

Technical Note

Electricity, hot water and cold water production from biomass. Energetic and economical analysis of the compact system of cogeneration run with woodgas from a small downdraft gasifier

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ABSTRACT

Wood gasification technologies to convert the biomass into fuel gas stand out. On the other hand, producing electrical energy from stationary engine is widely spread, and its application in rural communities where the electrical network doesn't exist is very required. The recovery of exhaust gases (engine) is a possibility that makes the system attractive when compared with the same components used to obtain individual heat such as electric power. This paper presents an energetic alternative to adapt a fixed bed gasifier with a compact cogeneration system in order to cover electrical and thermal demands in a rural area and showing an energy solution for small social communities using renewable fuels. Therefore, an energetic and economical analysis from a cogeneration system producing electric energy, hot and cold water, using wooden gas as fuel from a small-sized gasifier was calculated. The energy balance that includes the energy efficiency (electric generation as well as hot and cold water system; performance coefficient and the heat exchanger, among other items), was calculated. Considering the annual interest rates and the amortization periods, the costs of production of electrical energy, hot and cold water were calculated, taking into account the investment, the operation and the maintenance cost of the equipments.

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1. Introduction

Nowadays, the worldwide concern is not focused only on our main energy source exhaustion, which is petroleum, but also on environmental problems, which is the main focus. Looking for alternative answers for them, and to diverse human needs, this study will present ideas and data for a later evaluation of its possible practical application, especially in small-sized gasifying systems linked to the according small-sized cogeneration systems. The systems of the biomass gasification have been utilized for quite some time, and have demonstrated to be a good energetic alternative in relation to energy source problems. This type of setting up requires simple management and maintenance that give them high availability.

The gasification of the biomass presents itself as a sustainable alternative to energy generation, with low pollutant output which allows a little balance between consumption and the production of carbon gas in the global cycle of growth and consumption (burning)

of vegetables. Gasification consists in a thermochemical process, by which the biomass is converted into fuel gas through the partial air oxidation, partial oxygen oxidation or partial water steam oxidation at high temperatures from approximately 750 °C–850 °C. This fuel gas, whose low heat value (LHV) is from 4 to 6 MJ/Nm³ can be burned up directly or used as fuel for an internal combustion engine (ICE) or a gas turbine [1].

On the other hand, cogeneration has always demonstrated to be the best alternative concerning the best energy consumption with the highest energy efficiency, as well as concerning the implantation of distributive generation of electrical energy. The alternative stationary engines have demonstrated to be an excellent choice concerning the generation of electric energy on a small scale; that is the reason cogeneration with ICE presents itself as a viable alternative for residences and rural areas.

This project aims at an energetic analysis of wood gasifier with capacity of processing between 20 and 30 kg/h of lignocelulosic biomass coupled to a compact cogeneration system to produce electricity power of about 15 kW and hot and cold water. The purpose is to assess the viability of this alternative way of generating energy to places where the electricity and the public services (hot water and cold water) are not accessible.

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2. Biomass gas

The uses of “biomass gas” for running ICEs have had their first tests approximately during 1881. Around 1920, this gas was increasingly used for running trucks and tractors in Europe. Biomass is the term used in relation to organic material processed from vegetables and animals (algae, trees, vegetable residues, solid urban wastes, and biodegradable products). It is considered that every CO₂ released from the energetic use of biomass has been previously attached to the structures of vegetal matter during its growth and, as a result, it has not contributed to the increase in the concentration of greenhouse gases in the atmosphere. However, this balance is not practically zero, as a complete analysis of the life cycle demonstrates. Producing electricity with biomass requires transport (consumption of fossil fuels), power plants, etc. However, generally speaking, its balance can be considered nearly null.

Electricity production from hydropower plants decreases. According to the Brazilian Electricity Regulatory Agency (ANEEL), 90% of the electricity was produced in hydropower plants in 2000, decreasing to 80% in 2003, and to 76% in October. In 2009, 71% of the electricity was produced in hydropower plants because of the increase of the electricity production in thermal plants. In 2004, fossil fuels were globally representing 80.3% of the overall production of primary energy, in opposition to 13.2% of renewable sources whilst, in the same year fossil fuels were responsible for almost 50.3% of the overall production in opposition to 47.8% of renewable sources. The outstanding presence of renewable sources in Brazil is due to the sugarcane production with 15.4% used in food, drinks, paper, cellulose industries to obtain energy, wood-burning energy with 14.8%, still used in residences, ceramics, paper, and cellulose industries and in the farming sector; hydraulics-based energy for generating electricity with 14.5% [MME, 2005] [2]. The chief challenge of energy exploitation of the biomass is the electricity generation or the simultaneous generation [thermal energy and electricity (cogeneration)] on a high efficiency scale by employing ICEs, gas turbines and steam turbines or the combination of both.

The biomass combustion can be divided into six stages, according to Hellwig (1982) [3]: drying, emission of volatiles, ignition of the volatiles, burning of the volatiles into flames, volatile flame extinction and the combustion of the carbon residues (coke). It is recommended a reduction in the moisture content before the combustion by pre-drying the biomass in order to increase the overall energetic efficiency.

3. Gasification and cogeneration theory of small scale

Gasification is a process which converts biomass (solid) into fuel gas for partial oxidation at high temperatures. This gas, whose heat value is low (due to the oxidant being the air): 4–6 MJ/Nm³, can be burned directly or utilized in ICEs, gas turbines or boilers in order to produce electrical energy at a later stage. Gasification basically consists firstly of biomass drying, subsequently, when it reaches approximately 400 °C, the pyrolysis occurs. The combustion occurs at about 1000 °C and the gasification between 700 and 800 °C.

By means of a downdraft gasifier, the biomass also enters from above, but the air enters through an intermediary injector and descends into the same direction as the biomass. After going through the reduction process, the air ascends without getting direct contact with the incoming biomass, only exchanging heat to assist the pyrolysis process.

The air enters into the pyrolysis region and produces a flame, on account of the burning of most part of the volatiles. This flame is known as the pyrolytic combustion, on 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, carbon dioxide and water steam, coming from the combustion zone, reacting 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 downdraft gasifier is the most adequate to be used in engines, as the burning and heating up of volatiles produce a fuel gas almost without tar and condensable liquids.

3.1. Downdraft gasifier 20–30 kg/h

The downdraft gasifier built in the laboratory on the campus of São Paulo State University holds the following components: body of the gasifier, a vibrating grid that supports the biomass and regulates the ashes elimination, and a top lid where the valve system is installed for the entering of the biomass, an inferior region for gathering the solid residuals, an air tube around the throat region for air injection. The gasifier throat area is 0.0314 m² and its diameter is 0.2 m. The diameter of the pyrolysis region is twice as long as the throat region, which is 0.4 m. As for the throat, most authors consider the inclination to be at 45°. By means of the set-up gasifier, this value is 30°. It is recommended that the total height must be 2.5, doubling the diameter of the pyrolysis region. The volume of the reduction region is over 0.5 m³ per m² of the throat region. The reduction region is 0.04 m³. Details can be seen in Fig. 1.

For gasification thermal applications, when the gas is burned directly in a furnace, for example, it is more convenient to refer to “hot efficiency”, because the thermal energy of exhaust gases is used. For power applications, such as the ICE and gas turbines, as presented in the current paper, when the gas is cooled down during its conditioning (removal of particles and tar), so it is valid to refer to “cold efficiency”. The “hot efficiency” of the downdraft gasifier is 84.73% and the “cold efficiency” is 62.68%. [6].

4. Compact cogenerator system

4.1. Cogeneration and application with alternative engines

Cogeneration is a technique of primary energy conservation, which aims producing thermal and mechanical/electrical energy simultaneously. Some authors define it as a technique of simultaneous production of two ways of thermal energy and mechanical or electrical energy from burning only one fuel. The cogeneration cycle that uses the ICEs produce work (electrical energy or mechanical action), thereby recovering the residual thermal energy of the exhaust gases. The amount of the recovered residual energy is not one of the most expressive; for this reason its application takes place more often in installations which require little heating and moderate temperatures and a greater amount of electrical energy or mechanical energy. Cogeneration plants that use these cycles are common, potencies from a few dozens of kW up to potencies in the order of 20 MW or a little more [7].

The energy provided by the fuel in an ICE is distributed in four different ways. Approximately 32% are converted into work (axle power), while the remaining energy is eliminated in the form of heat. By means of an alternative engine adapted to cogeneration, part of this heat is recovered and applied to useful ends, especially for producing hot water, and in some cases, steam or even cold water, to which this paper refers.

The source of the most important recoverable heat is constituted by the refrigeration system of the engine, that is, the refrigeration water of the jackets. This heat, representing around 30% of the energy driven by fuel, can be recovered practically up to 100%.



Fig. 1. Prototype I and II. Downdraft wood gasifier (20–30 kg/h) [14].

There is another fraction of residual heat in the lubricating oil and that can also be recovered practically in its totality. Finally, the remaining energy of the fuel can be found in the engine exhaust gases, and approximately 60% of them are economically recoverable. A small portion is also lost through radiation (Table 1).

Fig. 2 shows a schematic drawing of an alternative engine with simultaneous electricity and hot water production. In an ICE, the value of 100% represents the energy introduced into the system (fuel). It is noted that 32% of this energy is recovered by the generator in form of electricity, whilst 30% is recovered by means of the refrigeration of the engine jackets water. 5% can also be recovered from the engine's lubricant oil. Another point of great importance is the energy available in the exhaust gases representing approximately 20%–25%, from which 80% of the containable energy can be recovered. It is observed that only 8% (5% from the engine and 3% from the generator) of the energy initially introduced is not recoverable [8].

4.2. Compact cogeneration system

The cogeneration system for simultaneous production of electrical energy, hot and cold water is built up and installed in the Engines Laboratory, Energy Department of the Campus of the University, is constituted by an ICE which is coupled to an electrical energy generator for obtaining power around 10–15 kW [9]. For the

utilization of the exhaust gases, a gas/water heat exchanger has been installed and for the utilization of the refrigeration water a water/water heat exchanger has been installed. Table 2 shows the data of the cogeneration system: ICE, absorption machine, electrical generator and heat exchangers. Details can be seen in Fig. 3.

4.3. System detailing

The cogeneration compact system consists of an ICE, model GM, 1.0 CORSA, manufacture date "1998", four strokes, MPFI-Delphi injection system, 9.4:1 compression rate, 44 kW maximum power, 81 N m maximum power torque and 6000 rpm maximum rotation (revolutions). A generator is coupled to the engine by means of a pulley and belt and through those that receive the mechanical energy produced by the combustion engine. The electrical generator (Three-phase) functions at 60 kHz frequency, 4 poles (polarizations), 20 kW–10 kW power, and a current of 220 V of 32.8 A, nominal values. The engine utilized in this study has a "Rodogás" fuel feeding system (pressure reducer) which allows the operation both on GLP or GNV and even on gasoline. Rodogás is an instrument, model TE-01, with capacity for up to 43 m³/h of fuel, good for engines with power up to 120 HP. Working pressures are: max input pressure = 250 bar and minimum = 26 bar; it is operated by an electro valve and fed by 12 V tension.

In the water/gas heat exchanger the water at a rate of 120 kg/h enters at 25 °C and it is heated to 65 °C. The gas circulating on the side of the tubes at a rate of 56 kg/h, enters at 541 °C and it is cooled to 307 °C. The carcass is made up of DIN 2440 steel, the tubes, chicanes and mirrors made up of carbon steel, the input and output connections of the carcass are of the BSP model, screw thread class and FLG model on the tubes, special class.

The absorption machine functions on ammonia/water, has a refrigeration capacity of 17.4 kW (5 TR), consumes the equivalent of 2.55 kg/h of PLG, if it is used with direct burning, and has an electrical consumption of 1.275 W.

Table 1
Comparisons between the several gasifier [1].

	Temperature [°C]		Tars	Particulate matter	MWe	
	Reaction	Output			Min	Max
Downdraft	1000	800	Very low	Moderate	0.1	1
Updraft	1000	250	Very high	Moderate	1	10
Bubbling	850	850	Average	High	1	50
Circulating	1000	850	Low	Very high	5	100

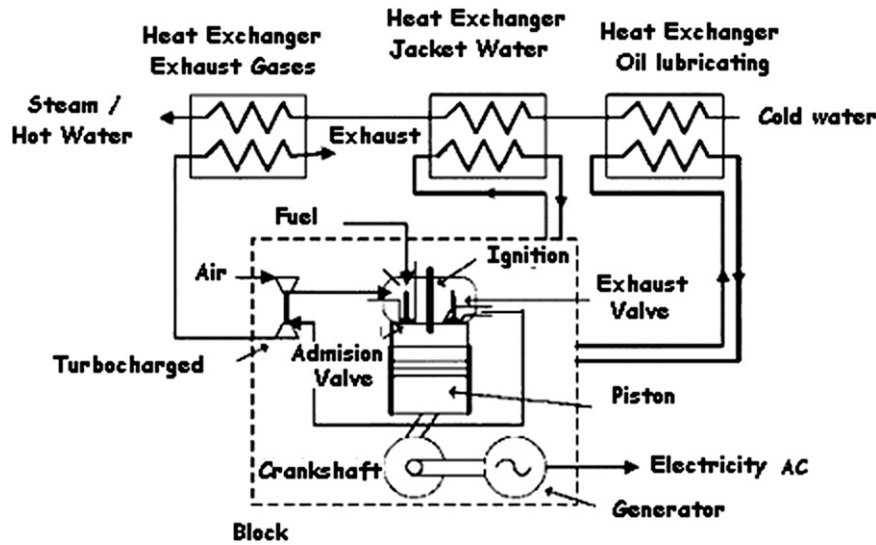


Fig. 2. Internal combustion engine with electricity and hot water production [13].

5. Methodology

In the energy analysis, the electricity generation efficiency (η_{GE}), the hot water generation efficiency (η_{GAQ}) and the cold water generation efficiency (η_{AF}) was first calculated, thus achieving the global efficiency of the system (η_{GLOBAL}). Knowing the massive flow (m_{SYN}) and the low heat value of fuel (LHV_{FUEL}), woodgas (syngas) the power supplied by fuel (E_{Comb}) can be calculated. Furthermore, knowing the efficiencies of the two heat exchangers (TC) (η_{TC}), such as water–water type as gas–water type, the hot water flow (m_{AQ}) produced by the exhaust gases flow (m_{GAS}) and the water jackets engine flow ($m_{A,Jack}$) were calculated. In the Absorption Refrigeration System-ARS, the performance coefficient (COP) was calculated, and the water cold flow generated (m_{AF}). In the economical analysis, as a first step, the price of the fuel (C_{Fuel}) (syngas) was calculated.

The electric energy generation cost (C_{EL}), the hot water generation cost (C_{AQ}), and the cold water generation cost (C_{AF}) were also calculated. Finally, the graphs of the generation costs will be showed, varying the annual interest rates and the amortization period of the equipments.

6. Energetic and economical analysis of the set gasifier–cogenerator

This section presents the equations used (Eqs. (1)–(17)) to develop the energy balance of a fixed bed gasifier downdraft type coupled with a compact cogeneration system. On the other hand, this part also includes the cost of electric and thermal power

generation, as well as the investment, the operation and the maintenance costs of the equipment altogether (Eqs. (18)–(30)). After listing the equations, the procedure which was calculated for each of them will be detailed. In Table 3, the fixed values of the system are presented. These values have been mentioned in the previous section and are presented in this part to monitor the energy balance.

$$\eta_{GE} = \frac{E_P}{E_{Fuel}} \quad (1)$$

$$\eta_{GAQ} = \frac{E_{AQ1} + E_{AQ2}}{E_{Fuel}} \quad (2)$$

$$\eta_{AF} = \frac{E_{AF}}{E_{Fuel}} \quad (3)$$

$$\eta_{GLOBAL} = \frac{E_P + E_{AQ} + E_{AF}}{E_{Fuel}} \quad (4)$$

$$E_{Comb} = m_{SYN} \cdot LHV_{SYN} \quad (5)$$

$$\eta_{TC1} = \frac{E_{AQ1}}{E_{A,Jack}} \quad (6)$$

$$E_{AQ1} = m_{AQ1} \cdot C_{p,Water} (T_{S,TC1} - T_{I,TC1}) \quad (7)$$

$$E_{AQ2} = m_{AQ2} \cdot C_{p,Water} (T_{S,TC2} - T_{I,TC2}) \quad (8)$$

Table 2
Data of cogenerator compact system.

ICE	Alternator three-phase	ARS	Heat exchangers
<ul style="list-style-type: none"> Model: GM Corsa Engine, 1.0 L "98" 4 stroke Injection System: MPFI-Delphi Compression value: 9.4:1 Max power: 44 kW Max power torque: 81 Nm. Max rotation: 6000 rpm 	<ul style="list-style-type: none"> Frequency: 60 Hz No of poles: 4 1800 rpm Cos φ: 0.8 Power: 12.5 kVA–10 kW 220 V: 32.8 A 	<ul style="list-style-type: none"> Refrigeration capacity: 17.4 kW (5 TR) Consumption of GLP: 2.55 kg/h. Electric consumption 1.275 W 	<ul style="list-style-type: none"> Model: Shell & Tube water/water and gas/water Number of tubes: 40 (water/water) and 76 (gas/water) Diameter of tubes: 9.525 mm (both) Thickness of tubes: 0.79 mm (both) Weigh of tubes: 12.5 mm (both) Number of deflectors: 7 (water/water) and 3 (gas/water)

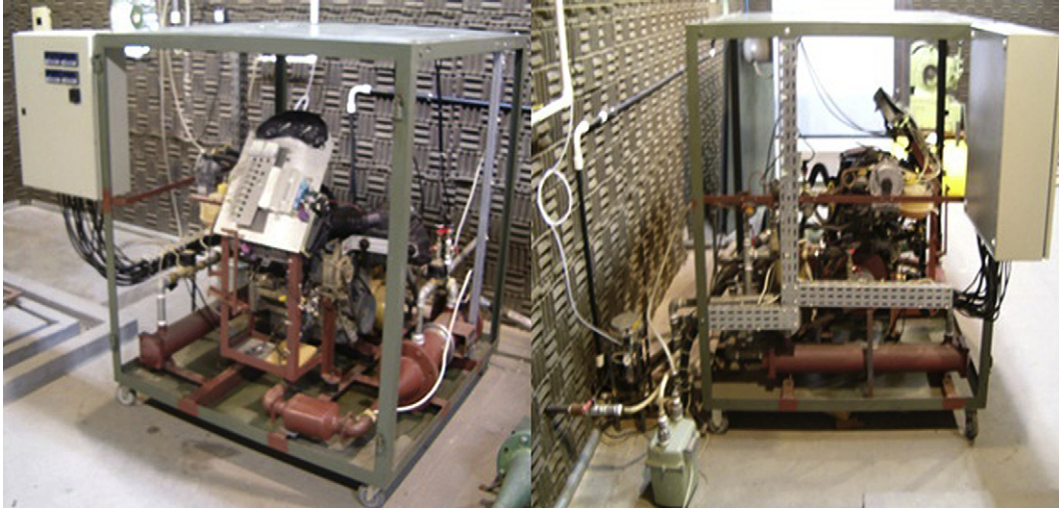


Fig. 3. Cogenerator compact system with alternative engine.

$$\eta_{TC2} = \frac{E_{AQ2}}{E_{Gas}} \quad (9)$$

$$E_{Gas} = m_{Gas} \cdot C_{p,Gas} (T_{S,TC2} - T_{I,TC2}) \quad (10)$$

$$E_{A,Jack} = m_{A,Jack} \cdot C_{p,Water} (T_{S,TC1} - T_{I,TC1}) \quad (11)$$

$$E_{Gas (ARS)} = m_{Gas} \cdot C_{p,Gas (ARS)} (T_{S,ARS} - T_{I,ARS}) \quad (12)$$

$$COP = \frac{E_{AF}}{E_{Gas (ARS)}} \quad (13)$$

$$E_{AF} = m_{AF} \cdot C_{p,Water} (T_{S,ARS} - T_{I,ARS}) \quad (14)$$

$$P_{Engine} = E_{Fuel} - \frac{E_p}{0,95} - E_{Gas,Exh(i)} - E_{A,Jack} \quad (15)$$

$$P_{Sys} = E_{Fuel} - E_p - E_{AQ1} - E_{AQ2} - E_{AF} \quad (16)$$

$$C_{p, Sysgas} = 0.976712 + \frac{1.02047 \cdot T}{10^4} + \frac{2.4370 \cdot T^2}{10^7} - \frac{1.1466 \cdot T^3}{10^{10}} \quad (17)$$

$$C = Cr \cdot \left(\frac{S}{Sr} \right)^m \quad (18)$$

$$I_{Gaseif} = 53800 \cdot \left(\frac{P}{50} \right)^{0,78} \quad (19)$$

$$C_{Syngas} = \frac{I_{Gaseif} \cdot f}{H \cdot E_{Fuel}} + \frac{C_W \cdot E_W}{E_{Fuel}} + CM_{Gaseif} \quad (20)$$

$$C_{EL} = \frac{I_{ENG.GER} \cdot f}{H \cdot E_p} + \frac{C_{Fuel} \cdot FP_E}{E_p} + CM_{E.G} \quad (21)$$

$$C_{AQ1} = \frac{I_{TC1} \cdot f}{H \cdot E_{AQ1}} + \frac{C_{Fuel} \cdot FP_{AQ1}}{E_{AQ1}} + CM_{TC1} \quad (22)$$

$$C_{AQ2} = \frac{I_{TC2} \cdot f}{H \cdot E_{AQ2}} + \frac{C_{Fuel} \cdot FP_{AQ2}}{E_{AQ2}} + CM_{TC2} \quad (23)$$

$$C_{AF} = \frac{I_{ARS} \cdot f}{H \cdot E_{AF}} + \frac{C_{Fuel} \cdot FP_{AQ2}}{E_{AQ2}} + CM_{TC2} \quad (24)$$

$$FP_E = \frac{E_p}{E_p + E_{AQ1} + E_{AQ2} + E_{AF}} \quad (25)$$

$$FP_{AQ1} = \frac{E_{AQ1}}{E_p + E_{AQ1} + E_{AQ2} + E_{AF}} \quad (26)$$

$$FP_{AQ2} = \frac{E_{AQ2}}{E_p + E_{AQ1} + E_{AQ2} + E_{AF}} \quad (27)$$

$$FP_{AF} = \frac{E_{AF}}{E_p + E_{AQ1} + E_{AQ2} + E_{AF}} \quad (28)$$

Table 3

Constant values of the cogeneration system. T° = Temperature.

Item	Value	Item	Value
Low heat value, LHV (syngas)	5000 kJ/Nm ³	T° inlet of water from TC2	25 °C
m _{SYN}	50 Nm ³ /h	T° output of water from TC2	65 °C
Electric energy produced, E _p	15 kW	T° inlet of exhaust gases into ARS	307 °C
T° output of water from jacket engine	90 °C	T° output of exhaust gases in atmosphere	150 °C
T° inlet of water from jacket engine	84 °C	T° inlet of water into ARS	25 °C
T° inlet of water from TC1 (water/water)	25 °C	T° output of water from ARS	7 °C
T° output of water from TC1 (water/water)	65 °C	Energy of water from TC1, E _{AQ1}	7 kW
T° of exhaust gases into TC2 (gas/water)	540 °C	Energy of water from TC2, E _{AQ2}	10 kW
T° of exhaust gases from TC2 (gas/water)	307 °C	Energy of water from ARS, E _{AF}	4 kW

$$f = \frac{q^k \cdot (q - 1)}{(q^k - 1)} \tag{29}$$

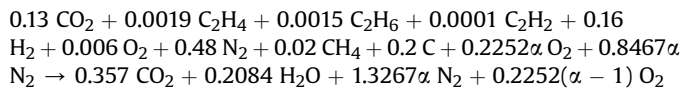
$$q = 1 + \frac{r}{100} \tag{30}$$

Using the Eqs. (1)–(3), the electricity generation efficiency, the hot water generation and the cold water generation efficiency are calculated respectively. Furthermore, in Eq. (4), the global efficiency of the system is calculated. The power supplied by the fuel can be calculated by Eq. (5) and the equations of the energetic efficiency of heat exchangers of the system (Eqs. (6) and (9)). The water jacket engine energy ($E_{A,Jack}$) and the exhaust gases energy ($E_{Gás}$) from the engine are calculated in Eqs. (10) and (11).

Using the Eqs. (7) and (8), the hot water flow generated from both heat exchangers can be calculated. With reference to the absorption refrigeration system (ARS), the exhaust gas energy at the exit ($E_{Gas,ARS}$) was calculated using Eq. (12). Using E_{AF} and $E_{Gas,ARS}$, COP is calculated in Eq. (13). Finally, the E_{AF} by Eq. (14) is calculated. The main results are presented in Table 4. By Eqs. (15) and (16), the energy loss or the dissipated energy in the engine (P_{Engine}) is calculated. It is considered a 5% of energy loss when the mechanical energy is converted into electrical energy. The energy losses in the IC engine are 11.20 kW (15.86%). The energy losses in the cogeneration compact system (P_{Sys}) are 34 kW (48.57%). The electric, thermal and global efficiencies of the plant are presented in Table 5. The thermal efficiency has been calculated using the energy in the water heating at the heat exchangers and the cooled water at the absorption refrigeration system.

6.1. Specific heat (C_p) calculations (woodgas)

The gas produced in the downdraft gasifier build in our university has the following chemical composition: 16% H₂, 20% CO, 13% CO₂, 2% CH₄, 0.6% O₂, 48% N₂, 0.19% C₂H₄, 0.15% C₂H₆ and 0.01% C₂H₂. The molecular mass of this gas is 25.692 g/mol and its specific mass is 1.147 kg/Nm³ [5]. The equation for the combustion of this gas burned with excess of air can be expressed as:



Using an excess air factor $\alpha = 1.4$, typical for an IC Engine, the composition of the combustion products is: 21.127% CO₂, 5.045% H₂O, 69.951% N₂ and 3.877% O₂. The molecular mass of this exhaust

Table 4 Main results of the technical and economical analysis.

Item	Value	Item	Value
$E_{A,Jack}$	10.0 kW	H	3000 h
$m_{A,Jack}$	0.398 kg/s	I_{TC1}	300 US\$
m_{AQ1} from TC1	0.042 kg/s	I_{TC2}	600 US\$
m_{AQ2} from TC2	0.06 kg/s	I_{ARS}	900 US\$
E_{Gas}	14.285 kW	I_{Gaseif}	84,000 US\$
m_{Gas}	0.057 kg/s	CM_{EG}	0.01 US\$/kWh
COP	0.439	CM_{TC1}	0.003 US\$/kWh
m_{AF}	0.039 kg/s	CM_{TC2}	0.002 US\$/kWh
C_{AF}	0.0288 US\$/kW	CM_{ARS}	0.008 US\$/kWh
$I_{ENG,GER}$	15 000 US\$	CM_{Gaseif}	0.02 US\$/kWh

$I_{ENG,GER}$: Investment of engine.
 I_{Gaseif} : Investment of gasifier system.
 CM_{EG} : Cost of maintenance of the engine.
 CM_{TC1} : Cost of maintenance of the TC1.
 CM_{TC2} : Cost of maintenance of the TC2.
 CM_{ARS} : Cost of maintenance of the ARS.
 CM_{Gaseif} : Cost of maintenance of the gasifier.

Table 5 Electrical, thermal and global efficiencies.

Efficiencies		
Electric, η_{GE}	Hot water TC1, η_{AQ1}	21.42%
	Hot water TC2, η_{AQ2}	10%
	Hot water TC2, η_{AQ2}	14.29%
	Cold water ARS, η_{GF}	5.71%
Global, η_{GLOBAL}		51.42%

gas is 74.382 g/mol. According to [Boehm, 1987] [10], by applying the percentage in mass of each component of the mix, it is possible to formulate an equation for the specific heat (C_p) of exhaust gases, according to temperature in case of woodgas burning Eq. (17).

7. Economical analysis of the gasifier–cogenerator system

7.1. Cost estimative of the gasifier

In the case of cost estimative, the technique of Boehm [10] adapted by Silveira [11] has been chosen to obtain the equipments costs. The technique is based on Eq. (18) and Fig. 4 illustrates this technique.

In this way, knowing the investment “Cr” for a plant with capacity “Sr”, the necessary investment “C” for a similar plant with another capacity “S” can be calculated, if “m”, the incidence factor indicating the economy scale (0.5–1) is available. This rule is also valid for equipments and machines in particular, but, in this case, it is necessary to know the price of the other or similar equipment. The necessary similarity implies in the same shape and the same building material. This study chose an incidence factor of 0.7, according to Vian (1991) [12].

In case of the engines/generators with downdraft reactors, the cost associated to the gasification includes: Feeding system, gasifier, cleaning equipments and equipments for the hot gas conditioning. The following values were obtained at the Zaragoza University (Spain) (Thermochemical Process Group): for a 50 kg/h gasifier, the estimated cost is 53,800 €, for a 250 kg/h gasifier, the estimated cost is 180,700 €, for a 500 kg/h reactor the estimated cost is 283,100 €, and finally, for a 600 kg/h reactor, the estimated cost is 374,000 €. [1,4–6].

The cleaning and hot gas conditioning system includes cyclones, wet scrubber, absorption towers, heat exchangers and gas driers. Any type of filter is included in the costs of gas cleaning. By following this technique, for a cost estimative, it could be obtained

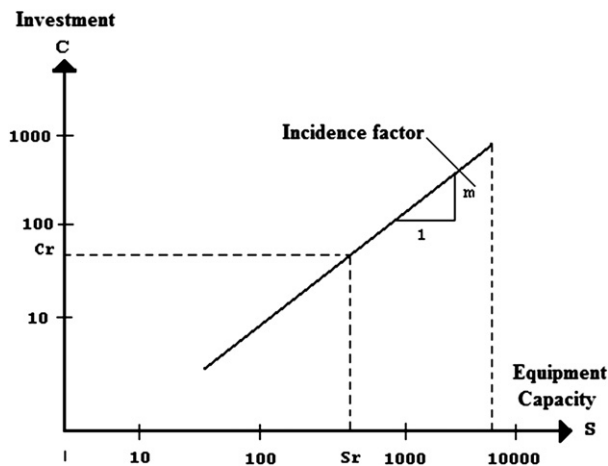


Fig. 4. Methodology for the determination of cost equipments [10].

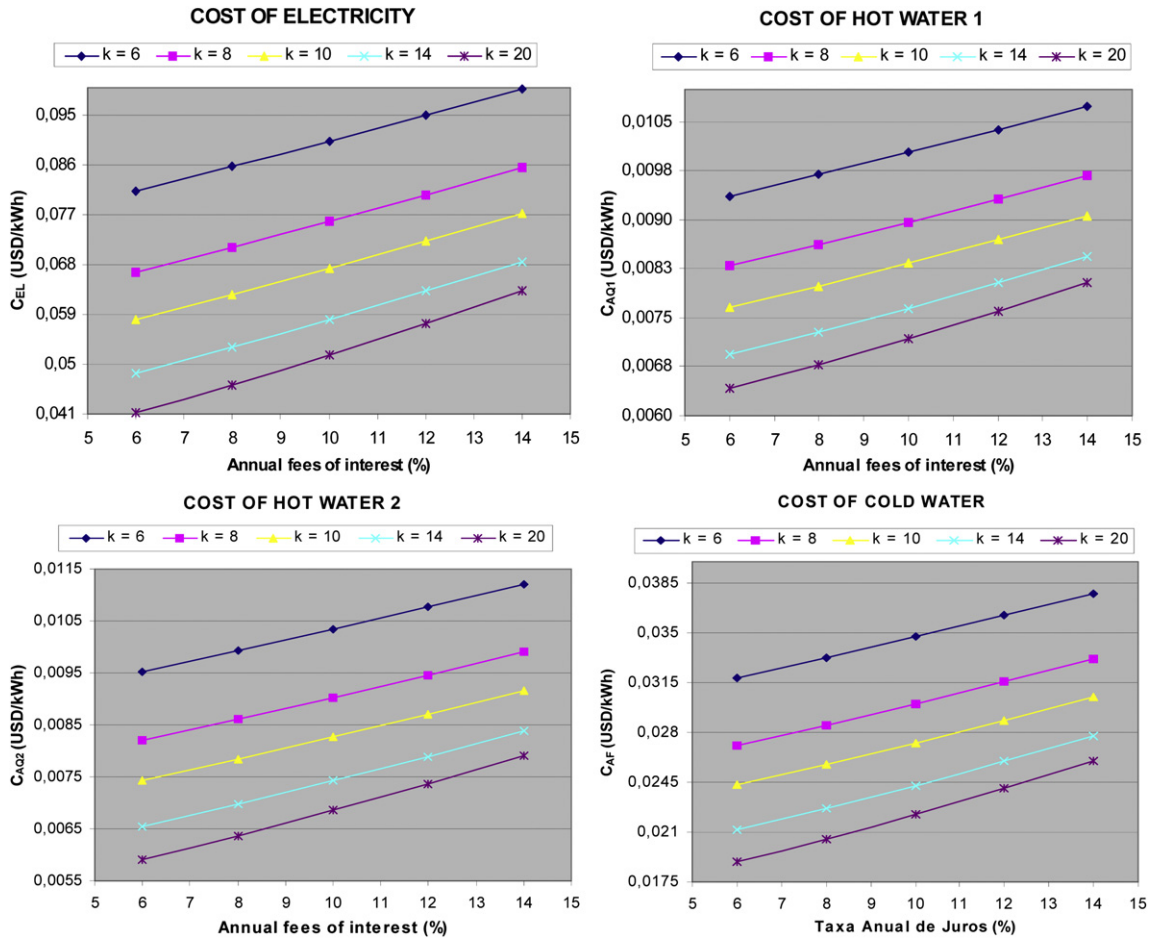


Fig. 5. Cost of the electricity, hot water and cold water according to annual fees of interest and depreciation period.

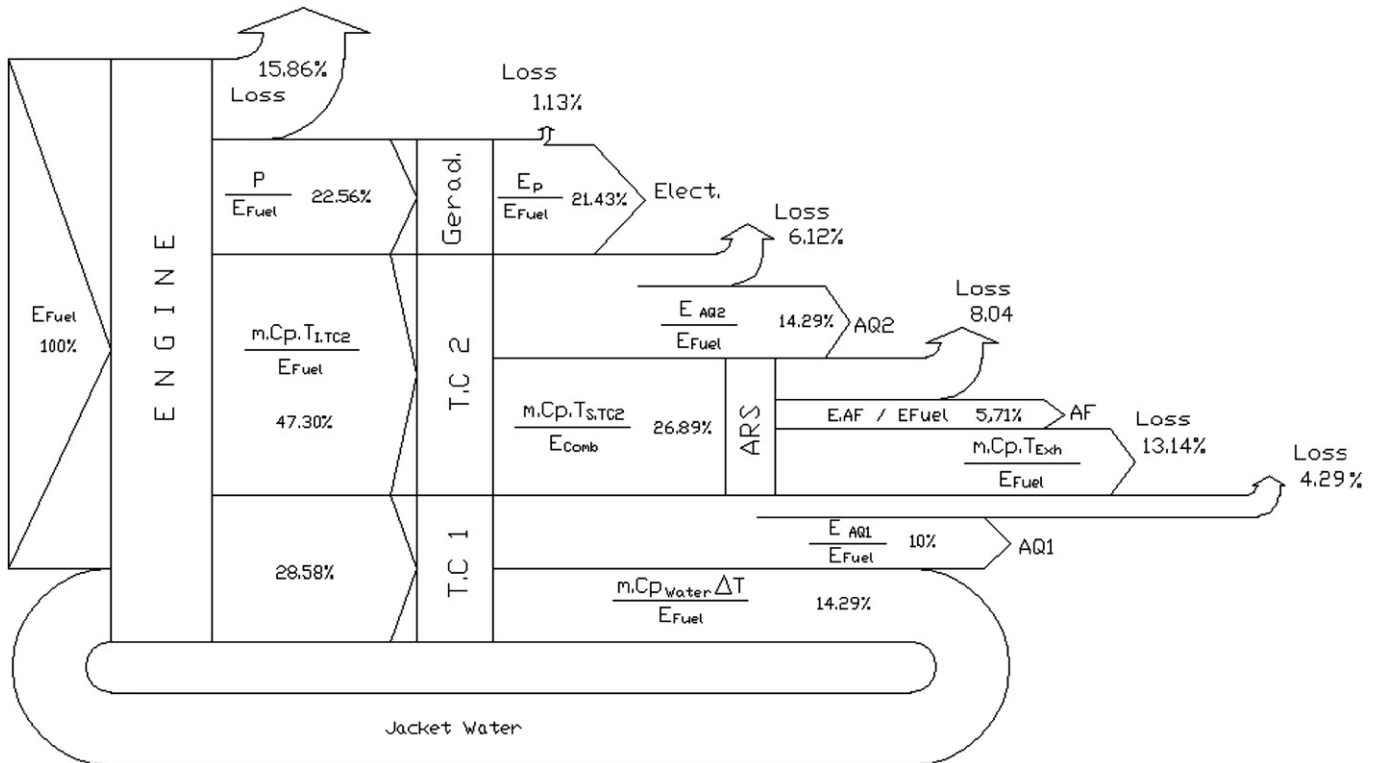


Fig. 6. Diagram of Sankey.

by using Eq. (19), the gasification system cost for 25 kg/h of biomass feeding will be approximately 54,000 USD.

The cost of instrumentation and electromechanical controls is considered 10% of the total installation cost, the civil work cost is 15% of the total installation cost and the project engineering cost is 30% of the total cost [4,6]. The cost for the gasifier system of 25 kg/h of feeding is approximately 84,000 USD.

7.2. Fuel cost (syngas)

The biomass utilized is eucalyptus wood, whose density is approximately 652 kg/m³. The cost of the biomass (C_W) is 42 USD/m³. This cost of the biomass could be considered null, because it is a renewable fuel and easily obtained in rural regions. Considering that the biomass feed in the gasifier, which is 25 kg/h, and that the woodgas production (syngas) is 50 Nm³/h, the syngas fuel price was calculated by using Eq. (20).

The electrical energy generation cost depends on the capital invested in the implantation and in the operation; the equipment cost (engine-cogenerator), the fuel cost, the operation time (H), the amount of generated electricity, the electrical energy generation efficiency and the operation and the maintenance cost (CM_{ARS} , CM_{Gaseif} , $CM_{E,G}$, CM_{TC}), Eq. (21). Thermal energy cost or hot water generation is constituted by similar factors in relation to the electrical energy generation cost, which is the investment capital cost (in this case the heat exchangers), the cost of the employed fuel, the heat generation efficiency, the operation time, the energetic flow, the production of hot water, the operation and maintenance costs, Eqs. (22) and (23).

Finally, the cold water production cost is similar to the previous ones but with a few differences in relation to the equipment cost which is directly linked to the Absorption Refrigeration System cost by, Eq. (24). Since the costs should be distributed to the three forms of energy produced (FP_{AF} , FP_{AQ} , FP_E) an adjustment factor (f) is used to separate the energetic flows cost. See Eqs. (25)–(28).

8. Results

In the graphs of Fig. 5 and Table 4 the main results of the energetic and economical analysis of the gasifier–cogeneration system are shown. The prices, considering several interest rates (r) valued and several amortization periods (k), are showed in Fig. 5. For more details, Sankey's diagram on the compact system of cogeneration coupled to downdraft gasifier was built and it is showed in Fig. 6.

9. Conclusions

In this work, an energetic and economical analysis from a cogeneration system producing electric energy, hot and cold

water, using wooden gas as fuel from a small-sized bed downdraft gasifier was calculated. The paper aimed at the presentation of an analysis based on the first law of thermodynamics of a cogeneration system, fed with woodgas from a downdraft gasifier. The η_{GLOBAL} of the gasifier coupled to the cogeneration system was 51.42%. The η_{GE} was 21.42%, the η_{GAQ} was 24.28% and the η_{GF} was 5.71%. The C_{Fuel} for an $r = 6\%$ and $k = 10$ years was 0.0976 US\$/kWh, the C_{EL} generated on the cogenerator system was 0.056 US\$/kWh. On the other hand, the C_{AQ} by the heat exchangers (TC1 and TC2) was 0.0047 US\$/kWh and 0.0079 US\$/kWh, respectively and finally the C_{AF} by ARS was 0.022 US\$/kWh. Finally, this paper showed an energetic alternative to adapt a fixed bed gasifier with a compact cogeneration system to cover electrical and thermal demand in a rural area where the shortage of fuel derived from petroleum and the abundance of the residual biomass prevails.

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