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ANALYSIS OF THE VIABILITY OF STIRLING ENGINES OPERATING WITH BIOGAS OF BRAZILIAN LIVESTOCK

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Abstract. *The spread of renewable resources is becoming the key to the advancement of new technologies for power generation. Stirling engine has become subject of interest due to its ability to obtain high thermal efficiency and its versatility, allowing the insertion of different sources of heat, which is transformed into useful work. One of the sources used in Stirling cycle is biogas. A better use of generated biogas from the decomposition of organic waste is to reduce the emission of methane and carbon dioxide gases in atmosphere, which is actually an environmental issue. Therefore, the goal of this paper is to develop a methodology to project a system capable to produce biogas to a Stirling engine. In order to do this, some important parameters to be estimated are: biogas flow rate, volume of biogas to work 24 hours per day, biodigester sizing and the correct quantity of animals that gives the total biomass to be digested. Some Stirling engines present in the literature were used as a basis of this work, making possible a socioeconomic viability study of this proposal. The results show that the use of biogas in Stirling engines can be implemented in the Brazilian agriculture, giving destination to the organic waste that normally are been thrown away.*
Keywords: *Stirling engine, Biogas, agricultural waste, biodigester, anaerobic biodigesters*

1. INTRODUCTION

Combined Heat and Power (CHP) systems are a new strategy to maximize the efficiency in distributed generation power, ensuring the supply of energy in isolated communities and diminishing CH_4 and CO_2 emissions. European Union (EU) and some countries are encouraging to widespread micro-CHP systems, in order to achieve a determined carbon emission level in atmosphere as a world objective. (Sonar *et al.*, 2014).

Stirling engines are experiencing a good market penetration of domestic micro generation due to their simple mechanisms and low levels of noise, particularly suitable for small scale units (Karabulut, 2011). These CHP units present an electrical efficiency in the range of 15%, could reaching the general efficiency of 90% when in co-generation, because the combustion gases keep a high temperature after provide energy to Stirling engine (Roselli *et al.*, 2011).

Biogas has some limitations when used as a fuel in thermal machines. In internal combustion engines, it cannot be used directly since it suffers a degradation process caused by acid substances and sulfidation. So, a filtration of sulfur compounds is required (Maizonnasse *et al.*, 2013). This filtration demands an extra cost, making biogas economically competitive only for facilities with production from 50 kW to 2000 kW (Walla and Schneeberger, 2008).

The biodigester is composed by a digester and a tank, where the generated biogas is stored. The process of digestion consists on using anaerobic bacterias to decompose waste of animal breeding, which is an organic material. It results in biogas, that can be used as fuel for micro generation; and digested remains, that can be used as high quality fertilizer, resulting in a production gain around 30% compared to use without digestion (Seixas *et al.*, 1981).

In scientific literature, some papers already explore the use of biogas combined with Stirling engine (Colmenar-Santos *et al.*, 2016; Bravo *et al.*, 2014; Monné *et al.*, 2014). However, only few of them has been studied specifically Brazilian regions. Therefore, the main motivation of this work is to analyze the feasibility of operating a Stirling engine for 24 hours a day using Brazilian agricultural data for micro generation. The proposed methodology aims to calculate the number of animals of each species are needed to operate the Stirling engines proposed by Podesser (1999), Pourmovahed *et al.* (2011), Cheng *et al.* (2013) and Hirata *et al.* (1997), as well as to calculate the volume of the biodigester and the amount of water for each type of biomass.

2. LITERATURE REVIEW

2.1 Stirling Engine

Stirling engines are classified in three different groups: α-, β- and γ-types. The β-type was chosen for this work, because they can generally achieve higher powers compared with another engine types. Besides that, it has a bigger number of works in the literature. Stirling engines allow the use of different heat sources due to its external combustion (Hirata, 2000), so it is possible to use biogas from the decomposition of agriculture manure.

In this paper, some Stirling engines available on scientific literature will be analyzed. The objective is to use these engines to dimension the complete system, including the biodigester. Four Stirling engines are used in this work: Podesser (1999) proposed a Stirling engine with pressurized nitrogen as working fluid, with rotation of 600 rpm and a shaft power of 3200 W. Pourmovahed *et al.* (2011) proposed the 24V DC WhisperGen Personal Power Station PPS16-24LG. This power station has a Stirling engine working with nitrogen at 2800 kPa and produce approximately 1051 W. A β-type Stirling engine was proposed in Cheng *et al.* (2013). This engine works with helium gas at 800 kPa and attend 390 W at 1400 rpm. And Hirata *et al.* (1997) proposed a Stirling engine Ecoboy-SCM81 at 800 kPa producing 100 W. The values of shaft power and efficiency of each engines are shown in Tab.1.

Table 1. **Stirling Engines**

	(Podesser, 1999)	**(Pourmovahed *et al.*, 2011)**	**(Cheng *et al.*, 2013)**	**(Hirata *et al.*, 1997)**
	[-]	WhisperGen	[-]	Eco-BoySCM81
Efficiency (%)	26.0	11.1	32.2	20.0
Shaft power (W)	3200	1051	390	100

According to Hirata (2000), the amount of heat necessary to the correct operation of the engine is determinate using the Eq. (1).

$$Q_{in} = \frac{W_s}{\eta_t} \tag{1}$$

In which Q_{in} is the heat input to the hot chamber from energy source, η_t is the thermal efficiency of the engine and W_s the engine's shaft power.

2.2 Biodigesters

To operate properly, some conditions on the biodigester must be established in such way that preset values of temperature, pH, nutrients, toxic substances and mixtures of solutions are respected. The anaerobic production efficiency increases when these values are reached (Noorollahi *et al.*, 2015; Hrubant *et al.*, 1978; Taleghani and Kia, 2005).

The Indian biodigester model has a simpler construction. It is composed by a wall with a floating bell that allows to control internal pressure. Its dome is made of iron or fiber, and it can float up or down, according to the gas production. In addition, this model takes advantage of the soil temperature to favor the bacteria action. With that, the biodigester could have a smaller volume (Veloso *et al.*, 2010).

Some livestock systems, such as confinements and farms, operate with a semi-continuous biomass offer. This is a consequence of the periodic cleaning of the establishments. The semi-continuous biodigester model is the most appropriate to this production process, because it is possible to insert biomass in small periods, as for example, daily. This model is best suited to the food industry and can also be used in cattle feedlots, pig and poultry farms (Sunarso *et al.*, 2010).

Figure (1) shows a schematic drawing of an Indian type biodigester that allows semi-continuous operation.

The total volume of the biodigester can be calculated using the Eq. (2).

$$V_B = M_A \times N_a \times (1 + R_W) \times H_{RT} \tag{2}$$

In which H_{RT} is the hydraulic retention time and has the value of 45 for goat biomass, 35 for bovine and swine, and 60 for birds. V_B is the volume of biodigester, M_A is the biomass produced per animal per day, R_W is the ratio between mass and amount of water to be added.

To calculate the biomass volume DLV to be added per day, the Eq.(3) is used with the data provided by Tab. 2 (OLIVER *et al.*, 2008).

$$DLV = M_A \times N_a \times (1 + R_W) \tag{3}$$

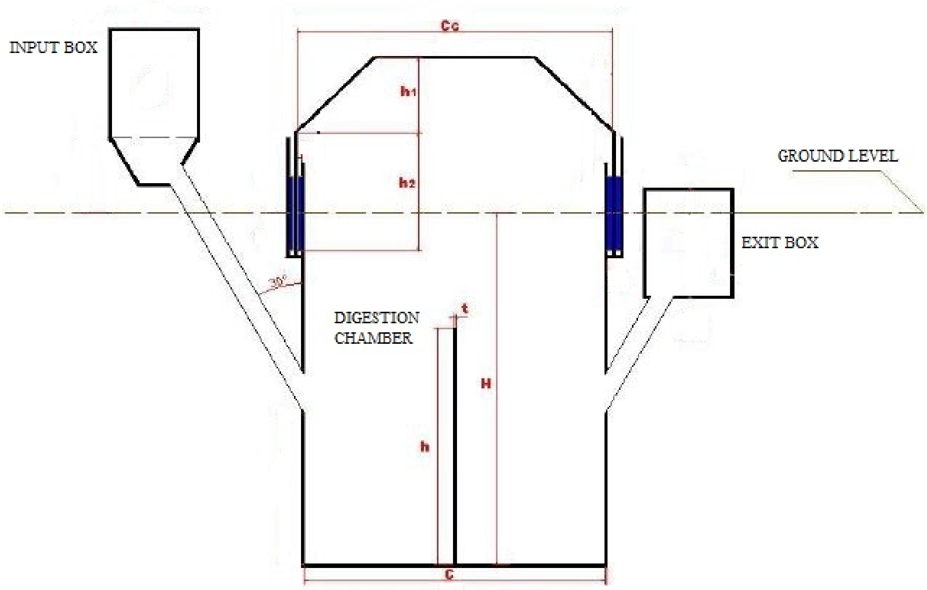

Figure 1. **Indian Model Biodigester (Veloso *et al.*, 2010)**

In which DLV is the daily loud volume.

Table 2 shows the biomass values produced by different species of animals and water ratio to be used (Oliver *et al.*, 2008).

Table 2. **Biomass production for different animals.**

Species	**Mass/animal/day (kg)**	**Ratio mass/water (kg/l)**
Goats	0.5	1:4 - 1:5
Cattle	7	1:1
Dairy Cattle	25	1:1
Bovines in confinement	15	1:1
Calves	2	1:1
Swine	4	1:1 - 1:3

According to Veloso *et al.* (2010), with the biodigester volume, (V_B), it is possible to calculate the height and the area of the transversal section with the presented relations in Eq. (4) to (6).

$$V_B = A \times H \geq 1,1V_B \tag{4}$$

In whiche H is the height of the substrate, A is the cross-sectional area of the biodigester,

$$A = c \times l \tag{5}$$

In which c is the length of the biodigester, l is the width of the biodigester,

$$0.532 \leq \frac{\sqrt{A}}{H} \leq 0.886 \tag{6}$$

The volume of the biodigester box is given by Eq. (7)

$$V_C = \frac{3}{8}(L_c \times h_1 \times C_c) + h_2 \times C_c \times L_C \tag{7}$$

In which C_c is the digestion chamber volume.

The volume of the discharge box is given by Eq. (8).

$$V_p = h \times l \times t \tag{8}$$

In which V_p is the volume of the discharge box and t is the wall thickness.

2.3 Biogas

Colmenar-Santos *et al.* (2016) present in their work a methodology for calculating the enthalpy of combustion of the biogas and also its mass flow. For this, the author presents the following conditions:

- Combustion occurs completely;
- It is considered that the air admitted to the burner consists of 21% of oxygen e 79% of nitrogen;
- The molar masses of C, H_2, O_2, N_2, S_2 and air are 12 kg/kmol, 2 kg/kmol, 32 kg/kmol, 28 kg/kmol, 64 kg/kmol e 29 kg/kmol, respectively;
- N_2 is considered as inert gas and does not generate sub-products.
- CO_2 does not oxidizes;
- 20% of air is introduced in excess from the stoichiometry amount required;
- The relative humidity if the dry air (RH) is 60%. The humidity in the air reacts with nothing, it simply appears as additional H_2O in the products. Therefore, the combustion equation using dry air presents the moisture on both sides of the equation;
- Biogas and air are considered under ideal gas conditions;
- It is considered 1 kmol of biogas;
- There are no heat losses between the burner and the engine, which means that all the heat obtained in the combustion flows to the engine.

The combustion reactions in terms of undetermined coefficients are shown in Eq. (9). With these coefficients, it is possible to calculate the enthalpy released in the biogas combustion and, thus, to calculate the volumetric flows of biogas and air required for the operation of each engine.

$$\begin{aligned} &65,324\%CH_4 + 34,672\%CO_2 + 0,003\%H_2S + 0,0001\%NH_3 + (1.568(O_2 + 3.76N_2)) + 6,609H_2O) \\ &= 1CO_2 + 7.930H_2O + 0,00003SO_2 + 5,895N_2 + (0.261)O_2 \end{aligned} \tag{9}$$

The required biogas mass flow rate, Eq (10), is based on the combustion enthalpy and in the mass flow of the biogas.

$$\dot{m}_b = \frac{Q_{in}}{h_c} \tag{10}$$

In which $\dot{m}_b$ is the biogas mass flow and h_c is the combustion enthalpy.

The rejects of each animal species have a different potential of biogas production. Tab. 3 shows the volume of biogas produced as a function of the biomass produced for each species.

Table 3. **Biogas production per kg of biomass for different species (Oliver *et al.*, 2008)**

Animal Species	m^3 of biogas per kg of biomass
Goats	0.04 - 0.061
Dairy Cattle	0.04 - 0.049
Calves	0.04
Swine	0.075 - 0.089

Throughout the various researches, it has been developed a structure that allows the burning of gases to heat the hot chamber of a Stirling engine. With this structure, there is a increase of the heat transfer among the burnt biogas and the hot chamber wall, which rises the power output and also the thermal efficiency. Fig. (2) shows the developed structure. It is possible to observe a combustion chamber where the burnt gases meet and exchange heat with the heater pipes. Furthermore, the degradation caused by acids and sulfidation is restricted to the outside of the engine (Li *et al.*, 2012).

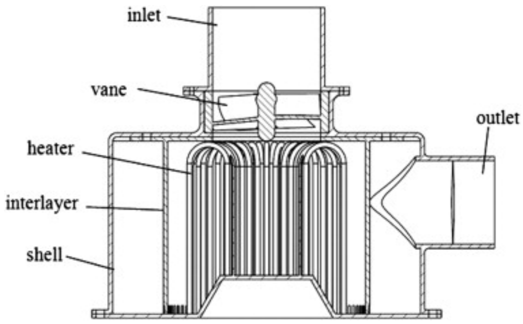

Figure 2. **Burner next to the hot chamber of the engine (Li *et al.*, 2012)**

3. METHODOLOGY

The heat to be inserted in each engine is necessary to determine the flow of biogas and the consequent volume of the biodigester. Tab. (4) shows the input heat Q_{and} for each engine chosen in the literature.

Table 4. **Selected engines specifications**

Selected engine	**Input heat [kW] - $\mathbf{Q_{and}}$**
Podesser	12307.7
WhisperGen	9468.5
Cheng	1211.2
Eco-BoySCM81	500.0

Figure (3) shows a schematic drawing of a biogas generation system, a combustion chamber and a Stirling engine. As the system is geared towards livestock industry, the cooling system of engine's cold chamber and the exhausted gases can generate hot water for the internal processes of the industry, like equipment's cleaning and sterilization.

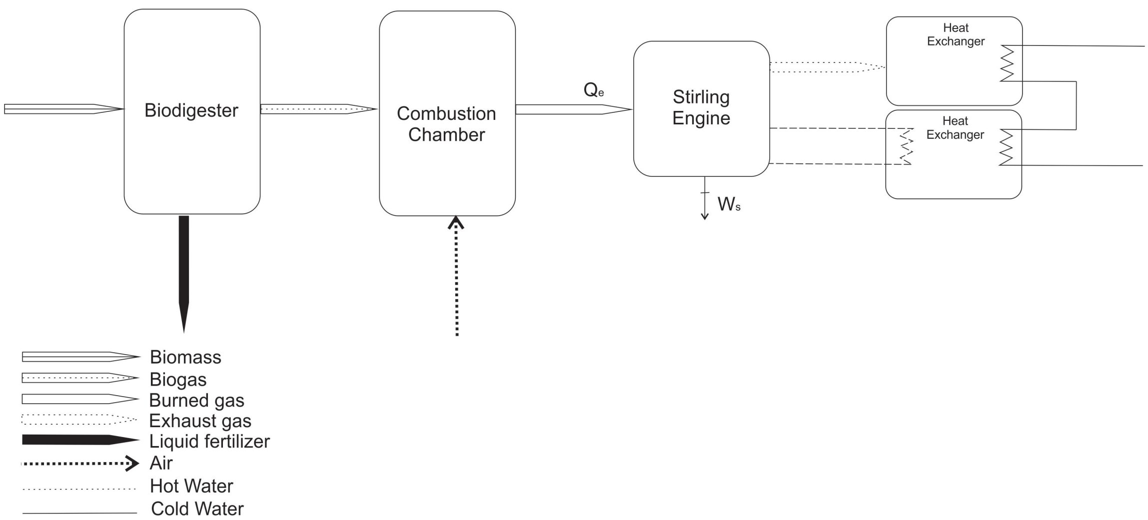

Figure 3. **schematic drawing of a biogas generation system, a combustion chamber and a Stirling engine**

Beginning from the incoming heat, the mass flow of biogas was calculated to reach the required heat using th Eq. (10). With the mass flow of fuel, the volume of biogas to be produced per day was calculated using the Eq. (11).

$$V_g = \dot{m}_b \times T_{op} \tag{11}$$

In which V_g is the daily volume of biogas and T_{op} is the operation time.

Based on the Tab. (2), the amount of biomass produced per animal per day was determined and thus, the amount of total biomass to be inserted in the biodigester every day was calculated using the Eq. (12).

$$m_b = \frac{V_g}{B_a} \tag{12}$$

In which m_b is the biomass to be inserted daily and B_a is the biomass produced per animal.

Knowing the amount of total biomass required per day using Eq. (13), it is possible to determinate the number of animals required to supply this demand. For this, the data provided in the Tab. 2 were used.

$$N_a = \frac{m_b}{P_a} \tag{13}$$

In which N_a is the Number of animals and P_a is the biomass diary production per animal.

4. RESULTS AND DISCUSSIONS

In the chemical balance explained in Eq. (9), the energy obtained was 46465.8 kJ per mole of biogas. One mole of biogas has molar mass of 25.73 g and density of 1.15 kg/m^3. The biogas consumptions were calculated for the selected engines in Tab. (5).

Table 5. **Biogas flows of the engines of interest**

	Podesser	**WhisperGen**	**Cheng**	**Eco-BoySCM81**
Mass flow (g/s)	6.82	5.25	0.67	0.28
Biogas volumetric flow rate (m^3/h)	0.36	0.27	0.04	0.01
Volume required for 24h operation (m^3)	8.54	6.57	0.84	0.35

This paper methodology was applied to calculate the number of required animals to operate three different engines. Tab. (6) shows the obtained values for the amount of biomass required daily for the selected engines to be able to work for 24 hours every day.

Table 6. **Amount of biomass to be inserted per day**

Species	**Podesser (kg/day)**	**WhisperGen (kg/day)**	**Cheng (kg/day)**	**Eco-BoySCM81 (kg/day)**
Goats	170.74	131.35	16.80	6.94
Dairy cattle	189.71	145.94	18.67	7.71
Calves	213.42	164.19	21.00	8.67
Swine	104.11	80.09	10.25	4.23

Table (7) shows the obtained values for the amount of water required daily for the biodigester to be able to operate correctly.

Table 7. **Volume of water to be inserted per day**

Species	**Podesser (l/day)**	**WhisperGen (l/day)**	**Cheng (l/day)**	**Eco-BoySCM81 (l/day)**
Goats	247.57	190.46	24.36	10.06
Dairy cattle	189.71	145.94	18.67	7.71
Calves	213.42	164.19	21.00	8.67
Swine	124.93	96.11	12.29	5.08

Goat residues have a great dependence on water insertion because they work with a 1:5 mass/water ratio. This means that twice as much water is needed to be added into biomass from goats in relation to dairy cattle and swine.

After the amount of biomass calculated, the amount of animals needed to supply the required demand was calculated. Tab. (8) shows the number of animals of each species to meet the need for each engine.

The total volume of the biodigester is presented in Tab. (9) for each Stirling engine studied.

Since the biomass from goats needs a large mass/water ratio, its biodigester must have a volume three times larger than the required volume for the other species. High volume biodigesters require great investments. Thus, this may be a

Table 8. **Number of animals required to operate each engine for 24 hours**

Species	Podesser (u.a.)	WhisperGen (u.a.)	Cheng (u.a.)	Eco-BoySCM81 (u.a.)
Goats	341	263	34	14
Dairy cattle	8	6	1	1
Calves	107	82	11	4
Swine	26	20	3	1

Table 9. **Total volume of the biodigester required to operate each engine for 24 hours in liters (l)**

Species	Podesser (l)	WhisperGen (l)	Cheng (l)	Eco-BoySCM81 (l)
Goats	46099	35464	4537	1873
Dairy cattle	13279	10216	1307	539
Calves	14939	11493	1470	607
Swine	14575	11213	1434	592

prohibitive factor for the use of goat's waste as a source of biomass. Furthermore, the number of goats proved to be more than ten times higher than the other species, turning more difficult to collect their residues. Another difficulty is that their confinement is not so common, mainly for a large number of animals.

In the Tab. (8) and (9), it is possible to affirm that the biomass from pigs presents the greatest viability among the presented species. Since pigs are mostly confined in farms, collecting swine residues is simple. Besides that, the amount of animals presented are easily practicable in small farms.

The number of calves needed to make each engine work during a 24 hours period presented in the Tab. (8) is more than ten times higher than the numbers of dairy cows. Only medium to large properties could practice a production of approximately 3.2 kW (Podesser Stirling engine) due to the large number of animals needed. However, calf rearing is almost always associated with raising dairy cows. So, it can be said that the biomass produced by both could be collect in the same property, enabling the application also on smaller properties.

5. CONCLUSIONS

Using the presented methodology, the amount of animals necessary to supply the biogas generation demand for the process for each engine was obtained. It was noticeable that generation of biogas using goat waste had a greater dependence on the amount of animals. Since the breeding of goats is not as widespread in Brazil as the breeding of pigs and cattle, the choice of goat's biomass source is unfeasible.

Comparing swine with dairy cattle biomass there was also a greater dependence on the amount of animals. However, pig breeding is more often done on big farms, where the animal is confined and it is easier to collect its waste. Dairy cattle are not always confined, which makes difficult to access their biomass .

Parameters of the Stirling engine operating with biogas can be calculated based on the methodology proposed in this work. Some considerations should be made in the future, such as calculating heat transfer losses from the burner to the engine.

The amount of water to be inserted into the biodigester was calculated based on the values presented for each type of waste. To operate the Podesser engine in order to generate 3200 W, the biodigester needs approximately 125 liters of water every day when operating with biomass from domestic pig. This value may seem irrelevant at first glance, but considering one month operation it is estimated that 3750 liters of water are needed.

The largest herds of goats in Brazil are found today in the northeast region of the country. This region suffers the smallest precipitations. Therefore, the anaerobic digestion of goat residue may be impracticable in these cases. For a single generation of 3.2 kW, it takes about 7500 liters of water per month. This is almost twice as much as it is necessary for the anaerobic digestion of pig waste.

A more rigorous study on the subject has yet to be carried out. Losses due to inefficient combustion and the heat transfer among the burnt gases and the hot chamber should be considered. However, it can be stated that the production of biogas from livestock waste is quite feasible. The biogas processing combined with Stirling engines has as its product, electric energy, high quality fertilizer and heat. The correct use of the biomass from livestock industries causes a positive impact on the environment by the burning of methane.

6. ACKNOWLEDGEMENTS

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