Design Optimisation of a Combined Heat and Power Supply Bio-Reactor: A Case of Koala Park Abattoir, Harare

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Abstract

This article proposes a dynamic design methodology for optimising bio-methane yield for applications in combined heat and power system for an identified urban abattoir. A discrete number of substrates were examined to obtain the physicochemical characteristics of each feedstock available at Koala Abattoir, located in urban Harare. Biochemical methane potential of each substrate was obtained through manipulating Chen–Hashimoto kinetic equations as applied in anaerobic digestion. Specific methane yielding equations at different volatile solid (VS) content for each discrete feedstock, thermal and electrical conversion efficiency equations and manipulated economic analysis equations were integrated into the Excel spreadsheet model. The proposed system can generate 1564 MWh of electrical energy and 2138 MWh of thermal energy per year. Economic performance metrics gave an IRR of 38.99%, an NPV of $887 298 and a pay-back period of 3.10 years. The system has a LCOE of $0.06/kWh with the potential to avert 1722 tons of GHG per year. It was postulated that when optimally integrated, the model can be successfully applied in assessing the viability of integrating any bio-reactor in a CHP system.

Keywords: *biogas model, combined heat and power, physicochemical characteristics, economic analysis.*

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INTRODUCTION

Abattoirs, are industrial places usually located in urban areas where animals, such as cattle, goats, sheep and others, are slaughtered in for consumption as food and they are often termed slaughterhouses. Livestock production in abattoirs is considered as potential food for the world's needy people in urban and rural areas. During meat production, a huge amount of abattoir waste is generated. Koala Park Butchery and Abattoir was established in 2002, operating in the business of livestock and meat processing. Owing to the past land reform and current land order, production modules have changed and exciting marketing initiatives have opened new opportunities to the abattoir to serve the small-scale productive sector. This under-funded sector will benefit from new technologies and better production methods.

With the current national herd at 4.5 million cattle, the same as when Cold Storage Commission (CSC) was exporting in 2000, it proves that cattle numbers are still healthy nearly two decades later. While the formal markets are being affected by liquidity constraints and high costs of regulation compliance, the industry has opened up to huge participation from the informal market. The need is to increase off-take percentage of the current base (commercialisation) and to carry out genetic restocking of the bull and heifer. Koala Park is continuously reforming through the introduction of a fully integrated production line from breeding, back grounding, feed-lotting, slaughter to retail and formal markets.

Currently, the total capacity utilisation for the Koala Park infrastructure is at 50% with an average annual slaughter weight for 50 000 head at 180kg. Presently, Koala Abattoir slaughters only 25% of the cattle from feedlots at 240kg with a return of 22% on this venture (Koala, 2020). By growing their own feed, generating own power from abattoir waste and through efficient utilisation of available products, Koala Park can significantly increase their market share and returns. The biogas or energy generated from the abattoir waste can replace firewood and charcoal and the expensive fossil fuels and grid electricity.

Biogas is a source of renewable energy which can be regarded as eco-friendly. It is a product of anaerobic digestion of organic matter. It is produced from a variety of raw materials, such as food waste, agricultural waste, municipal solid waste and sewage, among other biodegradable materials. Biogas production has not been developed on large commercial scales, especially, in Africa, and most people are still relying on non-renewable and quickly-running-out fossil fuel sources of energy (Ajenikoko, 2018). According to the Food and Agricultural Organisation (FAO, 2012), 327 hectares of woodlots were destroyed between 1990 and 2010 in Zimbabwe alone. In the developing countries, wood fuel is used for domestic and commercial purposes. There are many families, still relying on wood fuel and even cow dung, for their heating and lighting purposes, thereby posing a serious health hazard.

In Africa, there are more than 591 million people without access to electricity though with vast energy potentials yet to be exploited. A survey conducted in 2014 revealed that 1.2 billion people in the world were deprived of communication tools, proper health facilities and proper lighting, among other things, due to lack of access to reliable sources of energy. Of these 1.2 billion, more than 50% lived in sub-Saharan Africa. In areas where electricity is available, service delivery is poor, due to obsolete equipment (Van *et al.*, 2018; Gozan, 2018).

Most of the existing biogas generation systems in sub-Saharan Africa are not operating efficiently. The reasons for poor performance are inadequate and shortage of skilled manpower, unqualified consultants and contractors and use of substandard construction materials in the construction of the biogas systems. Another hindrance in the successful implementation of biogas systems is the availability of water. Inadequate water supply is a stumbling block in the successful implementation of biogas systems. All these factors contribute to biogas system failures and the negative image portrayed by such failures suppresses all the advantages of a well set up biogas system (Kasali, 2015).

Due to the lack of adequate knowledge and tools that can aid in design and construction of biogas systems, some of the existing biogas plants are becoming generators of methane. There are no set means of quantifying the gas demand and matching it with the gas produced. Excess gas is released into the atmosphere without flaring, that is very detrimental to the environment (Twumasi, 2016).

The huge potential of biogas systems lies in areas where large amounts of organic waste are generated. These areas include farms, slaughterhouses, sewage treatment plants and large institutions, such as prisons, and schools, that generate high volumes of human waste. On farms, the organic waste from animals is spread onto the field as organic manure. The organic matter undergoes anaerobic decomposition when it is heaped for prolonged periods and some amount of methane is released into the atmosphere. At the same time, this type of organic manure increases the cost of production to the farmers because of the weeds which grow as result of the untreated organic manure (Hildebrandt, 2017).

Waste disposal is becoming a hurdle for many abattoirs. Many different types of waste are generated from abattoirs. The waste includes rejected meat, undigested food from the stomach, bones, blood, gut contents and urine, among other things. In most cases, slaughterhouse waste is disposed of into water bodies and a percentage of it is disposed of into municipal sewer-systems contributing largely to pipe blockage, due to accumulation of fats. Thus, abattoir waste contributes to water, air and land pollution. To try and treat or dispose of the organic waste, composting, rendering, burial and incineration techniques are employed. However, all these techniques have various negative impacts on the environment (Brown, 2006; Herag, 2018).

Despite its potential to improve energy supply, sanitation and food supply, uptake of biogas systems has been trailing at a snail's pace. Investing in the biogas sector is regarded as a risk venture, making it difficult to obtain funds for setting up biogas systems be it from government or private institutions. In sub-Saharan Africa, political will is lagging behind, due to lack of proper policies to support implementation, research and development of biogas systems (Kasali, 2015).

The ever-rising prices of conventional power sources and the need for proper waste management techniques favours the implementation of biogas systems. Since the adoption of biogas systems can be deemed to be a viable option for renewable energy delivery system, waste management techniques and a source of organic fertiliser, there is need for the optimisation of the biogas generation process to allow for maximum biogas production, and, ultimately reduce the cost of designing and construction of biogas systems (Manjusha, 2016).

METHODOLOGY

The methodology involved developing a simple Microsoft Excel-based techno-economic model for determining and optimising biogas generation. An in-depth analysis of literature on biogas and Combined Heat and Power (CHP) system operations was conducted. The model included the capabilities to determine the integration of the biogas into CHP systems, carrying out economic analysis of such systems and determination of the most economic CHP system to operate. The developed model was applied to assess the potential of setting up a biogas CHP system at Koala Park in Harare.

A range of different biomass resources was analysed from the literature and the sources were categorised. The physicochemical characteristics of each resource in the study were determined.

The resource analysis for Koala Abattoir was conducted. The feed stocks considered in this study were cow dung, pig waste and solid waste from the separated slaughtering areas. The amount of cow dung and pig waste available was quantified by multiplying the average number of cattle waiting to be slaughtered by the average dung excreted by each beast. The amount of solid slaughterhouse waste was obtained by weighing the quantity of waste obtained at the end of each day, for three separate days. The final figure was the average of the three figures. Solid waste figures were compared with figures given by staff members at the abattoir.

The meteorological data of the site in question was found online as a Typical Metrological Year (TMY). The relevant information to the study was the average temperatures in Celsius degrees(°C). Chen-Hashimoto mechanistic equations were used to formulate the model that predicts biogas output using Microsoft Excel. The following equations were used to model biogas production:

$$B = B_0\left(1 - \frac{k}{\mu_m\theta - 1 + k}\right) \qquad (1)$$

Where,

B- Methane yield

B_0 – The ultimate methane yield

k- Kinetic parameter on the performance of the reactor

μ_m- Maximum specific growth rate of microorganisms

θ- Retention time

$$Bo = (415)\eta_C + (496)\eta_P + (1014)\eta_l \quad (2)$$

Where,

η_C- percentage of carbohydrates in slurry

η_P- percentage of proteins in slurry

η_l- percentage of lipids in slurry

$$\mu_m = 0.013T_0 - 0.129 \quad (3)$$

Where,

T_0- operating temperature of the bioreactor

$$k = 0.6 + 0.0006 \exp(0.1185 S_{TO}) \quad (4)$$

Where,

S_{TO}- Influent substrate concentration

The model predicts methane yield potential and to come up with the total biogas yield, it was assumed that the biogas contains 60% methane. This study concentrated on optimising biogas production by determining the optimum operating points of three physical parameters: temperature, organic loading rate and hydraulic retention time.

Determination of optimum operating temperature was done by plotting a graph of biogas output against temperature. Another graph of temperature against the rate of change of biogas output with an increase in temperature. After analysing the two graphs, an optimum operating temperature was chosen. Determination of the optimum organic loading rate (OLR) was done by plotting a graph of biogas output against different OLRs. After analysis of the graph an optimum OLR was chosen that would give an optimum biogas output without compromising the size of the digester. Determination of the optimum hydraulic retention time (HRT), a graph of biogas output and digester volume was plotted against varying values of HRT. A value was chosen that gives optimum biogas yield with the least possible digester size. To support the selection of the optimum HRT, a graph of OLR against HRT was plotted. The optimised OLR was then used to select the HRT.

For the effective operation of digester, it has to be supplied with thermal energy to maintain optimum operating temperatures and electrical energy to run the pumps and stirring machines. These two loads are referred to as parasitic loads. Either energy has to be supplied from an external source or supplied from the energy being generated on site. The latter reduces the overall energy output of the system.

The digester system has its own electrical load emanating from the use of pumps and stirrers. The electrical load is calculated using data from literature which states that for every cubic metre of a digester, the electrical power demand is 2kWh. Thus, 2kWh per each m^3 digester.

$$\textit{Electrical power demand} = 2kWh * \textit{digester volume} \qquad (5)$$

For economic analysis, the model was developed to assess the economic viability of the biogas-CHP project and also to enable the selection of the appropriate CHP technology to be implemented. Determination of cost savings was done by evaluating the costs of energy to be displaced by the energy from the CHP system, and revenue was determined by evaluating excess energy to be fed into the grid. The amount of excess energy to be fed into the grid was to be multiplied by the Feed-in tariff (FIT). A number of techniques were used and these include the Net Present Value (NPV), Internal Rate of return (IRR), Simple Payback Period (SPP) and Levelised Cost of Energy (LCOE).

The selection of the combined heat and power system was done using data from the operating parameters and efficiencies of different CHP technologies. These were found from literature, catalogues and different reputable companies. Selection of the CHP technology was based on capital cost, operating and maintenance, start-up time cost, electrical efficiencies and the heat to power ratio. A weighted decision matrix was used to select the best CHP system. A CHP system that scored the highest marks was chosen. Selection of the CHP unit was based on the daily available biogas energy, efficiency of the system and the time the CHP was going to operate. To make an informed decision, capital costs, LCOE, IRR, NPV and CHP capacity values were tabulated against the possible operating hours. Operating hours ranged from 1 to 24 hours. CHP operating hours were considered with the help of a load duration curve. The load duration curve showed the maximum demand, base load and the duration. A decision had to be made to support a particular load for a specified duration. An analysis was made on how the above-mentioned variables vary with different operating times of the CHP unit.

RESULTS AND DISCUSSION

The developed model has a user interface where inputs are entered and the calculated results are viewed on the outputs section of the model. The model requires a number of inputs for it to process and give the required results. Some input variables are found in the database of the model. Input variables, found in the model, include physicochemical characteristics of some biogas feed stocks, efficiency and cost parameters of CHP technologies and cost parameters of bio-digesters. The model is so flexible that it allows for the manipulation of certain entry values to suit the conditions of any particular project. The model has a number of outputs, including bio-digester size and operating parameters, CHP system technology and capacity, economic performance metrics and potential GHG to be averted.

Application of the model required quantification of the biomass resource available and energy demand analysis at Koala Abattoir. The abattoir slaughters 120 cattle and 70 pigs per day on average. The cattle are kept in a holding pen for a maximum of 24 hours and pigs for a maximum of 12 hours before they are slaughtered. So, there are stream lines of waste, one from the holding pens and the second is from inside the slaughterhouse. It was estimated that on average, cattle can excrete 8 kg of dung over a period of 24 hours and a pig can excrete 1 kg of waste over a period of 12 hours. In the slaughterhouse, each pig produces an average of 2 kg of solid waste. Total mass of feedstock available per day is 3 570 kg. Pig waste constitutes 5.88% of the waste available and the rest is cattle waste. Expected biogas production per day calculated from the biogas model, is 2283.76 m^3, with an energy content of 13702.56 kWh. Digester volume was calculated to be 446.25 m^3. High biogas output can be attributed to high concentration of protein and lipids in the feedstock. The biogas plants optimum operating conditions were determined.

Figure 1 shows how biogas output per day was affected by digester operating temperature. The graph corroborates with existing scholarship. The rate of increase in biogas output decreases as the digester temperatures reach 35°C. Thus, 35°C was the chosen optimum digester temperature in this study. This was in agreement with the optimum operating temperature for digesters operating within the mesophilic range. Figure 2 shows the rate of change of biogas yield with an increase in temperature. The graphs show results obtained from the developed model. More refined results would have been obtained by conducting experiments to obtain the maximum and minimum points that can give the actual optimum temperature.

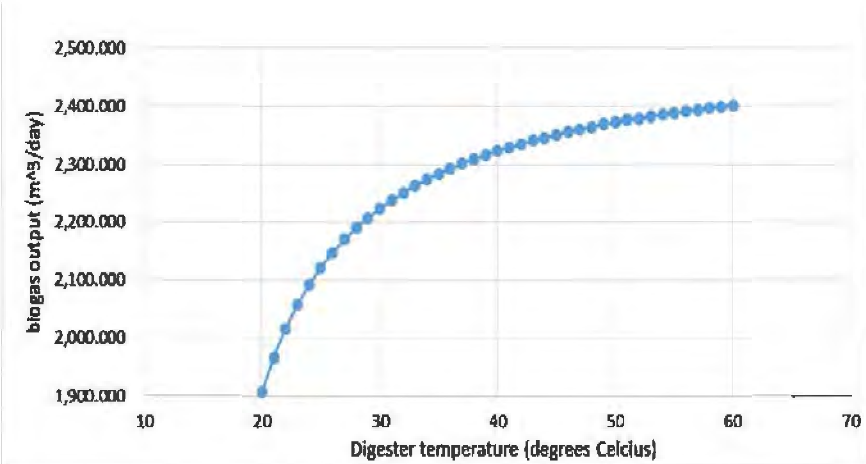

Figure 1: Daily Biogas Output Against Digester Operating Temperature.

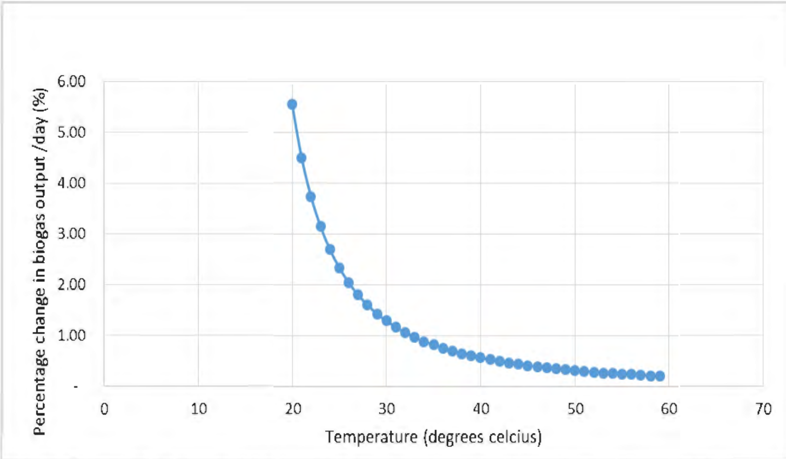

Figure 2: Rate of change in biogas output as temperature increases.

The daily influent volume was based on the value of OLR. The optimum value was obtained by plotting a graph of biogas yield against a different OLR. The optimum OLR was then chosen to be 2 kgVS/m^3 per day at the knee of the curve. Figure 3 shows how methane yield is affected by increasing the OLR.

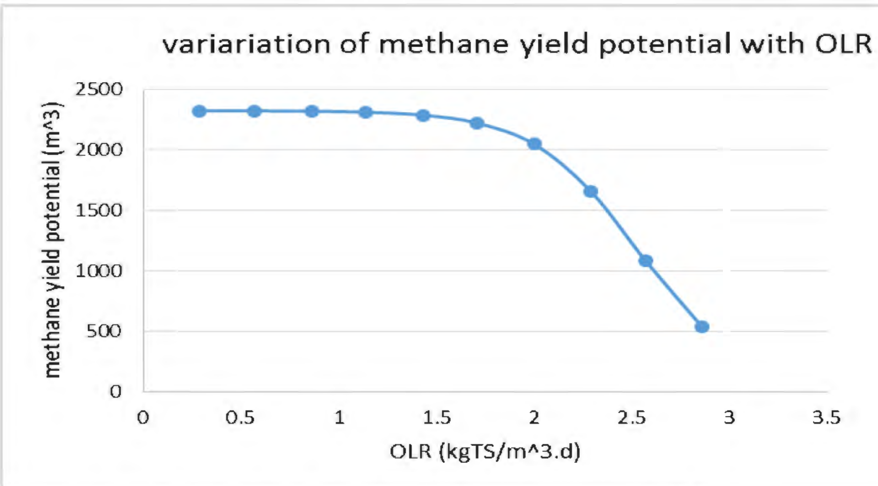

Figure 3: Variation of methane yield potential with varying OLR

Selection of the hydraulic retention time is achieved after optimisation of the digester operating temperature. Figure 4 shows that increasing the HRT increases the biogas yield but, up to a certain point, the rate increase in biogas yield becomes so small. It can be seen that increasing HRT also increases the digester volume. The rate of increase in the digester volume beyond 25 days is great such that the gain in biogas output becomes insignificant. The optimised value of HRT in this study was chosen as 25 days.

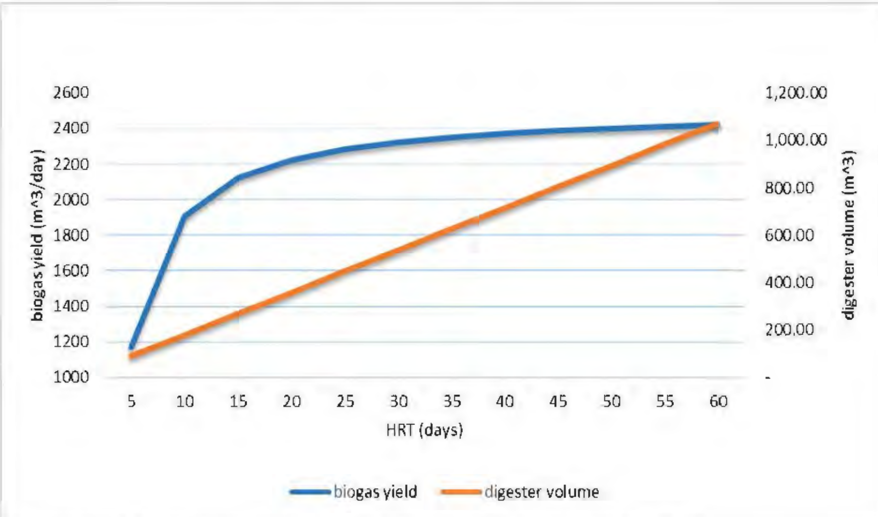

Figure 4: Variation of biogas and digester volume with HRT

Figure 5 shows a graph of OLR and biogas yield against HRT. An optimum value of OLR is also used to select the HRT value.

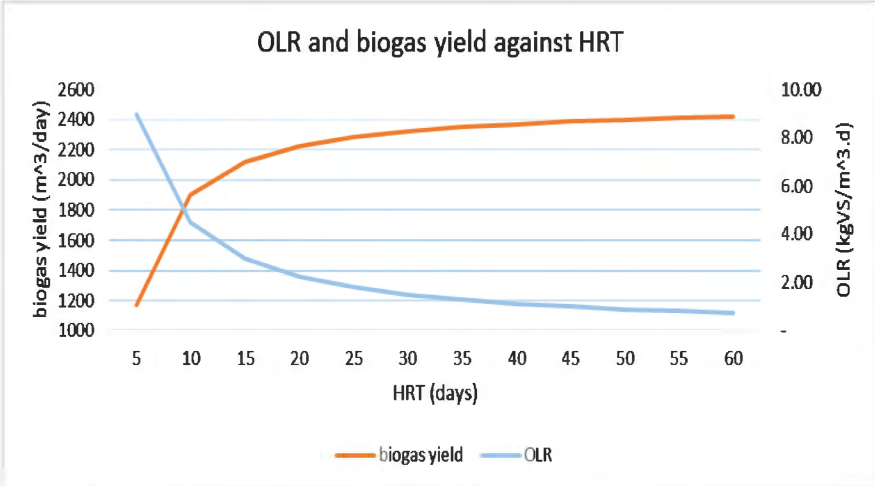

Figure 5: Variation of OLR and biogas yield with HRT.

Digester parasitic load comprises thermal load and electrical load.
The electrical load of the digester = 2kWh/m^3 digester * digester volume
= 2kWh/m^3 * 446.25 = 892 kWh/ day

Digester thermal load was the energy required to raise the influent temperature to the digester operating temperature. This demand increased with a decrease in ambient temperatures. The assumption was that the incoming influent had a temperature equal to ambient temperature. At an average, ambient temperature of 18°C thermal energy demand becomes:

Thermal energy demand = (17.850*1000)*(4.18/3600)*(35-8)/0.8
= 440 kWh/day

Average fraction of biogas energy consumed in maintaining digester temperature: (parasitic thermal load)/ (energy in biogas)
= (440 kWh)/13706.56kWh
= 3.21%

Assuming a worst-case scenario of an ambient temperature of 0°C, thermal energy demand becomes 906.76 kWh. This figure represents 6.6% of the energy in biogas.

Figure 6 shows how digester heat energy demand varies throughout the year. More energy is needed in winter to raise the influent temperature. The demand increases by 55% in June before accounting for thermal losses.

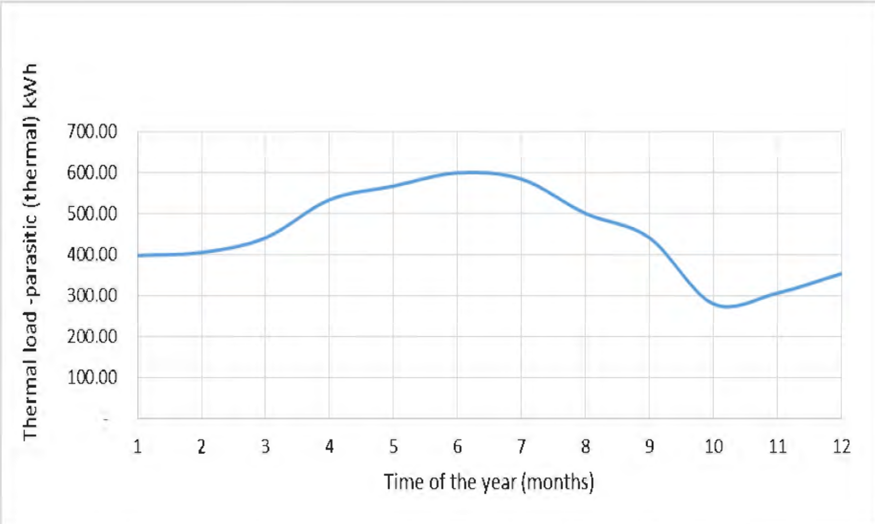

Figure 6: Variation of thermal parasitic load with time of the year.

Digester thermal losses vary with ambient temperature. But on average temperatures (18°C), the daily heat losses are as follows:

Thermal losses $= 2.84\times257\times(35\text{-}18)\times24/1000$

$=371$ kWh

This accounted for 67% of the digester energy demand. An extra 371 kWh of thermal energy on average was required to be supplied to keep the digester at the optimum temperature. This figure varies, depending on the seasons of the year. Figure 7 shows how thermal losses, influent energy demand and total parasitic thermal load vary with times of the year.

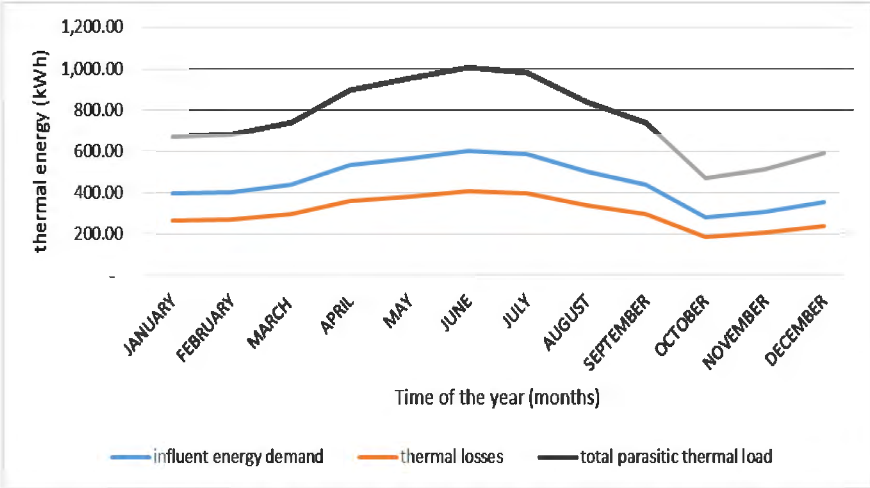

Figure 7: Variation of thermal losses, influent energy demand and total parasitic thermal load with time.

On average, energy supplied to CHP unit is 811 kWh. This figure fluctuates as the digesters' thermal demand changes. This ultimately results in fluctuation of electrical and thermal output from the CHP unit.

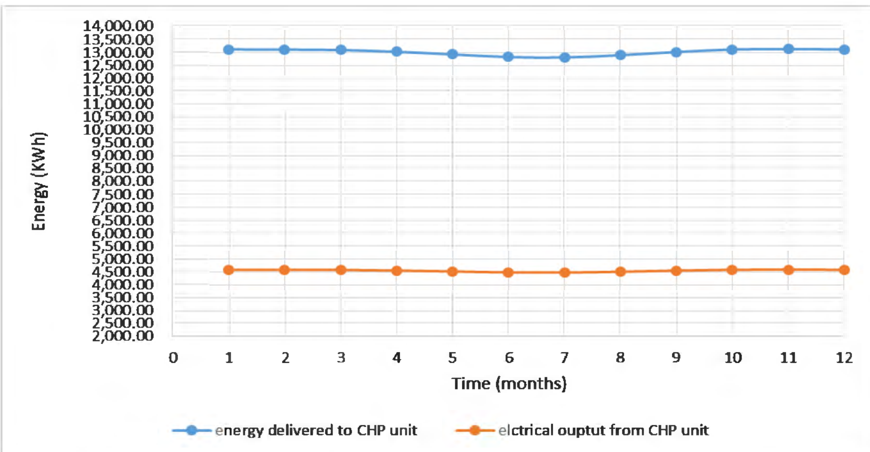

Figure 8: Variation of energy delivered to CHP and electrical output from the CHP

Electrical output varies from a minimum of 4484 kWh to a maximum 4594 kWh. a variation of 2.55%. As shown in Figure 8, the variation in electrical output is very minimal. Energy demand results are categorised in two sections, that is, electrical and thermal energy demand. The total load for each hour was recorded and hourly load was plotted against day hours. The daily energy demand is 2717.41 kWh and a maximum demand of 142.85 kWh.

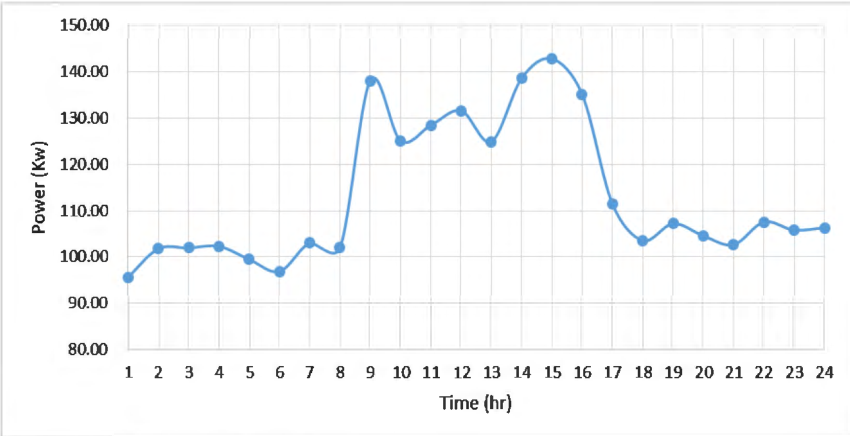

Figure 9: Electrical Load profile

Figure 10 shows the load duration curves. The load duration curves showing a base load and 91 kWh respectively.

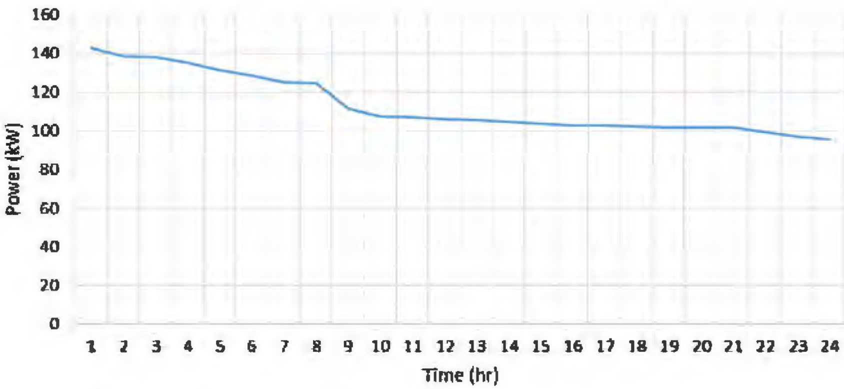

Figure 10: Load duration curve

1500 litres of water at 80°C is required daily from 0800hrs to 1600hrs. A coal-fired boiler is used to provide the hot water. A mass 60 kg of coal is used on each day to heat the water in the boiler. The coal is bought at a price of US26.50 per tonne.

At a yearly average ambient temperature of 18°C, thermal energy Q_{th} required to raise the water temperature to the required temperature is:

Thermal energy in water (Q_{th}) $= 1500 \times (4.18/(3600)) \times (80-18)$
$= 388.74$ kWh/day

The cost of coal used per day for heating up water is $1.59 and the cost of generating 1kWh$_{th}$ from coal is $0.0041/ kWh$_{th}$
The cost savings, arising from the use of the biogas system for thermal purposes, is then $580.35

The calculated value of thermal energy above is for yearly average ambient temperatures, but ambient temperatures change throughout the year. Figure 11 shows how thermal energy demand varies throughout the year as temperatures fluctuate, due to seasonal changes. Maximum thermal energy demand is experienced in June when ambient temperatures are at minimum levels. There is 13% increase in thermal energy demand in June, due to low ambient temperatures.

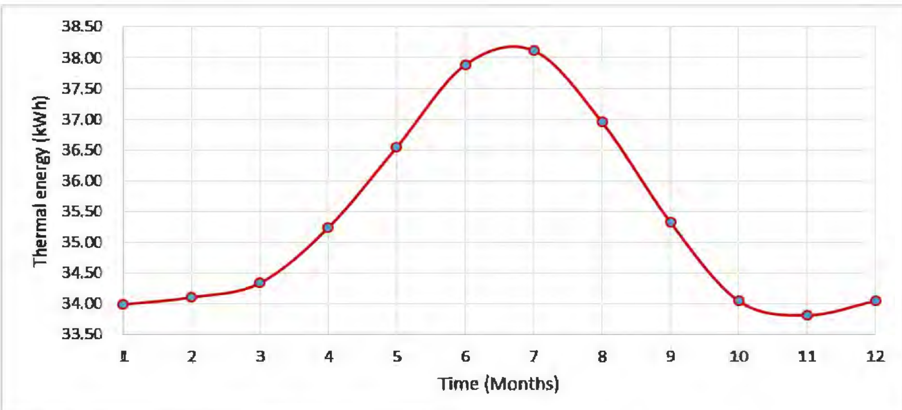

Figure 11: Variation thermal energy required to heat water required for abattoir purposes.

It is expected that thermal energy generated from the CHP unit is to be used to meet thermal energy demands of the abattoir.

Selection of the CHP system was based on the results of the weighted decision matrix. The site under study has a very low heat to power ratio of 0.07. A CHP system with the least heat to power ratio looks favourable when all other factors are not considered. Also considering CHP unit capital cost, the one with the least capital cost is considered first. The internal combustion engine was chosen for the CHP unit. In terms of capital cost, it is ranked second to steam turbines but it has an electrical efficiency higher than that of the steam turbine. In terms of the lowest heat to power ratio I.C engine is ranked third but the capital cost of the first and second ranked are much higher than that of an I.C engine. Adding to that, internal combustion engines have a well proven technology and have the lowest start up time. Thus, the selected CHP unit for this study is the I.C engine.

Sizing of the CHP capacity takes into account a number of considerations. Parameters considered are electrical load intended to be covered by the biogas system, capital costs and LCOE. Capital costs values in Figure 12 are for the overall system including the digester capital costs. The assumption is that the all the biogas produced must be utilised in the CHP unit. For this to happen an appropriate CHP capacity must be chosen. From Figure 13, it can be seen that CHP unit running time is inversely proportional to CHP capacity. This is a result of the condition set to utilise all the available gas on each day. Energy to be generated by any selected CHP unit size remains the same. The major difference is the capital cost of the system. In this study a decision is made to choose the CHP capacity on the basis of the least LCOE. A 187kWe CHP unit is selected. The CHP unit is to run for 24 hours and it results in a LCOE of $0.06/kWh.

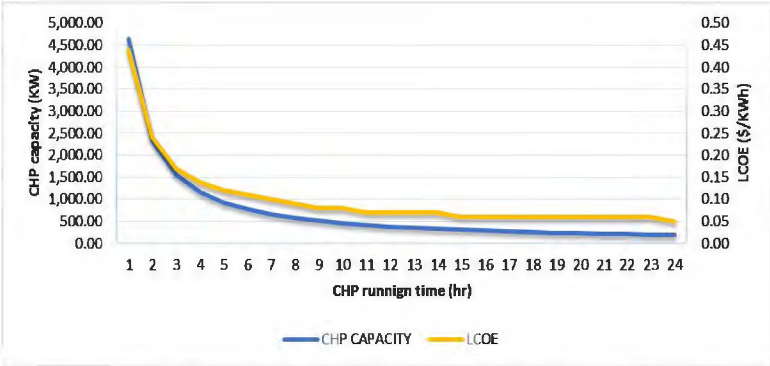

Figure 12: Variation of CHP capacity and LCOE with CHP running time

Increasing the CHP running time reduces its capacity and consequently its LCOE. The system has a potential to generate 1564 MWh of electrical energy and 2138 MWh of thermal energy per year. Electrical energy generated accounts for more than 100% of the energy demand. The biogas system has a potential to meet 100% of the thermal energy demand. In fact, thermal energy demand is only 6.5% of the generated thermal energy. This means that 93.5% of generated thermal energy is wasted. Figure 13 shows how electrical energy demand and potential electricity generation varies on a typical day. It can be observed that generation is always in excess and this means that the system can feed in extra energy into the grid.

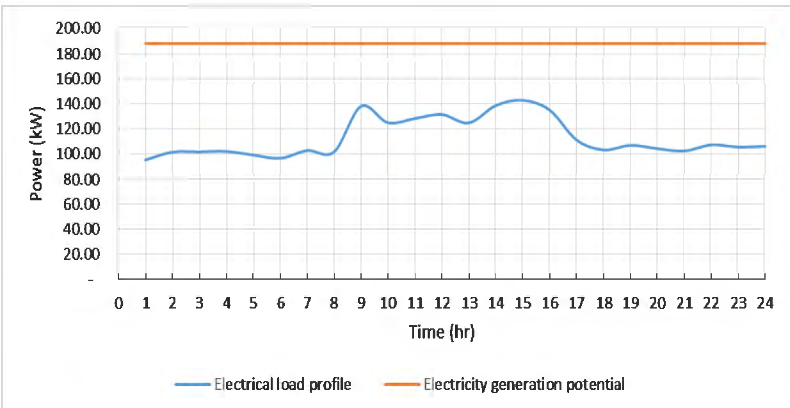

Figure 13: Electrical demand and electrical generation potential on a typical day (June17)

CONCLUSION

The biogas feed stocks were grouped into the following categories: agricultural waste, organic fraction of municipal solid waste, agro-industrial waste and sewage sludge. The model was successfully created and it can be used for any location in the assessment of biogas-CHP system viability. A mechanism for selecting a CHP system and its capacity was devised and implemented. The model was applied at Koala Park in urban Harare and it was deduced that a biogas-CHP system at Koala Abattoir is economically viable. The proposed system can generate 1564 MWh of electrical energy and 2138 MWh of thermal energy per year. The system is capable of meeting 100% of the energy demands at the institution. An economic analysis of the system revealed that all the economic performance metrics showed positive results, that is, an IRR of 38.99%, an NPV of $887 298 and a pay-back period of 3.10 years. The system has a LCOE of $0.06/kWh. The system has the potential to avert 1722 tonnes of GHG per year. Exploring the use of excess thermal energy for absorption cooling at Koala Park will be ideal as the system is generating excess thermal energy that is being lost to environment. It is also worthwhile to evaluate biogas upgrading to improve system efficiency and reduce the operating and maintenance cost of the CHP system. The model can further be improved by incorporating a section for actual digester design and present construction drawings so that the digester costing can be evaluated with precision.

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