Economic optimization of hybrid renewable energy resources for rural electrification

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ABSTRACT

In rural areas, grid expansions and diesel generators are commonly used to provide electricity, but their high maintenance costs and CO_2 emissions make renewable energy sources (RES) a more practical alternative. Traditional methods such as analytical, statistical, and numerical-based techniques are inadequate for designing an energy-efficient RES. Therefore, this study utilized the bat algorithm (BA) to optimize the use of hybrid RES for rural electrification. A feasibility study was conducted in the village of Kalema to assess energy consumption, and a diesel-only system was modeled to serve the entire community. The BA was used to determine the optimal size and cost-effectiveness of the hybrid RES, with MATLAB R (2021a) utilized for simulation. The BA's performance was compared with diesel only and GA using cost of energy (COE) and CO_2 emissions as metrics. Diesel generators only produced a COE of $6,562,000 and 1679.6 lb/hr of CO_2 emissions. COE with BA was $356,9781.37 (a 45.6% reduction) and CO_2 emissions were 635.29 lb/hr (a 62.2% drop). Genetic algorithm (GA) resulted in $364,3122.46 COE and 652.69 lb/hr CO_2 emissions, indicating 61.1% and 44.5% decreases, respectively. BA significantly reduced COE and CO_2 emissions over GA, according to the analysis.

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1. INTRODUCTION

Currently, there are approximately 1.3 billion people who do not have access to electricity, with an additional 2.4 billion experiencing insufficient or unreliable energy [1]. This lack of access is especially prevalent in rural areas of developing countries and can have a significant negative impact on economic growth and overall quality of life [2]. Access to reliable electricity is crucial for economic activities such as engineering, communication, medical care, and transportation and is closely linked to a country's growth and development [3], [4]. Despite efforts to improve access to electricity in Nigeria, only 55.4% of the population has access to it, with a significantly higher percentage of rural residents lacking access [5]. While grid extension and diesel generators have been common options for increasing access to electricity, the high cost of establishing and maintaining transmission lines has made it difficult to provide electricity to small towns and isolated areas [5]. To address this issue, implementing off-grid hybridization of renewable resources and diesel generators is a suitable strategy for providing more reliable energy and reducing emissions. However, optimizing the hybrid system design requires determining the best values for the renewable source's rated power, peak power, and storage capacity to meet the required reliability conditions for the system [3], [6]. To provide affordable and effective alternative energy for rural areas, many optimization techniques have been used, including traditional methods such as genetic algorithm (GA) and analytical, statistical, and numerical-based methods, as well as meta-heuristic methods like salp swarm optimization (SSA), firefly algorithm (FA) [7] dingo optimization algorithm [8].

Chaichan *et al.* [9] conducted a study to analyze the use of renewable energy sources, diesel generators, and battery systems to power a 10-kilometer roadway in Salalah, Iraq, with a total load of 33.06 kW. The study compared four systems (PV-only, wind-only, diesel-only, and PV/wind system) using HOMER software and concluded that the hybrid PV/wind/battery system was the most effective, affordable, and environmentally friendly option. Olatomiwa [10] assessed optimal configurations of hybrid renewable systems (PV, wind, diesel, and battery) for rural health clinics in Nigeria and found that optimal hybrid renewable energy configurations could reduce fuel consumption and prevent CO_2 emissions. Gallegos *et al.* [11] proposed an approach for optimizing the size and placement of batteries and solar photovoltaic panels in systems that use diesel generators, resulting in a PV hybrid system that reduced the levelized cost of energy, CO_2 emissions, and cumulative grid voltage variance. Kasaeian *et al.* [12] looked into the use of a hybrid PV, biomass, and diesel system to supply an Iranian community with grid-connected electricity, while Santos *et al.* [13] studied two hybrid plants in Brazil and found that PV/wind/battery energy systems were the most cost-effective and reliable choice for supplying electricity to remote loads. Ramoji *et al.* [14] optimized a PV/wind/battery energy system to lower the overall cost of components and ensure dependable load supply. Halabi *et al.* [15] conducted performance analyses on two operational decentralized power plants in Malaysia and found that renewable energy in conjunction with storage systems could help lower energy costs. Finally, Huneke *et al.* [16] employed linear programming techniques to configure the best possible electrical power supply system for off-grid energy systems in Colombia and India and found that renewable energy with storage systems could lower energy costs compared to standalone diesel generator sets.

Conventional methods for formulating the optimization problem using solar irradiance and wind speed data to determine system size have limitations that may lead to oversizing or under sizing. Meta-heuristic procedures such as the bat algorithm (BA) have been shown to outperform traditional techniques, as they can deal with a large number of energy sources and find a set of non-dominated solutions in a single run [17], [18]. This research utilizes BA to evolve an indigenous solution for the hybridization of renewable energy sources for rural electrification. The paper's main contribution is the comparison of BA's effectiveness in optimizing hybrid renewable energy sources to a traditional technique, genetic algorithm (GA).

2. METHOD

2.1. Problem formulation

This study's primary objective is to lower the annualized system cost (ASC) for the specified hybrid model. The ASC function adds the entire capital cost (C_a), replacement cost (C_r), and maintenance cost together (C_m). This is formulated as a single-objective optimization problem for determining the best setup of the hybrid power system. Mathematically, the objective function for this research is expressed in terms of ASC as in (1) [19].

$$ASC = C_a + C_m + C_r \quad (1)$$

In general, the wind turbine's service life and the photovoltaic generator is nearing the end of the system's lifetime, resulting in a zero-replacement cost. The capital cost can be expressed in (2) and the definition of all parameters involved are as in (3)-(6).

$$C_a = CRF * \left(C_{PV_{tot}} + N_{wt_{tot}} + C_{bat_{tot}} + C_{gen_{tot}}\right) \quad (2)$$

Where:

$$C_{PV_{tot}} = N_{pv} * C_{pv} \quad (3)$$

$$C_{wt_{tot}} = N_{wt} * C_{wt} \quad (4)$$

$$C_{bat_{tot}} = \left(\frac{n}{LS_{bat}}\right) N_{bat} * C_{bat} \quad (5)$$

$$C_{gen_{tot}} = \left(\frac{n}{LS_{gen}}\right) N_{gen} * C_{gen} \quad (6)$$

Where: C_{pv}, C_{wt}, C_{bat}, *and* C_{gen} = capital cost, respectively of photovoltaic panels, wind generators, batteries, and diesel generators, respectively, N_{pv}, N_{wt}, N_{bat}, N_{gen} are the number of solar panels, wind generators, batteries, and DG, respectively, LS_{bat} and LS_{gen} are the battery's life and generator's life, respectively. The capital recovery factor (CRF) is defined in (7).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (7)$$

Where i = rate, n= life span of the hybrid system. The maintenance cost {C_m) of a hybrid system is described as (8).

$$C_m = \left(C_{pv} * \sum_{t=1}^{T} P_{pv}(t) * \Delta t\right) + (C_{wt} * \sum_{t=1}^{T} P_{wt}(t) * \Delta t) + \left(C_{gen} * \sum_{t=1}^{T} P_{gen}(t) * \Delta t\right) * 365 \quad (8)$$

Where: P_{pv}, P_{wt}, and P_{gen} are photovoltaic panels, wind turbines, and diesel generator power, respectively. The replacement cost is zero since the simulation is run for 20 years, which is longer than the panel and turbine lifespans.

2.2. Constraints

To achieve an optimal hybrid system design, it is crucial to consider and fulfill all operational constraints. These constraints are represented by (9)-(14), which restricts the limits and requirements of the objective function. By incorporating these constraints into the design process, the hybrid system can be optimized to meet operational demands while adhering to the specified limitations.

$$0 \leq N_{pv} \leq N_{pvmax} \quad (9)$$

$$0 \leq N_{wt} \leq N_{wtmax} \quad (10)$$

$$0 \leq N_{bat} \leq N_{batmax} \quad (11)$$

$$0 \leq N_{gen} \leq N_{genmax} \quad (12)$$

$$0 = LPSP \quad (13)$$

$$REF \leq REF_{desired} \quad (14)$$

2.3. Data collection

To conduct this study, data was collected from the National Aeronautics and Space Administration Surface Meteorology and Solar Energy (NASA/SSE) website, including solar isolation, radiation, sunshine hours, and temperature. The researchers also gathered information about Kalema's location, altitude, and electricity demand. Lastly, solar and wind energy assessments were carried out for the village.

2.3.1. Site description

A techno-economic assessment of a hybrid PV/wind/diesel and battery system was conducted in Kalema Village, located in Niger State's Mokwa local government area (LGA) at latitude 9°12.5'N and longitude 4°46.6'E. The village is located near the Jebba hydroelectric dam and is known for fishing and farming. However, the lack of basic services and low-income level have negatively impacted the standard of living and well-being of the villagers. To improve their health, living standards, and local economy, it's crucial to model their energy needs and available resources to develop a feasible hybrid off-grid renewable power system. The village has 130 houses, which include a primary healthcare center, and a total population of 1040 people, with an average family size of eight individuals per home. To meet the power needs of the households, as well as those for domestic consumption, a primary healthcare facility, potable water supply, and business usage, a hybrid system architecture utilizing solar and wind as primary resources of power generation was built. The system is designed to fully meet the power needs of the community, with batteries and a DG serving as backup systems.

2.3.2. Electricity load estimate of the village

Load estimation involved gathering primary data from the community through assessments that included domestic, village, and business load sections based on energy demands. The village's primary healthcare center is currently operating below capacity due to a lack of electricity to power essential medical equipment. Based on hourly and monthly power demand, the overall power consumption in kWh per day and maximum load in the region were calculated to be 820.009 kW.

2.3.3. Solar/wind energy data and resource assessment

Incorporating the location of solar and wind sources is essential for an optimal energy mix. However, in the absence of ground measurement data, alternative sources were used, such as obtaining data for the past 30 years from the NASA/SSE website. The chosen location's latitude and longitude were used to obtain solar and wind resource data.

2.4. Mathematical modelling of the components of the hybrid system

The rural hybrid renewable energy system involves different components: solar panels, wind generators, batteries, and backup generators. Mathematical modeling and sizing expressions were employed to optimize each component's efficiency, which was based on the village's energy needs and renewable resources. The size of each component was determined based on the targeted village's energy consumption and available renewable resources.

2.4.1. Mathematic model of PV

A solar energy system uses solar radiation to generate electricity. It operates on the photoelectric effect: when sunlight reaches the outermost layer of solar cells, a DC current runs through the PV modules [20]. The mathematical formulation for determining the PV panels' power output from solar irradiance is given by (15) [21].

$$P_{pv} = N_{pv} * \left(P * \frac{G}{G_{ref}}\right) + \left(1 - m * \left(tc - tc_{ref}\right)\right) \tag{15}$$

Where: P_{pv} = PV arrays power output in watts, P = rated power under standard circumstances, N_{pv} = PV arrays number, G = solar irradiance in W/m^2, G_{ref} = 1000 W/m^2, m= −3.7 * 10−3 (1/°C), tc_{ref} = 25 °C, and tc = temperature of the PV cell. The temperature of the PV cell was determined using (16) [22].

$$t_c = t_a + \left[\left(\frac{NOCT-20}{800}\right)\right] * G \tag{16}$$

Where t_a = ambient temperature, $NOCT$ = cell nominal operating temperature.

2.4.2. Mathematical model of wind turbine

In this area, the presence of continuous winds with appropriate velocities can be harnessed to generate electricity. The wind speed is a crucial factor in determining the potential for electricity generation. According to (17) provides a means of calculating the wind speed in the area [23], [24].

$$\frac{V_1}{V} = \left(\frac{H1}{H}\right)^a \tag{17}$$

Where, v_1 = hub height speed and v = reference height speed, and a = friction coefficient. The wind generator power output is represented by a quadratic model based on rates power P_r and three-speed characteristics: rated V_r, cut-in V_c, and cut-out V_f: Where, N_{wt} = number of wind generators, and P_r = rated power of the wind generator [25].

$$P_{wt} = N_{wt} * \begin{cases} 0 \; if \; V < V_c, V > V_f \\ P_r * \frac{(V-V_c)}{(V_r-V_c)} \; if \; V_c \le V \le V_r \\ P_r \; if \; V_r \le V \le V_f \end{cases} \tag{18}$$

2.4.3. Mathematical model of battery

The lead-acid batteries are the most commonly utilized batteries in hybrid systems. The available power generated from PV and wind turbines, as well as the load demand, determine the battery's state of charge and discharge. According to (19) and (20) govern the expression of their charge-discharge relationship. The battery bank is charged when the overall power output generated by wind generators and PV panels surpasses the load. The state of charge (SOC) is derived in the following manner [26].

$$SOC(t) = SOC(t-1) + (Ppv(t) + Pwt(t) - Pdmd) * \eta_{ch} \tag{19}$$

Where, *SOC* (*t*) and *SOC* (*t*– 1) = battery bank charging energy at times *t*, *t*– 1, *Pdmd* = load demand, η_{ch} = battery bank charge efficiency. As the load demand surpasses the power generated, the battery bank discharges, as shown in (20) [27].

$$SOC(t) = SOC(t-1) - (Ppv(t) + Pwt(t) - Pdmd)/\eta_{disch} \quad (20)$$

Using (21), the system's battery capacity (kW) is computed depending on demand and autonomy days.

$$Cn = \frac{E_{dmd} * ad}{DOD * \eta_{inv} * \eta_{bat}} \quad (21)$$

Where *ad* = autonomy days, *DOD* = depth of discharge, η_{inv} and η_b = inverter and battery efficiencies.

2.4.4. Mathematical model of diesel generator

In this study, the hourly fuel usage *Q* (*t*) of the diesel generator was predicted through a linear based on the required power output to supply the load. This equation was derived from previous research, specifically [28]. The prediction of fuel usage is important for analyzing the costs and environmental impact of using diesel generators in rural electrification, the formula is (22).

$$Q(t) = \alpha\_DG \ 〖P(t)〗\_(DG.gen) + \beta\_DGP\_(DG.rat) \quad (22)$$

Where, α_{DG} and β_{DG}= consumption curve coefficients, $P(t)_{DG,gen}$, and $P_{DG,rat}$ = power generated and rated DG power. The magnitudes assigned to α_{DG} and β_{DG} are 0.246 and 0.08145 l/kW h, respectively. The DG efficiency (kWh/l) is given in (23) [29].

$$\eta_{DG} = \left[P(t)_{DG.gen}/Q(t)\right] = \left[1/\left(\alpha_{DG} + \beta_{DG} \times \frac{P_{DG.rat}}{P(t)_{DG.gen}}\right)\right] \quad (23)$$

The lower heating value (*LHV*) efficiency of the gas–oil is given in (24), *LHV* gas–oil range between 10- and 11.6-kW h/l.

$$\eta_{DG}\% = \frac{P(t)_{DG.gen}(kW)}{Q(t)(^{l}/_{h}) \times LHV_{Gas-oil}(^{kWh}/_{1})} \times 100 \quad (24)$$

2.4.5. Evaluation of loss of power supply probability

The loss of power supply probability (LPSP) for the hybrid system was evaluated using (25) [16]. The LPSP is a probabilistic indicator that indicates the likelihood of a power supply interruption owing to a lack of renewable resources or a technical failure to satisfy demand. It is also critical to ensuring the dependability of the micro-grid.

$$LPSP = \frac{\sum_{t=0}^{T} Power\ Outage\ Time}{t} \quad (25)$$

When the value of LPSP is zero, it indicates that the load has consistently been supplied, whereas a value of one indicates that the load will not be supplied. The length of time when a load demand is not satisfied is referred to as the power outage time (POT).

2.4.6. Evaluation of renewable energy fraction

In this study, one of the key considerations for designing the hybrid RES system was evaluating the renewable energy fraction (REF). The REF represents the overall portion of renewable energy that is supplied to the load and is calculated using (26) [16]. This evaluation of REF is crucial for the effective modeling of the hybrid system and ensuring that an optimal size of the hybrid system is selected for the specific energy demands of the community.

$$REF = \left(1 - \frac{E_{diesel}}{E_{Lserved}}\right) \times 100 \quad (26)$$

Where E_{diesel} = total amount of power generated by diesel. A traditional diesel generator system equals 0% of a REF, but a clean system equals 100% of a REF. The values used to represent the hybrid energy system ranged from 0 to 100%.

2.5. Optimization

Priority should be placed on scaling the system components in order to design a low-cost and incredibly effective hybrid micro-grid. The lifespan of the system and the ability to lower electricity costs for end users in remote places are both significantly influenced by the combination of generation sources and high-quality components. In this research, both GA and BA were employed as optimization algorithms. The outcomes of both approaches were compared using energy costs and CO_2 emissions as performance indicators. The findings will aid in determining the best economic, environmental, and cost-effective energy options for Kalema Village in Niger State's Mokwa local government area. Due to the intermittent nature of wind and PV, they were combined with DG and batteries to form hybrid power systems, and their optimal configuration was determined using GA and BA. The performance, robustness, and convergence of these optimization techniques were analyzed.

2.5.1. Implementation of genetic algorithm

The GA was employed to obtain the best solutions for the hybrid power system configuration. This was utilized to obtain the best configuration that minimizes energy costs and maximizes the classification accuracy of the hybrid power system model. A random population for GA was determined. The various parameters that were employed for the optimization process include fitness function, maximum iteration, population size, and number of features in the dataset. To solve the resulting optimization method using the objective functions given in (1), a script in MATLAB R(2021a) was written. In handling the operational constraints, the penalty factors are used to combine constraints with the objective function, as in (27).

$$ff = Max\left(\frac{1}{1+(\propto\cdot f_1+\beta\cdot f)^2}\right) \tag{27}$$

Where α and β are the weighing coefficients representing the relative importance of the objectives, $\alpha+\beta = 1$ for $0<\mu\leq 1$,μ is the weight operator.

In order to obtain the optimal hybrid power system configuration, the cost of energy (COE) and energy production were calculated for each population value. Figure 1 presents the flowchart of the GA model used for this purpose. The GA model aims to identify the best hybrid RES combination that can meet the energy demand of the community while minimizing the COE.

2.5.2. Implementation of bat algorithm

The BA begins by indiscriminately placing n bats in the search area. At iteration t, each bat has a velocity and a location X_i. The current best solution X^* exists among all the bats. As a result, (31) to (32) are used to update the bat's position and velocity [30].

$$V_i^t = V_i^{(t-1)} + f_i\left(X_i^{(t-1)} - X^*\right) \tag{31}$$

$$X_i^t = X_i^{(t-1)} + V_i^t \tag{32}$$

For the neighborhood search that changes the current best answer in accordance with (33) a random variable with direct exploitation was utilized.

$$X_{new} = X_{old} + \varepsilon A^t \tag{33}$$

Where: A^t = average loudness of all the bats and$\varepsilon \in [-1, 1]$= random number. To offer an efficient method to govern the exploration and exploitation stages and switch to the exploitation phase, when necessary, the loudness A_i and the rate, r_i of pulse emission are adjusted in the course of the iterations. Assuming A_{min} = 0, this indicates that the bat has just discovered the prey and has briefly ceased making noise. So, A_i^{t+1} is expressed as in (34) to (35):

$$A_i^{t+1} = \alpha A_i^t \tag{34}$$

$$r_1^t = r_1^0[1 - \exp(-\gamma t)] \tag{35}$$

where: r_i = pulse emission rate, α, and γ are constants. Figure 2 presents the flowchart of the BA model used for this purpose.

A MATLAB script was used to simulate and optimize the hybrid power system. The script implemented the BA and considered the objective functions in (1). The approach resulted in a more efficient and environmentally friendly design for rural electrification.

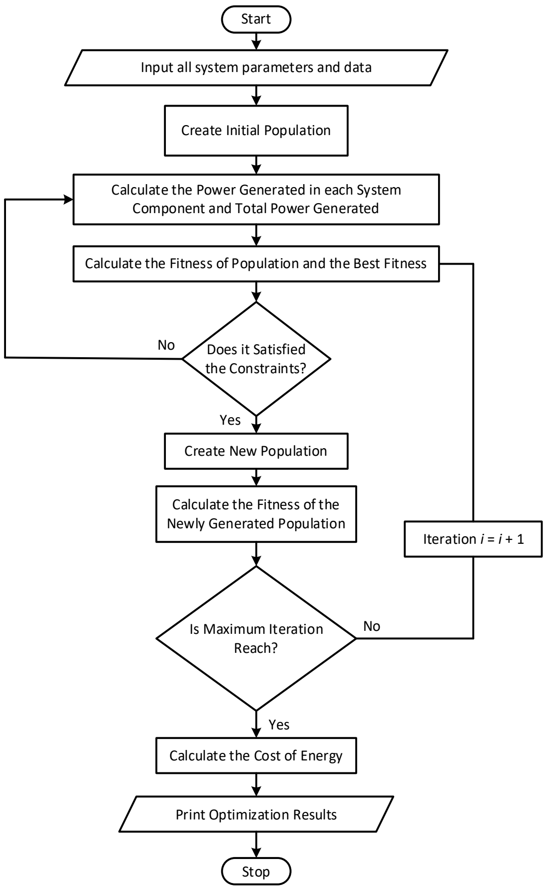

Figure 1. Flow chart of genetic algorithm

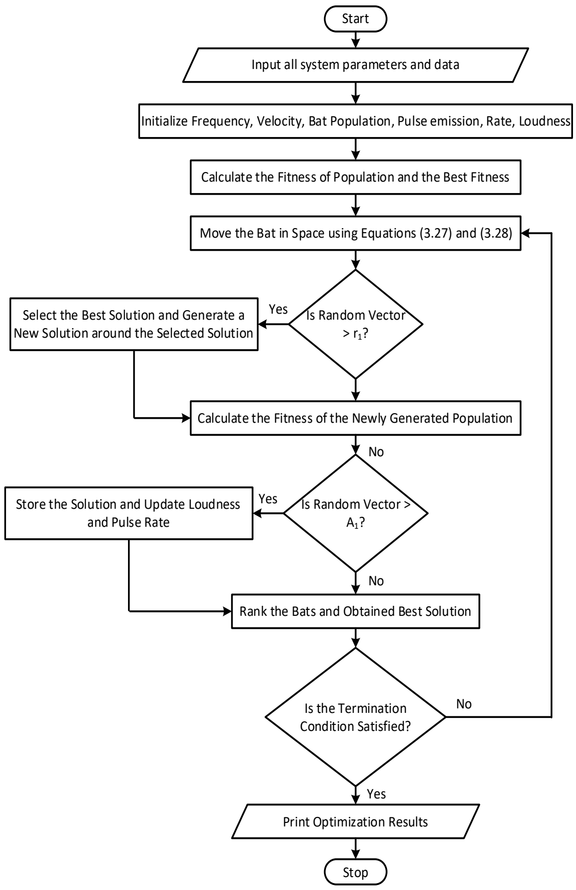

Figure 2. Flow chart of bat algorithm

2.6. Simulation results

The simulation parameter is presented in Table 1. The average monthly power generated from the wind generator and the solar panels is presented in Tables 2 and 3. For better illustration, Figure 3 showed the average monthly wind turbine-generated power, while Figure 4 depicted the average monthly solar PV-generated power.

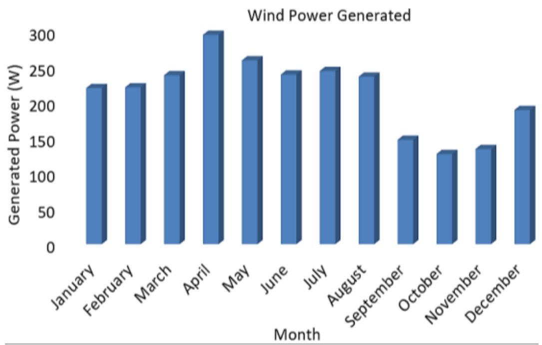

Figure 3. Monthly average wind turbine generated power

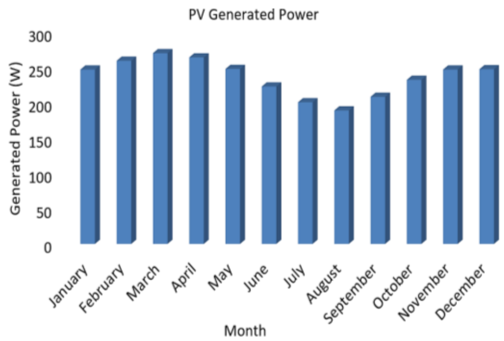

Figure 4. Monthly average PV generated power

Table 1. Simulation parameters

Content	Parameter	Installation cost	Maintenance cost
PV panel	300 watts	N59,000	-
Wind turbine	400 watts	N120,617	-
Diesel generator	5 kVA	N900,000	N45000/month
Battery	200 Ah	N167,500	-

Table 2. Monthly average wind turbine generated power

Month	Wind speed	Wind turbine generated power (W)
January	4.200	220.0000
February	4.210	221.0000
March	4.380	238.0000
April	4.950	295.0000
May	4.590	259.0000
June	4.390	239.0000
July	4.440	244.0000
August	4.360	236.0000
September	3.470	147.0000
October	3.270	127.0000
November	3.340	134.0000
December	3.890	189.0000

Table 3. Monthly average solar PV generated power

Month	Solar irradiance	PV Generated power (W)
January	5.730	247.5434
February	6.020	260.0203
March	6.270	270.7762
April	6.130	264.7529
May	5.750	248.4039
June	5.170	223.4503
July	4.650	201.0780
August	4.380	189.4617
September	4.830	208.8222
October	5.390	232.9154
November	5.730	247.5434
December	5.740	247.9737

2.7. Optimal configuration of hybrid power system

To design a hybrid renewable system with techno-economic benefits, the best configuration of the system components (PV, wind generator, DG, and battery) must be achieved. This was done using GA and BA. The total peak load of the community was used as the load demand, and the simulation was made for only DG; that is, DG was first designed to carry the load so that the comparison could be made. The result for this case is presented in Table 4. From Table 4, the number of DG sets required to carry the overall load of 820.009 kW was 194. The capital cost was $772,000, the maintenance cost was $5,790,000, and the system annualized cost (ASC) was $6,562,000. The excess energy was 214 W, and the total GHG (CO_2) emission recorded was 1679.6 lb/hr. The performance of GA and BA was analyzed based on this standard. Table 5 shows the best outcome for the hybrid system made up of solar modules, wind generators, DG, and batteries. From Table 5, a 44.5% reduction in ASC was achieved when GA was used, while a 45.6% reduction was achieved when BA was used. Capital and maintenance costs were also significantly reduced in comparison with the base case. The BA performance outweighed that of GA in terms of reduction in excessive energy supply, GHG emissions, capital cost, maintenance cost, ASC, and percentage cost reduction compared to only DG sets. The convergent characteristic curves for GA and BA are shown in Figure 5.

Table 4. Result for base case (DG set only)

Number of DG set	Capital cost ($)	Maintenance cost ($)	Annualized cost of the system (ACS) ($)	GHG Emission per hour (lb/hr)	REF%	Excessive energy supply (W)
194	772000	5790000	6562000	1679.6	0	241

Table 5. Optimal result for the hybrid power system

Content	GA	BA
Number of solar panels	1248	1250
Number of modules for wind generators	1248	1237
Number of diesel generator set	75	73
Number of battery module	185	185
Performance speed (s)	1.503243 seconds	1.567750 seconds
Peak load demand (W)	820009	820009
Total load supplied (W)	830622.69	820181.54
REF%	55	62
Excessive energy supply (W)	10613.69	172.54
GHG emission per hour (lb/hr)	652.69	635.29
% GHG emission reduction	61.14	62.18
Capital cost ($)	1421618.865	1379781.37
Maintenance cost ($)	2490000	2190000
Annualized cost of the system (ASC) ($)	3643122.46	3569781.37
% Cost reduction compare to only DG set	44.48	45.60

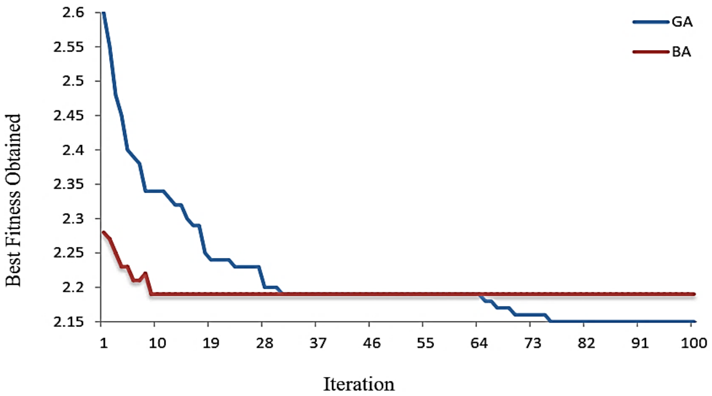

Figure 5. Comparison of convergent characteristics curve for GA and BA

Table 5 indicates that the optimal number of DGs required was reduced by 62% when using GA and BA, with 73 and 75 DGs required, respectively. This decrease resulted in a significant reduction of total system GHG (CO_2) emissions, from 1679.6 to 652.69 lb/hr for GA and 1679.6 to 635.29 lb/hr for BA. The simulation screenshots for both the BA and GA are as shown in Figures 6 and 7 respectively.

2.8. Availability factor variation scenario

The availability factor, which determines the accessibility of energy sources, can be affected by various factors such as system downtime, maintenance, or component malfunction. Three factors of 0.6, 0.8, and 1.0 were tested, and Table 6 illustrates their impact on the hybrid power system's ASC. The results show that higher availability factors resulted in lower ASC values, and while both GA and BA were tested under this condition, BA performed better than GA.

Table 6. Result for availability factor variation scenario

Content	GA			BA		
Availability (%)	60	80	100	60	80	100
Number of solar panels	1699	1373	1248	1992	1500	1250
Number of modules for wind generators	1925	1414	1248	1999	1489	1237
Number of diesel generator set	150	107	75	129	97	73
Number of battery module	162	166	185	178	178	185
Performance speed (s)	1.521602	1.571015	1.503243	1.534044	1.723688	1.567750
Peak load demand (W)	820009	820009	820009	820009	820009	820009
Total load supplied (kW)	829.416	821.281	830.623	820.059	820.116	820.182
Excessive energy supply (W)	9406.55	1271.97	10613.69	49.70	106.98	172.54
GHG emission (lb/hr)	1305.4	931.17	652.69	1122.6	844.15	635.29
Capital cost ($)	2010114.45	1575690.11	1421618.865	2043355.03	1613010.43	1379781.37
Maintenance cost (Naira)	4500000	3210000	2490000	3870000	2910000	2190000
Annual cost savings (ASC) ($)	6510114.45	4785690.11	3643122.46	5913355.03	4523010.43	3569781.37

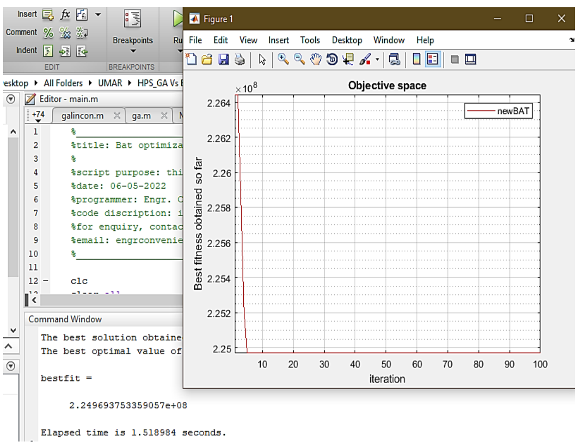

Figure 6. Simulation screenshot for the BA

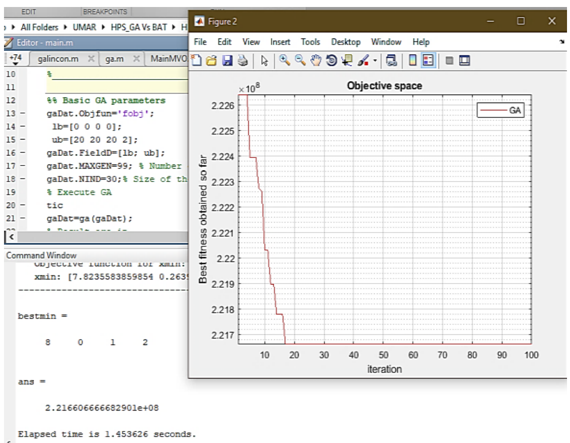

Figure 7. Simulation screenshot for the GA

3. CONCLUSION

This study optimized hybrid power systems using GA and BA to maximize technological and economic benefits by combining wind energy (for wind turbines), solar energy (for PV), fossil energy (for DG), and chemical energy (for batteries). The simulation was conducted on Kalema Village in Nigeria, resulting in a 45.6% reduction in the annualized cost of energy and a 62.18% reduction in CO_2 emissions when compared to a conventional power system using only DGs. The best system configuration was achieved using BA, which outperformed GA in terms of accuracy and computing speed. This study suggests that rural electrification problems caused by distance from the grid can be addressed using hybrid power systems optimized with BA.

REFERENCES

[1] S. Mandelli, J. Barbieri, R. Mereu, and E. Colombo, "Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review," *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 1621–1646, May 2016, doi: 10.1016/j.rser.2015.12.338.

[2] F. C. Robert and S. Gopalan, "Low cost, highly reliable rural electrification through a combination of grid extension and local renewable energy generation," *Sustainable Cities and Society*, vol. 42, pp. 344–354, Oct. 2018, doi: 10.1016/j.scs.2018.02.010.

[3] M. E. H. Arouri, A. Ben Youssef, H. M'Henni, and C. Rault, "Energy use and economic growth in Africa: a panel granger-causality investigation," *Economics Bulleetin*, vol. 34, no. 2, pp. 1247–1258, 2014.

[4] S. O. Ayanlade and O. A. Komolafe, "Distribution system voltage profile improvement based on network structural characteristics," in *Proceedings of the OAU Faculty of Technology Conference 2019*, 2019, pp. 75–79.

[5] Zervos REN21, "Global Status Report, Renewable 2020," *Renewable and Sustainable Energy Reviews*, vol. 72, no. October 2016, pp. 1–301, 2017, [Online]. Available: https://www.ren21.net/gsr-2020/.

[6] S. O. Ayanlade, E. I. Ogunwole, A. Jimoh, S. O. Ezekiel, D. E. Owolabi, and A. B. Jimoh, "STATCOM allocation using firefly algorithm for loss minimization and voltage profile enhancement," in *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, Nov. 2022, pp. 1–6, doi: 10.1109/ICECCME55909.2022.9988475.

[7] E. I. Ogunwole, S. O. Ayanlade, D. E. Owolabi, A. Jimoh, A. B. Jimoh, and F. M. Aremu, "Performance comparative evaluation of metaheuristic optimization algorithms for optimal placement of flexible alternating current transmission system device," in *2022 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, Jul. 2022, pp. 1–8, doi: 10.1109/ICECET55527.2022.9872866.

[8] A. Jimoh, S. O. Ayanlade, F. K. Ariyo, A. B. Jimoh, E. I. Ogunwole, and F. M. Aremu, "Multiple distributed generations optimization in distribution network using a novel dingo optimizer," in *Proceedings of International Joint Conference on Advances in Computational Intelligence*, 2023, pp. 125–138, doi: 10.1007/978-981-99-1435-7_12.

[9] T. Chaichan, "A hybrid system control approach abstract," vol. 2, pp. 1–10, 2016.

[10] L. Olatomiwa, "Optimal configuration assessments of hybrid renewable power supply for rural healthcare facilities," *Energy Reports*, vol. 2, pp. 141–146, Nov. 2016, doi: 10.1016/j.egyr.2016.06.001.

[11] C. D. R. Gallegos, D. Yang, O. Gandhi, M. Bieri, T. Reindl, and S. K. Panda, "A multi-objective and robust optimization approach for sizing and placement of PV and batteries in off-grid systems fully operated by diesel generators: An Indonesian case study," *Energy*, vol. 160, pp. 410–429, Oct. 2018, doi: 10.1016/j.energy.2018.06.185.

[12] A. Kasaeian, P. Rahdan, M. A. V. Rad, and W. M. Yan, "Optimal design and technical analysis of a grid-connected hybrid photovoltaic/diesel/biogas under different economic conditions: A case study," *Energy Conversion and Management*, vol. 198, 2019, doi: 10.1016/j.enconman.2019.111810.

[13] J. A. F. de A. Santos, P. de Jong, C. A. da Costa, and E. A. Torres, "Combining wind and solar energy sources: Potential for hybrid power generation in Brazil," *Utilities Policy*, vol. 67, p. 101084, Dec. 2020, doi: 10.1016/j.jup.2020.101084.

[14] S. K. Ramoji, B. B. Rath, and D. V. Kumar, "Optimization of hybrid PV/wind energy system using genetic algorithm (GA)," *International Journal of Engineering Research and Applications w*, vol. 4, no. 1, pp. 29–37, 2014.

[15] L. M. Halabi, S. Mekhilef, L. Olatomiwa, and J. Hazelton, "Performance analysis of hybrid PV/diesel/battery system using HOMER: A case study Sabah, Malaysia," *Energy Conversion and Management*, vol. 144, pp. 322–339, Jul. 2017, doi: 10.1016/j.enconman.2017.04.070.

[16] F. Huneke, J. Henkel, J. A. Benavides González, and G. Erdmann, "Optimisation of hybrid off-grid energy systems by linear programming," *Energy, Sustainability and Society*, vol. 2, no. 7, Dec. 2012, doi: 10.1186/2192-0567-2-7.

[17] H. R. E.-H. Bouchekara, M. S. Javaid, Y. A. Shaaban, M. S. Shahriar, M. A. M. Ramli, and Y. Latreche, "Decomposition based multiobjective evolutionary algorithm for PV/Wind/Diesel Hybrid Microgrid System design considering load uncertainty," *Energy Reports*, vol. 7, pp. 52–69, Nov. 2021, doi: 10.1016/j.egyr.2020.11.102.

[18] K. Sörensen, "Metaheuristics—the metaphor exposed," *International Transactions in Operational Research*, vol. 22, no. 1, pp. 3–18, Jan. 2015, doi: 10.1111/itor.12001.

[19] F. N. Nnadi, J. Chikaire, J. O. Ajaero, R. N. Nwakwasi, and M. N. Oguegbuchulam, "Renewable energy for sustainable food, feed and fibre production: A panacea to Nigeria's energy crisis," *Nature and Science*, vol. 9, no. 11, pp. 76–83, 2011.

[20] M. H. H. M. Rozlan, A. F. Zobaa, and S. H. E. A. Aleem, "The optimisation of stand-alone hybrid renewable energy systems using HOMER," *International Review of Electrical Engineering (IREE)*, vol. 6, no. 4, 2011.

[21] L. Mangal, V. . Idichandy, and C. Ganapathy, "Structural monitoring of offshore platforms using impulse and relaxation response," *Ocean Engineering*, vol. 28, no. 6, pp. 689–705, Jun. 2001, doi: 10.1016/S0029-8018(00)00018-4.

[22] M. Kalogera and P. Bauer, "Optimization of an off-grid hybrid system for supplying offshore platforms in arctic climates," in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, May 2014, pp. 1193–1200, doi: 10.1109/IPEC.2014.6869738.

[23] S. Diaf, D. Diaf, M. Belhamel, M. Haddadi, and A. Louche, "A methodology for optimal sizing of autonomous hybrid PV/wind system," *Energy Policy*, vol. 35, no. 11, pp. 5708–5718, Nov. 2007, doi: 10.1016/j.enpol.2007.06.020.

[24] K. B. M. Kiran, M. S. Indira, and S. N. Rao, "Mathematical modeling and evaluation of performance characteristics of a hybrid solar PV and wind energy system," *Journal of Applied Science and Engineering*, vol. 25, no. 4, 2021, doi: https://doi.org/10.6180/jase.202208_25(4).0014.

[25] H. Borhanazad, S. Mekhilef, V. Gounder Ganapathy, M. Modiri-Delshad, and A. Mirtaheri, "Optimization of micro-grid system using MOPSO," *Renewable Energy*, vol. 71, pp. 295–306, Nov. 2014, doi: 10.1016/j.renene.2014.05.006.

[26] Z. Civelek, M. Lüy, E. Çam, and N. Barışçı, "Control of pitch angle of wind turbine by fuzzy pid controller," *Intelligent Automation & Soft Computing*, vol. 22, no. 3, pp. 463–471, Jul. 2016, doi: 10.1080/10798587.2015.1095417.

[27] S. Dehghan, H. Saboori, A. Parizad, and B. Kiani, "Optimal sizing of a hydrogen-based wind/PV plant considering reliability indices," in *International Conference on Electric Power and Energy Conversion Systems, (EPECS)*, 2009, pp. 1–9.

[28] M. S. Ismail, M. Moghavvemi, and T. M. I. Mahlia, "Techno-economic analysis of an optimized photovoltaic and diesel generator hybrid power system for remote houses in a tropical climate," *Energy Conversion and Management*, vol. 69, pp. 163–173, May 2013, doi: 10.1016/j.enconman.2013.02.005.

[29] R. Dufo-López and J. L. Bernal-Agustín, "Design and control strategies of PV-Diesel systems using genetic algorithms," *Solar Energy*, vol. 79, no. 1, pp. 33–46, Jul. 2005, doi: 10.1016/j.solener.2004.10.004.

[30] A. Alihodzic and M. Tuba, "Framework for bat algorithm optimization metaheuristic," in *4th international conference on bioscience and bioinformatics (ICBB'13) Chania*, 2013, pp. 157–162.

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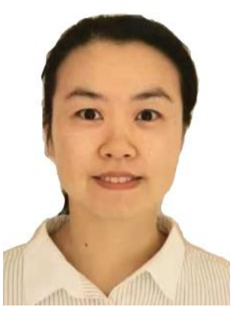

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