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Dairy Farm Bioreactor Sizing and Estimation of its Energy Capacity Case Study Elabered Estate, Eritrea

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A B S T R A C T

A case study for Elabered estate, a farm located 63km north-west of Asmara, Eritrea was conducted for a biogas plant implementation. Cow dung was taken to be the main feedstock for the biogas digester. The total quantity of manure estimated was 3000kg out of 300 cows per day. Having this, 173m^3/day biogas production was estimated. Assuming the produced biogas to be upgraded up to 95% CH_4 content the total energy generation potential is equivalent to 1089.7kWh/day. As the energy requirements for ploughing harrowing and cultivating 100ha farm was calculated the maximum daily energy requirement was 512.58kWh. In comparing the daily farm energy needs and biogas energy potential, it is inferred that the proposed biogas reactor energy output can sustainably run the selected farming activities. The remaining energy can be diverted to self-powering the biogas plant accessories such as collecting manure and distributing digestate to the field, transporting feed to the dairy farm and other miscellaneous energy consumptions.

Introduction

Agriculture is the production of crops and rising of livestock. Though food production is the primary goal of agriculture, its contribution in energy generation is not negligible. Currently the increased cost of fossil fuel and safety concerns of eco-systems has greatly affected and stimulated agriculturalists to make their farms self-powered and ecologically safe.

One of these revolutionary methods is the in-farm production of biogas. Biogas production involves the decomposition of organic matter where anaerobic bacterial respiration plays a major role. Out of many biogas production raw materials animal manure is popular and easily accessible. Using animal waste products as fertilizers has been the only thing considered as an advantage through time. However in this energy approach the farm will have a double advantage of energy and fertilizer production.

Employing farm wastes into energy generation requires estimation of the amount of waste materials produced within the farm so that the sizing of a biogas reactor can be done in an agreement with the daily energy requirement of a farm. As far as the energy requirement is concerned knowing either the household daily energy requirement or farming energy demands is a basic step.

Materials and Methods

Design of biogas reactor involves different parameters on top of the financial parameters mainly: the input parameters such as availability of water source, raw materials, climatic conditions of the area and location, output parameters such as energy required to be generated, methane requirement, and design parameters such as optimum temperature of operation and heating facility, retention time, C/N ratio and pH of the slurry, feed to water ratio and percentage of total solid, volatile solids in the feedstock, percentage of CH_4 in the gas (F_{CH4}) and gas productivity (m^3/m^3 of digester/day).

The study has put its focus on Elabered Estate, a farm located in the Anseba region of Eritrea, 68km north-west of Asmara the capital of Eritrea.

As it has been stated in an article by the Ministry of information of Eritrea apart from the field, horticultural and tree crops the farm is well known for its dairy and pork production. The farm comprises of around 200 *holstein* and 100 *barka* breed cows and 600 pigs, for this study however only cows are considered.

In estimating the daily manure production the average body weight of a cow is taken as 450kg (Jatupat and Kidakan, 2013). Its manure production is also 36kg/450kg body weight (USDA, 1995). Nevertheless, considering the feeding practice, cows being two types of breeds, manure collecting facilities and cows' age factor, the daily manure production per head are taken as 10kg.

The design is done based on the following approach:

Quantity of manure produced in kg per day

$$Q_m = N_c \times M_c \quad (1)$$

Where: Q_m: quantity of manure (Kg), N_c: Number of cows, and M_c: mass of manure (kg/cow).

Total volume of slurry in the bio digester.

$$Vs = m_s / \rho_s \quad (2)$$

Where: V_s: Total volume of slurry (m^3), m_s: mass of slurry (kg), ρ_s: density of slurry (kg/m^3).

The height and diameter of a cylindrical dome toped reactor is set as:

$$V_{slurry} = \frac{\pi D^2 H}{4} = \frac{\pi D^3}{8} \quad (3)$$

Where: V_{slurry}: volume of slurry (m^3), D reactor diameter (m), H: height of reactor (m).

The total volume of the reactor equals:

$$V_{reactor} = V_{slurry} \times f_g \quad (4)$$

Where: fg: air and fixture factor.

The height (h_d) of the dome shaped gas holder taking the volume of the dome V_d will be calculated from equation below.

$$V_d = \frac{\pi}{6} h_d \left[3\left(\frac{D}{2}\right)^2 + h_d^2 \right] \quad (5)$$

The total volume gas production per day follows as:

$$V_g = R_p \times m_{s/day} \times M_{\%} \quad (6)$$

Where: R_p: rate of gas production (m^3/kg dry matter), $m_{s/day}$: mass of slurry fed in (kg per day), $M_{\%}$: mass percent of dry matter in manure.

Farm energy requirements

In this section the energy requirement of farming activities is going to be addressed. Therefore using basic mathematical expressions the energy cost for farming activities in the field has been calculated. The equation given below shows the relationship between power and energy.

$$E = P \times t \quad (7)$$

Where: P: Power (kW), E energy (kWh) and t: time (h).

The energy requirements of each farming tool are related with the amount of force needed for traction, working speed and efficiency of the operation. The American society of Agricultural Engineers ASAE has set an empirical equation and table of standards ASAE Standards D497 to calculate the force required for traction and the equation is given below (Harrigan and Rotz, 1995). For the purpose of calculating the energy requirements the farming activities tabulated below are selected.

$$D = Fi \times [A + B \times S + C \times S^2] \times WT \quad (8)$$

Where: D: Pulling force (N) Fi: Parameter for type of soil (heavy, medium and light), S average working speed required for every type of tool (km/h), W: length of unit (m), T: tillage parameters (cm) and A, B and C: machine specific parameters.

Area covered in one hour with the different implements considered will be given by the equation below.

$$H_t = W \times S \times \eta \quad (9)$$

Where: W: Width of plough (m), η: efficiency of the operation.

Results and Discussion

Biogas has a density of 1.15kg/m^3 (Jørgensen, 2009) at standard pressure and temperature and can be produced at a rate of 0.24m^3/kg of dry matter (Jørgensen, 2009). The range of dry matter content of cattle dung varies from 0.9% to 23%, which is an average of 12% depending on livestock and husbandry conditions (Scheftelowitz and Thrän, 2016). Moreover according to (Deublein and Steinhauser, 2008) the dry matter content of slurry ranges 7% to 17%. Therefore, for the sake of convenience, an average dry matter content of 12% is taken as a basis for the design procedure.

The total daily quantity of manure in the farm available from cows is given by equation (1):

$$Q_m = 300 \times 10 = 3000 kg / day$$

Therefore the total quantity of manure for an assumed retention time of 30 days is 90000kg.

Assuming the water manure mass ratio to be 1:1 the total mass of the slurry retained in 30 days is

$$m_s = 90000 \times 2 = 180000 kg$$

To calculate the total volume of slurry in the bio-digester the density of the slurry is taken as 1090kg/m^3 (reference) and is calculated using equation (2).

$$V_s = 180000 kg / 1090 kg / m^3 = 165 m^3$$

Efficient biogas production also depends on the structural parameters of the reactor. Thus based on literatures the height-to-diameter ratio is taken as 1:2 (Igoni and Harry, 2017). Equation (3) gives:

$$165m^3 = \frac{\pi D^3}{8}, D = 7.5m$$

$$H = D/2 = 3.75m$$

A factor fg=1.25 needs to be assumed to take into consideration the volume for air and fixtures (Deublein and Steinhauser, 2008). Then the total volume of the reactor equals:

$$V_{reator} = 165 \times 1.25 = 206.25m^3$$

From the above expression the volume of the gas holder equals (206.25 m^3- 1695 m^3 = 41.25m^3).

To fix the height (h_d) of the dome shaped gas holder taking V_d=139m^3 equation (5) is used.

$$41.25 = \frac{\pi}{6} h_d \left[3\left(\frac{7.5}{2}\right)^2 + h_d^2 \right]$$

$$h_d = 1.7m$$

The total gas production per day is computed using the rate of biogas production per dry matter multiplied by mass percentage of dry matter of the slurry in the reactor as it is shown in equation (6).

$$V_g = (0.24m^3 / kg(drymatter)) \times (6000kg / day) \times (0.12)$$

$$V_g = 173m^3 / day$$

To upgrade a biogas up to 95% methane content, the CO_2 which comprises 40% by volume has to be removed. Elabered estate owns well organized and structured sustainable irrigation system networks. Hence in upgrading the biogas to the desired methane level it is conducive to make use of water scrubbing method. The scrubbing method can be explained as: Raw biogas containing different gases is compressed and fed to a scrubbing chamber. Meanwhile, pressurized water is sprinkled from the top entrance of the chamber dissolving the CO_2 and other soluble gases while the methane content remains in gaseous state. Then methane is allowed to pass through a drying chamber to completely remove water vapors. Finally the upgraded methane can be further compressed and filled into gas balloons where it becomes ready for use. The water used for scrubbing can be either recycled by exposing it to air so that the dissolved gases escape or can be directed to the irrigation field. Figure 1 shows the general process of scrubbing method.

As a result of the removal of CO_2 from the raw biogas the total volume of usable methane decreases significantly. In other words, of the total (173m^3/day) biogas produced only 60% is methane. Hence the daily volume of methane produced gets reduced to 103.7m^3/day.

Note that the volume calculation is done at atmospheric pressure.

Energy content of the produced biogas

Pure methane has a calorific value of 11.06kWh/m^3 (Jørgensen, 2009). For 95% methane biogas the calorific value is 10.51kWh/m^3. Based on this value from the total daily volume of methane produced the daily energy generated is 1089.7kWh/day.

For the energy requirement analysis of the farming activities three practices are selected. With the help of the ASAE standards (Table 1) the energy requirement are computed.

Thus for the first faming activity taking a four bottom disc plough LY(T)-425, with a working depth and width of 25cm and 100cm respectively the draft force is calculated using equation (8) the energy requirement analysis follows below (Harrigan and Rotz, 1995).

$$D = 0.7 \times \left[652 + 0 \times 7 + 5.1 \times 7^2 \right] \times 1 \times 25$$

$$D = 15783.3N$$

After calculating the force D the power in KW will be as follows:

$$P = \frac{D \times S}{1000}$$

$$P = \frac{15783.3 \times 7000}{1000 \times 3600} = 30.7Kw$$

The area in hectare ploughed in one houris

$$H_t = \frac{1 \times 7000 \times 0.7}{10000} = 0.49ha/hr$$

Finally the amount of energy required in KWh is calculated using expression (7).

$$E = 30.7 \times 2.04 = 51.6kwh/ha$$

Likewise the energy requirement of the other two farming activities are computed and presented in table 2. While computing the results tabulated below an area of 100ha and for the calculation of total working days 10 working hours were assumed.

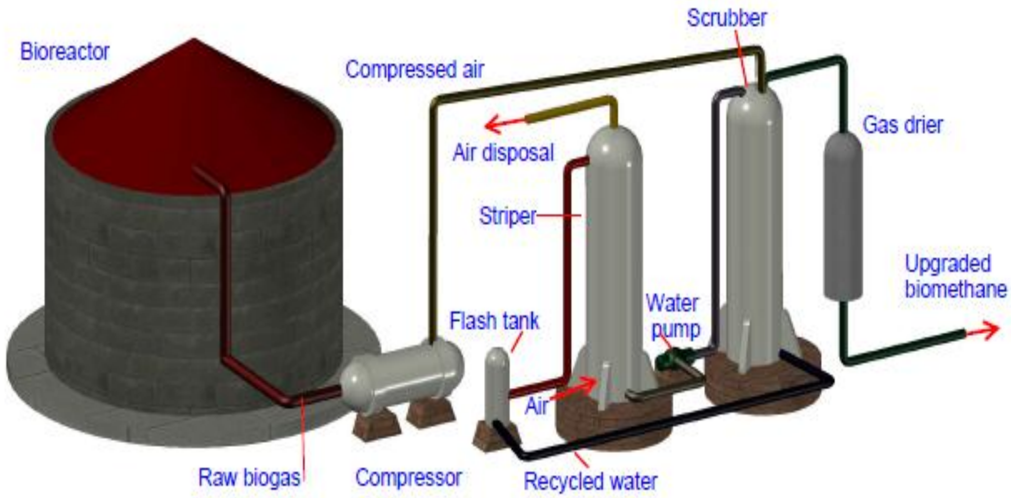
Table.1 ASAE Standards D497 Farming implements parameters

Farming tool	Speed Km/h	Efficiency	Farming tool's parameters			Soil parameters		
						F1	F2	F3
			A	B	C	Heavy	Medium	Light
Disc Plough	7	0.85	652	0	5.1	1	0.7	0.45
Disc harrow	10	0.8	309	16	0	1	0.88	0.78
Cultivators	10	0.85	46	2.8	0	1	0.85	0.65

Table.2 Energy requirements of farm activities

Implements	Parameters							
	Draft force(N)	Power kW	Area ha/hr	Time hr/ha	working hrs/100 ha	Energy kwh/ha	Energy kWh/100 ha	Total working days	kWh/day
Disc plow LY(T)-425	15783.25	30.69	0.6	1.68	168.07	51.58	5157.92	16.81	306.84
Disc harrow BDT-3	23073.6	51.27	1.92	0.52	52.08	26.71	2670.56	5.21	512.58
Cultivator KPS-8	2414	6.71	6.8	0.15	14.71	0.99	98.61	1.47	67.1

Fig.1 Scrubbing process of biogas



From the above computation the amount of energy that can be produced from the proposed biogas reactor is 1089.7kWh. Whereas the maximum daily energy requirement for ploughing with disc harrows of 100ha farm is 512.58kWh. It can be inferred that the proposed biogas reactor energy output can sustainably run the selected farming activities. The remaining energy can be diverted to self-powering the biogas plant accessories such as collecting manure and distributing digestate to the field, transporting feed to the dairy farm and other miscellaneous energy consumptions.

In conclusion, this case study implies that Elabered estate has a significant biogas production potential. The study considered only animal manure collected from the dairy farm. Employing only cow dung has shown that there is high energy generation capacity. However as the farm runs other activities like sheep and pig rearing, horticultural field and tree crop cultivation, it is clear that applying the maximum substrate inputs from all these waste yielding entities Elabered estate would contribute a considerable amount of energy to the national energy demand.

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