on the engine's performance and emissions through the study of a 5.5 kW_e spark-ignited engine operated by the producer gas of a downdraft atmospheric pressure gasifier fed with hardwood chips. The authors [18] found that the engine efficiency was 19.1% when the electrical power output was 1.39 kW. The results show that even though the power output when using the producer gas was lower than that when gasoline was used, the overall efficiency of the system at the maximum electrical power output with producer gas, was the same as that with gasoline.

Shuying et al. [19] report a technical and economic study of a modern biomass-fueled CHP system, located in Jilin, China. The preliminary cost estimated for the CHP system indicated 8.7 year of return on investment. Prado et al. [20] performed an evaluating study of the energy performance of a biomass small CHP system of 31 kW_e for residential applications. The overall energy performance was evaluated for various contexts, different thicknesses for the insulating polystyrene layer and operation time of the generation system and different building configurations.

A theoretical study of the biomass-fueled small scale CHP plant with downdraft gasifier gas engine and bottoming Organic Rankine Cycle module was presented by Kalina [17]. Different setups of the plant were examined. The total electricity generation efficiency reported varies from 23.6% to 28.3% depending on the setup configuration. The cost of electricity was about 172 USD/MWh, with a payback time from 7.9 to 8.2 years and an internal rate of return of 13.5%.

Zabaniotou et al. [21] presented a study of a prototype for CHP production based on the technology of biomass gasification coupled to an internal combustion engine. This unit delivers a maximum power output of approximately 12 kW_{th} and 5 kW_e, working with different types of residues generated in Greek rural areas. The thermal efficiency and electric efficiency reported by the authors [21] were 42% and 20% respectively.

Another study specifically developed in the Cuban context was conducted by Jimenez et al. [22], the authors report a conceptual study to meet the demand for electricity and heat in rural settlements of up to 60 houses using gasification technology coupled with a diesel MCI for power generation, part of the gas produced in the gasification process is used for the preparation of food in kitchens adapted for burn this fuel. In this study it is demonstrated the feasibility of this technology from a global perspective without proposing specific configurations for the system.

The main contribution of this work is the design, construction, and theoretical evaluation of a small CHP system, using resources available in the Cuban context, to supply electricity and heat to isolated communities from the national electric grid.

3. Proposed plant

In Fig. 1, a scheme of the proposed plant is shown. The main components of the proposed small scale CHP system are the modified downdraft gasifier and a ZIL-130 four-stroke Otto-cycle spark-ignition engine. The ICE was adapted to run on producer gas. An electric generator is coupled to the ICE via coupling rod-type caps designed and calculated to the system's actual working conditions. The three-phase electric generator characteristics 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.

Four shell and tube heat exchangers are designed and constructed following the methodology reported by Ref. [23,24], for heat recovery; their characteristics are depicted in Table 1.

3.1. Downdraft gasifier

The gasifier used in this research is an Imbert-type downdraft modified reactor, feeding with approximately 60 kg/h of biomass, which was designed and built in the Laboratory of Fluid Mechanics at the University of Camagüey following the methodology reported in Refs. [25], (Fig. 2). The main advantage of this type of reactor is the lower tar concentration present in the producer gas, which is of primary importance for the durability of the ICE that will be fed with this gas. The lower tar concentration results from the fact the gas is conducted through a high temperature zone (the combustion zone), which enables the cracking of the tars formed during the gasification process. Other advantages of the Imbert-type downdraft gasifier are the high char conversion and the lower ash transfer since gases pass through the charcoal bed allowing its filtration and catalysis and a quick response to any load change [26].

To use the producer gas obtained in the process of biomass gasification for electricity generation in both diesel and spark ignition engines it is necessary to ensure that the quality of the gas is sufficiently high in terms of tar and particulates content to maintain the reliable engine's operation and to provide an adequate durability of major engine components, such as the valves, the combustion chamber, the pistons, etc [26].

According to Hasler and Nussbaumer [27] the allowed particle and tar concentration in the producer gas for satisfactory operation of the ICE must be less than 50 mg/Nm³ and 100 mg/Nm³, respectively.

In the gasifier design proposed in the present work, three major changes reported by Refs. [28–30] were adopted with the aim of reduce tar concentration in the producer gas, based in avoid the formation of cool zones, through the modification of the fluid dynamic behavior of the mixture formed by the pyrolysis gases and the gasification agent in the combustion chamber of the gasifier.

Considering these modifications and design standards mentioned above where determined the main dimensions of the gasifier proposed as shown in Table 2 and Fig. 2.

These modifications allowed obtaining up to 10 mg/Nm³ of tar, figure 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 *Dichrostachys Cinerea*, (Marabou), in the University of Sassari, Italy. The gas composition obtained from the gasification of *Dichrostachys cinerea*, (Marabou) which is the type of biomass analyzed in the present work, is reported by Ref. [28] and was determined using a chromatograph type GC/MSD Hewlett Packard 5973 and for sampling of tar was used standardized methodology reported in regulations TC BT/TF 143 WI CSC 03002.4 [31,32]. The results are presented in Table 3.

These experimental results will be used in the modeling of the proposed CHP installation behavior.

The lower heating value for the biomass producer gas was calculated as follows [33]:

$$LHV_{gas} = 0.126C_{CO} + 0.358C_{CH_4} + 0.107C_{H_2} \quad (1)$$

The thermodynamic efficiency of the gasifier was calculated using Equation (2).

$$\eta_{gasifier} = \frac{\dot{m}_{gas} \cdot LHV_{gas}}{\dot{m}_{bio} \cdot LHV_{bio}} \cdot 100 \quad (2)$$

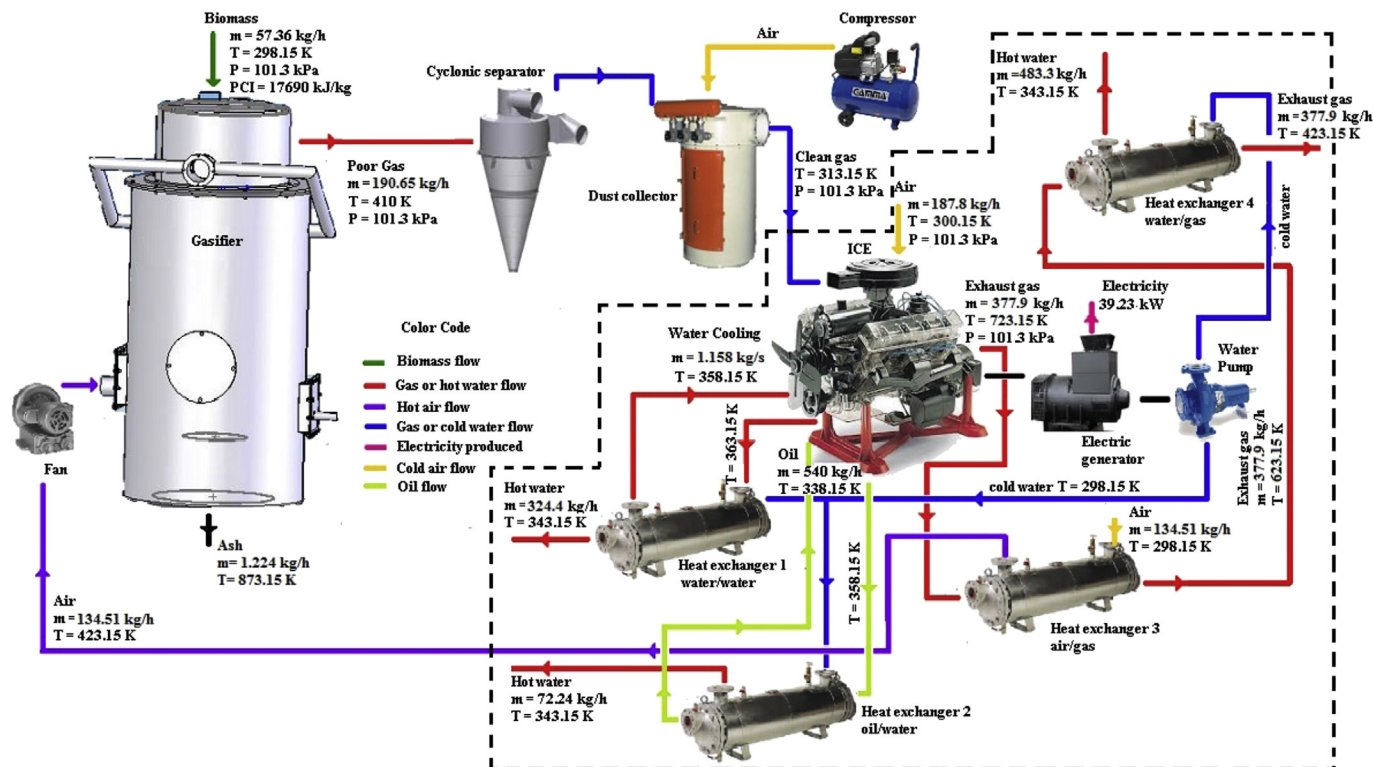


Fig. 1. Layout of the proposed biomass-fueled CHP system.

Table 1
Characteristics of the Heat Exchangers employed in the proposed system.

	Unit	Heats exchangers			
		Water/water (HE1)	Oil/water (HE2)	Air/gas (HE3)	Water/gas (HE4)
Numbers of tubes	—	50	40	15	22
Diameter of the tubes	mm	17.15	17.15	26.67	17.15
Thickness of the tubes	mm	2.31	2.31	2.87	2.31
Pitch of the tubes	mm	12.5	12.5	20	15
Number of deflectors	U	5	5	4	3
Trim of the deflectors	%	32	32	30	27
Total area of heat exchange	m ²	2.68	2.17	1.182	1.077
LMTD(logarithmic mean temperature difference)	K	36.41	21.64	362.35	218.16
Fouling factor	m ² ·K/W	0.0001	0.0003	0.0001	0.0001
Effectiveness	%	85	85	70	77
Material of shell		steel 20			
Material of tubes		copper	copper	stainless steel	copper
Material of deflectors		carbon steel			

3.2. Feedstock

The biomass selected for gasification, the *Dichrostachys Cinerea* (Marabou), has spread all throughout the country like a plague, according to the last census it covers more than 1.25 million hectares, an equivalent of 20% of the arable land in Cuba or 12% of the country's territory [34]. In the territory of Camagüey, area selected for the implementation of the proposed system, the area covered by this plant reaches 32% with different degrees of contamination [3]. The gasification system is fed with Marabou with a moisture content of approximately 9.2% wt.b.

The main fuel properties of *Dichrostachys Cinerea* such as composition, proximate analysis, ultimate analysis, ashes composition and lower heating value was reported by Pedrosa and Kaltschmitt [35], and shown that compared to other woody and

herbaceous biomass, Marabou shows similar fuel properties. In average, the fuel properties are closer to woody biomass than to herbaceous biomass.

3.3. Internal combustion engine

The ZIL-130 engine used in the system is a four-stroke Otto-cycle spark-ignition engine, fabricated in Russia. Table 4 presents its main specifications 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 producer gas applications, the engine's speed is fixed to 1800 rpm by a governor.

In order to use the ICE in the proposed system, only two adaptations were necessary. Firstly, the gasoline carburetor was

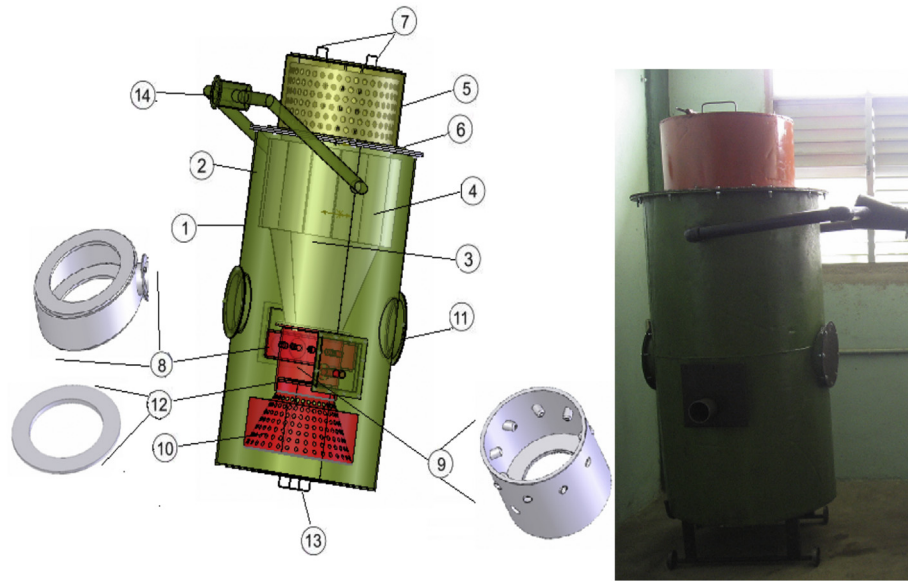


Fig. 2. Modified downdraft gasifier.

Table 2
Main gasifier dimensions.

Gasificador imbert									
dh mm	d _t mm	h _{nt} mm	h _r mm	d _{nt} mm	n	d _n mm	L _n mm	d _b mm	h _b mm
340	145	100	130	240	9	12	50	630	840

Where: d_b – diameter of the combustion chamber of the gasifier, h_b – height from top to the throat, d_t – diameter of the throat, d_n – diameter of the injector nozzle, d_{nt} – diameter of the upper nozzle ring, L_n – Length of the nozzle, h_{nt} – Height of the plane of the nozzles on the narrowest cross section of the throat, h_r – distance from the throat to the grid, n – number of nozzles.

Table 3
Experimental results from *Dichrostachys cinerea* (Marabou) gasification [28].

Gas analysis	Unit	Composition
CO	(% vol)	16.5
H ₂	(% vol)	12.5
CO ₂	(% vol)	12.0
CH ₄	(% vol)	0.4
O ₂	(% vol)	0.9
N ₂	(% vol)	57.7
HHV	(MJ/Nm ³)	3.86
Tar	(mg/Nm ³)	8.73
Water	(g/Nm ³)	102
Char and ashes	(kg/Nm ³)	0.125
Density	(kg/Nm ³)	1.119

replaced with a gas carburetor (fuel intake manifold) for supplying the required fuel mixture. Secondly, it was installed a governor to control the throttle valve for regulating the fuel flow according to the operating load, and hence maintaining the desired engine speed. Fig. 3 shows a picture of the actual engine.

Table 4
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 ignition timing in engines working with producer gas are 10°–15° advanced, while the ignition timing for conventional spark ignition engines fueled with gasoline vary between 10° and 40° before top dead center [36]. This is mainly due to a low heating value of the producer gas, which decreases the speed of the mixture combustion. According to Sridhar et al. [37] the ignition timing has to be retarded with an increase in the compression ratio in order to achieve the maximum brake torque point.

The maximum flame temperature attainable with producer gas is lower compared to conventional fuels such as natural gas and



Fig. 3. ZIL-130 internal combustion engine.

therefore a better knock resistance could be expected when an engine runs on gasification gas [37]. This fact permits to run the ICE with producer gas with a higher compression ratio. In this study the compression ratio is increased to 10:1 without increasing the knocking tendency [38].

The operation of the ICE fueled with gasoline was simulated using the following equations [39]:

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

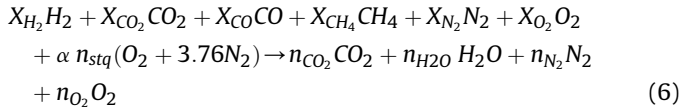
$$ge_i = ge_N \left[1.2 - \frac{n_i}{n_N} + 0.8 \left(\frac{n_i}{n_N} \right)^2 \right] \quad (4)$$

$$Tr_i = 716.2 \frac{N_i}{n_i} \text{ [Ni is express in metric system (cv)]} \quad (5)$$

In the case of the ICE working with producer gas, the methodology reported [25] was adopted, to simulate engine operation which is developed in the following section.

4. Calculating the exhaust gases' specific heat

In order to calculate the specific heat value (C_p) of the exhaust gases, we use the *Dichrostachys cinerea* producer gas composition reported in Table 3, and the complete combustion equation with air excess, as follows:



The composition of the exhaust gases is obtained through mass balance, considering complete combustion with excess oxygen. The oxygen present in the products is the difference between the supplied oxygen and the stoichiometric oxygen, being the products molar composition 28.9% CO_2 , 13.3% H_2O , 4% O_2 and 53.8% N_2 . With a total mass of 51.88 g for the combustion of 1 mol of producer gas and molar mass of 31.45 g/mol.

Then, the specific heat of the exhaust gases can be calculated through an empirical equation as function of the outlet temperature [40]:

$$C_p = 0.976712 + \frac{1.02047 T}{10^4} + \frac{2.4370 T^2}{10^7} - \frac{1.1466 T^3}{10^{10}} \quad (7)$$

5. Energetic analysis

In this section, the efficiencies related to electricity and heat generation, as well as the overall efficiency for the proposed cogeneration plant are calculated.

The Equations (8)–(14) are used for determining the parameters involved in the energy balance. Using Equations (8) and (9) the efficiencies for electricity and heat generation in the cogeneration systems can be calculated, respectively. Thus, the overall cogeneration system efficiency would be the sum of these two efficiencies.

$$\eta_{elec} = \frac{E_p}{E_{fuel}} \quad (8)$$

$$\eta_{th} = \frac{E_{hwHE1} + E_{hwHE2} + E_{airHE3} + E_{hwHE4}}{E_{fuel}} \quad (9)$$

The efficiency for the overall integrated system, considering the gasifier efficiency, can be determine by the Equation (10):

$$\eta_{global} = \eta_{gasifier} \cdot \eta_{csys} \quad (10)$$

The power supplied by the fuel is determined using Equation (11), and knowing the effectiveness of the heat exchangers, can be determined the energy of the different streams flowing through the four heat exchangers taking account the fluid type and inlet and outlet temperatures.

$$E_{fuel} = \dot{m}_{gas} \cdot LHV_{gas} \quad (11)$$

$$E_{hwi} = \dot{m}_{hwi} \cdot C_{pi} \cdot (T_{out_i} - T_{in_i}) \quad (12)$$

The energy dissipated or lost in the internal combustion engine is estimated by using Equation (13), which for the present case resulted in 13.36 kW (8%). For the cogeneration system, the energy losses equal 63.56 kW (37.86%) according to Equation (14).

$$E_{lossICE} = E_{fuel} - N_{net} - E_{exh} - E_{cw} - E_{oil} \quad (13)$$

$$E_{losssys} = E_{fuel} - N_e - E_{hwHE1} - E_{hwHE2} - E_{airHE3} - E_{hwHE4} \quad (14)$$

Finally, the efficiencies for electricity and thermal generation and the overall cogeneration system's efficiency are presented in Table 5.

6. Economic analysis

In this section, it is presented a methodology for determining the cost electricity and hot water produced (USD/kWh) using the producer gas derived from the gasification of *Dichrostachys Cinerea* in the proposed configuration, as well as the investment, operation and maintenance costs of the equipment in order to determine the project economic feasibility.

The costs of the equipment that compose the facility were estimated according to Boehm's methodology [40], adapted by Ref. [41] by the following equipment:

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

Equation (15), implies that knowing the investment cost (C_r) for a particular plant with a capacity (S_r), the investment cost (C) for a plant with similar characteristics but with capacity (S) can be calculated, if the incidence factor (m) indicating the economy scale (0.5–1) is available. This relationship is valid for equipment and machines, being necessary to know the price of a similar equipment. The necessary similarity refers to a machine or equipment with same purpose and built with the same materials. The present study assumes an incidence factor of 0.7, according to [42].

Table 5
Electricity, thermal and overall efficiencies for the proposed 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%

With respect to the cost of the ICE/generator set adapted to run with producer gas, it is known that for a gasifier with processing capacity of 250 kg/h of biomass, the estimated cost is € 180,700, with $m = 0.78$. This value was obtained from actual manufacturer data found in an internal report of the thermochemical processes laboratory at the University of Zaragoza, Spain [43,44]. The cost of the gasifier includes the gas cleaning and conditioning equipment, like cyclones, gas scrubbers venturi type, absorption towers, heat exchangers and gas dryers, but it is not considered filters of any kind. With the above considerations, it is possible to estimate the cost of a 57 kg/h gasifier through Equation (15).

$$I_{\text{gasif}} = 180,700 \left(\frac{P}{250} \right)^{0.78} \quad (16)$$

The installation costs for the necessary auxiliary equipment and 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 [45]. The cost of electricity generated depends on the initial investment for the installation of equipment ($I_{\text{eng/ger}}$), the fuel cost ($C_{\text{producer gas}}$), working hours of the plant (H), and the operation and maintenance costs ($C_{\text{Meng/ger}}$, C_{Mgasif}). Equations (17)–(19) are used for calculating these costs.

$$C_{\text{producer gas}} = \frac{I_{\text{gasifier}} \cdot f}{H \cdot E_{\text{fuel}}} + \frac{C_{\text{bio}} \cdot E_{\text{bio}}}{E_{\text{fuel}}} + C_{\text{Mgasifier}} \quad (17)$$

$$C_{\text{elec}} = \frac{I_{\text{eng/ger}} \cdot f}{H \cdot E_{\text{fuel}}} + \frac{C_{\text{producer gas}} \cdot F_{\text{Pelec}}}{E_{\text{fuel}}} + C_{\text{Meng/ger}} \quad (18)$$

$$C_{\text{hw}_i} = \frac{I_{\text{HE}_i} \cdot f}{H \cdot E_{\text{hw}_i}} + \frac{C_{\text{producer gas}} \cdot F_{\text{PHE}_i}}{E_{\text{hw}_i}} + C_{\text{MHE}_i} \quad (19)$$

For calculating the producer gas production cost using Equation (17) it is assumed a cost of the *Dichrostachys Cinerea* ready to be introduced into the reactor equal to 200.00 USD per cubic meter [46] or 0.25 USD per kg. The cost of thermal generation is calculated through Equation (19), this cost is associated to the initial investment cost (in this case, the cost of the heat exchangers) (I_{HE_i}), the cost of the fuel ($C_{\text{producer gas}}$), the efficiency of heat generation (η_{th}), the energy flows (E_{hw_i}), the hot water production and the costs of equipment operation and maintenance (C_{MHE_i}).

For the economic calculations it is assumed that the plant operates 2400 h per year. This is because the selected engine is not designed to work with gaseous fuel, so assuming the worst case scenario, we consider a total of 8 h per day during the year, leaving a margin of approximately 60 days for repairs, maintenance and other contingencies during the operation of the facility.

The figures used in the economic analysis of the proposed plant are shown in Table 6.

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:

$$F_{p_i} = \frac{E_i}{E_{\text{elec}} + E_{\text{hw}_1} + E_{\text{hw}_2} + E_{\text{hw}_4} + E_{\text{air}}} \quad (20)$$

The initial cash flow analysis is performed using representative values of the variables considered, allowing the calculation of deterministic financial indicators as Net Present Value (NPV), Internal Rate of Return (IRR), and time of return on investment (TRI) (payback), see Equation (21), in this case the method of Discount

Table 6

Economic figures for the proposed system.

Parameter	Cost	Unit
Investment costs		
$I_{\text{eng/ger}}$	15,000	\$
I_{gasif}	56,014	\$
I_{HE1}	300	\$
I_{HE2}	300	\$
I_{HE3}	600	\$
I_{HE4}	600	\$
Instrumentation	5781	\$
Civil works	7515	\$
Engendering project	17,344	\$
Operation and maintenance costs [47]		
$C_{\text{Meng/ger}}$	0.010	\$/kWh
C_{Mgasif}	0.020	\$/kWh
C_{MHE1}	0.003	\$/kWh
C_{MHE2}	0.003	\$/kWh
C_{MHE3}	0.002	\$/kWh
C_{MHE4}	0.002	\$/kWh

Cash Flow [48] is used. The annuity factor (f) is determined from Equations (22) and (23).

$$NPV = \sum_t^n \frac{ELC}{(1+j)^t} \quad (21)$$

where ELC is the project's cash flow (revenues minus costs) in time t , with t taking values from year 0 to year n and j is the discount rate (an interest rate used to calculate the present value of future cash flows). When the calculated NPV is positive, the investment results in a rate of return greater than our minimum rate j , and in the absence of alternatives this would be a profitable investment. However, when the NPV is negative, the investment would not give a return at the minimum rate j , and indicates a non-profitable investment.

$$f = \frac{q^t \cdot (q - 1)}{q^t - 1} \quad (22)$$

$$q = 1 + \frac{r}{100} \quad (23)$$

As an initial estimation, it is assumed 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 [3].

7. Results and discussion

The gasification efficiency determined by Equation (2) resulted in 59.8%. This value is relatively low when compared with other values reported in the literature [49–51]. This could be explained by the reactor modifications, that can affect core process variables like productivity and the calorific value of the producer gas; also the Boundard reactions not occur with the desired extent, obtaining a value of $LHV = 3.56 \text{ MJ/Nm}^3$ of producer gas.

In Fig. 4 the theoretical operation of the ICE running on producer gas and gasoline is presented. Obtaining a maximum power output of 45.04 kW and maximum torque of 19.0 kgf·m at 2500 rpm. It can be observed that when using producer gas, the power output is reduced in approximately 37%, with a compression ratio of 10:1. From previous studies it is expected that in gaseous-fueled engines or dual-fuel engines running with producer gas, the reduction of power output is in the order of 20–30% [52]. Sridhar, G. and Yarasu,

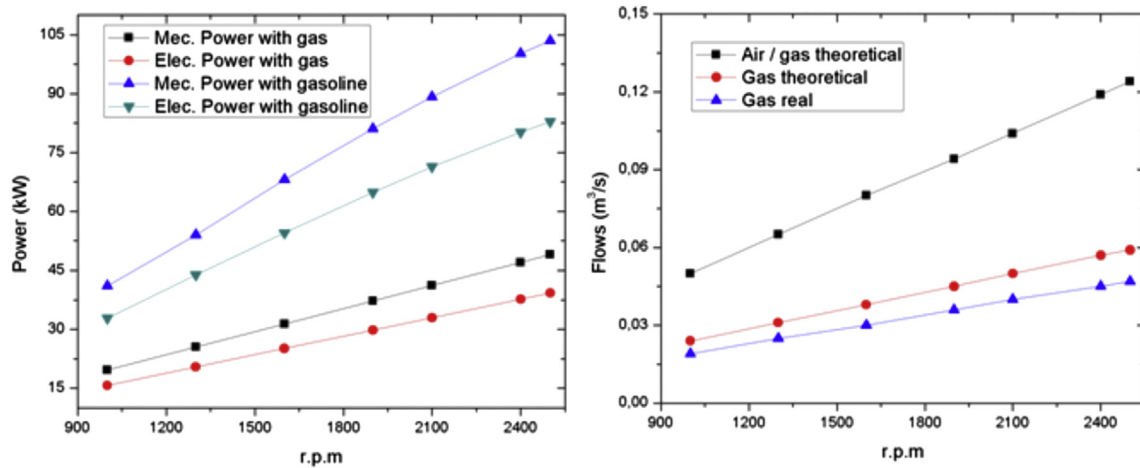


Fig. 4. Fuel consumption and theoretical power output achieved by the ZIL–130 engine.

R.B [53]. report an engine operating with producer gas 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. The differences between the values reported by other studies and ours are firstly motivated by the characteristics of the engines used. In Refs. [19,20] the used engines diesel and gas respectively, adapted to run with producer gas, that were designed to work at relatively low speed (2500 rpm) and a high compression ratio 17: 1. In our case an spark ignition Otto cycle engine, the revolutions are higher (3600 rpm) and the compression ration lower 6.5: 1 this single fact represents a loss of more power in Otto cycle engines when compared with diesel cycle adapted to work with producer gas. Other element is the calorific value of the producer gas used in the referenced case and in our study; in the investigation conducted by Ref. [20] the PCI gas is 4.8 MJ/kg and in our case the PCI is 3.9 MJ/kg. Another factor is the volumetric efficiency of the engine and the air-fuel ratio.

To have a better appreciation of the energy flows of the proposed system, it is presented in Fig. 5 the Sankey diagram. This diagram represents in a quantitative way, the distribution of all existing energetic flows in the studied ICE fueled with producer gas in steady-state conditions.

As observed in Fig. 5, a large portion of the energy supplied to the engine is carried away by the exhaust gases. When operating with producer gas, the energy loss associated with the exhausting gases resulted in 78.39 kW. The heat energy flow through the HE1, which acts as a radiator, was estimated in 41.97 kW. The energy losses not included in the exhaust gases or in the HE1 correspond to losses of heat through the walls of the engine block and through the oil circuit. The energy losses related to the engine and its component accounts for 8% of the total energy input (167.88 kW). The engine's thermal efficiency resulted in 24.60%, which is in the range of other values reported in the literature for diesel engines working with producer gas [54,55]. The total energy losses in the cogeneration proposed systems reached 37.88% of the total fuel energy input.

The proposed system produces 880 l/h of hot water, representing an annual recipe of 7728 USD. The cost of producer gas production, the cost of generated electricity and the cost of hot water derived from the three heat exchangers were calculated considering various annual interest rates (r) and amortization periods (t). The results of these calculations are shown in Fig. 6 and Fig. 7.

Fig. 6b shown the cost of the generated electricity as function of time. It can be observed that a variation of 4–9% in the annual interest rate does not greatly affect the electricity cost.

For the proposed system be profitable it is required a selling price of electricity between 0.25 and 0.30 USD/kWh, this price is relatively high if compared with the mean price that large consumers pay in the EE.UU (0.075 USD/kWh) [56]. However, if is compare price rate suggested in the present project with the price that Europe Community pay for the electricity generated by biomass gasification plants (0.13 USD/kWh) [56], it results a little more than twice. This is without taking into account that for small biomass plants the scale economy result poor and consequently the specific capital costs are very high, raising the capital amortization, overheads and maintenance costs. Under these circumstances it is vital to ensure the system's viability to maintain the operating hours as high as possible in order to maximize the annual production and reduce the unit production costs.

Considering an annual interest rate of 12% and a selling price of electricity of 0.30 USD/kWh the TRI resulted in approximately 5.3 years. In this scenario, the producer gas cost totaled 0.165 USD/kWh, the electricity cost was 0.022 USD/kWh and the average cost of producing hot water in all heat exchangers was 0.01 USD/kWh respectively, as can be observed in Figs. 5 and 6. The contribution from the sale of each of these products in the annual gross revenue, shows that electricity contributes with 78.42% of the revenue, complemented by hot water (21.58%), using as sale reference prices, established by Refs. [17,18]. The total thermal production in one year amounts to 110,400 kWh, while the production of electricity was 93,600 kWh.

In Fig. 8 it is shown a comparison of the hot water price produced by heat exchangers HE1, HE2 and HE4. It is observed that the HE4 produces the cheapest hot water; this is mainly due to the high energy content of the exhaust gases passing through it, which enables heating a greater volume of water. The cost of hot water production in HE2 almost doubles the value achieved in HE1 and HE4, this may be a consequence to its low hot water productivity.

A sensitivity analysis is shown in Fig. 9 and Fig. 10 by varying the price of biomass $\pm 50\%$ of the reported value of 0.25 USD/kg. Among the various factors that influence the biomass price are the cost of collecting, complexity of processing and distance from the supply source. For this analysis it is considered that the installation is located in an area near to the supply source area, and is harvested with the use of a machine able to cut and chop the biomass to the required dimensions.

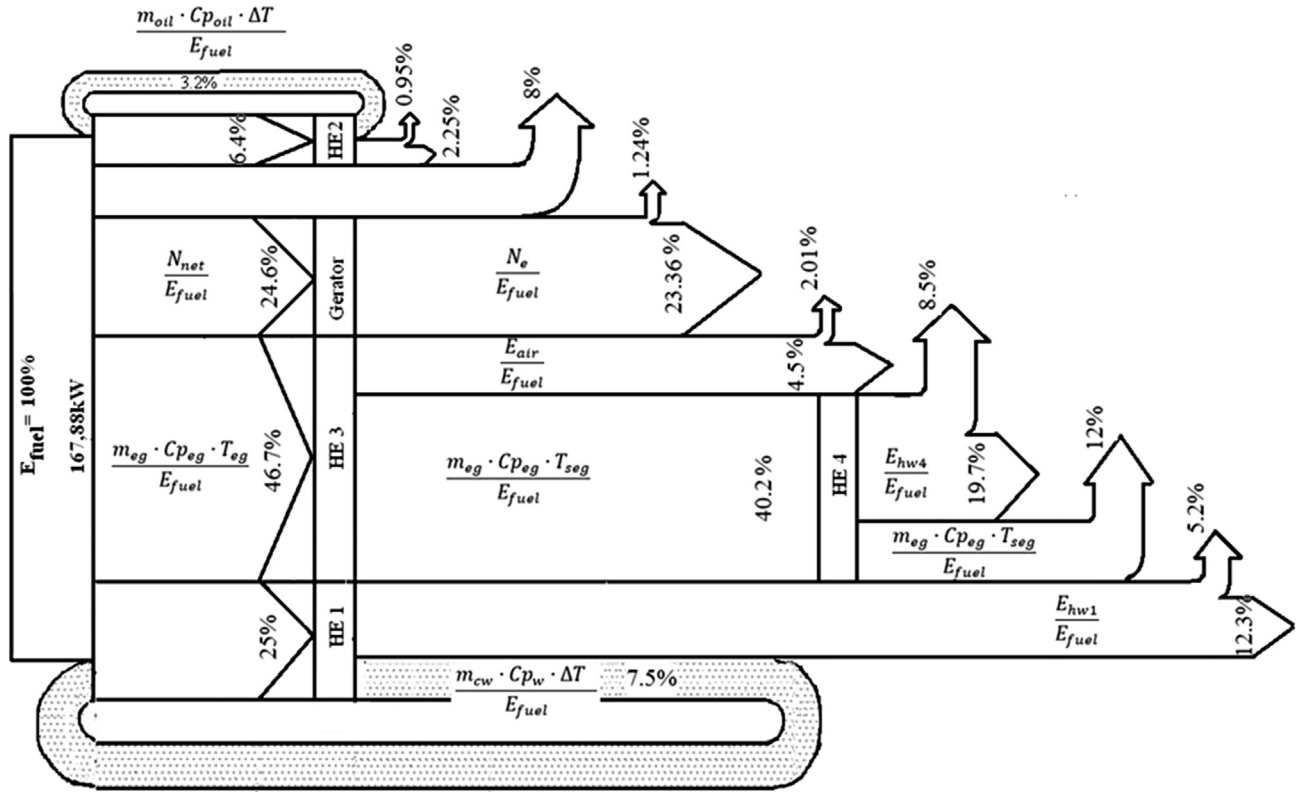


Fig. 5. Sankey diagram of the proposed systems.

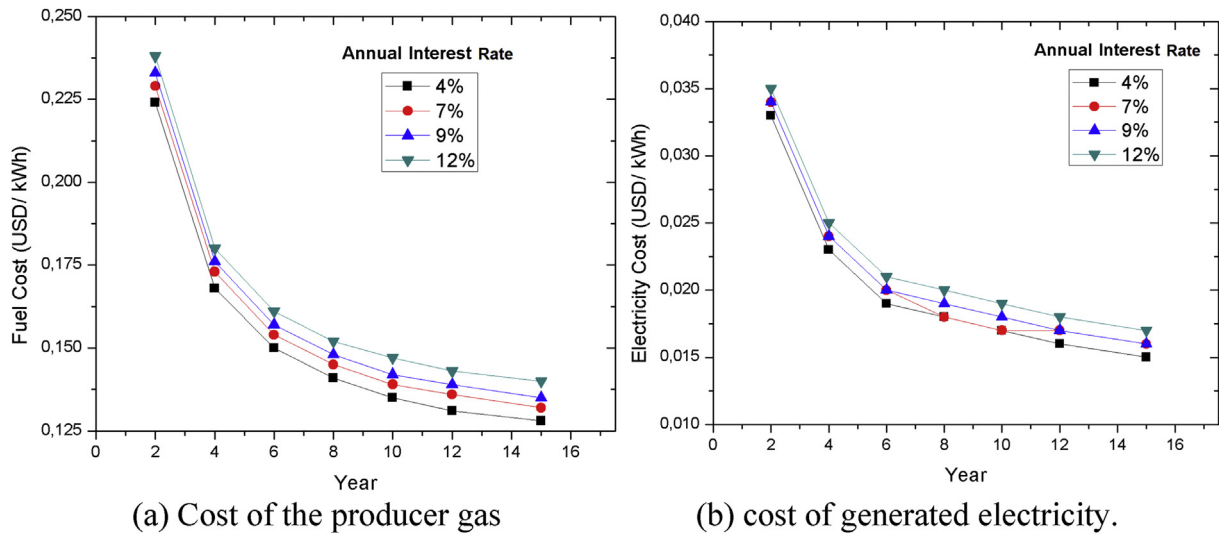


Fig. 6. Cost of producer gas and electricity.

The Fig. 9 shows the variation of the cost of producer gas with the variation of biomass cost, reaching values between 0.184 and 0.287 USD/kWh in the first two years of operation with an annual interest rate of 12%. It can be seen that the cost variations of biomass not significantly affect the cost of production of electricity, remaining practically constant, due to approximately 62% of the value obtaining by Equation (18) corresponds to the term that involves the initial investment in equipment (engine, gasifier, etc), and the term involving the cost of producer gas represents only

about 9%, the remaining 29% corresponds to the costs of maintenance.

The Fig. 10 shown the influence of the biomass price variation, on the average cost of thermal energy produced in the heat exchangers. It can be seen in this case that the price variation of biomass slightly affects the cost of production of hot water ranging from 0.01471 to 0.01566 USD/kWh. In these case the contribution of the cost of producer gas in equation (19) represents approximately 17% of the final value.

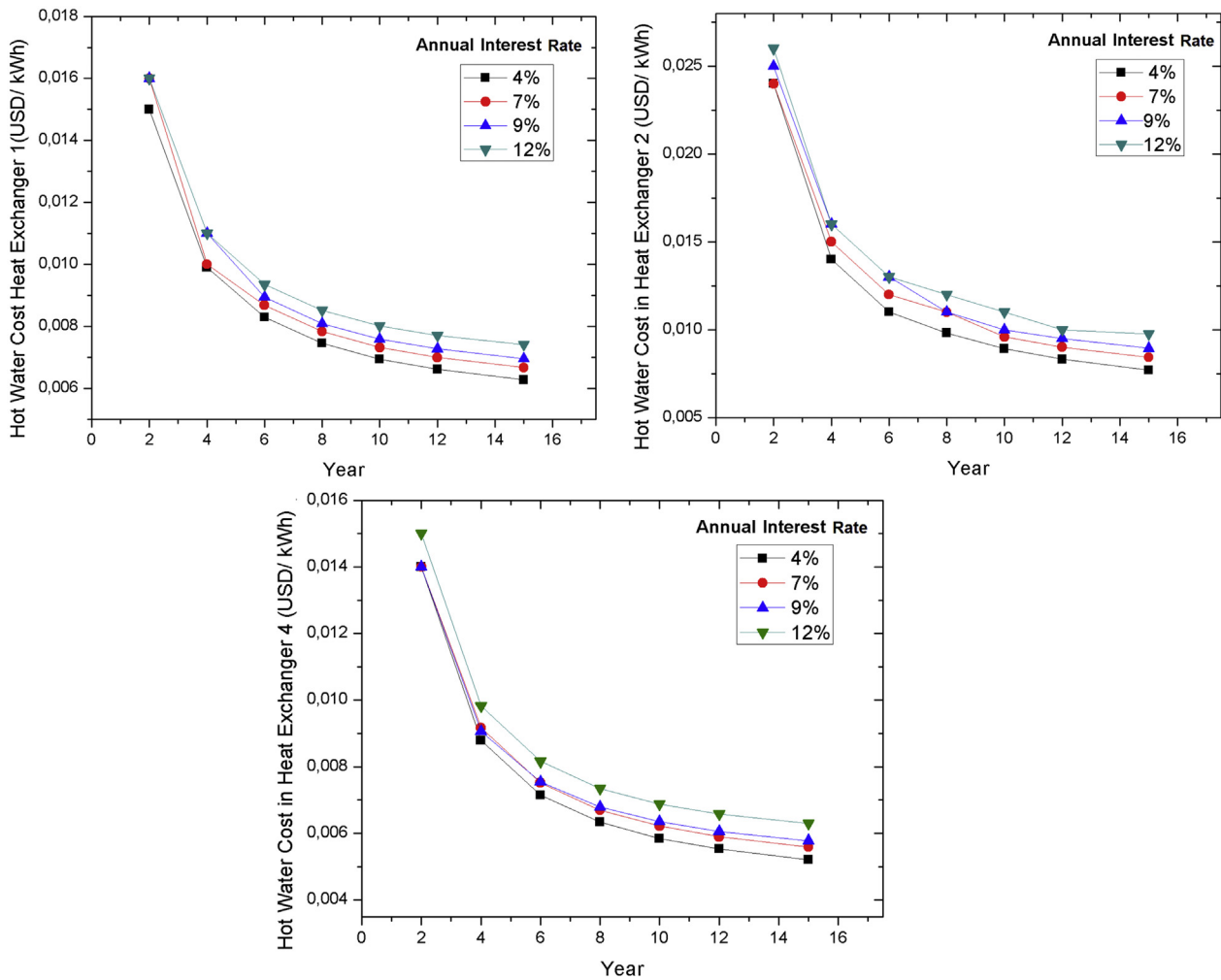


Fig. 7. Cost of hot water produced in HE1, HE2 and HE4.

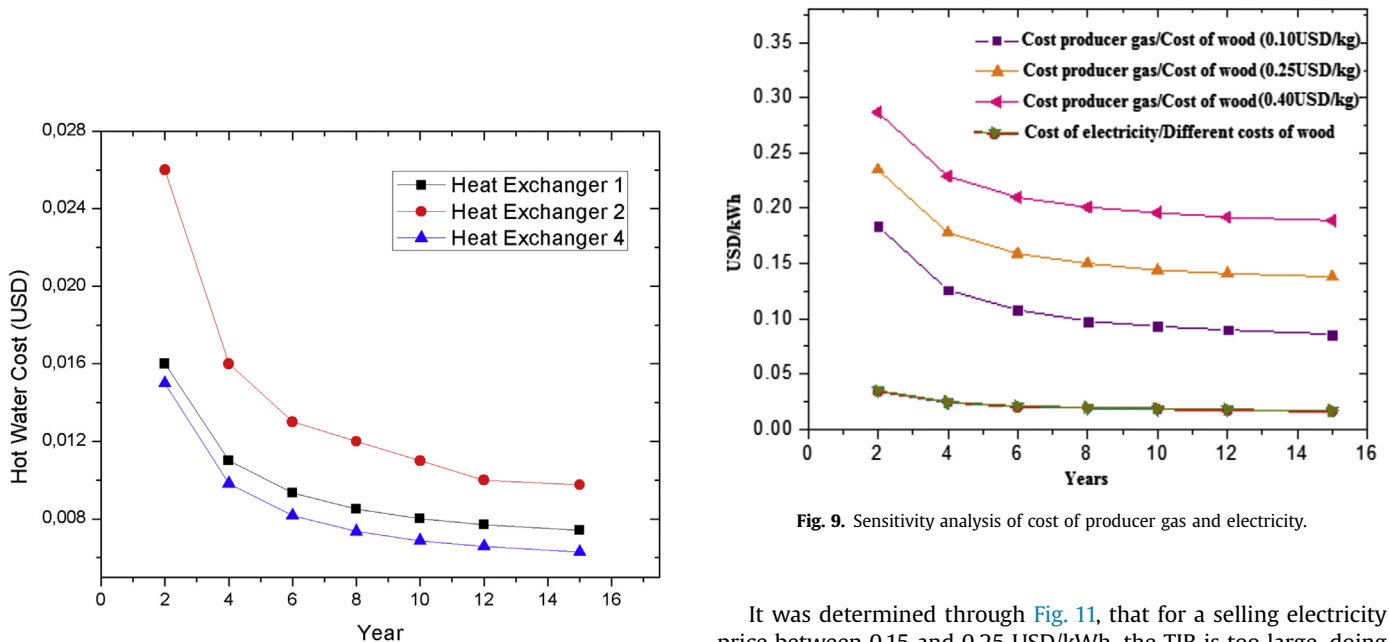


Fig. 9. Sensitivity analysis of cost of producer gas and electricity.

Fig. 8. Comparison of the hot water cost for three of the heat exchangers used in the system with a 12% annual interest rate.

It was determined through Fig. 11, that for a selling electricity price between 0.15 and 0.25 USD/kWh, the TIR is too large, doing unfeasible the project implementation, thus they are not attractive price for the present system configuration. With a selling price of

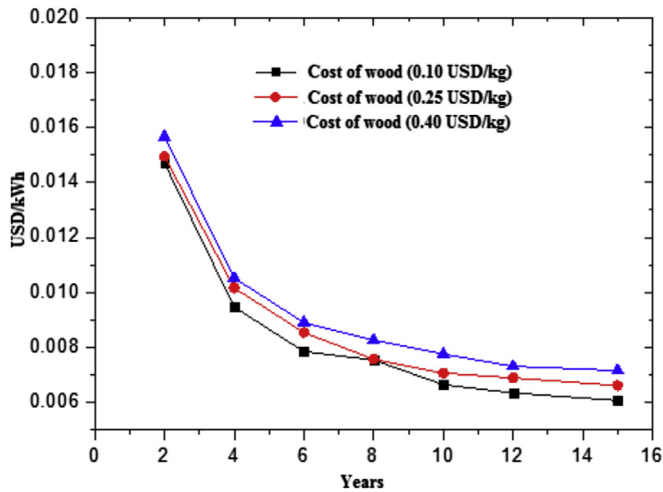


Fig. 10. Sensitivity analysis of thermal energy cost.

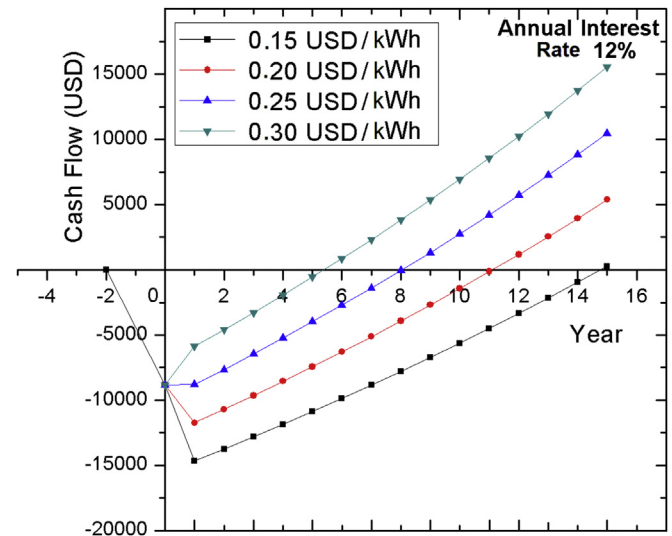


Fig. 12. Payback time at an annual interest rate of 12%.

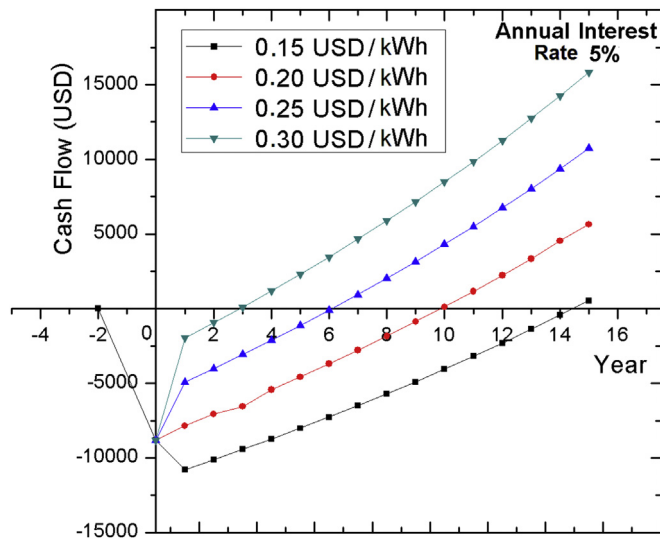


Fig. 11. Payback time at an annual interest rate of 5%.

electricity between 0.25 and 0.30 USD/kWh, and considering an annual interest of 5%, the investment becomes more attractive resulting in an IRR between of 7 and 23%, an NPV between 5290 and 44,602 USD and a payback time between 6 and 3 years.

If the annual interest rate is set to 12%, the investment would be feasible only with a selling electricity price of 0.3 USD/kWh, leading in an IRR of 12%, an NPV of 20,571 USD and a payback time of approximately 5.3 years, as observed in Fig. 12.

8. Conclusions

The theoretical study of a biomass-fueled small-scale CHP system with a downdraft gasifier and a spark ignition internal combustion engine is presented in the present paper. The authors propose an integrated approach for assessing the energy and economic performance of a biomass gasification cogeneration system to be installed in isolated communities where the access to fossil fuels is difficult but there is abundance of the residual biomass. The heating value of the producer gas resulted in 3.557 MJ/Nm³ based on the combustible gas components present in the producer gas. The engine's power output efficiency using a 100% of producer gas

resulted in 23.4% at maximum load. Considering a mechanical-to-electric power conversion efficiency of 95%, the maximum efficiency of the producer gas engine works out to be 24%. The heat efficiency of the proposed cogeneration system was 32.4%, reaching an overall efficiency of 55.8%. The global efficiency of the gasifier-cogeneration system was 33%. Finally, the specific fuel consumption (*Dichrostachys cinerea* biomass) for power generation using the ICE fueled with producer gas equaled 1.46 kg/kWh and the specific fuel consumption (producer gas) was 2.68 Nm³/kWh.

It was also concluded that for a feasible implementation of the proposed system, the electricity produced must be sold to end users between 0.25 and 0.30 USD/kWh, where the payback time is between 6 and 3 years for annual interest rate of 12%. Finally the cost of the proposed cogeneration system for the production of electricity and hot water was 1214 USD/kW.

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