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# OPTIMAL DESIGN OF HYBRID PHOTOVOLTAIC-DIESEL-BATTERY POWER SYSTEM MODEL FOR RURAL ELECTRIFICATION USING WHALE OPTIMIZATION ALGORITHM

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## Abstract

*The electrification of remote rural areas remains a significant challenge in developing nations like Nigeria, where grid extension is often economically unviable. Hybrid renewable energy systems (HRES) present a sustainable solution, but their effectiveness hinges on optimal component sizing to balance cost and reliability. This study proposes a novel application of the Whale Optimization Algorithm (WOA) for the optimal design of a standalone hybrid PV-Diesel-Battery system for Agbokeke, rural community of Oyo State Nigeria. The multi-objective optimization model aims to minimize the Total Annualized Cost (TAC) and Total Annual Pollution (TAP). System components are modeled in MATLAB/Simulink, and the load and solar resource data are based on field surveys and national databases. The WOA-derived optimal configuration is compared against two baseline scenarios (Diesel-only and PV-Battery-only) and a standard tool (HOMER Pro). Results show that the WOA-optimized system (73 PV panels, 69 batteries, 50 kVA DG) achieved a TAC of ₦19,546,453 and a TAP of 35.73 Mg of $CO_2$, outperforming the HOMER Pro solution by 11.34% in cost and 9.8% in emissions reduction. The findings demonstrate that WOA is a superior, efficient tool for the techno-economic optimization of HRES, providing a viable pathway for cost-effective and environmentally friendly rural electrification.*

## 1. INTRODUCTION

In recent times, the continuous availability of electrical energy has offered vital roles for a comfortable life in both rural and urban settlements. Electrical Energy is essential and one of the most critical amenities in our everyday life which help drives some sectors such as healthcare, education, entertainment and transportation in the world of technological development. However, according to the statistics from the International Energy Agency

(IEA), more than 1.5 billion people, representing 14 % of the world's population have zero access to energy as of 2020. Moreover, the larger percentage of this population is located in developing countries, especially in south Asia and the sub-Saharan Africa. One of such country is Nigeria, the most populous black nation located in the south-east of West Africa (Oladigbolu et al., 2020).

Despite its status as one of the fastest growing Africa countries, the country still shows discrepancy in the electrification rate between rural and urban areas. In rural areas, extending the power grid is often a challenging task due to various factors such as rugged terrain, dense jungles, geographic remoteness, high supply costs, low electricity consumption, inadequate road infrastructure, and dispersed settlements of consumers. Hybrid energy systems are best suited to reduce dependence on fossil fuel using available wind speed and solar radiation As a result, many people in remote areas may need to rely on other sources of power, such as diesel or petrol generators, to meet their electricity needs. There are drawbacks of noise pollution, green-house gas emission, and still very much requires the frequent maintenance cost of fuelling and oiling (Oladigbolu et al., 2020; Diab et al., 2019).

The design of hybrid power system has been attempted by some researchers using simulation software tools. However, the evaluation of the software's limitations, climatic condition of the location and type of system configurations has limited the outcome of expected results (Mostafa et al., 2018). Therefore an optimisation techniques help eliminate some of this limitation (Bhandari et al., 2014; Mostafa et al., 2018). Therefore, in this study, the optimisation algorithm namely Whale Optimisation Algorithm (WOA) was used to optimally design a hybrid PV-diesel-battery power system model for a remote location in western part of Nigeria.

## 2.1 Problem Statement

The persistent energy deficit in rural areas of developing nations, particularly in sub-Saharan Africa, represents a critical barrier to socio-economic development. In Nigeria, despite having a national installed grid capacity of over 13,000 MW, actual generation often falls below 5,000 MW, leaving millions of people, especially in remote villages, without reliable electricity (Esan, 2019). Extending the central grid to these areas is frequently economically prohibitive due to factors such as difficult terrain, low population density, and high transmission losses (Oladigbolu et al., 2020). Consequently, communities like Agbokeke village in Oyo State, Nigeria, often resort to standalone diesel generators. However, this solution is plagued by exorbitant operational costs due to volatile fossil fuel prices, significant greenhouse gas emissions contributing to environmental pollution, and high maintenance requirements (Ali et al., 2019; Diab et al., 2019).

Renewable energy sources, particularly solar photovoltaic (PV) systems, offer a clean and abundant alternative, harnessing Nigeria's substantial solar potential of approximately 5.12 $kWh/m^2/day$ on average (Sambo, 2008). Nevertheless, the inherent intermittency and stochastic nature of solar radiation threaten the reliability of a standalone PV system, often necessitating massive battery storage banks to ensure uninterrupted power supply. This requirement for oversizing leads to substantial initial capital investment, making a PV-battery-only system financially unviable for many rural applications (Bhandari et al., 2014; Garcia et al., 2017). Therefore, the specific research problem addressed in this study is the lack of an efficient and robust optimization framework for determining the techno-economically optimal configuration of a standalone PV-Diesel-Battery hybrid system that minimizes total cost and environmental impact for rural electrification in Nigeria. This study investigates whether the

Whale Optimization Algorithm can effectively solve this multi-objective design problem and deliver a superior configuration compared to conventional methods like HOMER.

## 2. MATERIALS AND METHODS

### 2.1. Case Study and Input Data

The study focuses on Agbokeke village (8° 41.2' N, 3° 37.3' E) in Oyo State, Nigeria. The village, with an estimated 750 households, has no grid access. The average daily solar radiation is 5.12 kWh/m²/day, with a average temperature of 23.29°C (Table 1). The load profile was determined through surveys, showing a peak demand of 35 kW and daily energy consumption ranging from 304 kWh (rainy season) to 415 kWh (dry season).

**Table 1.** Monthly Solar Resource and Climatic Data for Agbokeke, Nigeria

| S/N | Months | Average Ambient Temperature (°C) | Average Solar Irradiance (kWh/m²/day) | Average Clearness Index |
|---|---|---|---|---|
| 1 | January | 24.570 | 5.630 | 0.622 |
| 2 | February | 26.670 | 5.870 | 0.606 |
| 3 | March | 27.550 | 6.020 | 0.585 |
| 4 | April | 27.240 | 5.730 | 0.546 |
| 5 | May | 26.280 | 5.430 | 0.525 |
| 6 | June | 25.130 | 4.780 | 0.471 |
| 7 | July | 24.130 | 4.120 | 0.404 |
| 8 | August | 23.830 | 3.830 | 0.370 |
| 9 | September | 24.270 | 4.220 | 0.410 |
| 10 | October | 24.860 | 4.760 | 0.485 |
| 11 | November | 24.910 | 5.380 | 0.587 |
| 12 | December | 24.140 | 5.560 | 0.631 |
|  | Annual Average | 5.12 | 25.05 | 0.520 |

### 2.2. System Architecture and Component Modeling

The proposed HRES comprises PV panels, a diesel generator (DG), a battery bank, and a bi-directional converter (Figure 1). The mathematical models for each component are based on standard energy engineering principles.

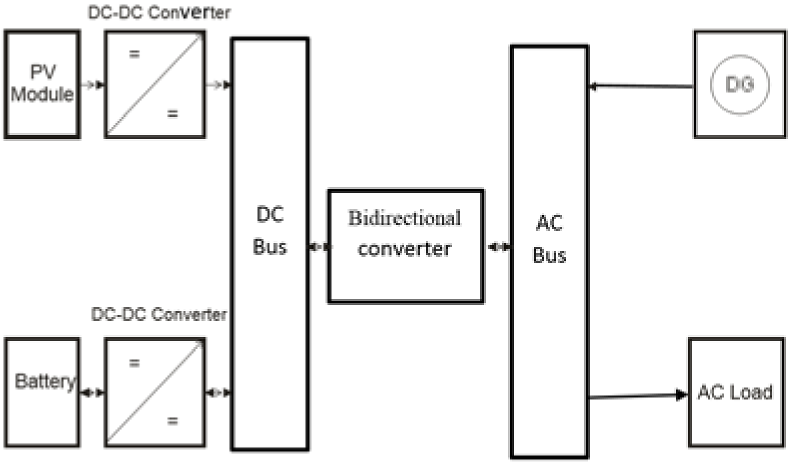

**Figure 1.** Block Diagram of the Off-Grid standalone PV-Diesel-Battery hybrid system

1. **PV Array Model:** The hourly output power of the PV array, $P_{PV}(t)$, is calculated as: $P_{PV}(t) = N_{PV} \times P_{rated,PV} \times (G(t)/G_{STC}) \times [1 - \alpha\ (T_c(t) - T_{STC})]$

where $N_{PV}$ is the number of panels, $P_{rated,PV}$ is rated power under standard test conditions (STC), G(t) is solar irradiance, $G_{STC}$ is irradiance at STC, α is the temperature coefficient, and Tc(t) is the cell temperature.

2. **Diesel Generator Model:** The fuel consumption of the DG, F(t), is modeled using a linear fuel curve:

3. $F(t)=F_0 \text{ x } P_{rated,DG} + F_1 \times P_{DG}(t)$

4. where $F_0$ and $F_1$ are fuel curve coefficients, and $P_{DG}(t)$ is the generator's output power.
5. **Battery Bank Model:** The State of Charge (SOC) of the battery bank is dynamically modeled as:

6. $SOC(t) = SOC(t-1)\times(1-\sigma)+(P_{ch}(t)\times\eta ch-P_{dis}(t)/\eta_{dis})\times\Delta t/C_{rated}$

Where σ is the self-discharge rate, $P_{ch}$ and $P_{dis}$ are charging/discharging power, $\eta_{ch}$ and $\eta_{dis}$ are efficiencies, and $C_{rated}$ is the nominal battery capacity.

## 2.3. Problem Formulation

### *2.3.1. Objective Functions*

A multi-objective function is formulated to minimize both the Total Annualized Cost (TAC) and Total Annual Pollution (TAP).

$$\text{Min } F = w_1 \times TAC + w_2 \times TAP$$

Where $w_1$and $w_2$ are weighting factors ($w_1+w_2=1$), set to 0.7 and 0.3 respectively to prioritize cost while considering emissions. The TAC includes initial capital cost (CC), replacement cost (RC), operation and maintenance cost (O&M), fuel cost, and salvage value (SV) over the project's 25-year lifespan, annualized using a 5% interest rate.
The TAP is calculated from the DG's emissions based on its fuel consumption.

### *2.3.2. Decision Variables and Constraints*

The decision variables optimized by the WOA are:

- $N_{PV}$: Number of PV panels
- $N_{Bat}$: Number of batteries
- $P_{DG}$: Capacity of the diesel generator (kW)

The optimization is subject to the following constraints:

- Power Balance: $P_{PV}(t) + P_{DG}(t) \pm P_{Bat}(t) = P_{Load}(t)$
- Battery SOC: $SOC_{min} \leq SOC(t) \leq SOC_{max}$
- DG Operating Limit: $P_{DG,min} \leq P_{DG}(t) \leq P_{DG,\ rated}$

## 2.4. Whale Optimization Algorithm (WOA) Implementation

The WOA mimics the hunting behavior of humpback whales, which involves encircling prey, bubble-net attacking (exploitation), and searching for prey (exploration) . Each "whale" in the population represents a potential system configuration ($N_{PV}$, $N_{Bat}$, $P_{DG}$). The algorithm proceeds as follows:

1. *Initialization*: A population of whales (candidate solutions) is randomly initialized.
2. *Fitness Evaluation*: Each solution is evaluated by simulating the HRES over one year (8760 hours) and calculating the objective function F.

3. *Update Positions*: The positions of the whales are updated based on the WOA's equations for encircling, spiral bubble-net feeding, or random search.
4. *Termination*: Steps 2-3 repeat until a maximum number of iterations is reached (set to 500 in this study).
5. The best solution found represents the optimal system configuration.

## 3. RESULTS AND DISCUSSION

### 3.1. Optimal Configuration and Comparative Analysis

Three scenarios were analyzed to evaluate the proposed system's performance:

- Scenario 1: Diesel Generator only.
- Scenario 2: PV-Battery only.
- Scenario 3: WOA-Optimized PV-Diesel-Battery system.

The results are summarized in Table 2. The Diesel-only system has the lowest capital cost but the highest TAC due to exorbitant fuel expenses and the highest TAP. The PV-Battery system produces zero emissions but has the highest TAC due to the massive over-sizing required to ensure reliability during low-sunlight periods. The WOA-optimized hybrid system strikes an optimal balance, achieving the lowest TAC and a significantly reduced TAP.

**Table 2.** Performance Comparison of Different System Configurations

| Description | Configuration | Total Annual Cost (TAC) | Total Annual Pollution (TAP) |
|---|---|---|---|
| Scenario One (DG Only) | 50KVA | ₦41,754,160 | 234.85 Mg |
| Scenario Two (PV-Battery) | 210 PV; 210 BATT. | ₦51,450,000 | 0.00 Mg |
| Scenario Three: WOA-Optimized | 50KVA DG, 73 PV, 69 BATT. | ₦19,546,453 | 35.73 Mg |

### 6.2. Validation against HOMER Pro

The WOA-optimized configuration was compared with a design from HOMER Pro software. HOMER suggested a configuration with 79 PV panels and 72 batteries. The comparative results (Table 3) demonstrate the superior performance of the WOA, yielding an 11.34% reduction in TAC and a 9.8% reduction in TAP.

**Table 3.** Comparison of Optimal system configuration with HOMER software

| Serial Number | Metric | HOMER Pro | Optimal System Configuration using WOA | % Improvement by WOA |
|---|---|---|---|---|
| 1 | Number of PV Panels | 79 | 73 | - |
| 2 | Number of Batteries | 72 | 69 | - |
| 3 | TAC (₦) | 22,047,000 | 19,546,453 | 11.34% |
| 4 | TAP (Mg of $CO_2$) | 39.62 | 35.73 | 9.80% |

This superior performance is attributed to WOA's effective global search capability, which allows it to escape local optima and find a more efficient balance between component sizes and operational strategy, thereby minimizing fuel consumption and associated costs more effectively than HOMER's iterative search method.

## 4. CONCLUSION

This study successfully demonstrated the application of the Whale Optimization Algorithm for the optimal design of a hybrid PV-Diesel-Battery system for rural electrification. The results of the optimal system configuration were compared with those of HOMER software, the TAC and TAP obtained using HOMER are ₦22,047,000 and 39.62; as compared with ₦19,546,453and 35.73 Mg respectively, which is about is 11.34 % and 9.8 % savings achieved with optimal system configuration using WOA. The WOA proved to be a highly effective tool, outperforming standard software (HOMER Pro) by significantly reducing both the total annual cost and environmental impact. The optimized system configuration provides a reliable, cost-effective, and cleaner energy solution for the remote community of Agbokeke.

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**Conflicts of Interest**

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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