SIMULATION AND ANALYSIS OF STANDALONE POWER SYSTEM BASED ON BIOMASS AND DIESEL SOURCES FOR REMOTE HOUSEHOLDS

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Abstract:

This paper presents the simulation and analysis of biomass/diesel system for remote households. It assumes a location in the southeast of Nigeria as a test case where biomass feedstock such as rice husk is available for electricity generation. The work considers the use of biogas produced from rice husk to run a generator that can power a demand of 106.38 kWh/d by 18 households. HOMER tool was employed to simulate the power system and three scenarios are examined such as the biogas-only, diesel-only, and biogas/diesel options; the performances of these systems are compared in terms of the annual energy delivered, availability, and the emissions produced. The size of the biogas-only generating (gen) system is 13 kW and it produces 42,237 kWh/yr of energy with availability (avb) of 100 %. For the diesel-only system, a 13 kW diesel gen system is obtained which delivers 42, 237 kWh/yr of energy with avb of 100 %. However, the biogas-only gen achieves avb of less than 100 % for 20 % increase in demand. A 2.3 kW diesel gen capacity is then added to the biogas system to realize avb of 100 %. The values of CO_2, CO, unburned hydrocarbon (UH), particulate matter (PM), SO_2 and NO_x emissions by the three scenarios are 3.44, 0.357, 0.0157, 0 and 0.335; 42,113, 265, 11.6, 1.61, 103 and 249; and 3,976, 25.4, 1.11, 0.154, 9.73 and 23.8, respectively. These results present the biogas/diesel power as a suitable option in terms of availability and avoiding significant quantity of emissions compared to the other two options that have the issue of availability and emissions, respectively. The paper will help to understand local energy planning and design.

Keywords: Availability, biomass, biogas power, diesel power, emissions, energy ladder

Introduction

Energy is one of the critical factors for human existence, growth and development (Twidell and Weir, 2006). The utilization of energy is key to manufacturing, transportation system, residential, commercial and agricultural industries and processes. This signifies the fact that social and economic development largely depends on the energy system of a particular community or nation. Nigeria, for instance, is experiencing the issue of energy shortage and erratic power, which is why economic development is hampered in certain parts of the country (Okakwu *et al*., 2021). This development calls for strengthening the country’s energy mix.

Energy resources are classified into conventional and non-conventional sources. The conventional resources include resources such as diesel, petrol, natural gas, coal, etc., while the non-conventional resources are referred to as renewable energies (Twidell and Weir, 2006). The renewable energy resources include the following: solar, wind, biomass, water, geothermal, etc. One of the benefits of the renewable energy sources is the fact that they are environment-friendly, compared to the conventional resources that produce emissions that can affect the people’s health. Biomass is one among the mentioned renewable energy resources that are eco-friendly and has the potential for electricity generation in developed and developing countries (Balat and Ayar, 2006).

In Nigeria, the issues of energy poverty, energy shortage and erratic poor supply have been persistent problems in the electricity parlance. The country’s current electricity generation capacity is believed to be unable to cater for the load capacity of a population of about 200 million. Several communities or locations, especially rural areas either have electricity access problem or the issue of erratic power supply (Akinbami *et al.*, 2001). The overarching goal of this paper is to simulate and analyse a biogas/diesel-based power system for rural households.

Some similar studies exist in the literature that considers biogas-hybrid system. For instance, a research work has presented the design and simulation of hybrid biomass-solar renewable energy system for rural dwellers in Nigeria (Njoku *et al*., 2018). The study focused on the design and modelling of a stand-alone hybrid electricity plant based on solar and biomass renewable energies for rural areas in Nigeria.

A study has focused on the techno-economic feasibility assessment of a solar/biomass/diesel power system for a remote rural health center in Nigeria (Achirgbenda *et al.*, 2020). Another research study has been done to design and plan biomass power plant system for residential building energy system (Rahman *et al*., 2015), while the authors in (Sofimieari *et al.*, 2019) modelled and analyzed a PV/wind/diesel hybrid standalone system for rural electricity supply for a location in Kaduna Nigeria. Also, the comparative evaluation of a hybrid system has been considered for sustainable multi-generation in Nigeria (Diyoke *et al*., 2021). The paper considered gas turbine and biomass systems in MATLAB environment using techno-economic (TE) and environmental evaluation approach. Ariyo *et al*., (2018) discussed the optimization analysis of an off-grid hybrid power system for the senate building of University of Ilorin, Nigeria. The work is based on PV/wind/diesel analysis using TE assessments.

Another study discussed an integrated model of waste-to-energy system for sustainable communities (Babalola *et al*., 2022). The authors considered different microgrid solutions based on PV/biogas/diesel, PV/diesel/battery, and waste-to-energy/PV/battery systems. The work is based on the TE and environmental evaluation approach. The paper by Onojo *et al*., (2013) considered the feasibility investigation of a hybrid RE system for backup in an ICT building of Federal University of Technology, Owerri, Imo State, Nigeria. The model proposed is based on hydro, solar and biomass energy mix.

(Njoku *et al*., 2018; Achirgbenda *et al.,* 2020; Rahman *et al*., 2015; Sofimieari *et al.*, 2019; Diyoke *et al*., 2021; Ariyo *et al*., 2018; Babalola *et al*., 2022; Onojo *et al*., 2013) have made useful contributions in the area of hybrid energy simulation and analysis based on different resources such as solar, hydro, wind, biomass, natural gas and biomass. Also, (Njoku *et al*., 2018; Achirgbenda *et al.*, 2020; Rahman *et al*., 2015; Sofimieari *et al.*, 2019 ; Ariyo *et al*., 2018; Onojo *et al*., 2013) used the Hybrid Optimization of Multiple Energy Resources (HOMER) Pro tool for their different models. This current paper, however, considers the utilization of biogas resource to produce electricity while using diesel energy resource as a backup. It uses a location in the Southeastern area of Nigeria as a case study because of the availability of rice husk in this area that can be used to generate electricity. The rice husk is used to generate biogas for driving a generator to produce electricity for a demand of 106.38 kWh/day assumed for 18 households. The information about the location and the biomass resources data are obtained from Ejiofor *et al.,* (2020). This paper also employs HOMER tool to model different configurations such as biogas-only, diesel-only and biogas/diesel generating systems. These systems are then compared using the performance metrics such as annual electricity delivered, availability, sensitivity analysis based on the load demand increase and the quantity of emissions produced. The paper can be useful for local energy planning and analysis.

Methods and Materials

Case study

The Adani location in Enugu, Southeast Nigeria is assumed as the case study for this research work based on the existing work by Ejiofor *et al*. This location is one of the villages in Uzo-Uwani local government area (LGA). Rice plantation and processing and mills are prominent around this location; thus, the dwellers produce a high quantity of rice.

Instead of disposing such huge biomass resource, it will be reasonable to harness them for useful venture, such as heat and/or electricity generation. With the availability of a biomass resource such as the rice husk (waste), it is possible to produce biogas or producer gas which is eco-friendly and can help to address the electricity shortage issue. This is because of the fact that rice husk is biodegradable (Contretas *et al*., 2012).

In biomass gasification systems, solid biomass waste or residue such as rice husk or straw used in this work, is converted into a gaseous fuel that is then employed for electricity production (Sigh *et al*., 2016). Under partial combustion, a producer gas is formed, which is a combustible gas containing 20% of H_2, 20% of CO, and 1 to 2% of CH_4, including inert gases. The study assumes rural households where there is abundance of biomass residues for the analysis; in this case, the system design and simulation are based on the biomass resource of the proposed location, i.e., Adani.

Energy demand

The energy demand in kWh by a particular appliance or load in a single household may be calculated based on Equation (1):

$$E = P \cdot n \cdot t \quad (1)$$

Where *P* is the rating of the household appliance (kW), *n* is the total number of the appliance and *t* is the time in hours during the appliance is operated in the household. The appliance here may be lighting, TV, refrigerator, radio, fan, etc. Let the demand by these appliances be represented by: $(P.n.t)_1, (P.n.t)_2, (P.n.t)_3, \dots\dots\dots\dots (P.n.t)_n$. The total energy demand in a single household may then be represented by Equation (2) suppose there are up to *m* different appliances:

$$E_d = (P.n.t)_1 + (P.n.t)_2 + (P.n.t)_3 +..+(P.n.t)_m \quad (2)$$

Suppose there are *q* households, the total demand of all the households under consideration will then be represented by Equation (3)

$$E_{td} = E_{d1} + E_{d2} + E_{d3} + \cdots + E_{dq} \quad (3)$$

WhereE_{d1}, E_{d2}, E_{d3}, and E_{dq} represent the total energy demand of the first, second, third, up to the *qth* households. The users' demand on which this study is based is 106.38 kWh/d for 18 households based on the requirements for a single household presented in Table 1. This load requirement has been obtained from the authors' practical experience in electrical installation practice. The load profile for this research is shown in Figure 1, which has been obtained by adjusting the existing community-based profiles in HOMER software to a total daily demand value of 106.38 kWh used for the study analysis. This approach is employed because of unavailability of the users' consumption profile data at the time the study was conducted.

Table 1. Load details for a household

Appliance	Power rating (W)	Quantity	Total Power (W)	Duration of operation (hr)	Energy demand per household (kWh/d)
Lighting	10	6	60	12	0.72
Fan	60	3	180	8	1.44
TV	65	2	130	5	0.65
Radio	20	1	20	5	0.10
Refrigerator	300	1	300	10	3.00
					5.91

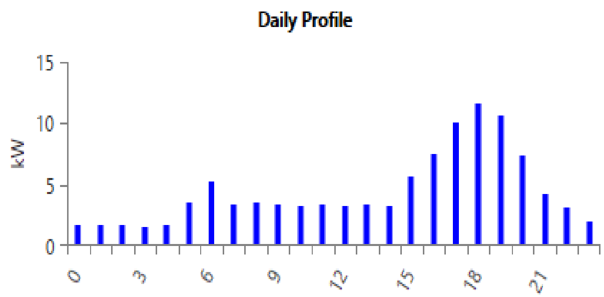

Figure 1. Load profile used for the simulation

Biomass data

The rice husk data used in this work is based on the existing data published by Ejiofor *et al.*, which was reported for Adani location from a period of November 2018 to October 2019. The quantity of rice husk presented by these authors served as the total rice residues for the whole location. However, this research work is proposing a small-scale biomass/diesel power system for 18 households within assuming the same location and not for the whole area. This involves scaling down the biomass data by dividing the original monthly values by 1000. The biomass data used for the study is shown in Figure 2 with the permission of the corresponding author in Ejiofor *et al*.

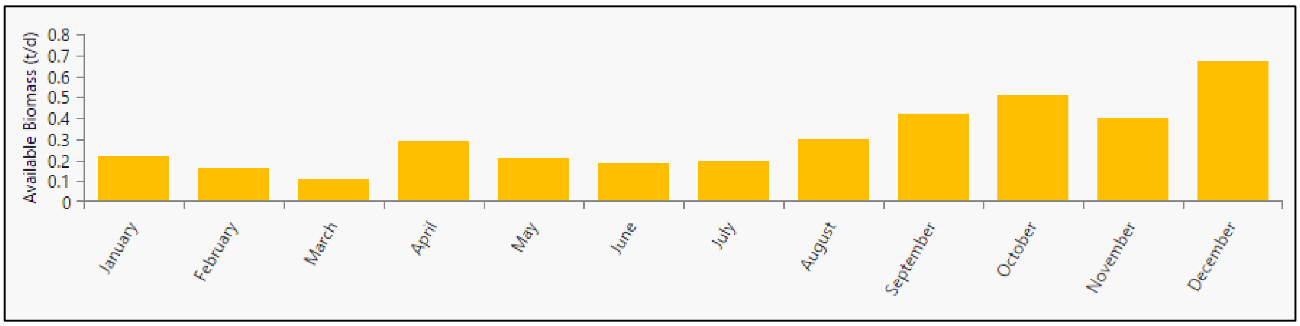

Figure 2. Rice husk data

Biogas system

In HOMER simulation environment, the word "biogas" is essentially a gasified biomass. It is possible to gasify biomass materials, i.e., feedstock like wood waste, energy crops or agricultural residue by thermo-chemical or biological/bio-chemical processes. The output may refer to one of these: synthesis gas, syngas, producer gas, or wood gas. Whatever the type of biomass feedstock and the means of achieving gasification, the main biogas gases are typically carbon monoxide, hydrogen, and carbon dioxide, including a high quantity of nitrogen (i.e., around half by weight) of thermal gasification is conducted in the presence of air. The minor component gases include methane and water vapor. Biogas has a low heating value (LHV) compared to the fossil fuels as presented in HOMER library. The HOMER tool also provides that the biogas fuel has the low heating value (LHV), density, carbon and sulfur values of 5.5 (MJ/kg), 0.720 (kg/m^3), 2 (%) and 0 (%), respectively.

In biomass gasification systems, solid biomass waste or residue such as rice husk or straw is converted into a gaseous fuel that is then employed for electricity production (Ariyo *et al.*, 2018). Under partial combustion, a producer gas is formed, which is a combustible gas containing 20 % of H_2, 20 % of CO, and 1 to 2 % of CH_4, including inert gases. The energy output of a biomass gasifier is given by Equation (4) (Singh *et al.*, 2016; Malik *et al.*, 2021)

$$E_{BPP} = P_{BPP} \times 8760 \times k \quad (4)$$

where E_{BPP} is the energy generation of biomass power plant in kWh, P_{BPP} is the rating of the biomass gasifier plant, k is the capacity utilization factor of the power plant and 8760 is the total number of hours in a year. Singh *et al*., (2016) also presented how the maximum rated capacity of a biomass gasifier installed at a particular location may be estimated.

Diesel generator

Generators are operated to meet the maximum or peak load of the users, and are required to generate continuous power. Importantly, generators need to be rated more than the users' peak load requirements, i.e., at least 10 – 20 % more than the peak load. In this study, diesel generator is used as a backup for the renewable energy resource (i.e., biomass); it may also be used to directly supply the load when the biomass resource or system is not available. The diesel generator is integrated with the biomass generator to form a hybrid power system, and this may be achieved through the auto sizing function of HOMER simulation tool. The fuel consumption of a diesel generator (gen), for instance, is given by Equation (5) based on HOMER methodology (Akinyele *et al*., 2022).

$$F = x \cdot G_c + y \cdot G_{po} \quad (5)$$

where x is the fuel curve intercept coefficient; G_c is the rated capacity of the generator; y is the fuel curve slope and G_{po} is the generator power output. HOMER software provides that the diesel fuel has the LHV, density, carbon and sulfur values of 43.2 (MJ/kg), 820 (kg/m^3), 88 (%) and 0.4 (%), respectively.

Availability

The availability (avb) of the system can be estimated by employing Equation (6) (Posadillo and Luque, 2008; Akinyele *et al*., 2021)

$$avb\ (\%) = \left(1 - \frac{\sum_{i=1}^{8760}(D_{un})_i}{\sum_{i=1}^{8760}(E_{td})_i}\right) \times 100 \quad (6)$$

where D_{un} and E_{td} represent the unmet demand and total demand, respectively. For instance, an *avb* of 100 % implies that D_{un} or the quantity $\frac{\sum_{i=1}^{8760}(D_{un})_i}{\sum_{i=1}^{8760}(E_{td})_i}$ is 0.

Biogas fraction in the hybrid power option

The contribution of the biogas resource in the biogas/diesel hybrid power system in this study can be calculated using Equation (7) (Akinyele *et al*., 2021): $BioGenF\ (\%) = \left(1 - \frac{E_{BioGen}}{E_{totGen}}\right) \times 100$ (7)

Where $BioGenF$, E_{BioGen} and E_{totGen} represent biogas gen fraction, electricity delivered by biogas gen and the total electricity generated by the biogas/diesel power system, respectively.

Results and Discussion

Biogas-only option

The biogas-only option with the users' load is shown in Figure 3, which has been simulated in HOMER from a generic small genset that is fueled by biogas. The size of the generator is 13 kW, and it generates 42,237 kWh/yr of electricity, which is enough to satisfy a daily load demand of 106.38 kWh/d over the year. The system availability (avb) is 100% as the generator adequately satisfies the load requirements.

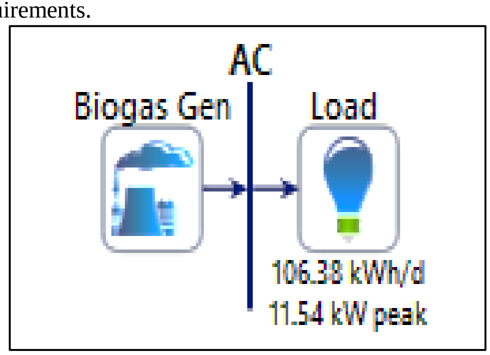

Figure 3. Biogas generator and the load

The gen consumes 21.8 tonnes of feedstock per year to generate the fuel to run the generator. Also, it emits CO_2, CO, UH, PM, SO_2, and NO_x of 3.44, 0.357, 0.0157, 0.00214, 0 and 0.335 kg/yr, respectively. These results justify the fact that a biogas fuel is not 100 % free of emissions because of the carbon content in its energy mix.

Diesel-only option

A 13 kW size diesel gen is obtained from the simulation to support the users' demand. The system configuration is shown in Figure 4. The total annual electricity generation obtained from this gen is 42, 237 kWh, which is enough to support the households' demand. This implies an avb of 100% since there is no unmet demand.

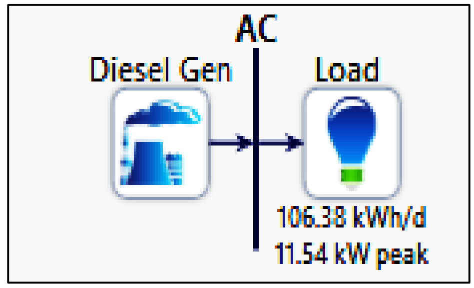

Figure 4. Diesel generator and the load

The total diesel consumption is 16088 L/yr. The gen emits CO_2, CO, UH, PM, SO_2, and NO_x of 42,113, 265, 11.6, 1.61, 103 and 249 kg/yr, respectively. These results explain the carbon-intensiveness of the diesel power generating system compared to a biogas system which is a cleaner option.

Sensitivity analysis: effect of energy ladder

The previous results demonstrate that the biogas and diesel-only options present a reliable energy supply to the intended energy consumers. This is evident in the amount of energy produced against the users' load demand requirements. However, in practical sense, there is the tendency for the users' load demand requirements to increase, i.e., the households are susceptible to climbing the energy ladder (Louie *et al.*, 2014). The size of the load growth will determine whether or not the existing power system will still be able to support the load. The biogas-only model is then tested with 10 and 20 % increase in load demand. The new values of load demand are 117 and 127.65 kWh/d, respectively. The corresponding peak demand values are 12.69 and 13.85 kW. The two new load profiles are shown in Figure 5 compared with the initial load.

The simulation reveals that the gas gen is able to support a 10 % load increase. This is evident in the new peak load of 12.69 kW being lower than the generator's capacity of 13 kW, making the gen to achieve availability of 100%. However, the 13 kW biogas gen is unable to support a 20% load increase, thus presenting unmet demand of 309 kWh translating to avb of less than 100%. This result justifies the integration of a backup source with the biogas gen so as to meet the shortfall in generation and achieve avb of 100 %.

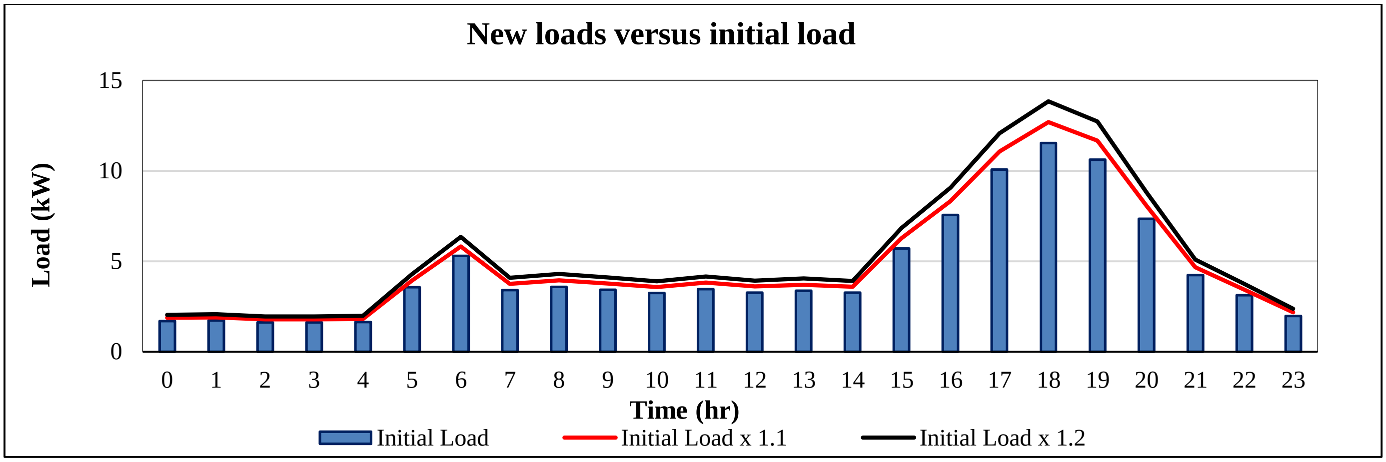

Figure 5. New and initial loads

Biogas/diesel option

A diesel gen system is included with the existing biogas gen system as shown in Figure 6. HOMER models the diesel generator to address the unmet demand as an "auto size" generator; this implies that it is able to simulate the capacity needed to achieve 100% availability. A generator size of 2.3 kW is obtained from HOMER tool, which provides the additional capacity to support the new load. The biogas gen produces 42,541 kWh/yr, while the diesel gen produces 4,375 kWh/yr translating to a total energy of 46,916 kWh/yr. The biogas and the diesel gen systems contribute 90.7 and 9.3%, respectively.

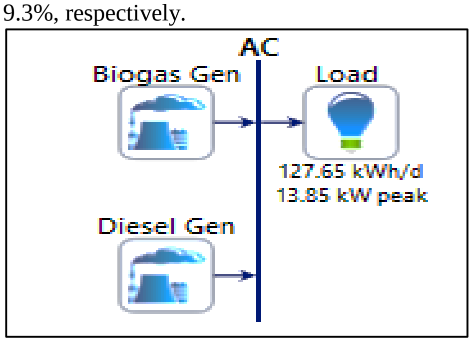

Figure 6. Biogas/diesel option and the new load

The total generation of 46,916 kWh/yr is higher than the new demand (i.e., total load demand with 20% load increase) of 46,594 kWh/yr. An avb value of 100 % is obtained. The biogas and the diesel gen systems consume 20.8 tonnes/yr of biomass feedstock and 1,518 L/yr of diesel, respectively. The biogas/diesel power system option emits CO_2, CO, UH, PM, SO_2, and NO_x of 3,976, 25.4, 1.11, 0.154, 9.73 and 23.8 kg/yr, respectively. These values are very much lower than the values obtained when the diesel-only option is being explored.

In this study, the biogas/diesel configuration presents the biogas as the main source while the diesel generator is used as backup. There may be the need to have a higher rated capacity of the diesel gen system. This situation will be determined by the level of load demand increase in case the households climb the energy ladder or a shortage in biomass feedstock. Therefore, a hybrid source system is expected to provide a reliable supply compared to a single- source system (Olabode *et al.*, 2021).

Comparison of the energy options

The results have shown that the three configurations can all support the users' load demand over the year, yet, it is necessary to compare the different features of the energy systems. In terms of reliability, a two-source energy system like the biogas/diesel option is most preferable because of the complementary characteristics of the participating fuels. Such a system can help to respond to load increase or the unavailability or low performance of one of the two sources. The biogas-only and the diesel-only systems have the lowest and the highest emissions, respectively. The values of emissions obtained for the biogas/diesel lies between the values obtained for biogas- and diesel-only options as shown in Table 2.

The results demonstrate that the higher the value of diesel utilized, the higher the emissions, but moderate use may be necessary where it is needed to achieve high system reliability.

Table 2. Emissions produced by the energy options

Emission (kg/yr)	Biogas option	Diesel option	Biogas/diesel option
CO_2	3.44	42,113	3,976
CO	0.357	265	25.4
UH	0.0157	11.6	1.11
PM	0.00214	1.61	0.154
SO_2	0	103	9.73
NO_x	0.335	249	23.8

Conclusion

This paper has presented the simulation and analysis of biomass and diesel hybrid system for remote households using a location within the Southeastern area of Nigeria as a case study. The research work has considered the application of biogas produced from biomass feedstock - rice husk to run a generator to power 18 households that consume 106.38 kWh of electrical energy per day. HOMER tool was used in the study to simulate the power system and three scenarios were considered such as the biogas-only, diesel-only, and biogas/diesel options. The performances of these electrical power systems have been compared in terms of the annual energy delivered, availability, and the emissions produced.

For the biogas-only option, the simulation result presented the size of the biogas-only generating (gen) system to be 13 kW and this gen delivered 42,237 kWh/yr of energy with system availability (avb) of 100 %. For the diesel-only system, a 13 kW diesel gen system was obtained, which generated 42, 237 kWh/yr of energy also with avb of 100 %. However, the sensitivity analysis revealed that the biogas-only gen achieved avb of less than 100 % when there was a 20 % increase in load demand. This then led to the addition of 2.3 kW diesel gen capacity to the biogas system to achieve avb of 100 %. The values of CO_2, CO, UH, PM, SO_2 and NO_x emissions obtained for the three scenarios were 3.44, 0.357, 0.0157, 0 and 0.335; 42,113, 265, 11.6, 1.61, 103 and 249; and 3,976, 25.4, 1.11, 0.154, 9.73 and 23.8, respectively. These results demonstrated that the biogas/diesel power option is a suitable option in terms of system availability and avoiding high carbon footprints compared to the two other options. The paper will be useful local energy planning and analysis purposes.

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