Potential of Off-grid Solar PV/Biogas Power Generation System: Case Study of Ado Ekiti Slaughterhouse

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Abstract- In Nigeria, some economically important facilities are not functioning optimally due to lack of/inadequate electricity from the national grid. To solve this problem, these facilities result to using diesel generators which are mostly uneconomical and environmentally unfriendly. Improving comparative economic advantage means that Renewable Energy Sources (RES) with reduced emission and long term cost of energy is a viable alternative. This work describes the potentials of using solar PV/biogas power system to supply the slaughterhouse located in Ado Ekiti, South West Nigeria through an optimal design and techno-economic analysis. With an annual average daily radiation of 4.93 kWh/m2/d, the facility slaughters an average of 25 cows daily to yield a biomass supply of about 1150 kg/day. Simulation results from HOMER software present an optimal PV/biogas generator/battery/converter system that is able to supply the 164 kWh daily load requirement of the facility. The PV system supplied 38% of the annual total electricity production which stood at 76,384 kWh/yr. Cost analysis also indicates that the system has levelized cost of energy of $ 0.236/kWh and a Net Present Cost (NPC) of $ 92,988. 60% of this cost is shared equally between the PV and battery storage system while the biogas generator and digester and converter cost make up 25% and 15% respectively.

Keywords Biogas generator; HOMER; Off-grid; Renewable energy; Slaughterhouse; Solar PV; Techno-economic optimization.

1. Introduction

Insufficient capacity to meet the growing demand for electricity has remained an impediment for most developing economies of the world. Existing interconnected power systems dominated by fossil fuel power plants are becoming a cause of concern. This is due to recurrent natural disasters such as flooding, heat waves, increased air pollution, etc. caused by greenhouse gas (GHG) emissions. This phenomenon known as global warming has realigned the policy agenda for many countries of the world by drawing their attention to the consequence of their negligence. Besides, depleting available reserve of fossil fuels resources caused by increasing human population and volatile oil prices has brought to the fore the need to find a more economical and sustainable alternative. Renewable energy sources (RES) such as hydro, solar (PV and thermal) energy, wind power and biomass have shown to be sustainable replacements for traditional methods of power generation from fossil fuel power stations. While solar photovoltaic (PV) application has been largely successful due to its advanced technology and reduced cost over the years, others like biomass are still gaining traction.

Nigeria is endowed with abundant solar radiations where potentials range between 4 kWh/m^2 and 7 kWh/m^2 [1]. Moreover, it is not uncommon to find places where solar PV systems have been used to electrify critical infrastructure such as health centres, schools, domestic and agricultural water pumping, traffic and street lighting [2]. Biogas is the by-product of anaerobic digestion of organic matter (biomass) by bacteria in the absence of oxygen. Organic raw materials used in this process include sewage sludge, domestic food waste, industrial waste, animal manure, agricultural residues and water hyacinth [3]. Biogas is an environmentally friendly gas whose composition is made up of about 60% - 70% methane, 30% - 40% carbon dioxide and traces of other gases which include nitrogen (N_2), hydrogen (H_2), ammonia (NH_3), hydrogen sulphide (H_2S), oxygen (O_2), and carbon monoxide (CO) [3], [4]. This gas can be burnt to produce heat or used to generate electricity for power supply. With an estimated 227,500 t of fresh animal waste produced daily, Nigeria has the potential of producing about 6.8 million m^3 of biogas daily if 1 kg of animal waste produces 0.03 m^3 of biogas daily [1], [5]. This means bioelectricity can be deployed to support the quest for adequate and sustainable power supply in the country.

To this end, several researchers have presented the use of different integrated RES as alternative power sources for various application [6] – [9]. Some of these studies proposed the use of off-grid solutions for rural electrification [10] – [13]. while others proposed grid backup solutions for specialized facilities. [14], [15]. Aziz [16] presented an off-grid wind/PV/battery hybrid system to replace diesel-powered generators for a safari camp in the UAE. Results from HOMER simulations show that all possible renewable energy configuration was able to meet the load demand at a cheaper rate even with the prevailing cost of diesel. [17] conducted investigations into the optimal sizing of photovoltaic (PV) array and inverters for a grid-connected PV system.

An evaluation of the feasibility of electricity generation from poultry waste in Pakistan is presented in [18]. The study concluded that if renewable energy sources are adopted, about 280 MWh/day of electricity can be generated from poultry waste through biogas and this will go a long way towards the country's energy security. Some other works such as [19] – [21] investigated the techno-economic feasibility of biogas to electricity for different application. Comparative studies of hybrid energy systems for rural area using economic and environmental indices is presented in [22] and [23]. [22] looked into the feasibility micro hydro/PV/biomass and biogas/diesel/battery in an off-grid application for a rural area in Uttarakhand state, India. Results support three best configurations as they all have nearly the same COE and a high renewable fraction (low CO2 emission). [23] compared a design of PV/biomass and wind/biomass system with results showing that the PV/biomass system is more reliable, economical and environmentally friendly than the wind/biomass hybrid system. [24] proposed a deterministic sizing methodology for a stand-alone PV/ESS/Biogas system power plant. Calculated costs show that the hybrid energy is more economical than a stand-alone biogas power plant when the discount rate drops below 8% at prevailing technology costs. However, the load curve used for the study is assumed constant all year; which is not realistic

Slaughterhouses generate enormous wastes which are mostly disposed inappropriately, causing serious environmental and health hazard. However, if this waste can be converted to biogas for electricity, it will solve both waste disposal problem associated with these facilities as well as providing the much-needed electricity for the same facility and its environs [25]. The slaughterhouse presented as a case study in this research has an option of using abundant animal waste effluents from slaughter activities as feedstock for a bio-digester to generate biogas for electricity. Therefore, this work is one of the few studies where a hybrid of solar PV and biogas is used to provide Electricity for such facility. A hybrid system is proposed to take advantage of the reported solar PV performances and available cheap biomass as a sustainable solution to the power supply problem of the facility. This research uniquely keys into the need for developing countries like Nigeria to meet the UNDP sustainable developments goals which include affordable and clean energy.

2. Methodology

The aim of this study is to provide electrical power to the slaughterhouse through a PV/Biogas system. To ascertain the potential of PV/biogas generation, preliminary steps taken involved collection of data from the slaughterhouse. These data include load demand and hour of operation, existing power supply system, number and type (cattle, goat sheep) of slaughtered animals per day and size of the animal waste produced as well as current methods of disposal. This is followed by system design and simulation of a reliable and cost-efficient system which ensures adequate security of power supply for the everyday need of the slaughterhouse.

HOMER software was used to model and simulate the system. HOMER is an optimization tool for distributed power, developed by National Renewable Energy Laboratory, USA. Fig. 1a illustrates the structure for typical system modelling and simulation in HOMER. It builds an optimized system that can adequately meet the system load demand requirements based on defined input parameters and system constraints using a techno-economic algorithm. Economic input parameters in the optimization search space gives an optimal system design with a minimized net present cost (NPC) while the technical parameters ensure that the energy demand of the system is met at the least NPC. Fig. 1b illustrate how the input parameters and defined constraints produce an optimal solution. The optimization results also provide a list of different system configuration arranged in increasing order of Cost of Energy (COE) for every optimized system. In addition, sensitivity analysis may be

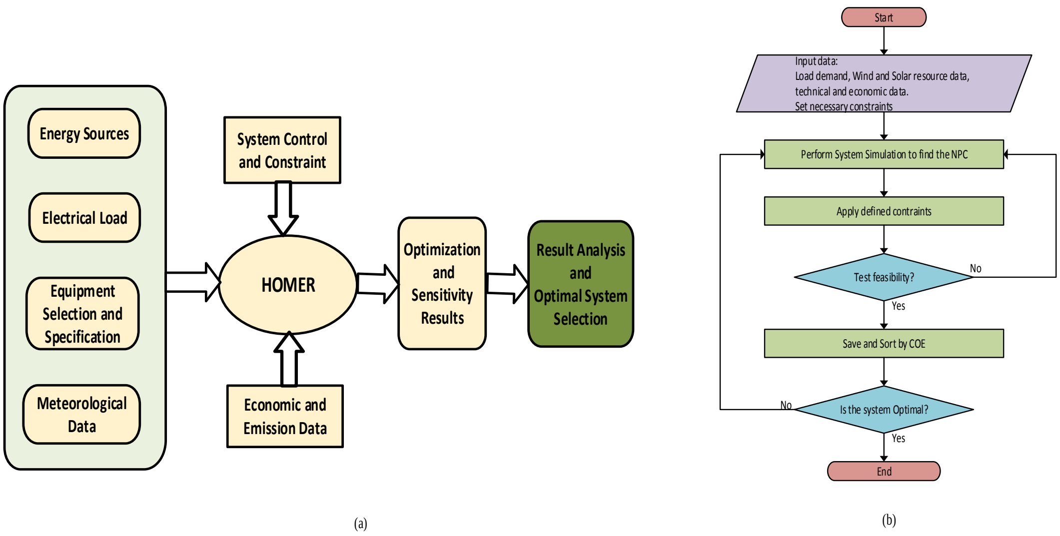

Fig. 1. Structure of HOMER software (a) System modelling and simulation (b) Optimization process [9]

conducted to understand the effect of uncertainty in input parameters on the results.

3. System Model

This section describes the components of the entire system along with their input parameters within HOMER and how the input data were processed.

3.1. Primary energy sources

The energy sources used in this study and their availability are considered in this section. Biogas production from cattle dung and rumen collected from slaughtered cattle is the primary system of power generation considered in this study. However, solar PV generator is also included in this system to serve critical loads (e.g. cold room) when output from the biogas generator is interrupted. The potential for solar energy in Nigeria is also not in short supply where the average is about 5.64 kWh/m^2/day.

3.1.1. Solar energy

The site under study shown in Fig. 2 is located at latitude 7° 32' N and longitude 5° 32' E in the city of Ado Ekiti, southwest Nigeria. HOMER calculates the global horizontal solar radiation and optimum size of the system based on this coordinate. From the data obtained from NASA surface meteorology and solar energy website, annual average solar radiation in Ado Ekiti is about 4.93 kWh/m^2/day. Figure 3 Illustrate the monthly average global horizontal solar radiation of the city.

3.1.2. Biogas

The source of raw material required for biogas formation is the waste from slaughtered ruminant and poultry animals. These substances are organic in nature and their availability gives an idea of how much potential there is for biogas production. Available data from the slaughterhouse shows that between 20-30 cattle are slaughtered daily with little or no figures for goat, sheep, and poultry. However, the waste from the slaughter process is dumped into the surrounding area with its attendant risk to human health and environment. This study assumes an average of 25 cows are slaughtered daily and if the average weight of the commonly slaughtered white Fulani cow is 350 kg, 13 % of this weight is taken as the rumen content. This gives an available biomass of 1150 kg/day while the amount of biogas produced estimated as 0.3 m^3/ kg of fresh material. This assumption is used as one of the constraints in HOMER model. Figure 4 shows the biomass resources input parameter used for simulation in this study.

Fig. 2. Aerial map showing the study site

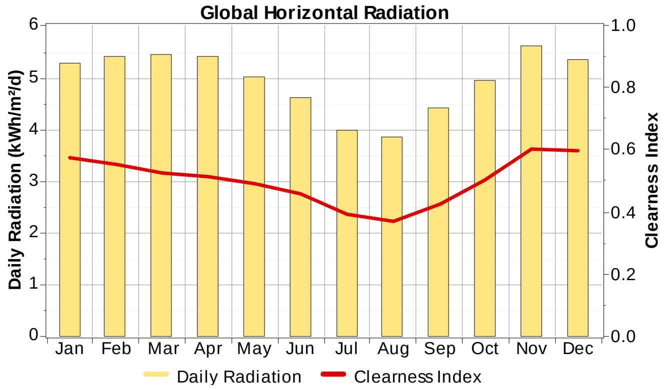

Fig. 3. Average monthly solar radiation for the study site.

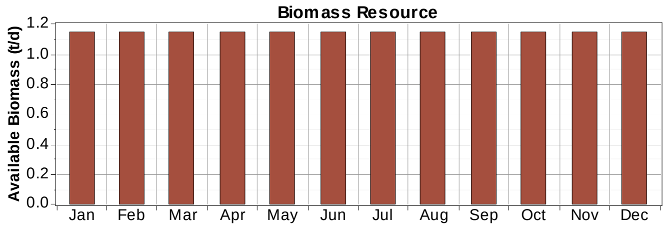

Fig. 4. Cattle dung and undigested rumen biomass resource input

3.2. Loads

A survey of the slaughterhouse shows that some existing electrical loads are not operational and a daily load profile is not available. This is because the facility is not connected to the grid and the standby power generator is rarely used. This means that fresh beef is stored in private facilities outside the slaughterhouse. In this study, a 24 hr load profile was assumed based on the data obtained from the site visit and typical electrical appliance for such a facility. The resulting load profile is illustrated in Fig. 5 while Table 1 presents the electrical loads considered in this study where daily AC load consumption is about 164 kWh/day.

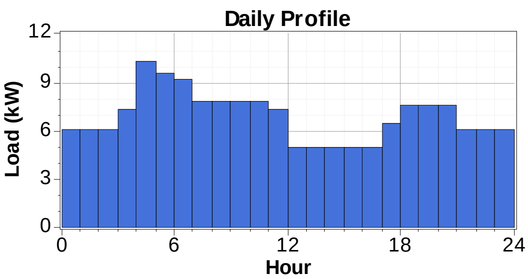

Fig. 5. Daily load profile

3.3. System Configuration

The system configuration of the power system is made up of PV panels, biogas engine generator, converter and battery storage. The PV panels and the battery system are connected to the DC bus while the biogas generator is connected to the AC bus as shown in the schematic of Fig 6. A bi-directional converter serves as the means of communication between the two buses.

Table 1. Estimated load for the slaughterhouse

Load type	Equipment Load (kW)	Energy demand (kWh/day)
Submersible pumps for borehole (2 Units)	2.4	9.6
Cold Rooms	5	72
Lighting Load	3	34.5
Small Power Loads	8	48
Total	18.4	164.1

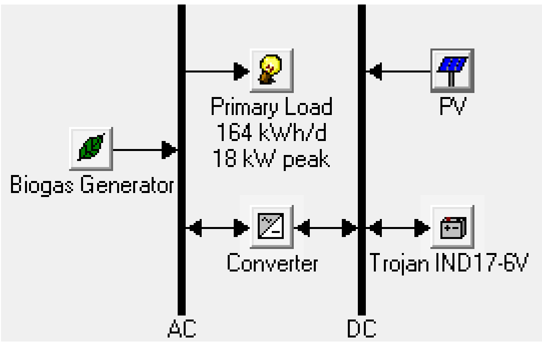

Fig. 6. Schematic of system configuration.

3.4. Component specifications

This section describes the specification of all the system components along with their associated costs.

3.4.1. Solar PV

Solar PV systems convert the solar irradiance into electricity using photovoltaic principle. In this study, the solar panel has a capital cost of $ 1400/kW including the cost of installation and charge controller since HOMER does not model charge a controller separately [9]. The replacement and an O&M cost of the PV panels is assumed to be $ 1300/kW and $ 0/year respectively. The system has a fixed orientation with a lifetime of 20 years and a de-rating factor of 80%. The expected energy production from the system is expressed in equation (1).

$$E_{spv}(t)=G(t)\times\eta_{spv}\times A \tag{1}$$

where $G(t)$ is hourly irradiance in kWh/m^2, η_{spv} is the efficiency of PV panel and A is the area of the PV modules.

3.4.2. Battery

Although the primary source of power proposed for this system is the generator, an energy storage system is considered to store excess energy from the biogas generator/PV system for use when there is a shortage of biogas. The battery charging and discharge cycle are regulated by a charge controller system which function to prevent overcharging and deep discharge of the batteries. Equation (2) gives the expression for the battery storage capacity. In this design, a 6 V, 1202 Ah battery type given as Trojan IND17-6V Industrial Line Flooded Battery (6 V 1202 Ah) is chosen from HOMER database. 8 batteries are required per string to create a DC bus voltage of 48 V. Initial capital cost, replacement cost and O&M cost input was set at $ 1300, $ 1300 and $ 22 respectively.

$$E_{bat} = \frac{E_{ang} \times DA}{\eta_{inv} \times \eta_{bat} \times DOD} \qquad (2)$$

Where E_{ang} is the total energy demand, *DA* is the Daily autonomy, *DOD* is the battery's depth of discharge, η_{inv} is the inverter efficiency and η_b is the battery efficiency.

3.4.3. Converter

The converter comprises an inverter-rectifier system whose function is to link the DC bus of the system to the AC bus. A Schneider electric converter is selected for this study with capital cost input of $ 1700, $ 4200, $ 6305 for a 3, 6.8 and 10 kW respectively. The sizes to consider range between 10 and 25 kW in steps of 5 kW. At an estimated lifetime of 20 years and a conversion efficiency of 90%, the energy output of the bidirectional system is given as

$$E_{dc-ac}(t) = \eta_{inv} \times E_{bat.load}(t) \qquad (3)$$

$$E_{ac-dc}(t) = \eta_{rec} \times E_{biosur}(t) \qquad (4)$$

where $E_{ac\text{-}dc}(t)$ and $E_{dc\text{-}ac}(t)$ is the hourly energy input and output of inverter respectively, η_{rec} and η_{inv} is rectifier and inverter efficiency respectively $E_{bat.load}(t)$ is the hourly energy output of the battery to supply load, and $E_{biosur}(t)$, the hourly surplus energy from biogas generator.

3.4.4. Biogas electricity generator and digester

Availability of cattle manure from the slaughterhouse which ensures the continuous supply of biogas for electricity is the primary aim of this study. With an estimated daily waste production of 1150 kg and assuming equal volume of water (1150 litres) is required to make a slurry, the digester should have the capability to handle solid material input of 2300 litres/day (2.3 m^3/day). The cost of biogas electricity generator, digester, and associated installation works make up the total capital cost input of $ 12000 while the replacement cost of the system is set at $ 10000. The fuel price is zero since the biogas is produced from waste available within the facility. The O&M cost of the system is set at $ 0.4/hr which consist of the routine engine maintenance cost and labour cost for substrate collection, preparation, and feeding of the digester. The operating schedule of the biogas generator shown in Fig. 7 indicates that it is forced on for about 7 hours early in the day when the peak load occurs and forced off for the rest of the day during weekdays and optimized for weekends. The electric energy generated from the biogas is expressed as

$$e_{biogas} = E_{biogas} \times \eta_{biogas} \qquad (5)$$

where e_{biogas} is the quantity of generated electricity, E_{biogas} is the unconverted raw energy in the biogas and the η_{biogas} denotes the overall efficiency of the conversion of biogas to electricity.

3.5. Economic parameters

Input economic parameters are the interest rate and project lifetime. These are used to determine the system net present cost (NPC) and the levelized cost of energy (COE) in this study. The lifetime of the project is taken as 20 years and the annual real interest rate from the central bank of Nigeria is assumed to be 14%. Economic output from system simulation in terms of NPC and COE is expressed as

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \qquad (6)$$

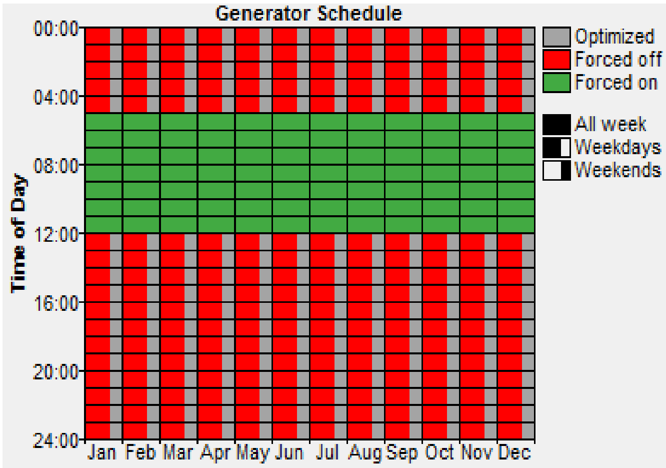

Fig. 7. Biogas generator annual operating schedule

CRF (i, R_{proj}) is the capital recovery factor given by

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (7)$$

Where $C_{ann,tot}$ is the total annualized cost, *i* is the interest rate, *N* is the project lifetime in years.

The levelized cost of energy is expressed as

$$COE = \frac{C_{ann,\ tot}}{E_{served}} \qquad (8)$$

Where E_{served} is the total energy served by the system.

4. Results and Discussion

This section presents the analysis of results obtained from system simulation, optimization and sensitivity analysis.

4.1. Optimization results

The input parameters defined for each component in the previous section is used by HOMER to determine feasible system solutions that can adequately meet the load requirements. These feasible systems are presented in groups of optimized results which may contain all or selected equipment types under consideration. However, results from this study suggested a single group of result which has a solar PV and biogas generator component as primary energy sources. The five top-ranked optimized systems based on increasing NPC is shown in Fig. 8. It is observed that the most optimal system with the least NPC at $ 89,393 which consist of a 20 kW PV-Array, 20 kW biogas generator, 15 kW inverter and 16 Trojan IND 17-6V batteries system. However, this system with the least cost is not suitable in this study because the converter size cannot supply system peak load (18 kW) alone except backup power is supplied by the biogas generator. Hence, this study made a trade-off between this consideration and system cost by selecting the next optimized system. This system is composed of a 20 kW PV-Array, 16 Trojan IND 17-6V batteries, a 20 kW biogas engine generator set and a 20 kW inverter. The selected optimal system has an initial capital of $ 73,683, an annual operating cost of $ 2915/year, NPC of $ 92,988 and a COE of $ 0.236/kWh. Cost summary based on system components is shown in Fig 9. It is apparent that the system attracts no fuel cost and the PV, battery and converter components make up about 80% of the capital cost and the remaining 20% is due to the battery bank. Besides, the cash flow summary of the system over the 20 years' project lifetime as illustrated in Figure 10, shows that the biogas generator and battery system will continue to incur a total recurrent annual maintenance cost of $ 1,382. Further analysis also indicates that the biogas generating set, battery, and converter have an operational life of 7.77 years, expected life of 11.3 years and 15 years respectively. This means that the generator will be replaced at least twice in the project lifetime.

PV (kW)	Gas (kW)	IND17-6V	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Biomass (t)	Gas (hrs)
20	20	16	15	$ 70,394	2,871	$ 89,412	0.227	1.00	0.01	151	2,581
20	20	16	20	$ 73,683	2,915	$ 92,988	0.236	1.00	0.01	150	2,575
25	20	16	15	$ 77,394	2,855	$ 96,301	0.243	1.00	0.00	143	2,569
20	20	16	25	$ 76,972	2,960	$ 96,578	0.245	1.00	0.01	150	2,575
20	20	24	15	$ 80,794	2,617	$ 98,129	0.248	1.00	0.00	151	2,577

Fig. 8. Best-ranked optimization results according to system NPC

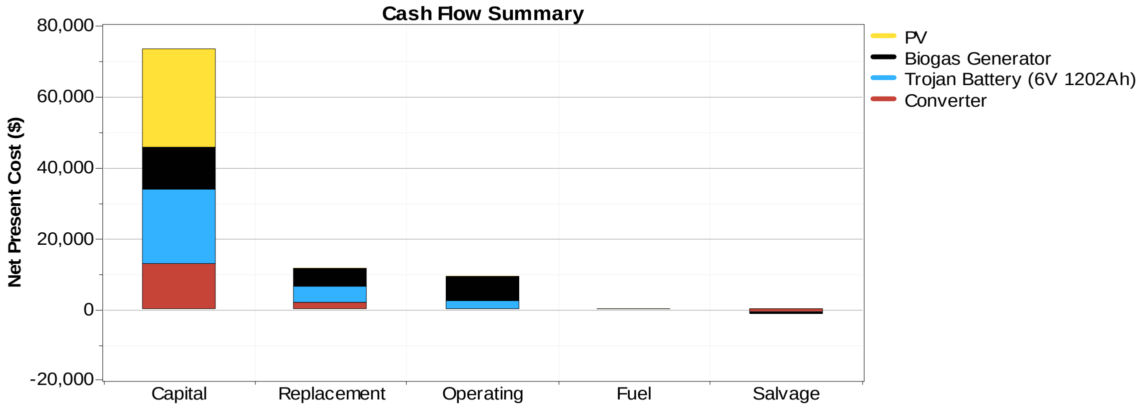

Fig. 9. Cost summary of the PV/biogas power system.

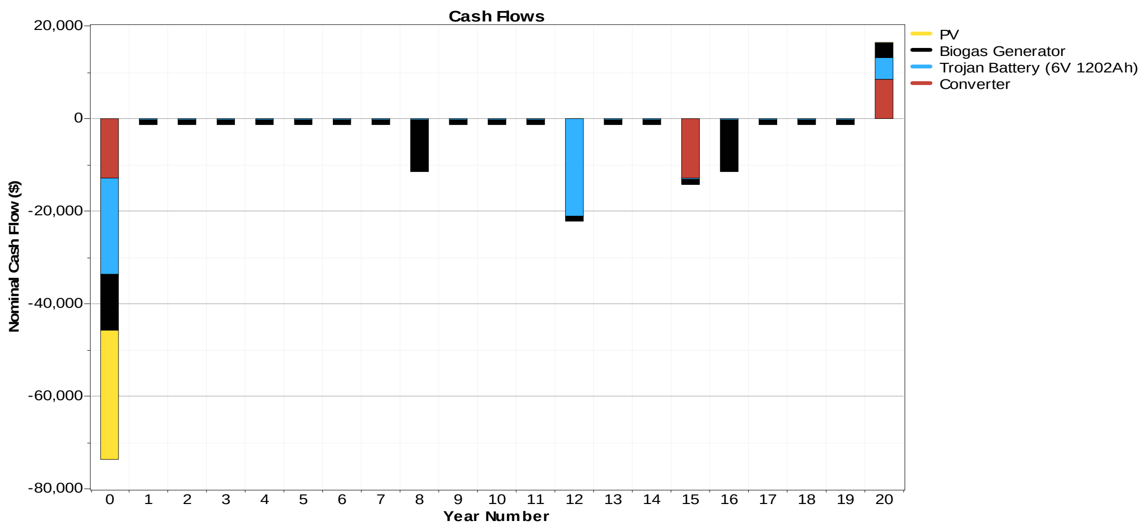

Fig. 10. Cash flow summary of the PV/biogas power system.

Figure 11 illustrates the monthly average power production by this system. It is observed that a substantial portion of the load requirements is served by the biogas generator. An assessment of one-year energy production and consumption operation of the system indicates that biogas generator supplied 62% of total production while the remaining 38% is provided by the PV system. Figure 12 and 13 show how these productions are achieved by the biogas generator and PV-array. The inverter output power during this period is also shown in Fig 14. Table 2 gives the summary of generated power, load demanded and share of power generation by each component of the system.

From table 2, the system produced annual excess electricity of 3096 kWh/yr (4.05%) but loads to the tune of 317 kWh/yr (0.53%) were unmet during this period although, the maximum capacity shortage constraint was set at 1%. To better understand the reason for this, all unmet load conditions were investigated and the maximum unmet load is discovered to have occurred on August 23 between the hours of 1:30 am and 5:30 am. A 24 h analysis of the PV power, biogas generator power, inverter output power and battery state of charge when this condition occurred are shown in Fig 15. It could be inferred that some loads could not be met because the biogas generator was shut down and the PV array was not generating for lack of insolation. In addition, the inverter could not provide backup power supply since the battery state of charge is low. This situation could be avoided with appropriate demand-side management strategies that prevent deep discharge of the batteries.

4.2. Sensitivity analysis

In other to understand the effect of variation in some component parameters on the study system, a sensitivity analysis is conducted. Different values in the range of a 50% drop in biomass resource input and 50% increase in the daily average load of the slaughterhouse were considered as sensitivity input. This is to understand how the drop in biogas generation and increased load will affect the system results. The surface plot of the system NPC response to changing biomass and daily average load input is presented in Fig 16. It is observed that the NPC is only affected by an increase in average daily load demand while the drop in biomass input has no influence on the NPC. The result of superimposing the COE on the same plot produced a similar trend.

Table. 2. One-year operational power generation and consumption by the PV/biogas system

	Quantity	**kWh/yr**	**%**
Production	PV array	29,130	38
	Biogas Generator	47254	62
	Total	76,384	100
Consumption	AC primary load	59,544	100
Others	Excess electricity	3096	4.05
	Unmet electric load	317	0.53
	Capacity shortage	357	0.60

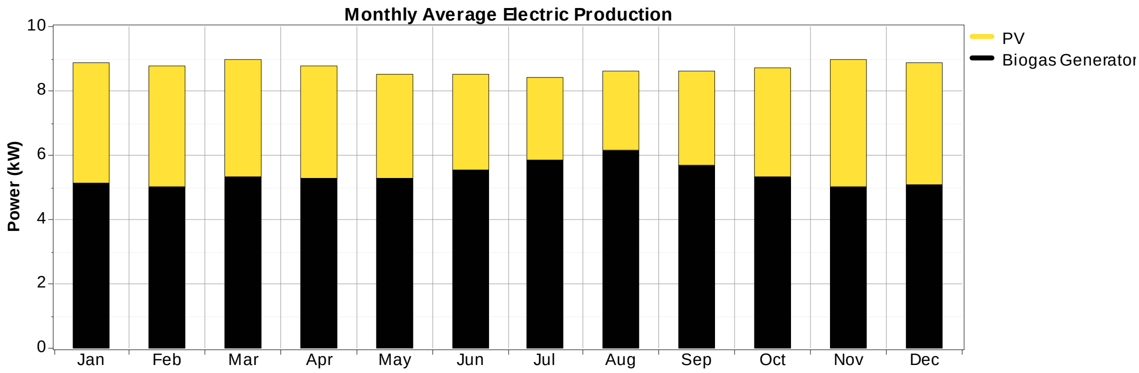

Fig. 11. Monthly average production from optimized PV/biogas power system.

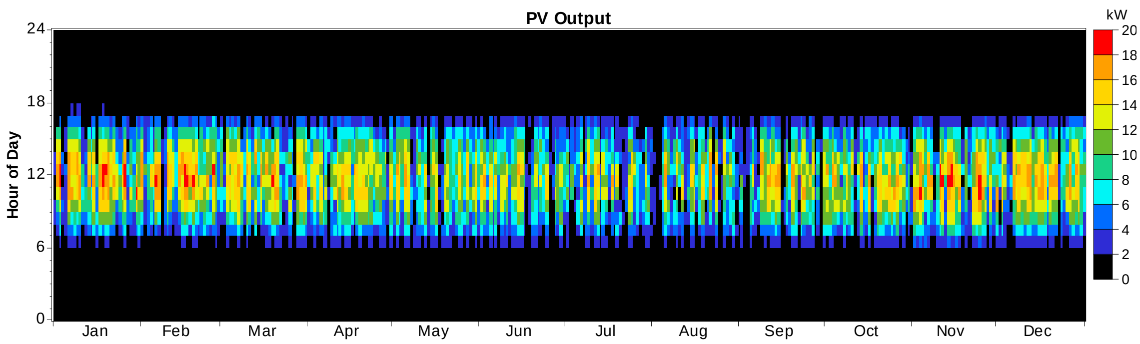

Fig. 12. PV output power of optimized PV/biogas power system.

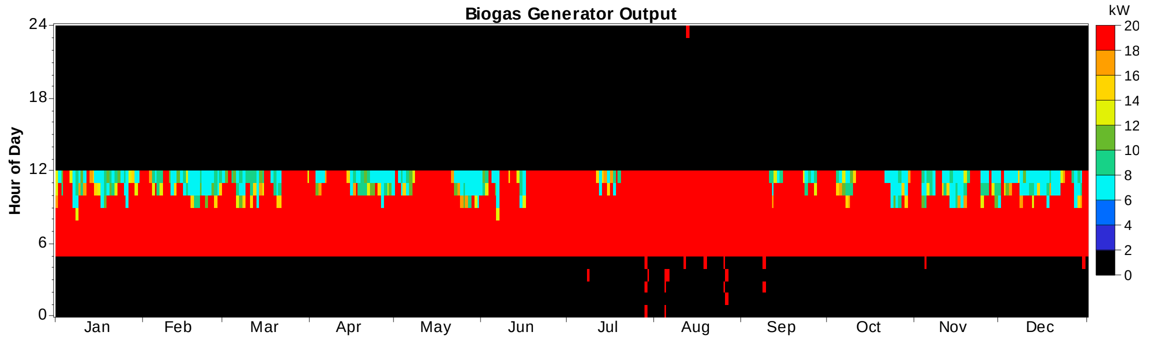

Fig. 13. Biogas power generator output optimized PV/biogas power system.

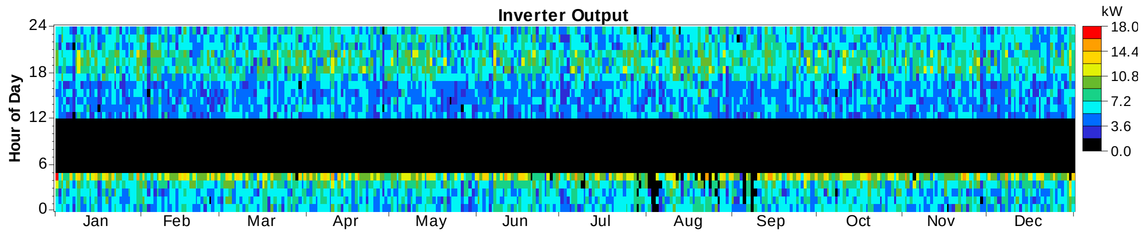

Fig. 14. Inverter output power of the optimized PV/biogas power system.

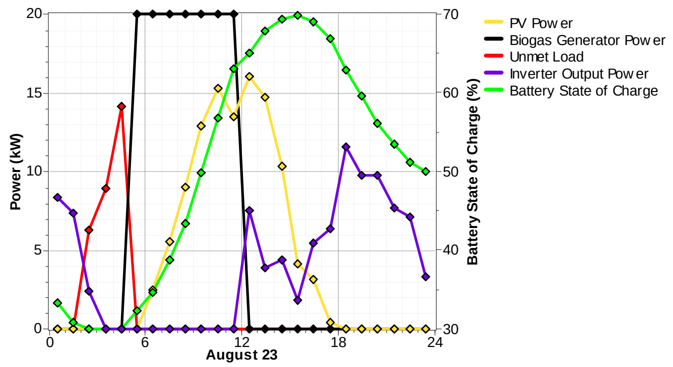

Fig. 15. 24 h profile of unmet load, battery state of charge and generated power by PV, biogas generator and Inverter (August 23)

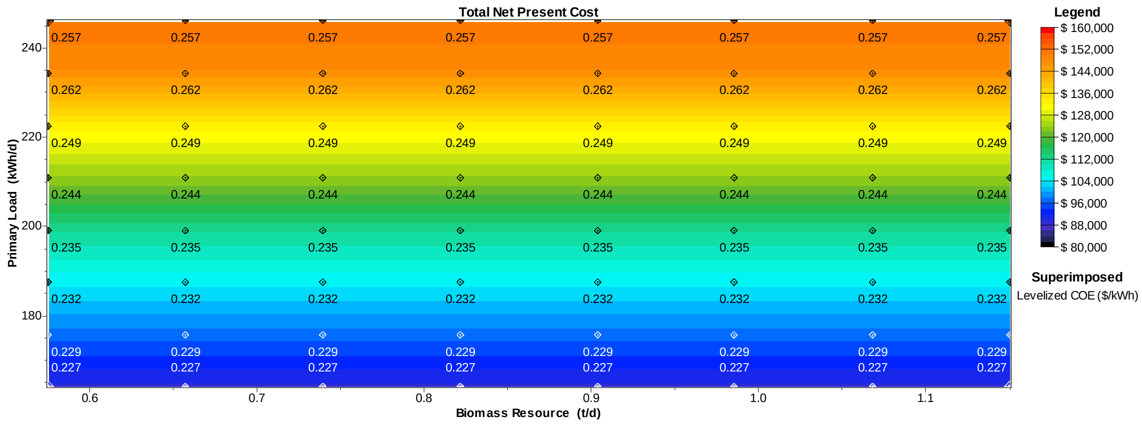

Fig.16. Surface Plot of Net Present Cost

5. Conclusions

As the demand for energy grows, diminishing fossil fuel reserve and its resultant environmental problems will continue to be a source of concern to humanity. This is because sustainable development can only be assured in a healthy environment. A healthy environment can be realized by replacing fossil fuel based energy sources with sustainable renewable energy systems. Biomass renewable energy source from animal waste in livestock husbandries and slaughterhouses can provide a sustainable method of making up this energy deficiency and enhancing economic development. This study presents an investigation into the potential of using off-grid power system to electrify the central slaughterhouse in Ado Ekiti, Nigeria using a PV/biogas system. Electricity generated by the system supplies the power demand of the slaughterhouse. HOMER software was used to design and simulate different operating scenario that meets the slaughterhouse load requirements based on input techno-economic parameters.

A configuration which includes PV/biogas generator/battery/converter system which had an NPC of $ 92,988 and COE of $ 0.232/kWh was selected as the most suitable system. To achieve this, the biogas generator produced 62% of the total annual power delivered to the load while the PV system supplied the remaining 38%. Although the cost of biogas fuel is taken as zero and biogas generator operational time was limited, lifecycle analysis reveals that the generator will require replacement every 7.77 years. Moreover, PV system components such as the battery, and converter will also need to be replaced after 11.3 years and 15 years respectively. This shows that deploying this type of power system has a high potential for meeting the energy requirements of this facility and similar ones over a long period of time thereby ensuring the sustainability of energy supply.

Developing countries of the world with acute shortage of grid electricity can take advantage of such independent electrification projects for specialized facilities. This will improve the quality of services offered and translate into better economic advantage. This is to further enhance the goal of finding a sustainable energy source that will offer opportunities within several areas such as the environment, technology, economic and social fields.

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