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Modeling and optimization of PV-diesel-biogas hybrid microgrid energy system for sustainability of electricity in Rural Area

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ABSTRACT

The paper presented a hybrid micro-grid renewable energy of different energy sources to generate uninterrupted electricity for the Agu-Amede village using PV, diesel, biogas, and battery. The system optimization was performed to determine techno-economic analysis and energy generated using HOMER software. The energy generated by the hybrid system was able to meet the demand load of the village at all levels of biomass production with surplus electricity in each case when the production of the biogas system varied between 0.5 tons to 3 tons. At biomass production of 3 tons, the total energy generated demand is 480693 kWh with a surplus of 121762 kWh. Again, the hybrid PV and biogas system generate total energy of 98714 kWh (20.50%) and 381979 kWh (79.50%), respectively. The net present cost (NPC) and cost of energy (COE) of the base case architecture (diesel) measured are $1230000 and $0.267/kWh, respectively. Therefore, between 2.5 tons and 3.0 tons of biomass penetration, the energy production of biogas increased, and the diesel system was removed from the hybrid system setup. This is because the availability of biogas is almost sufficient to meet the load demand at a lower cost and solar PV architecture was added to the hybrid system to balance energy production.

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1. INTRODUCTION

Interest in alternative energy sources has significantly expanded recently as a result of the issue of resource depletion brought on by the careless use of fossil fuels and environmental challenges brought on by the emission of greenhouse gases [1]. In light of the fact that fossil fuels like natural gas, coal and oil are thought to be the primary global emitters of greenhouse gases, measures to restrict their use are also being developed. Rural grid expansion is rigorously difficult due to the rough terrain, dense jungles, regional isolation, high prices in supply, reduced consumption, diminished household earnings, deficient transportation infrastructures, as well as distributed consumer colony [2]–[4]. As a result, most residents in local regions look up to other means of generating electricity, primarily generators which depends on diesel for the mode of operation. This mode of generation has the downsides of causing pollution from noise and emitting greenhouse gases. Also, most importantly, routine periodic maintenance at a high fuel price is a factor as well [5]–[7]. A distributed power generation approach known as a microgrid is more effective than a traditional centralized power generation method because it can minimize power loss caused by long-distance transmission. Additionally, huge energy independence can be achieved because stand-alone operation distributed electricity is obtainable without the microgrid being connected to existing systems [8], [9]. Furthermore, the generated power quantity by renewable energy systems (RESs), like photovoltaic and wind power used to supply microgrids, is impacted by climate changes like variations in solar radiation and wind speed.

Therefore, an energy management system (EMS) based on an energy storage system (ESS) is essential for sustaining the power supply and ensuring that distribution networks operate at their peak performance [10]–[12]. Kother *et al.* [13] analyzed renewable energy system based on techno-economics evaluation for hospital in remote area of southern Iraq. Gandhi *et al.* [14] provides insight into the various efficient resources and approaches commonly used to control power dispatch. Araoye *et al.* [15] developed an analysis of a techno-economic hybrid microgrid with a biogas-diesel generator system. The researcher used HOMER and MATLAB software to model, simulate, and optimize the hybrid microgrid system when the base case was taken to be diesel. Liu and Rodriguez [16] developed algorithm based on Sparrow adaptive search optimization for generating electricity through renewable energy systems in a residential building. Mohd Tumari *et al.* [17] proposed grey wolf modifier optimization to improve the parameter controller of wind turbines and total energy generated under various environmental condition. The significant drawbacks of renewable energy utilization are associated with low efficiency and unreliable because of resource fluctuation and intermittent, leading to an increase in investment cost and system over-size. The hybrid renewable energy system is an effective method to mitigate the drawback that is associated with a renewable energy system. Hybrid renewable energy comprises two or more renewable power plants combined with fossil fuel or renewable energy with load supply and energy storage. The major benefits of hybrid renewable energy systems include reduction of storage energy capacity, reliability, high efficiency, and low power cost levelized life-cycle [18].

With Nigeria's ongoing power restructuring and privatization, remote regions have become inaccessible due to a lack of decent road systems. The rural population is socially regressive, and their economic potential is unrealized due to a lack of sustainable electricity supply [19]. Nigeria's energy contingency is a perplexing problem when an estimated seventy-three (73) million people (which makes up 45% of the total country's population) are being denied to enjoy electricity [20]. Establishing non-centralized power availability via a scheme tagged off-grid electrification strategy is one of the other solutions proposed by the Nigerian Rural Electrification Agency (REA) to this problem. This program aims to use renewable energy resources to generate electricity in standalone installations, microgrids, and mini-grids [21].

This study designed a hybrid microgrid energy system based on biomass, solar PV, battery, and diesel for energy generation in the Agu-Amede village, Enugu State, Nigeria. As a result of the community's lack of access to electricity, hybrid micro-grid models are designed for the region's sake to increase electricity supply using animal dung and solar systems. Consequently, the generation of power through this proposed means is indeed very low-cost and has high technical viability since animal dung and sunlight are easily accessible, and it also improves the community's social life. Also, the economic analysis is performed to determine the feasibility of a microgrid system in the village with a hybrid renewable system using HOMER pro software. The analysis of the village microgrid is performed to improve energy reliability, environmental impacts and economic feasibility.

2. MATERIALS AND METHODS

This article designs a hybrid micro-grid system of electric production for Agu-Amede village located in Enugu state. Agu-Amede village was subjected to a load audit, and the load profile was determined. HOMER was used to compute the daily peak power used. The equations of the biogas and PV system were modeled in HOMER to establish the capacity needed for each generator. The optimization of the system was done in a HOMER optimizer which is subject to maximization of generated energy and cost minimization. The implementation of optimizer is done through propriety derivative-based algorithm to evaluate the minimum-cost system and presents different system design options. It works on three different steps. In the first step, the system configuration, electric load demand of Agu-Amede village and the meteorological data such as solar irradiation, biomass, diesel price and ambient temperature. The technical details and costs of all the hardware components required for this system are designed in HOMER. In the second step, performance of lower COE and NPC analysis with different system configurations was performed. In this context, each of the system configurations is designed to satisfy the specified load demand and some other technical and environmental constraints such as energy production by each renewable energy resources, excess energy, renewable penetration and battery characteristics was examined. In the final stage, the results are then compared based on the techno-economic and environmental preferences and the optimized system configuration is chosen. The compression proportion must be high to enhance methane efficiency as discussed previously from the paper published [15]. Figure 1 shows the diagrammatic connection of a PV-diesel-battery-biogas hybrid operational renewable energy microgrid system.

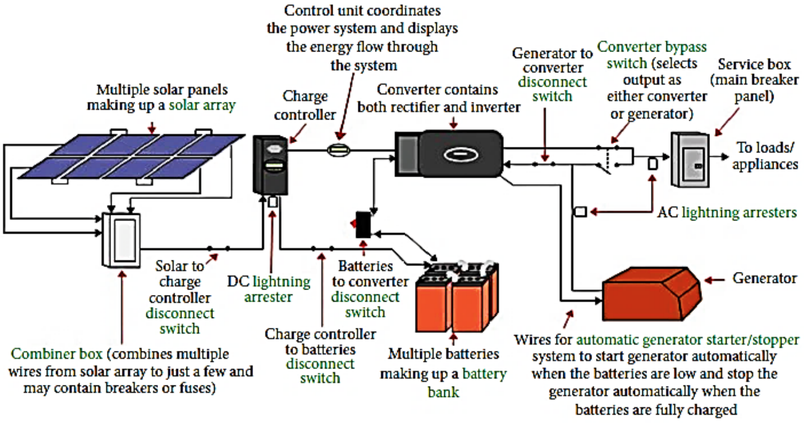

Figure 1. Hybrid micro-grid renewable energy system [22]

2.1. Photovoltaic system mathematical modeling

The following formulas can be used to compute the PV system's power output [23]:

$$P_{pv}(t) = P_{pv}^{ac}(t) \times N_{pm} \times \left(\frac{I_o}{I_s}\right) \times (1 + T_{co}(T_k - T_{op}) \tag{1}$$

where $P_{pv}^{ac}(t)$ is the PV array capacity (kW), N_{pn} is the derating factor, I_o is irradiance of PV plate (kW/m^2), I_s is standard condition of irradiance, T_{co} is coefficient of temperature. T_k is PV cell temperature, T_{op} is the standard condition test of PV cell temperature.

2.2. Mathematical modeling of battery bank

The total electricity consumed and produced is analyzed by the batteries connected and the condition of each battery at specific time. The equation below expresses the battery bank at a specific period [24]:

$$E_{Batt}(t) = E_B(t-1) + E_{Em}(t) \times \alpha_{CC} \times \sigma_{CHG} \tag{2}$$

where $E_{Em}(t)$remaining attainable energy from renewable energy is α_{CC} is the charging system regulator and σ_{CHG} is the battery charging level efficiency. The (3) shows the battery charging quality, where, SOC_{min} is the SOC least value, SOC is the battery state of charge, while SOC_{max} is the SOC highest value.

$$SOC_{min} \le SOC(t) \le SOC_{max} \tag{3}$$

The lowest SOC value is:

$$SOC_{min} = 1 - DOD \tag{4}$$

DOD (%) is the discharging batteries' depths.

2.3. Biogas' design mechanism

The total (in mass) of solid dung for electricity production is defined as [25]:

$$\text{The solid dry } waste \text{ mass } (M_x) = N_v \times C_e \tag{5}$$

N_v is the animal's total number, while C_e is the animal mixed manure (kg/day).

$$\text{Biogas' volume } (V_s) = Y \times M_d \tag{6}$$

M_d is input mass manure; Y is generated biogas of total dry mass between 0.2 m^{3}kg^{-1} to 0.4 m^{3}kg^{-1}.

The (7) and (8) show the empirical methanogens theorem [26]:

$$\frac{d(X_{meth})}{dt} = \left[\frac{\mu_m}{\frac{K_{sc}}{SV}+1} - K_{dc} - \left(\frac{F_{fed}/b}{V}\right)\right] X_{meth} \quad (7)$$

$$\mu_m(T_{react}) = \mu_{mc}(T_{react}) = T_{react} * \ 0.013 - 0.129 \quad (8)$$

meanwhile, T_{react} is the reactor's measure of hotness or coldness (°C), and $\mu_{mc}$is the highest measure rate of methanogens (d^{-1}).

K_{dc} is the methanogens' mortality rate/24hrs, and $X_{meth}$is the methanogens' level of concentration (kg/m^3). Also, the biogas energy generated can be calculated using the (9).

$$E = \eta \times V_b \times H_b \quad (9)$$

Here H_b represents the burning heat volume of the biogas, and η stands for the efficacy of combustion of combustors. The method of deriving the size of the generator is via the use of the (10) [27]:

$$P_t = V_b \times \mu \times \frac{1\,day}{24h} \times \frac{kWh}{3412Btu} \quad (10)$$

where μ is the sum efficiency of conversion and P_t is the generator quantity in kW.

2.4. Mathematical modeling of diesel generator system

The Diesel Generator power output is defined as [28]:

$$P_{gen} = C_{o\$m} + \frac{C_{br}}{R_f} + F_t H_{Gen} Z_{eff} \quad (11)$$

where $C_{o\$m}$ is the maintenance and operational cost ($/hr), $C_{br}$is the Replacement cost ($), F_t is the intercept fuel curve coefficient (fuel/hr/kw), $R_{.f.}$ is the Generator lifetime (hrs), H_{Gen} is diesel generator capacity (kW) and Z_{eff} is the effective fuel price ($/L).

2.5. Optimization of hybrid micro-grid energy system using HOMER

The biomass production in the village is increased from 0.5 tons to 3tons. The Agu-Amede village Load profile is shown in Figure 2. This illustrates the village's seasonal, daily and annual profiles load. The average annual energy demand is 974 kwh/day, the load average is 40.58 kW, and 104.10 kW is the peak load. Figure 3 shows the hybrid system schematic diagram. In Figure 3, the village's average annual energy demand load audit is 355284 kWh/yr. The biogas and diesel systems are both connected to an AC; also, PV and battery are connected to the DC bus.

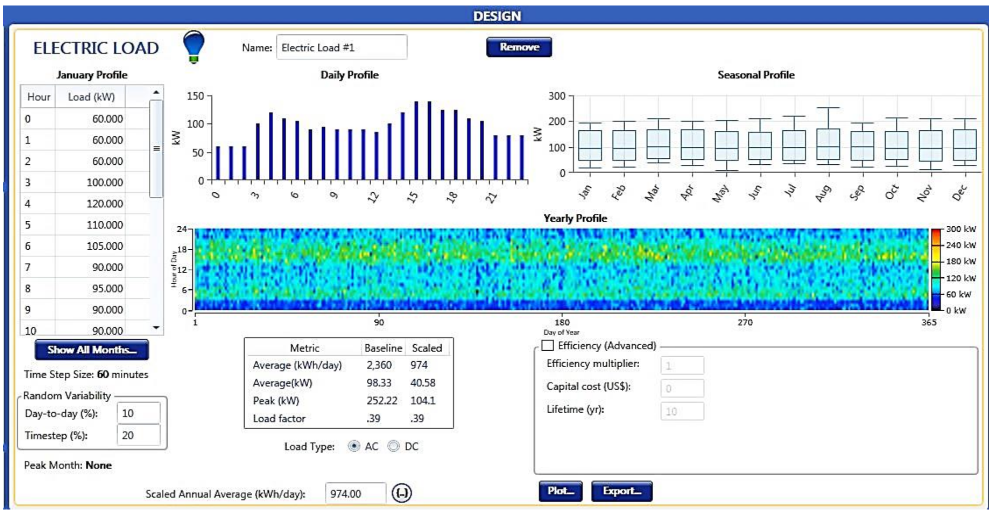

Figure 2. Agu-amede village load profile using HOMER

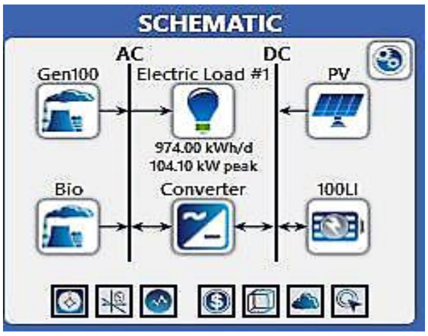

Figure 3. Hybrid system schematic diagram

3. RESULTS AND DISCUSSION

The hybrid system optimization result is shown in table1. The base case used for the optimization was the diesel system, while the price of diesel fuel was constant at $0.625/liter when the biomass production varies from 0.5 tons to 3tons. The system NPV and generated energy results in each mass were presented.

Table 1. Hybrid microgrid optimization result

Biomass (Tons)	NPC ($)	COE ($)	Renewable Penetration (KWh)	Renewable Penetration (%)	Diesel Genset Production (kWh/yr)	Flat plate PV Production (kWh/yr)	Biogas Genset Production (kWh/yr)	Total Energy Production (kWh/yr)	Excess Electricity (kWh/yr)
0.5	894845	0.1947	239822.31	53.5	165470 (36.91%)	218940 (49%)	63856 (14.25%)	448266	81296
1	736311.2	0.1602	312415.3	68.7	111098 (24.43%)	215928 (47%)	127727 (28.09%)	454753	86629
1.5	582882.6	0.1268	391051.65	83.2	59649 (12.69%)	218758 (47%)	191608 (40.77%)	470014	101257
2	511954	0.1114	370908.92	84.7	54288 (12.4%)	128166 (29%)	255455 (58.38%)	437909	71275
2.5	388824.1	0.0846	556114	100	-	240273 (43%)	315841 (56.8%)	556114	194711
3	303312.5	0.066	480693	100	-	98714 (21%)	381979 (79.5%)	480693	121762

3.1. Energy production

The total energy consumption of the community is 355284 kWh/yr, and the diesel architecture was chosen as the base case system. Figures 4 to 9 show the percentage of energy generated per annum by each architecture when the mass of biomass produced is 0.5, 1, 1.5, 2, 2.5, and 3 tons. Running the microgrid on biogas will not meet the load demand; however, running on diesel alone or only solar or PV increases energy generation costs. Thus, at each ton of biomass produced with maximum load demand, the fuzzy controller juxtaposes the availability and cost of biogas, diesel, and solar PV to optimally select the proportion of energy to be supplied by each of the architectures constrained by the meeting of load demand at the lowest cost possible.

The total energy generated by the hybrid system at 0.5 tons of biomass is 448266 kWh/yr with an excess electric energy of 81296 kWh/yr. The diesel Genset produced 165470 kWh/yr (36.91%), the PV system produced 218290 kWh/yr (48.84%), and the biogas genset produced 63856 kWh/yr (14.25%) of the total generated energy. Therefore, at 0.5 tons of biomass, the hybrid system comprising the three architectures must be used to meet the load demand of the village because biogas, the least expensive of the three architectures, cannot meet the load demand alone. At 1 ton of biomass, the total generated energy by the hybrid system is 454755 kWh/yr resulting in excess energy of 86629 kWh/yr. The diesel genset produced 111098 kWh/yr (24.43%), the PV system produced 215928 kWh/yr (47.48%), and the biogas genset contributed 127727 kWh/yr (28.09%) of the total energy.

There is an increase in the energy produced by biogas architecture; the load demand can only be met by a hybrid system of the three DGs, with PV contributing the highest to energy generation. Thus, at this level of biomass penetration, the hybrid system of Biogas, diesel, and solar PV is still the preferred system. At 1.5 tons of biomass, the total generated energy by the hybrid system is 470014kWh/yr indicating an excess of 101257 kWh/yr in energy generated. The contribution of the diesel genset to the total energy is 59649 kWh/yr (12.69%), the PV system produced 218758 kWh/yr (46.54%), and the biogas genset produced 191608 kWh/yr (40.77%). There is a further increase in the contribution of biogas to energy production and a reduction in energy produced by diesel and solar PV. However, energy generated by biogas alone is not adequate to meet the demand of the community; hence, the hybrid system comprising the three architectures is the best solution.

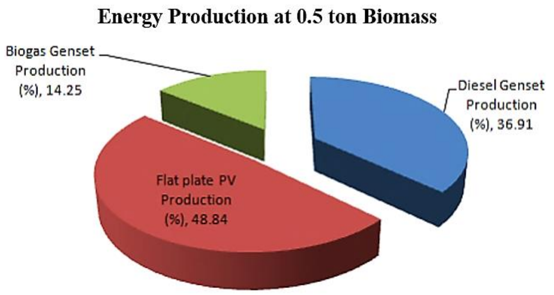

Figure 4. Energy production at 0.5 tons of biomass

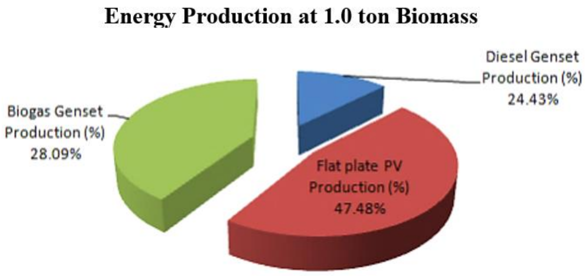

Figure 5. Energy production at 1 ton of biomass

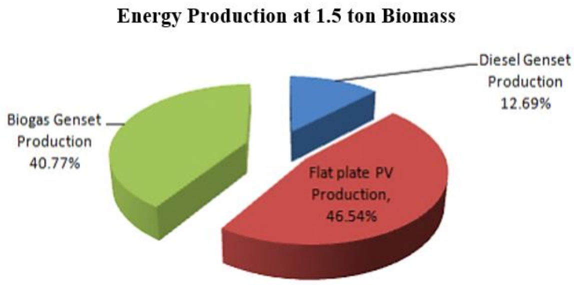

Figure 6. Energy production at 1.5 tons of biomass

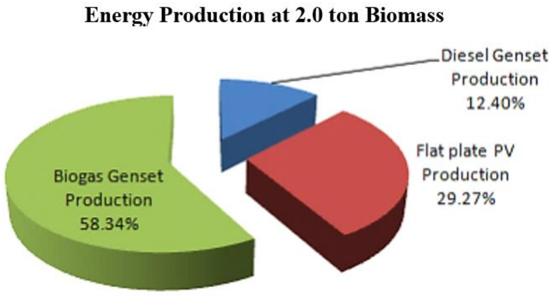

Figure 7. Energy production at 2tons of biomass

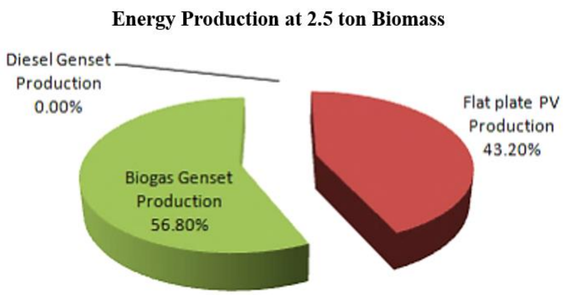

Figure 8. Energy production at 2.5 tons of biomass

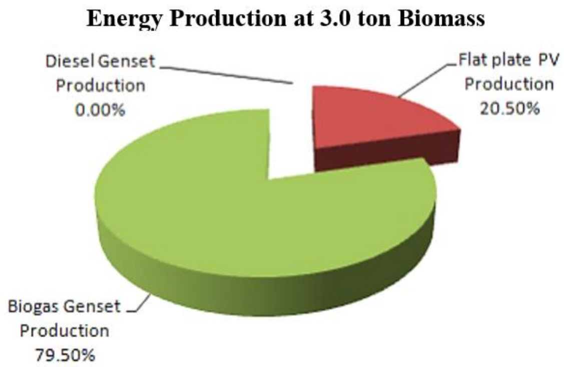

Figure 9. Energy production at 3 tons of biomass

The total energy generated at 2 tons of biomass is 437909 kWh/yr signifying energy production of over 71275 kWh/yr. Diesel genset contributed 54288 kWh/yr (12.40%), PV system, 128166 kWh/yr (29.27%), and the biogas genset contributes 255455 kWh/yr (58.34%). The biogas architecture contributes the highest percentage of the energy required. Therefore, there is a further reduction in diesel contribution to energy generation. However, the energy production of biogas alone cannot still meet the load demand; therefore, a hybrid system of the three architectures is used for power generation.

The total energy generated at 2.5 tons of biomass is 556114 kWh/yr indicating an excess of 194111 kWh/yr of energy. At this level of biomass penetration, the hybrid system completely operates on PV and biogas systems, with PV contributing 240273 kWh/yr (43.20%) and biogas genset producing 315841 kWh/yr (56.80%) of the total energy.

At biomass production of 3 tons, the total energy generated 480693 kWh/yr with a surplus of 121762 kWh/yr. Again, the hybrid system generates electricity from the PV system and the biogas genset, with each producing 98714 kWh/yr (20.50%) and 381979 kWh/yr (79.50%) of the total energy, respectively. At

2.5 and 3.0 tons of biomass penetration, the energy production of biogas increased, and the diesel system was removed from the hybrid system setup.

This is because the availability of biogas is almost sufficient to meet the load demand, and it is at a lower cost. The solar PV architecture was added to the hybrid system to balance energy production owing to its relatively lower cost compared with the diesel architecture. This shows that a further increase in biomass penetration will further reduce solar PV contribution to energy production, and at some higher level of biomass, the hybrid system will solely run on biogas.

3.2. Result of NPC and COE

Figure 10 and Figure 11 shows the NPC and COE of the base case architecture (diesel genset) measured for 25 years is $1230000 and $0.267/kWh. At Biomass production of 0.5, 1, 1.5, 2, 2.5, and 3 tons, the NPC were $894845, $736311.2, $582882.6, $511954, $388824.1, and $303312.5 respectively over the 25 years. The COE at the listed varying tons of biomass is $0.1947, $0.1602, $0.1268, $0.1114, $0.0846, and $0.066, respectively. The COE for the village is high as biomass production gradually reduces because the radiation of sunlight is slightly low. Hence, it needs ample battery capacity storage, which finally constitutes the high energy unit cost. Therefore, at 2.5 tons to 3 tons of biomass, diesel is not economical due to the availability of biomass resources produced in the village, which can supply conveniently to the demand load. Also, the COE and NPC of PV and Biogas hybrid systems are tremendously low compared to other architecture. The renewable energy penetration at each level of biomass at 0.5, 1, 1.5, 2, 2.5, and 3 tons of biomass, the percentage representation of renewable energy penetration in the total energy generated in each case is 53.50%, 68.70%, 83.20%, 84.70%, 100%, and 100% respectively. This indicates an increase in renewable energy penetration with increasing production of biomass. Also, at 2.5 tons and more, the diesel system is excluded from producing energy in the hybrid system, thus, making the system a completely renewable energy-generating system.

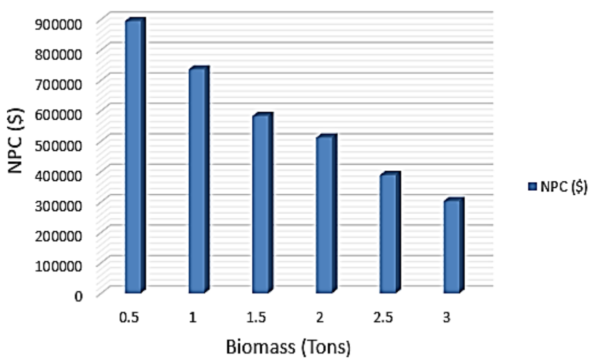

Figure 10. NPC at each level of biomass

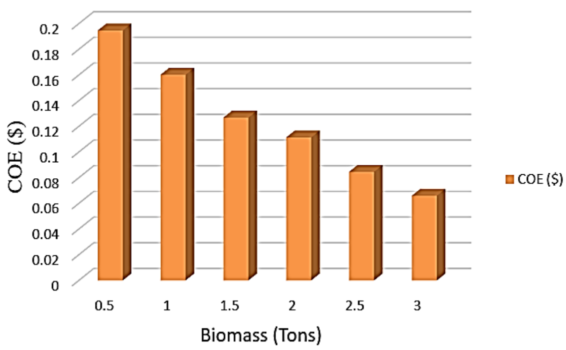

Figure 11.COE at each level of biomass

4. CONCLUSION

This research discussed the optimization of solar PV, biogas, diesel, and battery hybrid micro-grid for Agu-Amede village. The methane gas yield for the anaerobic digestion is 95.04 kg/day, which varied with temperatures between 25 °C and 55 °C. The optimization results from the hybrid microgrid indicated a better system techno-economic performance compared to the base case system (diesel). Furthermore, at all the levels of biomass production considered, the energy generated by the hybrid system can meet the load demand of the village, and there was surplus electricity in each case. There is a reduction in COE and NPC of the proposed hybrid system with increased biomass production. Also, at all the levels of biomass production considered, the energy generated by the hybrid system met the load demand of the village, and there was surplus electricity in each case. This excess energy can be used to meet the potential increase in load demand or serve other rural communities that are not electrified which are closer to the village. Increasing the penetration of renewable energy resources reduces NPC and COE of the hybrid system in the long run. This makes the proposed system an economically viable solution to the energy demand of the considered community.

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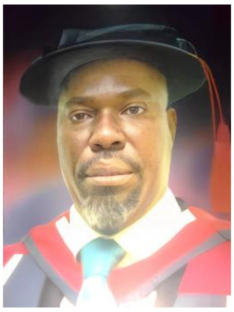

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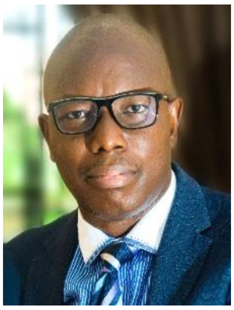

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