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A possible design and justification for a biogas plant at Nyazura Adventist High School, Rusape, Zimbabwe

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Abstract
The research study was carried out to assess the biogas potential at Nyazura Adventist High School, Rusape, Zimbabwe, a co-educational school with a total enrolment of 700 boarders. The school is connected to the national grid electricity. The electricity is in short supply due to long hours of load shedding. Firewood to be used for heating and cooking purposes is in short supply. The main objective of the study was to make an assessment of biogas potential at the school. The energy demand for the whole school was calculated and it was found to be 2 710 kWh per day. The biogas yields for the feedstocks at the school were estimated. The total biogas yield that could be obtained from the feedstocks was 50 m3 per day. The digesters volume for the feedstocks was estimated and the material requirements for the digesters were also determined. The techno-economic analysis of the proposed project was done. The results suggested that the proposed project was feasible, and it was concluded that the school is capable of producing enough biogas from its feedstocks to support a feasible project. The daily 50 m3 biogas yield is adequate to supply enough electricity for lighting purposes during the load shedding periods.

Keywords: biogas potential, techno-economic analysis, biogas digesters

1. Introduction

Biogas refers to a gas produced by anaerobic fermentation of organic matter in the absence of oxygen in airtight containers called biogas digesters (Walekwa et al., 2009; Sibisi and Green, 2005). The composition of biogas varies depending on the raw materials, the organic load applied, the retention period and temperature. The gas consists mainly of methane, which is generally between 55%-80% (Jemmett, 2006). Biogas contains about 9 kWh/m3 of available energy (Thouars, 2006).

Biogas is about 20% lighter than air and has an ignition temperature in the range of 650-750 °C (Deublein & Steinhauser, 2008). It is an odourless and colourless gas that burns with a blue flame similar to that of liquid petroleum gas (Sathianathan, 1975).The biogas anaerobic process is divided into four steps as follows: hydrolysis, fermentation (acidogenesis), anaerobic oxidation (acetogenesis) and methanization (Davidsson, 2007; Goswami & Kreith, 2008; Leksell, 2005). Figure 1 shows the degradation pathways to produce methane.

Biogas technology can be viewed as a vehicle to reduce rural poverty and leads to rural development. Biogas can be an energy substitute for animal waste, fire wood, agricultural residues, diesel, paraffin, petrol and electricity. In addition, eutrophication and air pollution are minimized (Lantz *et al*., 2007). Furthermore, it eliminates the daily task of fire wood gathering (Mwakaje, 2007). Biogas can be regarded as an eco-friendly fuel and can be used as a substitute for compressed natural gas.

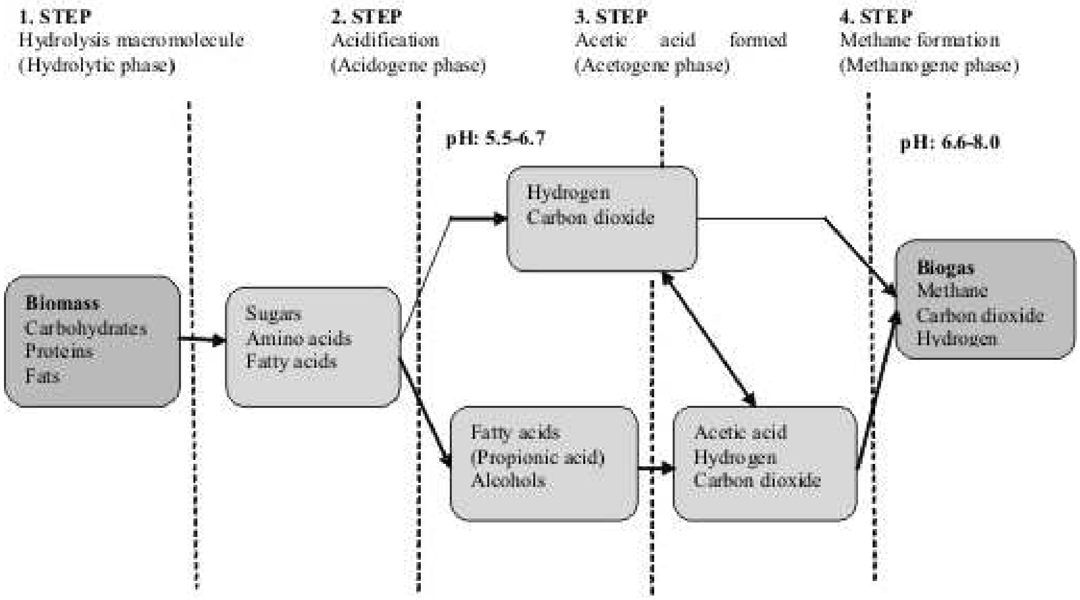

Figure 1: Four steps of anaerobic digestion (Gerardi, 2003)

Zimbabwe is endowed with plenty of anaerobic digestion feedstocks but the technology is not optimally applied in the conversion of these feedstocks (Jingura & Matengaifa, 2009). Zimbabwe is heavily dependent on fossil fuel imported from the Middle East. To worsen the situation, the country has a shortage of foreign currency for importing fossil fuel.

There are a number of biogas digesters producing biogas in Zimbabwe, at Glen View Firle and Crowborough sewage treatment works in Harare. However, the biogas from the primary biogas digesters is carried to biogas tanks and burnt in air without being utilised (Mukumba, 2007). The biogas digesters were installed at these activated sewage treatment plants as a way to treat sewage but not to produce biogas for utilisation. These digesters are producing biogas that has enough energy to drive several other industrial operations that require large amounts of power. There are some biogas digesters that were installed in Chishawasha, Harare and Kushinga Agricultural College. However, these digesters are not operational due to lack of knowledge for operating these digesters.

The main objective of this paper is to assess daily biogas potential for Nyazura Adventist High School and use the information to design the biogas digesters for the mission high school.

2. Description of the study area

The study was carried out at Nyazura Adventist High School. The school is 1200 m above sea level and was established in 1910. It is located closer to the Harare-Mutare highway and is 33 kilometres from Rusape town and 63 kilometres from the city of Mutare. It is a co-educational boarding school with a total enrolment of 700 students.

The school is located at the foot of Mount Matukashiri. The school area is covered with stable rocks. These rocks are granitic in nature. The area is free from earthquakes and earth tremors due to good rock stability and therefore, building a biogas digester is advantageous to the school since rock stability prevents cracking of digesters thereby preventing gas leakages through the digester walls. In addition, the school area has sandy soils that are suitable for growing of crops such as tobacco. Figure 2 shows Nyazura Adventist High School.

2.1 The school's energy requirements

The boarding school is connected to the national power utility grid. However, like most other consumers in Zimbabwe, it suffers from electricity supply interruptions due to recurring load shedding. To relieve the situation, a 60kVA diesel generator was installed to supply electricity during load shedding. However, the rising costs make it impractical to run the generator for long hours as operating costs become very high and unaffordable. The other two generators (100 kVA and 80 kVA) donated by the Reserve Bank are not in use. The water for the school comes from a nearby school dam. Before the water is harnessed, high-powered centrifugal pumps first pump it into reservoirs. These pumps are powered with electricity. The school bus, a Mazda T35 truck, tractors, generator set and diesel pumps use diesel as fuel.

Eutrophication is a process in which bodies of water such as lakes, ponds, and rivers receive excess nutrients for example nitrogen and phosphorous that stimulates excessive growth of algae.

Firewood is now a popular fuel at the school because grid electricity is no longer reliable. The firewood is used for cooking and heating purposes especially during load shedding periods that can last up to 15 hours. This paper seeks to assess biogas potential at the school so as to minimise energy problems at the school by using biogas as an alternative fuel for mainly lighting the whole school. The study came as result of current energy related problems the school is facing such as shortage of water due to long hours of load shedding and shortage of firewood. To worsen the situation, the copper cables supplying the electricity to the school are often vandalised. The most recent vandalisation of copper cables was in November, 2011. This adversely affected students' reading hours especially Upper Sixth and Form Four students. Due to the current price of diesel, the generator set is operated only for few hours a day.

However, the school has plenty of biogas substrates, namely, cow dung, human excreta and vegetable wastes. The importance of the waste materials in meeting the needs of the school is not being realised. These substrates when fed into the digester produce biogas and the digester sludge is ploughed back into the fields thereby improving soil fertility. The biogas from this waste material can be used by the school as a source of cheap energy.

3. Methodology

3.1. Biogas feedstocks

The study examined the total gas yield of the following feedstocks at the school; human excreta, cow dung, and chicken manure. This involved physical counting of learners, teaching and non-teaching staff, chicken and cattle at the school. Total biogas for all the feedstocks was then estimated.

3.2. Energy requirements

Premises at Nyazura High School that consume electricity were identified and these were: the school library, school church, administration block, computer laboratory, classrooms, boys' dormitories, girls' dormitories, dining halls, workshop and tuckshop, staff houses, pumps (7.5 hp and 10 hp), and the home economics department. Table 1 is an example of how total energy demand for dining halls was obtained.

3.3. Biogas digester sizing

The volumes of the digesters were calculated from the following equations (Shonhiwa, 2005):

$$V_d = S_d \text{ x } R_t \qquad (1)$$

where:
V_d = volume of the digester in cubic meters
S_d = amount of substrate in kilograms
R_t = retention time in days

Therefore,

$$V_d = (B + W)R_t \qquad (2)$$

where:
B = Biomass (kg)
W = Water (litres)

Biogas production was calculated using equation 3.

$$G = V_s \text{ x } G_y \qquad (3)$$

where:
V_s = weight of feedstock available per day in kilograms
G_y = Gas yield in cubic meters
G = biogas production in cubic meters

Gas production rate was calculated using equation 4.

Table 1: Energy requirements for dining halls

Load (Devices)	*Number of each device*	*Power rating [W]*	*Power rating [kW]*	*Operating tim e [h]*	*Total energy [kWh/ day]*
Dining hall (F1-4)	24	40	0.040	4	4
Dining hall (F1-4)	3	60	0.060	4	1
'A' Level dining hall					
14	40	0.040	4	2	
'A' Level dining hall	14				
	60	0.060	4	2	
Cookers	6	2 000	2	12	
	144				
Refrigerator	1	41 500	41.5	24	
	996				
Oven	1	25 000	25	12	
	300				
Total					1449

$$G_p = G/V_d \quad (4)$$

where:
G_P = gas production rate in cubic metres per day
G = biogas production in cubic metres
V_d = digester volume in cubic meters

Recalling equation (3), equation (4) can be written as:

$$G_p = G\,V_d = V_S G_Y \quad (5)$$

Figure 2 shows the fixed dome digester design for the cow dung, chicken manure and human excreta. Fixed dome plants were chosen because they can last for over fifty years and they are easily insulated and scum formation is less due to the digester slurry that is displaced (pushed out) by incoming feed (influent). A fixed dome digester is an underground biogas digester lined with brick, with a dome-shaped cover made from concrete. The cover is fixed and held in place with earth piled over the top to resist the pressure of the gas inside. A second pit, the slurry reservoir, is built above and to the side of the digester. As the gas is given off by slurry, it collects in the dome and displaces some of the slurry into the reservoir. As the gas is used, the slurry flows back into the digester to replace it.

The digester presented in Figure 2 would be modified to include a heating system for optimum biogas production. Figure 3 shows the heating system proposed. The heating system would involve

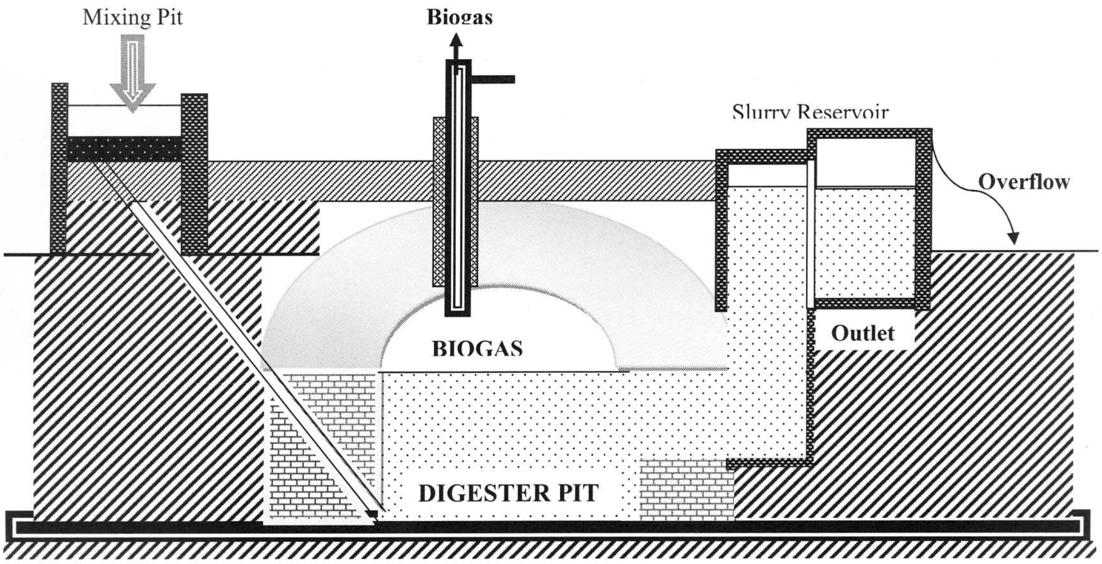

Figure 2: Fixed dome digester for the substrates
(Adapted from Fulford, 2001)

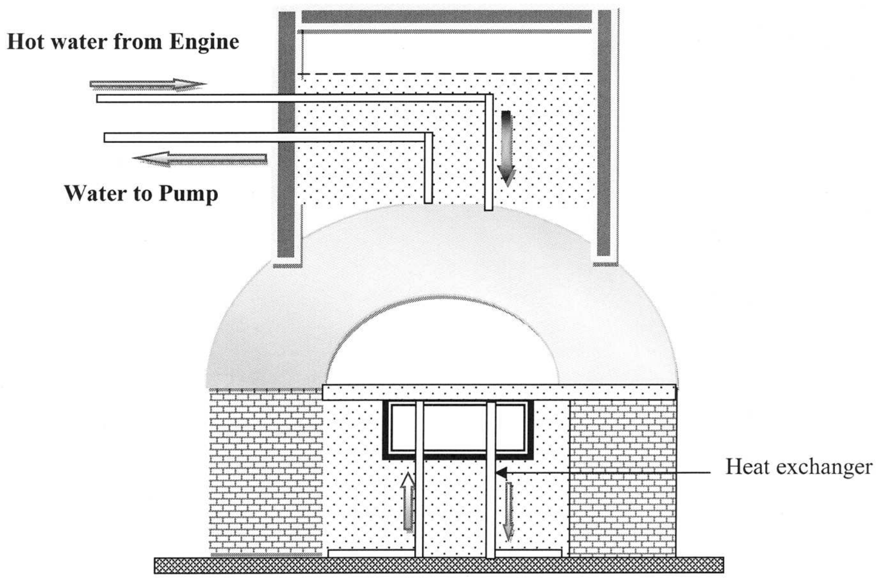

Figure 3: Biogas digester with heat exchanger (own design)

the use of the engine cooling water, which would be at 65°C. This water would be transported from the engine to the digester by means of copper tubes. The tubes would be placed at the bottom of the digester. The heat would flow from the tubes to the slurry thereby maintaining desirable temperature for maximum biogas production.

3.4. Material requirements for the digester

The material requirements for the biogas digester construction were estimated, such as cement, steel, wire mesh, paint, aggregate, sand, bricks and labour costs.

3.5. Economic analysis methods

The techno-economic analysis for the project was used to evaluate the favourability and profitability of the biogas investment project. The economic indicators considered were the investment costs, the liquidation yield, the total operational costs, total income and revenues, cost comparison, cost annuity comparison, profitability, static Pay Back Period (PBP), Net Present Value (NPV) and Internal Rate of Return (IRR).

3.5.1. Procedure for financial evaluation

The procedure for financial evaluation is determined by Finck and Oelert (1985).

3.5.1.1. Cost annuity comparison, A_k

Cost annuity is the annual total cost of the biogas digester

$$A_K = K_0 + (1_0 - L) \text{ x } R_F(i,t) + L \text{ x } i) \quad (6)$$

where:
A_K = cost annuity (US $)
K_0 = the operating costs per unit of time (US $)
I_0 = investment costs (US $)
L = liquidation yield (years)
R_F = recovery period (years) and is a function of assumed interest rate and the project duration
i = assumed interest rate (%)
t = the project duration (years)

3.5.1.2. Profitability

Profitability or return on investment (ROI) is the average profit per time interval on an investment project or the profit of the plant per annum.

$$ROI = \frac{N_p}{K_A} \times 100 \quad (7)$$

where:
ROI = return on investment [US $]
N_P = average net profit per time interval
K_A = average capital invested

3.5.1.3. Pay-back period

Pay-back period is the time at which the capital invested in an investment project will be recovered by the annual returns.

$$n = \frac{\text{capital investment}}{\text{annual return}} \quad (8)$$

where:
n = payback period (years)

3.5.1.4. Net present value

Net present value (NPV) of an investment project is the sum of the present values of all the cash inflows and outflows linked to the investment.

$$NPV = -I_0 = (R \times PF) + L_T \times q^{-T} \quad (9)$$

where:
NPV = Net present balue (US $)
I_0 = investment costs (US $)
PF = present value factor (years)
R = annual returns (US $)
L_T = liquidation yield at the end of service life (years)
q^{-T} = discount factor (years)

3.5.1.5. Internal rate of return

Internal rate of return of an investment project is the achievable interest tied-up in the investment.

$$IRR = i_1 - NPV_1\left(\frac{i_2 - i_2}{NPV_2 - NPV_1}\right) \quad (10)$$

where:
IRR = Internal rate of return
NPV_1 = Net present value 1
NPV_2 = Net present value 2
i_1 and i_2 are discount rates

3.5.1.6. Annuity method

The annuity is the constant annual payment for an investment.

$$A = NP \times RF\ (iT) \quad (11)$$

where:
A = annuity
T = a known planning period in years
i = discount rate

3.5.1.7. Present value factor

$$PF = \frac{q^t - 1}{q^t (q - 1)} \quad (12)$$

$$q = 1 + \frac{i^*}{100} \quad (13)$$

where:
i* = market interest rate
t = time of payment (years)

$$i = \left(\frac{1 + i^*}{1 + f} \right) - 1 \quad (14)$$

where:
f = inflation rate

Liquidation yield is the estimated value of a plant at the end of its useful life or fixed service life.

Recovery period is the designated period for depreciation of a plant.

An annual return (R) from an investment of a project is the difference between total incomes and operating costs (Finck & Oelert, 1985).

Present value factor (PF) is a factor used to calculate present value of money on a future period.

NPV of an investment project is the sum of present value of money moving into or out of an investment project.

Market interest rate (i*) is the interest rate for external or internal financing (Finck & Oelert, 1985).

3.6. Sizing of the electric generators

For the sizing of the electric generators, the following equation was used:

$$P_{(kW)} = S_{(kVA)} \times Pf \quad (15)$$

Where;
$P_{(kW)}$ = power in kilowatts
S (kVA) = generator size in kVA
Pf = power factor

The power factor (Pf) for each electric biogas generator was assumed to be 0.8 and the average electric efficiency of each biogas generator was assumed to be 40% due to lower heating of biogas. Furthermore, it was assumed that 1 m^3 would produce energy equivalent to 9 kWh.

4. Results and discussions

4.1. Electricity requirements

The total electricity requirements for Nyazura Adventist High School are shown in Table 2.

The highest proportion of energy is consumed by activities in the dining halls. The school has a total energy requirement of 2 751 kWh/ day. The total energy requirements for the two dining halls are 1449 kWh/day. Dining halls are consuming 53% of the electricity supplied to the school because they have the following devices that consume large amounts of electricity; cold room (996 kWh/day), one oven (300 kWh/day) and six cookers (144 kWh/day). The electricity supplied to the boarding school is used mainly for water heating, cooking, lighting, welding and water pumping.

Table 2: Electricity needs for the whole school

Energy demand areas	Total energy (kWh/day)
Computer laboratory	32
Classrooms	39
Administration	14
School library	4
Boys' dormitories	37
Girls' dormitories	33
Dining halls	1449
Workshop and Tuck-shop	93
Pumps (10 Hp and 7.5 Hp)	403
Staff houses	600
School church	7
Home economics department	40
Total	2 751

4.2. Total gas yield per feedstock

The dung produced by cattle per day per animal is 10 kg, and 1 kg dung of cattle produces 0.036 m^3 of biogas (Nijaguna, 2002). Since the cattle are not pastured, it was assumed that collectable waste per day was 5 kg. In addition, 1 kg chicken manure and 1 kg human waste produce 0.062 m^3 and 0.070 m^3 per day respectively. Table 3 shows the estimated gas yield per feedstock available at the school.

It is clear from Table 3 that the total biogas yield for the feedstocks is 50 m^3/day. Human waste had a total gas potential of 27 m^3 /day, chicken manure a total gas yield of 4 m^3/day and cow dung a total gas yield of 18 m^3. Assuming that 1m^3 of gas produces 9 kWh of energy, the 50 m^3 of biogas could produce 450 kWh/day of energy. The school is capable of producing energy of 13 500 kWh from its waste material per month. The installation of the

Table 3: Total estimated gas yield per feedstock

Feedstock Type	Total number of animals	Gas yield m^3/kg	Manure per animal per day (kg)	Gas yield per day (m^3)	Total gas yield per day (m^3)
Cattle dung	100	0.036	5.00	0.18	18
Chicken manure	500	0.062	0.18	0.011	4
Human waste	960 (secondary school learners & families)	0.070	0.40	0.028	27
Human waste	50 [primary school pupils]	0.070	0.10	0.007	1
Total					50

digesters at the school can therefore reduce the energy shortage in the school. The total daily biogas produced at the school would meet 16% of the total energy demand. The quantity of daily biogas production would be increased by increasing the number of cattle and chicken kept at the school. Since the demand for biogas would be low during school holidays, the school would pump excess biogas by means of biogas pumps into the bio-bags for storage.

4.3. Digester volume for each feedstock

Table 4 shows the calculations results of digester volume for cattle dung, chicken manure and human waste. Equations 1 and 2 were used to calculate the digester volume. The mixing ratio of the biomass (cow dung) to water was 1: 1 and the retention time was 50 days. In addition, the mixing ratio of the biomass (chicken manure) to water was 1: 5 at a retention time of 50 days and furthermore, the mixing ratio of the biomass (human excreta) to water was 1: 1, 5 at a retention time of 40 days.

Table 4: Digester volume for each feedstock type

Feedstock type	Volume of the digester (m^3)
Cattle dung	50
Chicken manure	27
Human waste	37

The volume of the digester for cattle dung was 50 m^3, and for chicken manure was 27 m^3 and finally, for human waste was 37 m^3. The school would build three fixed dome biogas digesters for the feedstocks so that the digesters would be used concurrently and in addition, when one digester is under maintenance the other digesters would be producing biogas. Furthermore, it would be expensive to have one biogas digester that would use a mixture of cow dung, human waste and chicken manure since this would involve carrying some feedstocks from longer distances to the digester. Therefore, the chicken manure digester would be closer to the chicken broilers and cattle dung digester could be constructed in the cattle pastures.

4.4. Construction materials for the digesters

Table 5 shows the construction materials for the biogas digesters and these include cement, steel bars mesh wire, oil paint, aggregate, sand and bricks. In calculation of the material requirements for the biogas digesters, the gas production rate was calculated first from equation 3. For the equation, the value for biogas yield in m^3/kg for each feedstock was obtained from Table 3 and in addition, the weight of dung available per day (kg/day) was also obtained from the same table. For example for cow dung, $G = 500 \times 0.04 = 20\ m^3$, where 500 represents weight of cattle dung (kg) available per day and 0.04 was the estimated biogas yield of cattle per kg (Table 3).

Tractors at the school could be used to transport cement, bricks and sand to the construction sites. Farm bricks would be used for the construction because they are cheap and locally available. The permanently employed mission workers would be involved in the construction of the digesters. These workers included builders, welders, farm brick moulders, carpenters, drivers and groundsmen.

4.5. Calculation of the electric biogas generator sizes

Equation 15 was used to size the three electric biogas generators for cow dung, chicken manure and human waste. The assumptions made in the calculations are in section 3.6. For the cow dung having a biogas yield of 18 m^3, the size of the electric generator would be 80 kVA, and for the 4 m^3 biogas yield from chicken manure a 20 kVA generator set would be used. Lastly, the 28 m^3 biogas yield from human waste would require 120 kVA generator set. Therefore, the three generators at the high school would be used to harness the biogas for the electricity generation.

4.6. Biogas production and distribution

Figure 4 shows a schematic diagram for the biogas production and distribution system. Sewage from the school community would be carried by means of pipes to the sewage sump. The sewage sump gate directs the sewage either into the sewage pond or mixing pit. When sump gate A is open while gate B is closed, the sewage gets into the sewage pond. When gate A is closed while gate B is open, the sludge gets into the mixing pit. In the mixing pit, water is continuously added to the sludge until a correct sludge water-mixing ratio is obtained. A homogeneous mixture of water and slurry in the mixing pit is maintained by using a mechanical stir-

Table 5: Material estimates for the digesters
(Nijaguna, 2002)

Feedstock	*G (m^3)*	*Cement bags*	*Bricks No*	*Sand (m^3)*	*Aggregate (m^3)*	*Steel (kg)*	*Mason (days)*	*Mesh wire (kg)*	*Labour (days)*	*Paint (L)*
Cattle dung	20	91	10 184	10.85	3.89	221	33	66	148	7.0
Chicken manure	6	40	5 121	5.05	1.29	74	16	31	68	3.0
Human waste	27	115	13 239	13.0	5.06	276	41	85	192	9.0

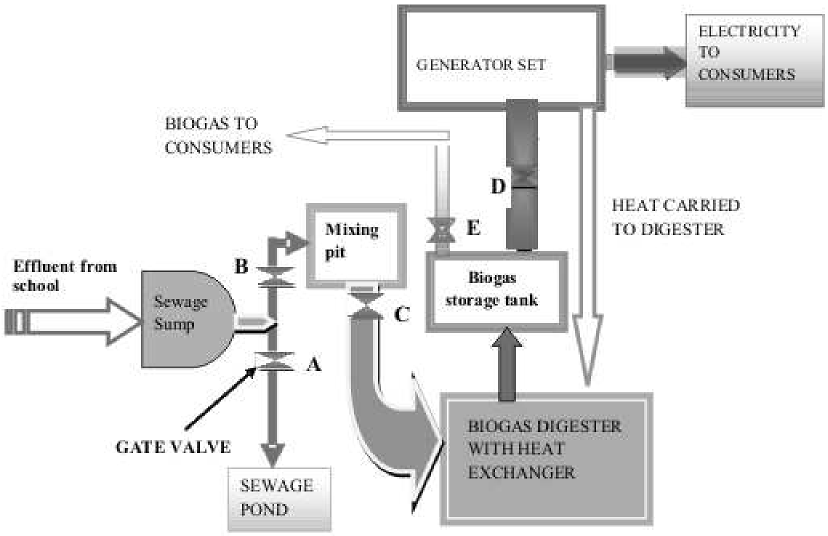

Figure 4: Schematic diagram showing biogas production and distribution

rer. When the desired mixture is obtained, gate C is opened, and the sludge then enters the dome digester. The biogas is produced in the biogas digester by anaerobic digestion process.

The heat exchanger system at the bottom would provide suitable temperature around 35°C, for anaerobic digestion. The mechanical stirrers distribute heat evenly in the biogas digester. From the digester the biogas is collected in the storage tank. When valve D is open biogas would flow to the generator set. The generator would use the biogas to produce electricity. The electrical energy from the biogas generator would be used for lighting and heating purposes at the school. When biogas is used as fuel for the diesel generator, the modification required for the generator would be replacing the diesel injector by a spark plug. The electricity from the generator set would be mainly used for lighting classrooms, dormitories, houses and for cooking. In addition, biogas can also be utilized directly from the biogas storage tank to fuel gas stoves, gas heaters and gas refrigerators.

Table 6: Total investment costs

Description	Quantity	Unit price (US$)	Total (US$)
50 kg cement	230	7.00	1,610
Bricks	27 000	0.01888	510
6m length of 27 mm gas pipes	10	30.00	300
4 m length asbestos pipes-110 mm	15	35.00	525
Steel (kg)	552	2.00	1 104
Mesh wire (m^2)	82	1.00	82
6 m length of copper			
tubes-25 mm	6	30.00	180
Sand (m^3)	26	19.00	500
Aggregate (m^3)	10	30.00	300
Paint (litres)	18	10.00	180
Generator modifications	2	1,200	2 400
Heat exchangers	1	600	600
Others			666
Labour			1 000
Total			9 957

4.7. Economic analysis of the biogas project

The investment costs for the digesters were calculated and the results are summarized in Table 6. From Table 6, the total investment costs for the biogas digesters are US$ 6957.

Table 7 shows the techno-economic analysis data for the investment project. The calculated values on Table 7 were obtained through equations 6 to 14 on procedures for the financial evaluation.

Table 7: Techno-economic analysis data for the investment project

Parameter	*Calculated value (US$)*
Investment costs	9 957
Operating costs	58 334
Manpower costs	1 500
Repair and maintenance costs	2 000
Energy related costs	300
Revenues	1 152
Other income and subsidies	8 000
Total income	9 152
Returns	5 485
Cost comparison, K	6 857
Cost annuity	6 845
Profitability (ROI)	87%
Payback period	2 years
NPV	22 435
Annuity	5,048
Dynamic payback period	2 years

From Table 7, the repair and maintenance costs were US$ 2 000, the energy related costs were US$ 300.00 and the cost comparison was US$ 6 857. The cost annuity was US$ 6845 and the Net Present Value was US$ 22 435. The dynamic payback period was one year.

The economic analysis of the biogas project showed that the project is financially feasible. The Net Present Value is high and positive showing the feasibility of the investment on the project. The payback period was short implying that the project pays itself off within the service life or within a set payback limit, which must be shorter than the technical service period of 5 years.

5. Conclusion and recommendations

The total energy requirement for the school is 2 710 kWh per day and the total energy from biogas of the feedstocks was 450 kWh/day. Therefore, the biogas would contribute to 16% of the total energy needs of the school. The total energy for lighting was 135 kWh/per day. It can be concluded that lighting for the whole school takes only 30% of electricity that is generated from the biogas. Therefore, the other 60% of electricity from biogas would be enough for all electricity requirements in the following; computer laboratory, classrooms, administration block, school library, boys and girls laboratories. The remainder 10% of electricity from biogas would add to the cooking needs supported by the electricity from the grid. The calculated annuity, the dynamic payback period and the net present value (NPV) are high. This can be concluded that the project is favourable, profitable and worth undertaking.

Technical problems of the digesters include a lack of trained operators, poor equipment design and failure to feed the digester regularly. It can be recommended that operators require induction courses for the digesters to be operated more efficiently. The school should have ready information on operation of digesters and in addition operators should be kept updated with relevant information on biogas digesters. Furthermore, the opening and closing of the gas outlet and main gate valves must not be cumbersome and the feedstock should be fed into the digester when correct amount of water is mixed with it. The most favourable total solids (TS) value desired for better biogas production is 8% (Ituen *et al.,* 2007). The pH changes in the digester would affect methane formation process and therefore, pH fluctuation would be controlled by the addition of wooden ash at zero cost. However, temperature fluctuations in the digesters would be minimal since the digesters would be constructed underground.

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