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Utilization of Anaerobic Co-Digestion for Biogas Production for Institutional Cooking: A Case of Nkumbi International College

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ABSTRACT: Studies have linked the use of wood fuel to deforestation leading to greenhouse gas emissions which cause climate change. Despite these concerns, some institutions located in the rural areas of Zambia like boarding schools and colleges still use firewood as a fuel for cooking and heating. Additionally, electricity, where available, is usually based on fossil fuel combustion, and often has high tariffs if connected to the national electricity grid and is also unreliable. On the other hand, biogas produced from animal and other organic wastes has demonstrated to be a cleaner alternative source of energy that can be used for cooking and supply of heat.

A case of Nkumbi international college was selected to consider the economic viability of using the animal and agriculture waste from the institutional farm as a feedstock in an anaerobic co-digester to generate biogas for use as fuel for cooking to replace firewood and grid electricity, the current sources of energy for cooking. Results showed that installing a biogas system at the college and using the biogas to replace a combination of firewood and electricity is highly viable with a positive net present value of USD 19,747, a payback period of 3.1 years, and an internal rate of return of 35.5% over a period of 20 years.

KEYWORDS: Anaerobic codigestion, biogas technology, digester, feedstock.

1. INTRODUCTION

Energy stands at the centre stage of the economic and social development of any country. Countries with poor energy services also struggle to attain economic and social development. For most developing countries, especially those in the sub-Saharan Africa, lack of development has been linked to poor energy services (UNDP & WHO, 2009). And Zambia happens to be among those countries.

In Zambia the energy consumption pattern is largely dominated by households and the mining sector. The household sector alone accounts for 58% of total energy consumption in Zambia. The largest share of energy consumption by household is attributed to the dependency on firewood which accounts for about 80% of total household energy consumption (ERB, 2014). The significance of the pattern of energy production, conversion, and consumption in ensuring sustainable development necessitates stock taking of national energy supplies and demands, so as to enable adequate policy formulation. Fuel from wood, the only noncommercial energy resource, constitutes 70% of the energy consumed in the country through its use as firewood in rural areas and as charcoal in urban areas. Hydropower with an existing installed capacity of 2,800MW supplies 94% of the country's electricity and meets 31% of the national energy demand. Shares of electrical energy consumed in mining, industry, household, government, and agriculture sectors are 72%, 10%, 8%, 7% and 3%, respectively. With average annual output of about 470,000 tonnes and enormous reserves of over 80 million tonnes, coal is also abundant and meets 2% of the national energy demand. Mining and industry have nearly equal share to account for over 90% of the domestic coal consumption. Petroleum contributes 12% of the energy demand and is totally imported. Its share in transportation, mining, industry, household, agriculture, and services sectors is 49%, 27%, 14%, 4%, 3% and 3%, respectively (Masiliso, 2008).

In Zambia, energy sources include renewable sources such as water, solar, wind and biomass as well as fossil fuels such as petroleum. Given the substantial unexploited reserves of renewable sources, Zambia has the potential to be self-sufficient in energy (Zambia Development Agency, 2014). The main source of energy for the country is traditional biomass in the form of charcoal and firewood, which accounts for 83% of the total energy use (Shane et al., 2016). However, the use of traditional biomass in this manner is closely linked to an increase in the emission of greenhouse and toxic gas that eventually bring about climate change and causes respiratory diseases. The efficient and effective use of biomass in modern bioenergy systems on the other hand, such as in biogas improved cooking stoves and gasification, have shown to a great extent the reduction on the emission greenhouse gas, an increase in the hours of production and an improve in the health status of communities (Gurung & Oh, 2013; Subedi, 2015).

2. LITERATURE REVIEW

2.1 Biogas production

Biogas is produced from the anaerobic digestion of animal and plant matter by methanogenic bacteria (Caruana & Olsen, 2012; Roopnarain & Adeleke, 2017). It mainly contains methane, water, hydrogen sulphide and carbon dioxide (da Rosa, 2013; Korres, O'Kiely, Benzie, & West, 2013). Biogas as a natural gas has methane as the main gas, therefore the biogas can be used as a fuel. Variations exist on the exact content of methane in biogas depending on the feedstock and digestion process. Authors use different ranges for the share of methane in biogas. For example, Shane et al. (2017) gives a 50-70% range whilst the Zambia Bureau of Standards (2014) offers a range of 55-90%. Therefore, in this study, biogas is defined as gas produced from the anaerobic digestion of organic waste containing more than 50% of methane.

2.2 The benefits of biogas technology

Biogas could be used as fuel in many applications. These include domestic cooking and heating, transport fuel for internal combustion engines, electricity generation in power plants, domestic heating lighting and cooking and in the treatment of manure to produce the sludge which is used as a soil conditioner for agricultural benefits (Shane et al., 2017; Subedi, 2015; Walekhwa et al., 2014).

2.3 Biogas conditioning and utilization

Depending on the final use, different biogas (raw or crude biogas) treatment steps are necessary since the raw gas is mainly composed of methane. The three main contaminants in biogas are: carbon dioxide (CO_2), hydrogen sulfide (H_2S), and water vapour which can lead to setbacks when utilizing biogas as a renewable source of energy such as Renewable Natural Gas (RNG) (Hidolgo et al, 2016).

2.4 Types of digesters, operation, and design

There are hundreds of different designs of digesters used for biogas production and different ways of classifying them. The Two popular simple designs of biogas plants have been developed; the Chinese fixed dome digester and the Indian floating cover biogas digester (Marchaim, 1992).

2.4 Operation of a biogas digester system

Operating the biogas involves mixing organic feedstock with water to produce a liquid slurry which is then fed to the digester. Stewart and Trangmar (2008) suggest that the amount of biogas that may be produced could be estimated using the following equations.

$$M_{TR} = A\ (R_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(I)}$$

$$M_{TS} = M_{TR}\ (\%TS) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(II)}$$

$$V_{BG} = M_{TS}\ (V_{TS}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(III)}$$

$$V_{MH4} = V_{BG}\ (\%M_{BG}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(IV)}$$

Where:

$\mathbf{M_{TR}}$, is the total raw manure (kg/day), **A**, is the number of each type of animal (head),

$\mathbf{R_i}$ Is the raw manure per animal per day (kg), $\mathbf{M_{TS}}$, Is the manure total solids (kg/day),

%TS, is the per cent total solids (%), $\mathbf{V_{BG}}$, Is the potential volume of biogas (m^3/day),

$\mathbf{V_{TS}}$, is the typical volume of biogas produced per kg total solids (m^3/kg TS), $\mathbf{V_{MH4}}$, Is the potential volume of methane (m^3 CH4/day), %$\mathbf{M_{BG}}$, is the percentage methane in the biogas.

2.5 Anaerobic Codigestion theory

Codigestion is the simultaneous anaerobic digestion of multiple organic wastes in one digester. Codigestion is used to increase methane production from low-yielding or difficult to digest materials or feedstocks. For the codigestion process, care must be taken to select compatible codigestion feedstocks that enhance methane production and also to avoid materials that may inhibit methane generation. Codigestion of various organic feedstocks may enhance the biogas and methane production from a biogas digester (EPA, 2012).

2.6 Biogas economics, models, and concepts

For renewable energy technologies such as biogas plants to be successfully implemented, they are required to pass an economic feasibility assessment (Urmee & Md, 2016). The economic concepts and models frequently used in biogas economics studies are the linear programming method and the economic decision criteria such as net present value (NPV), payback period (PP), and internal rate of return (IRR) (Flammini et al., 2018; Gebrezgabher, Meuwissen, Lansink, & Prins, 2010; Shane et al., 2017).

3. RESEARCH METHODOLOGY

In order to conduct a research on utilization of anaerobic co-digestion for biogas production for institutional cooking at Nkumbi international college, the following information was critical to be identified.

i. Biomass resource at Nkumbi international college.
ii. Data sourcing.
iii. Feed stock selection.
iv. Biogas digester design, calculations, and analysis.

A case study approach was adopted in this research, in order to compare systems within the same context. In this case, comparing a combined use of firewood and electricity with using a biogas system to supply fuel needed to cook three meals to students during term times. In such situations, a case study is recommended as it isolates the main variables and allows for an in-depth analysis (Yin, 2014). Furthermore, the case study approach has been effectively used in other studies on the application of biogas technology in Zambia and Uganda (Shane et al., 2017; Walekhwa, Lars, & Mugisha, 2014). The details of the methodology were outlined in chapter three, where the research methodology outlines the research roadmap and avail the tools that were used to carry out the research by measuring the feedstock resource (animal and agriculture waste), designing, and costing the digester system, and applying a financial feasibility analysis using the model "RETScreen" to determine the economic viability of this research.

4. RESULTS ANALYSIS AND DISCUSSION

4.1 Animal population

The figure 1 shows the animal population at Nkumbi international College, and the steady population growth of the respective farm animals. From the results obtained it is evident that animal population on cattle, goats and pigs is low at Nkumbi international college, and animal manure has a high methene yield. This means that the biogas yield required for biogas production at the institution can be affected by the animal population and the institutional farm.

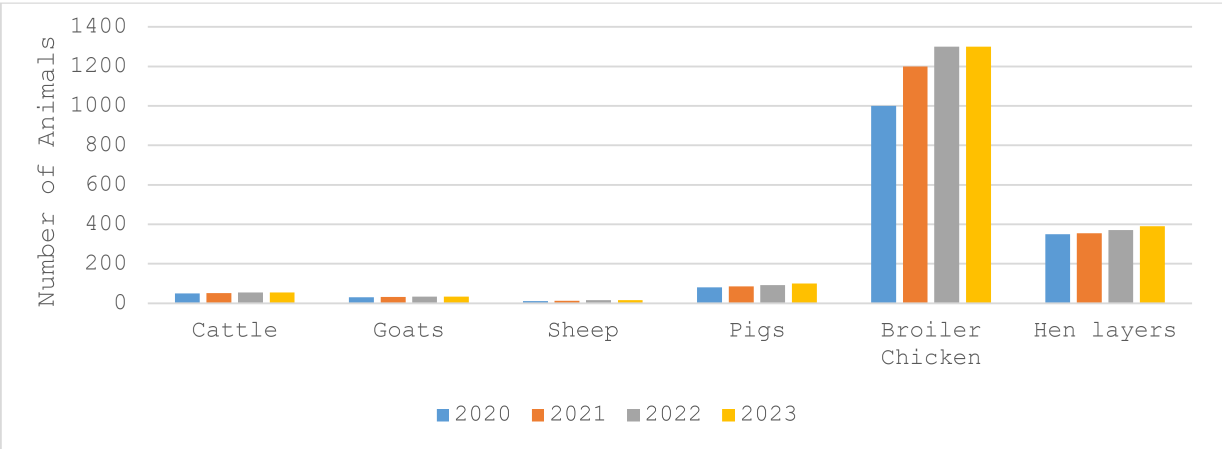

Figure 1: Variation in annual number of livestock farmed at Nkumbi international college from 2020 to 2023(Author).

4.2 Quantity of daily biogas consumption

With the fact that the institution consumes an average of 58968 kWh of energy per month to cook on the energy inefficient electrical stoves and that 3.6 MJ is equivalent to 1 kWh; also, that biogas has a thermal energy of about 22 MJ/m^3; this translated in to 6.1 kWh of energy per 1m^3 of biogas. The above relationship was used in this work to have an optimum quantity of biogas, and feedstock from the two selected biomass resources. Taking biogas design factors into account the daily biogas consumption was calculated and tabulated in Table 1.

Table 1: Quantity of biogas required to cook meals for 250 students (Author).

Number of Students	9	50	100	150	200	250
Biogas (cubic meter per day)	2.5	14	28	42	56	69

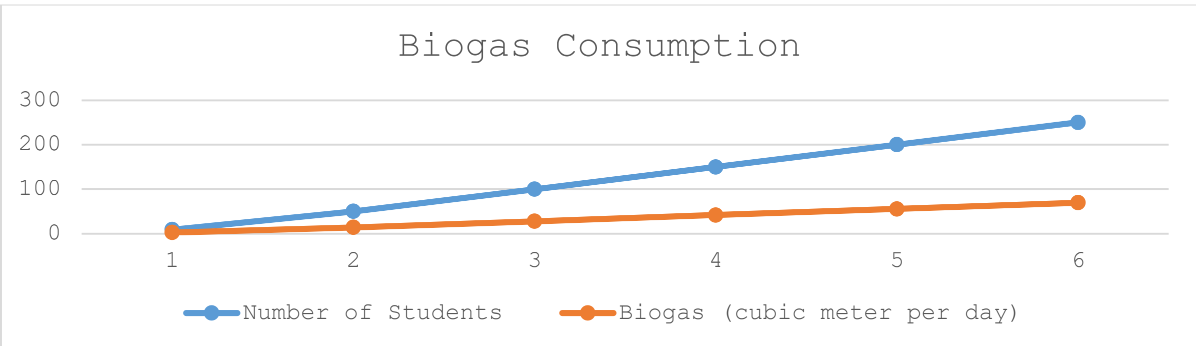

Figure 2: Relationship between Biogas required in correspondence to the number of students (Author).

The feedstock characteristics in this work were: density and specific biogas yield for respective biomass resources. These were constants for a particular feedstock and were obtained from empirical research literature.

Table 2 Feedstock characteristics of the respective different biomass resources

S/N	Feedstock	Density (m^3per Kg)	Biogas Yield (m^3per Kg)
1	Cow Dung manure	1090	0.281
2	Swine manure	1000	0.058
3	Chicken droppings	450	0.069
4	Vegetable waste	640	0.072
5	Corn silage	1000	0.138

4.3 Determination of daily biomass collection

This was the mass of digestible manure that would be collected each day considering the seasonal collectability variations and total solids. The amount of diurnal digestible manure that could be collected and its corresponding biogas generation for each month were calculated using Equations (i) to (iv) (Section 2.4), considering the collectability factors and methane yields from the literature. This assumed that the amount of manure collected each day of the month was the same. However, the biomass resource from the institutional farm comprised of different sources of manure, each with its own specific biogas yield. Therefore, the biogas yield for the manure with the largest contribution was used, in this case cattle (0.281m^3/kg). At this conversion efficiency rate, 420kg of manure would be required to produce 118m^3 of biogas (420kg × 0.281m^3/kg=118m^3).

Table 3: Daily manure Collection over a period of one year (Author)

Month	Wet Manure (kg per day)	Biogas Volume (square meters per day)	season
January	420	118	Rain Season
February	420	118	Rain Season
March	420	118	Rain Season
April	420	118	Cool dry Season
May	420	118	Cool dry Season
June	420	118	Cool dry Season
July	420	118	Cool dry Season
August	420	118	Cool dry Season
September	410	115	Hot dry Season
October	410	115	Hot dry Season
November	410	115	Hot dry Season
December	410	115	Hot dry Season

4.4 Characterization of farm waste

4.4.1 Farm animal waste

Determination of farm animal waste from the institutional farm for biogas production involved the collection of data on each farm animal type between 2020 and 2023. Broilers and layer hens represent the largest proportion of animal numbers with broiler chickens increasing steadily from 2021 to 2022 and remaining constant thereafter. The numbers for the other animals have been constant with a consistent distribution from 2020 to 2023. This shows that the college farm would likely have a consistent supply of manure.

4.4.2 Farm agricultural waste

Determination of farm agriculture waste for biogas production involved assessing the type and quantity of waste generated from crop residues and other agricultural by-products. Data on the identified agricultural waste such as maize stalks and vegetable leaves. Quantification of agricultural waste was done by weighing and measuring the amount of agricultural waste generated during different seasons or crop cycles.

4.5 Determining the digester size.

Taking biogas design factors into account, a 69m^3 was estimated to generate enough gas for the average number of students which is 250. However, an additional size of 17m^3 (quarter of operating volume) was allowed for pressure buffering to avoid creating high pressure in the digester (Energypedia, 2015; Meshach, 2008). Hence an 86m^3 digester was determined as an optimum size for Nkumbi International College.

4.6 Determining the Gasholder size.

The size of the gasholder depended on the consumption rate at peak time, and the ability of the gasholder to hold the gas produced during the longest period of non-consumption

(Energypedia, 2015). These parameters were determined using Equations (1) and (2) respectively.

$V_{g1} = C_{g(max)} \times C_{t(max)}$ ………………………………………………………… ….. Eq 1

$V_{g2} = Y_g \times C_{ot(max)}$ ……………………………………………………… ………… Eq 2

Where:

$\mathbf{V_{g1}}$ = the volume under peak consumption, $\mathbf{V_{g2}}$ = maximum zero consumption periods in cubic meters, $C_{g(max)}$, $C_{t(max)}$, Y_g and $C_{ot(max)}$ are the maximum gas consumption rate (m^3 /h), maximum consumption time (h), hourly gas yield (m^3 /h) and maximum zero consumption time (h) respectively.

The largest number between V_{g1} and V_{g2} determined the volume of the gasholder that should be used. In the case of Nkumbi International College, $C_{g(max)}$, $C_{t(max)}$, Y_g and $C_{ot(max)}$ and eventually, Equations (1) and (2) were calculated based on the following assumptions.

a. The same amount of time was spent cooking on biogas stoves as on electric stoves.
b. A daily cattle manure yield of $0.281m^3$ was used since cattle contributed the most feedstock.

$$C_{g(max)} = \frac{118m^3 \text{ per day}}{24 \text{ hours}} = 5m^3 \text{ per day}$$

$$C_{t(max)} = 6 \text{ hours}$$

$$Y_g = \frac{0.281m^3 \text{ per day}}{24 \text{ hours}} = 11.7 \times 10^3 m^3$$

$$C_{ot(max)} = 18 \text{ hours}$$

$$V_{g1} = C_{g(max)} \times C_{t(max)} = 5m^3 \text{ per day} \times 6 \text{ hours} = \mathbf{30m^3}$$

$$V_{g2} = Y_g \times C_{ot(max)} = 11.7 \times 10^3 m^3 \times 18 \text{ hours} = \mathbf{0.211m^3}$$

4.7 Modelling in RETScreen

The simulation comprised of an energy model, a cost analysis, financial analysis, and sensitivity analysis.

4.7.1 Financial Analysis Model

In this model, financial parameters were assumed. These were put in the financial model of RETScreen.

1. **A discount rate of 12% was used.**
   Different criteria for determining discount rate such as municipal bonds, central banks' lending interest rates were considered (Folger, 2018; Sandler, 2017). On the other hand, the discount rate used in most renewable energy projects is 12% (Shane et al., 2017; Walekhwa et al., 2014)
2. **A project lifecycle of 20 years was used.**
   20 years is the most widely used lifespan of biogas systems (Gebrezgabher et al., 2010; Walekhwa et al., 2014).
3. **An inflation rate of 13.1% was used.**
   This was the projected inflation rate for Zambia for the year ending July 2023 (ZamStats, 2023)
4. **There were neither incentives, grants, nor debts involved.**
   It was assumed that the institution would pay the upfront capital costs without receiving any grants or taking on debts. This was done to simplify the analysis as the main emphasis was the financial feasibility of biogas replacing electricity and firewood.

4.8 Energy Model for Nkumbi International College

The energy model in RETScreen allowed the annual costs to be entered for the base case (cost of firewood and electricity) and the proposed system. It also allowed for the incremental initial costs of the proposed system to be entered. In this study, the base annual case was estimated to be USD 5,366.1 per year based on the calculated costs of electricity, and the cost of firewood collection that is saved for the institution. On the other hand, the annual costs for the proposed system were the cost of managing the biogas digester. The capital cost of the biogas plant was estimated to be USD 7,381 based on SNV guidelines (Table 4).

Table 4: Capital Cost estimates of Constructing and Installing a digester system at Nkumbi International College

No.	Item	Amount (USD)	Comment
1	Construction materials	4, 482	Detailed cost breakdowns shown in Appendix A
2	Pipe, Fittings, and accessories	1, 072	Detailed cost breakdowns shown in Appendix A
3	Gas Stove	400	Industrial Kitchen scale gas stove suitable for burning biogas can be sourced from Ogaz Zambia Limited.
4	Labour Costs of Constructing the plant	1, 427	Skilled labour Cost USD657, unskilled labour cost USD770 Appendix A
	Total Capital Cost	**7, 381**	

4.9 Cost analysis model for Nkumbi International College

A 30% of pipe, fittings and accessories costs was set aside for spare parts, whereas a USD 600 was set aside for transportation, training, and commissioning. The operations and maintenance (O&M) cost were estimated at 4% of the capital costs. Walekhwa et al., 2014) (Table 5).

Table 5: Other initial costs estimate of constructing and installing a digester system at Nkumbi International College

S/N	ITEM	AMOUNT (USD)	JUSTIFICATION
1	Spare parts	322	This was 30% of pipe, fittings and accessories that was set aside for spare parts, 30% was chosen as recommended by the RETScreen guide for small projects.
2	Transportation	600	The college has a small truck which may be used for transportation of construction materials. Fuel costs including vehicle maintenance, driver payment and toll gates would cost about USD200 for two round trips (Assuming materials are bought from Lusaka). Three round trips may be sufficient for this project.
3	Training and Commissioning	369	A 5% of the initial capital costs was reserved for training and commissioning. This would mainly be the cost of hiring a biogas expert to train the biogas system operators in biogas operation and maintenance.
4	Contingencies	434	The minimum recommended amount of 5% of initial cost according to the RETScreen guide.
	Total Initial Costs	**1724**	

4.10 Economic Viability

The results of the RETScreen analysis indicate a very high positive NPV of USD 19,747, and a payback period of 3.1 years (Table 6). This seems to suggest that installing a biogas plant at Nkumbi International College would be viable.

Table 5.6: Economic Viability of installing a digester at Nkumbi International College and using biogas to replace firewood and electricity at a discount rate of 12% and inflation rate of 13.1%.

S/N	PARAMETER	VALUE
1	IRR	35.5%
2	Payback Period	3.1 years
3	Net Present Value (NPV)	$19, 747

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. **To determine the amount of daily farm animal and agriculture waste and estimate the biogas resource at Nkumbi international College.**

From the study it was reviewed that the farm has the potential to collect an average 420kg of manure per day during the year which could generate a daily biogas volume of about 118 cubic meters per day throughout the year. Which means the project is viable.

2. **To determine the size of a biogas digester required to generate sufficient biogas to cook three meals per day for students in boarding at Nkumbi international College.**

From the study it was reviewed that a fixed dome biogas system with digester size of 69 cubic meters coupled to a gas holder volume of 17 cubic meters can be installed at the college. This system could take in about 420kg of wet manure which could generate enough biogas to cook three meals a day for an average of 250 students.

3. **To determine the costs relating to the constructing and installation of the biogas system.**

From a bill of quantity and quotation (Appendix A), and cost functions developed from the literature, the capital cost of this system was estimated at USD 7,381 (Table 4.1). Other initial capital costs were estimated at USD 1,724. Annual costs and operations and maintenance costs were estimated at USD 1,714 and USD 273 respectively. This will reduce the monthly electricity bills and costs associated with firewood collection by 69.16%.

5.2 Recommendations

1. **Design and incorporate a pressure regulating systems.**

The design of the biogas digester system for Nkumbi International College did not consider any pressure regulation mechanism due to the scope and time limitation of this project. However, pressure regulation may have to be considered as this would affect the efficiency of gas use and temperature control of the gas cookers.

2. **Perform more sensitivity analysis on the benefits of the sludge at different discount rates.**

The value of the sludge was fixed at an estimated value. However, more sensitivity may have to be done to consider how different values of the sludge would affect the project viability.

3. **Perform a cost benefit analysis that incorporates the financial, environmental and health benefits of avoiding greenhouse gas emissions.**

The environmental, social, and financial benefits associated with reduced greenhouse gas emissions were not fully explored. In fact, the analysis did not consider the emissions produced from the generation of the grid electricity which is also used to power electric stoves at Nkumbi International College. Therefore, there might be missed benefits that could increase the viability of this project at Nkumbi International College.

REFERENCES

1. Anaerobic Digestion.Com (2016). "Mesophilic Anaerobic Digestion." Plants in Africa. Resources, Conservation and Recycling: 55, 63-57.
2. Bernd Althusmann, S. B. (2016). Perspectives on energy security and renewable energies in Subsaharan Africa. Windhoek, Namibia, Macmillan Education Namibia.
3. Biotech (2016). Renewable Energy. National Algal Bio fuels Technology Review
4. Banks C. (2009) Optimizing Anaerobic Digestion. Evaluating the Potential for AD to provide Energy and Soil Management. niversity of Southampton.
5. Chen Y., Yang G., Sweeney S. and Feng Y. (2010). Household Biogas Use in Rural China: A Study of Opportunities and Constraints Renewable and Sustainable Energy Reviews: 14, 545-549.
6. CIMAC (2015). "Impact of gas quality on gas engine performance."
7. Claus Von Mitzlaff (1988). "Energies for biogas." Theory, modification economic operations. (GTZ) Gmb
8. Denis Debila (2011). In der Entwicklungshilfe scheitern viele Projekte, weil sie zu wenig Rücksicht auf die Umstände vor Ort nehmen. Ein Verein ehrenamtlich tätiger Technik-Profis hat daraus Lehren gezogen. Deutschland.
9. Deogratias K., Quais H., Soundar K., Goudong S. (2015) Integrating data analytics and simulation meyhods to support manufacturing decision making. Morgan State University, Baltimore, MD, Huntington Beach, California.
10. Dobre P. et al (2014). "Main factors affecting biogas production - an overview." 19(3).
11. Energypedia.info (2016). "Electricity Generation from Biogas."
12. Dolores Hidolgo, Martin-Marroquín J. M., Coronas F. (20160). Biogas upgrading technologies
13. ERB (2014). Energy Sector Report 2014. Zambia, ERB: 8.
14. Feiges S (2015) Climate change mitigation and adaptation potential of basic energy services: Overview of potential heating and decentralized electricity generation. GIZ, 14.2242.7-001.00, Zurich, Switzerland.
15. Foundation, U. N. (2013). ACHIEVING UNIVERSAL ENERGY ACCESS.
16. G. W. Roth, A. J. H. (2016). "Corn silage production and management." 6.
17. Georg Friedl (2016). Biogas production in Germany: Status quo and future trends.
18. Hahn h, K. b., Wachendor M., (2014). "Renewable and Sustainable Energy Reviews."