Design and optimization of hybrid microgrid renewable energy system for electricity sustainability in remote area

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ABSTRACT

Off-grid hybrid electrical systems have become a viable option for sustainable energy solutions, meeting the energy supply needs of rural communities. These systems use a broad approach to tackle sustainability, dependability, and environmental protection problems. The suggested hybrid system combines battery storage, biogas generators, and solar photovoltaic (PV) to provide a reliable and strong energy source for Ivoko Village in Enugu State using particle swarm optimization (PSO) and HOMER Pro Software. The paper compares three different configurations of sustainable power systems (HRES) to determine the best architecture that is suitable for rural areas. The result shows that case-1 (biogas/PV/bat) is the best option, with net present cost (NPC) and cost of energy (COE) values of $1,225,914 and 0.2865$/kWh, respectively. The results show that the PSO-based hybrid power system is more cost-effective than the HOMER-based optimizer. The NPC and lower COE for meeting peak demands emphasize the increasing role of biogas system generators as a cost-effective local power source. This highlights the PSO's potential in maximizing hybrid renewable power systems for rural areas, offering a financially viable and sustainable energy solution.

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1. INTRODUCTION

In many developing countries, inadequate power generation, inefficient transmission, or outdated distribution infrastructure can lead to frequent power shortages, affecting the population in various ways [1], [2]. These energy deficiencies adversely impact industrial and commercial productivity, safety, and overall social well-being [3]. To mitigate the effects of these shortages, load shedding is often employed as a temporary solution. This practice involves disconnecting electricity in specific areas for a few hours each day. When power demand exceeds the network's capacity, utility operators implement load shedding by reducing or cutting off electricity to certain areas [4]. This approach helps prevent widespread system failures by addressing the imbalance between electricity supply and demand, ensuring that a sufficient amount of power remains available for all users [5]. For many consumers, installing independent diesel generators or uninterruptible power supplies (UPS) with battery backups is a practical solution to address power shortages. While these traditional methods are simple and commonly used, they come with several drawbacks. UPS systems, for example, rely on the already strained power grid for charging, which exacerbates the issue of insufficient generation and high demand. Additionally, UPS systems can waste up to 25% of power during charging and discharging due to poor construction and low efficiency [6], [7]. Diesel generators, while effective, are less efficient, noisy, and require frequent maintenance. Energy from these localized sources is typically costlier than grid-supplied energy. Moreover, their uncontrolled operation contributes significantly to environmental pollution by increasing greenhouse gas emissions [8]. As environmental concerns grow, there is increasing pressure on the energy sector to shift towards renewable energy sources rather than relying on fossil fuels [9], [10]. Developing countries face a dual challenge: they need to participate in the global shift toward clean, sustainable energy while simultaneously addressing the energy needs of their growing populations, who still lack basic power access [11], [12].

Nevertheless, many of these countries have ample and cost-effective renewable resources. Wind and solar power, in particular, are viewed as highly promising due to their widespread availability and environmental benefits [13], [14]. These renewable energy systems do not require fuel, are easy to install, and need minimal maintenance. Moreover, recent advancements in renewable energy technology have shown that these systems can effectively replace traditional ones at a lower cost, addressing many of their limitations. Technologies such as wind turbines, power converters, and solar panels are notable examples. However, the inherent variability of wind and solar energy, which depends on weather conditions, makes it challenging to rely solely on these sources to replace the electrical grid during load-shedding events. Therefore, combining various renewable energy sources with backup solutions like batteries and diesel generators is often necessary [15]-[23]. An inventive hybrid renewable electrical system that incorporates photovoltaic (PV) arrays, energy storage units (ESUs), wind turbines, and a standby diesel engine is being proposed to solve the load-shedding problem. It is anticipated that hybridization will result in a significant increase in infrastructure costs overall. Furthermore, the complex nature of the plant may be further enhanced by the interaction between the intermittent sources of renewable power and the disturbed grid (resulting from load shedding). Optimization and effective energy management are therefore much more crucial because poor design might have detrimental effects, such as turning off supply to an essential service (medical and military-related) [24]-[27].

This project modeled a hybrid renewable power system that uses solar PV, biomass, diesel generators, and batteries to produce energy for the Ivoko village in Enugu State, Nigeria. Hybrid renewable energy designs are created primarily for region that utilizes solar energy and animal waste to boost the availability of electricity because the region does not have enough access to energy. Therefore, the proposed way of producing power is affordable and has excellent technical viability because animal waste and sunlight are abundantly available. Furthermore, an economic assessment is conducted using particle swarm optimization (PSO) and HOMER Pro software to ascertain the feasibility of a microgrid structure that is an interconnected renewable power plant within the community. Improving energy reliability, environmental effects, and economic viability are the main objectives of a rural microgrid analysis.

The main contributions of the paper are as follows: i) Integrating PSO with HOMER for hybrid microgrid optimization provides new insights into efficient system design. While HOMER provides detailed modeling and simulation, PSO enhance optimization by exploring a broader solution space; ii) The study utilized an energy management system (EMS) concept to efficiently manage energy within a self-sufficient community, employing an optimal sizing model to find the most cost-effective HRES design using PSO and HOMER Pro software; iii) Develop and test customized variants of PSO deals with the specific challenges of hybrid microgrid optimization. The adaptive PSO adjusts parameters based on the optimization stage or problem-specific enhancements that improve convergence speed and solution quality.

2. METHOD

In this study, a hybrid microgrid was designed for Ivoko village in Enugu State, Nigeria, utilizing PSO and HOMER. The main objectives of this microgrid design are to lower the village's electricity consumption costs and ensure a continuous energy supply. However, predicting how well this proposed microgrid will perform over its 25-year lifespan is challenging. The design is based on current and relatively ideal conditions, but several real-world factors could significantly impact its performance. These factors, referred to as performance variables, include the aging of PV modules, potential increases in energy demand over time, the frequency and severity of grid interruptions, and variations in biomass production, which is expected to rise annually. Therefore, it is crucial to assess and understand the impact of these variables. Evaluating such a system involves addressing numerous variables and their effects simultaneously, making it a complex challenge. The HOMER analysis detailed load profiles with resource availability data was applied to perform simulations of different system configurations under various scenarios as illustrated in Figures 1 and 2. PSO determines a multi-objective function that balances cost, reliability, and environmental impact, which incorporates technical, economic, and environmental constraints. The implementation of a dynamic re-optimization approach where design to update new data and changing conditions. This ensures the system adapts to evolving uncertainties.

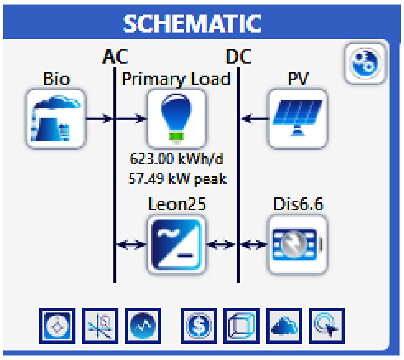

Figure 1. Schematic of the hybrid configuration

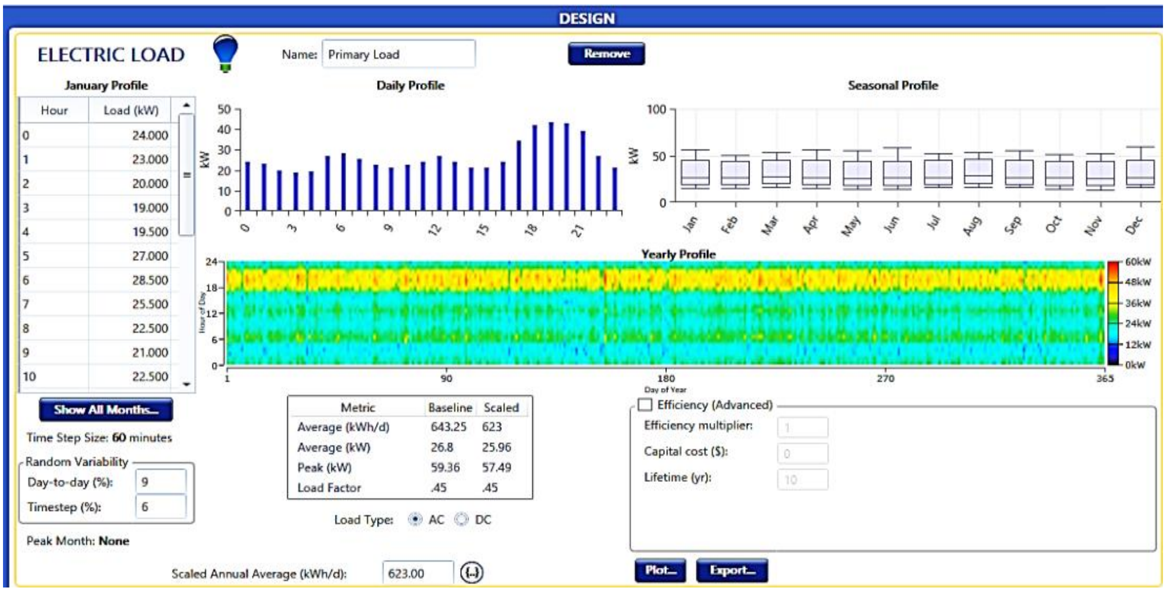

Figure 2. Electric load of the hybrid configuration

2.1. Modeling of photovoltaic system

The PV system power output can be evaluated using (1) [22]:

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

where $P_{pv}^{ac}(t)$ is the PV module maximum size(kW), N_{pv} is the derating coefficient, I_o is PV plate irradiance, $I_s$is nominal irradiance conditions, T_{co} is the temperature index. T_k is PV temperature cell, T_{wp} is the typical PV cell temperature test conditions.

2.2. Battery bank modeling

The state of each battery and connected batteries at a particular stage is applied to determine the total amount of energy produced and consumed. The battery bank at a particular time is analyzed in (2) [22]:

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

where $E_{Em}(t)$is residual reference energy α_{CC} is the system charging controller and σ_{CHG} is the efficiency of battery charging factor. The (3) illustrates the quality of battery charging:

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

where, SOC_{min} is the SOC minimum coefficient, SOC is the battery state of charge, and SOC_{max} is the SOC maximum coefficient. The minimum SOC coefficient is:

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

DOD is the level of battery discharging.

2.3. Modeling of the biogas system

The total (in mass) of solid dung for electricity production is defined in (5) to (8). The solid dry waste mass:

$$(M_x) = N_v \times C_e \tag{5}$$

N_v is the animal's total number, while C_e is the soluble animal manure per day (kg). Biogas' volume,

$$(V_s) = Y \times M_d \tag{6}$$

Y is generated biogas of total dry mass between $0.2\ m^3kg^{-1}$ to $0.4\ m^3kg^{-1}$, M_d is the input mass of dung. Also, the biogas energy generated can be calculated using (7).

$$E = \eta \times V_b \times H_b \tag{7}$$

Here, H_b represents the burning heat volume of the biogas, and η stands for the efficacy of combustion of the combustors. The method of deriving the size of the generator is via the use of the (8) [27]: Where μ is the sum efficiency of conversion and P_t is the generator quantity in kW.

$$P_t = V_b \times \mu \times \frac{1\,day}{24h} \times \frac{kWh}{3412Btu} \tag{8}$$

2.4. Optimization model of the objective function

The optimization objective problem deals with the minimization of operational costs. The objective function is defined as [22]:

$$Min(C_{total}) = \sum P_{bio}C_{bio} + P_{pv}C_{pv} + P_{bat}C_{bat} + P_{conv}C_{conv} \tag{9}$$

Where each component cost, including operation costs, capital costs, maintenance costs, fuel costs, and replacement, is analyzed (10):

$$C_{element} = \sum C_{capital} + C_{replacement} + C_{O\&M} + C_{fuel} \tag{10}$$

The constraint power balance occurs between load demand and generation.
Constraints:

$$P_{bio} + P_{pv} + P_{bat} + P_{conv} \geq P_{load} \tag{11}$$

2.5. Load energy estimation demand

The load data comes from analyses that are sent to the communities. The surveys have sections on household load, business load, community demand, and agricultural demand, depending on the energy needs that are covered by the study. Most of the energy was used by the health center, elementary school, shops, and street lights. Figures 1 and 2 illustrate the hybrid system's estimated daily total energy demand in kWh and peak load, which are 623 kWh and 57.49 kW, respectively.

2.6. Pseudo code of the PSO

i) Initialize the particle velocities V_i, positions X_i, iteration counter, global best, $gbest$, and personal best $pbest$
ii) Generate a set of random particles (P)
iii) For every particle (i)
 - Evaluate fitness function (fi)
 - Update the global best, gbest, and the particle's personal pbest
iv) Repeat until the maximum number of iterations is reached:
 - For every particle (i)

- Update the particle's position X_i, and velocity V_i
- If the position X_i exceeds the defined limit, setX_i *to the limit*
- Recalculate the fitness fi
- Update the global best, gbest, and personal pbest

v) End for
vi) End while

3. RESULTS AND DISCUSSION

Tables 1 and 2 show the optimization results of the hybrid system of Oji-River Community using HOMER and PSO, respectively. The biogas system was selected as the base case system, and the biogas system diesel price was assumed to be constant at 3 tons while the mass of diesel price varied. The results of energy generated and the NPC of the systems in each case were also presented. Figure 3 shows the monthly average solar global horizontal irradiance, and Figure 4 shows the monthly average available biomass.

Table 1. Optimization result of the hybrid system using HOMER

Architecture	PV Size (Kw)	Biogas Gen (Kw)	Battery (Kw)	COE ($/kWh)	NPC ($)
PV/Biogas/Bat	70	100	20	0.3638	1,661,164
Biogas Gen/Bat	-	100	20	0.659	2,361,653
PV/Biogas Gen	6.5	100	-	0.4665	2,387,542

Table 2. Optimization result of the hybrid system using PSO

Architecture	PV Size (Kw)	Biogas Gen (Kw)	Battery (Kw)	COE ($/kWh)	NPC ($)
PV/Biogas/Bat	60	80	15	0.2865	1,225,914
Biogas Gen/Bat	-	80	15	0.4196	2,078,129
PV/Biogas Gen	5	80	-	0.3473	2,140,251

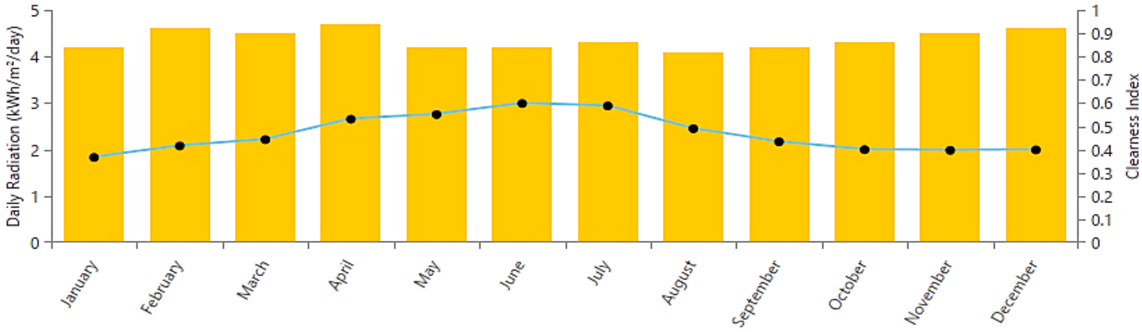

Figure 3. Monthly average solar global horizontal irradiance

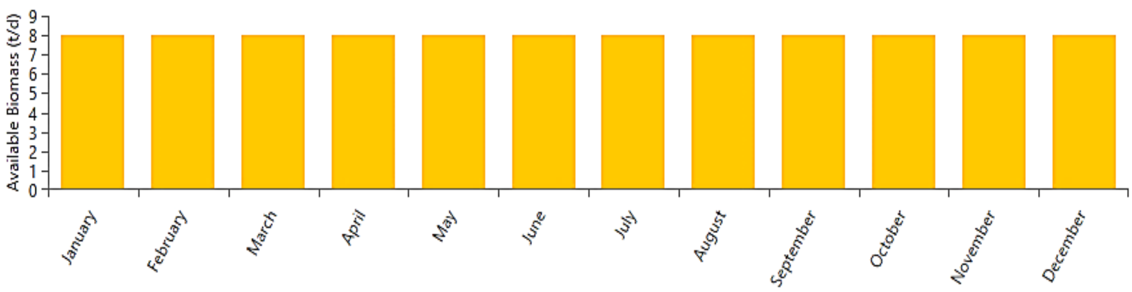

Figure 4. Monthly average available biomass

3.1. Case-1: PV/biogas/battery

The HOMER result in scenario 1 shows that the energy sources allotted to meet the village's energy requirement are batteries, biogas generators, and solar PV. The system's three sizes are 20 kW, 100 kW, and 70 kW for the solar, biogas generator, and battery, respectively. The 5,217,22 kWh of energy are expected to be consumed annually, while 15.9% of that energy is available as surplus. There was a $1,661,164 net present cost

(NPC) and a 0.3638/kWh cost of energy. The PSO suggests that sizes are 15 kW, 80 kW, and 60 kW for solar, biogas generator, and battery, respectively, with NPC of $2,140,251 and COE of 0.3473$/kWh.

3.2. Case-2: Biogas/Battery

Batteries and biogas engines are considered in Case 2. The energy sources for the system have a capacity of 100 kW for biogas and 20 kW for batteries, respectively. There is a potential supply of extra energy at 6.19%, and the estimated yearly energy usage is 4,951,64 kWh. Furthermore, the cost of energy (COE) is 0.659$/kWh, and the net present cost (NPC) is $2,361,653. The PSO sinuates that sizes are 80 kW for biogas and 15 kW for batteries, respectively, with NPC of $2,078,129 and COE of 0.419$/kWh.

3.3. Case-3: PV/Biogas

In case 3, PV and biogas generators are taken into consideration. The PV system has a capacity of 6.5 kW, while the biogas generator has a capacity of 100 kW. The estimated annual energy consumption is 112,948 kWh, and the estimated quantity of excess energy is 18.31%. The PSO sinuates that sizes are 5 kW, while the biogas generator has a capacity of 80 kW with NPC of $2,078,129 and COE of 0.3473$/kWh. Tables 1 and 2 show the optimization results for HOMER and PSO, respectively. The PV/biogas/Batt structure is shown to be the cheapest approach with both NPC and COE. It also generates a significant quantity of excess energy, making it appropriate in cases of anticipated expansion. Out of all the components, the biogas generator has the cheapest overall cost, while the battery backup mechanism has the most. The abundance of readily available animal excrement causes this, which in turn reduces the demand for costly diesel and photovoltaic systems, as shown in Figures 5 to 9. The findings indicate that, in comparison to HOMER, PSO-based optimization is more economical.

Integrating biogas generators with PV panels in a microgrid system is an effective approach to ensure a continuous energy supply. However, to achieve realistic long-term performance results, it is essential to account for several factors, including the aging of PV modules, annual increases in energy demand, the frequency of power outages, the time required to repair faults, and fluctuations in biomass production.

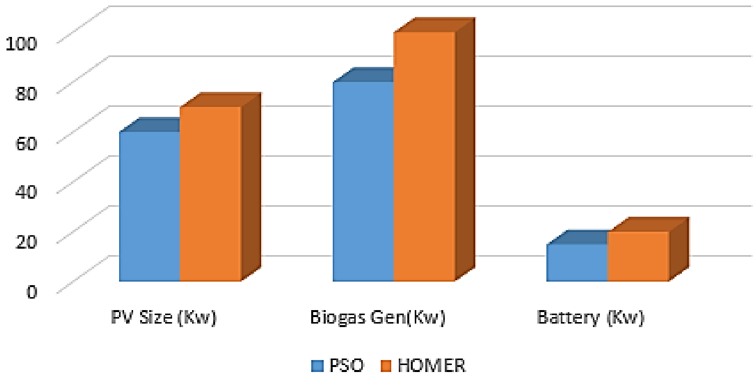

Figure 5. Sizing of PV/biogas/bat

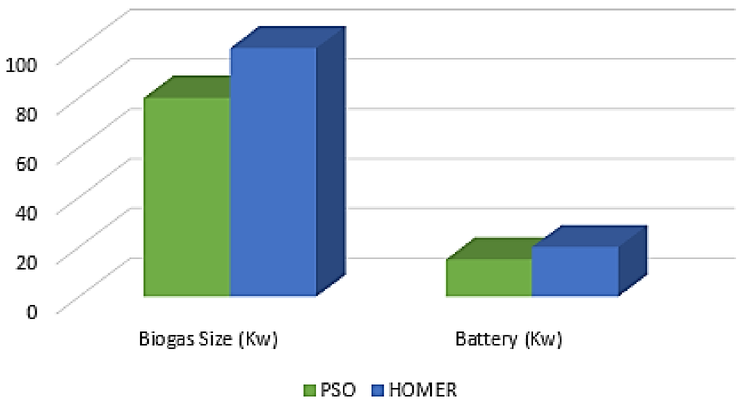

Figure 6. Sizing of biogas/bat

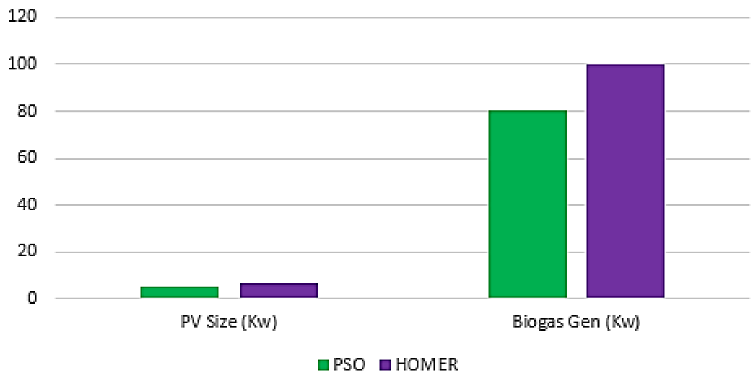

Figure 7. Sizing of PV/biogas

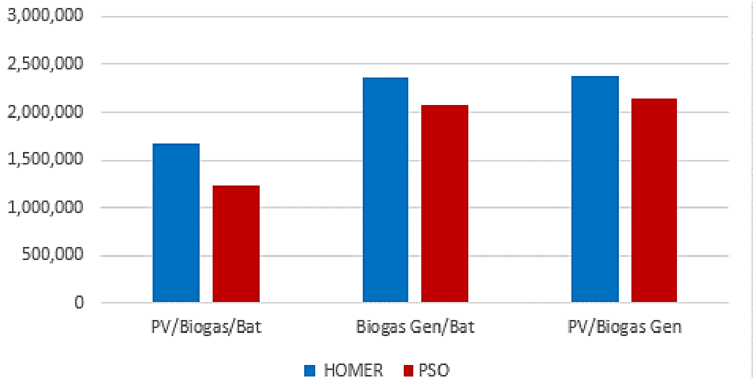

Figure 8. NPC of architecture

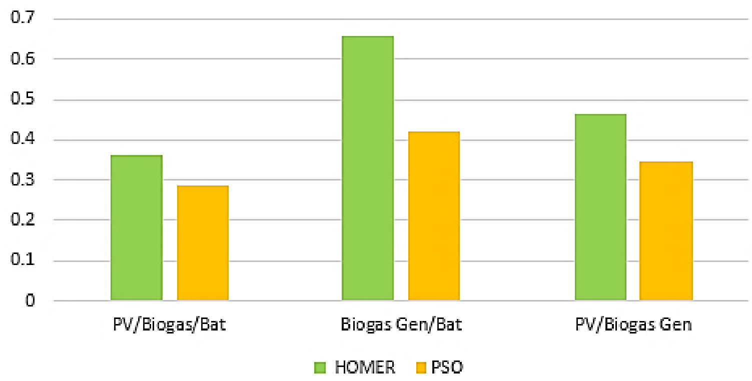

Figure 9. COE of Architecture

4. CONCLUSION

This research specified the modeling and optimization of the hybrid isolated power system for remote areas, utilizing Ivoko as a case study. Several factors were considered in the development of the system operating plan, including source distribution, energy demand estimation and comparison of economic aspects. Furthermore, three distinct hybrid energy system cases, which are PV/biogas/battery, biogas Gen/Bat, and PV/biogas gen, have been evaluated using PSO and HOMER Pro. Among all cases, the combination of biogas, PV, and battery produces the lowest COE and least NPC, at 0.3638$/kWh and $1,661,164, respectively for HOMER and PSO generates 0.2865$/kWh and $1,225,914 of COE and NPC, respectively. Therefore, a thorough analysis from an economic and technological perspective highlights the feasibility of the suggested hybrid PV-biogas system strengthened with batteries for installation in the Ivoko Village. Compared to HOMER, the PSO-based system achieves lower CO2 emissions and features a greater integration of biogas and PV systems. The proposed biogas capacity is above the village's peak load demand, which helps to minimize excess electricity production while adequately meeting demand. In contrast to

HOMER, the PSO approach forecasts a more streamlined biogas setup that precisely matches the peak load demand, thus ensuring minimal excess electricity generation.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Taiwo Felix Adebayo	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	j	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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