International Academic Journal of Information, Communication, Technology & Engineering
ISSN: 5741-2605 | Volume 8, Issue 8 | January, 2025 | pages 63 – 76
OTL: 222-3942-8342-542-877-1
Double Blind Peer Reviewed International Research Journal
https://accexgate.com
journalsaccexgate@gmail.com

ELECTRICAL POWER GENERATION OF HYBRID POWER WIND DIESEL BATTERY SYSTEM FOR GUBIO VILLAGE, BORNO STATE

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Abstract: *The use of photovoltaic (PV) energy sources has recently gained significant attention due to their renewability. However, several challenges, particularly in accurately designing PV systems, remain. Proper sizing of PV cells and battery storage in off-grid PV systems is crucial for improving efficiency and system reliability. This project focuses on Gubio Village in northern Nigeria, where a stand-alone system combining wind, photovoltaic, and diesel power is proposed. The primary goal is to determine the optimal number of PV modules and battery sizes for the case study. The proposed system was tested using MATLAB simulations under desirable test conditions, considering variations in irradiance patterns and other uncertainties associated with the system. The search ranges for PV, battery, wind turbine, and diesel components, along with their objective functions, are also outlined. In this project, the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE) algorithms were compared for the optimal sizing of an off-grid PV, wind turbine, and diesel system for Gubio Village. The optimization results revealed that PSO provided the best solution in terms of cost and convergence time, with the lowest Loss of Power Supply Probability (LPSP) and highest Levelized Cost of Energy (LCOE) at 0.012 and 0.3564, respectively. Compared to DE and GA, the PSO algorithm demonstrated greater efficiency, requiring less computational time and memory due to its faster convergence. Thus, the project successfully achieved its objectives by designing a hybrid PV/wind/diesel battery power generation system for Gubio Village in Borno State, Nigeria.*

Keywords: *Photovoltaic (PV) energy; Off-grid PV system; Optimization algorithms; Hybrid power generation.*

1.0 Introduction

Fossil fuels have been the primary global energy source for decades; however, their production and use pose serious environmental concerns. Energy is a critical component for human survival, development, and progress. As the world enters a new phase of energy demand, it becomes imperative to adopt clean and low-carbon energy sources to sustain the environment (Meysam, 2015). While fossil fuels have dominated energy supply, the last four decades have witnessed a strategic push toward energy independence, which is transforming global energy patterns and profoundly impacting economic development (Amir et al., 2021). Historically, energy consumption has evolved from wood to coal and then to fossil fuels. The future, however, is expected to pivot toward renewable energy, driven by the ecological and environmental challenges caused by the intensive use of high-carbon energy sources. These challenges include desertification in Africa, fog in Europe, and severe haze in other regions (Amir et al., 2021). Efforts are being made globally to transition to renewable energy sources, with power generation at the forefront of renewable energy utilization. Advances in wind, solar, and other renewable technologies have significantly contributed to reducing reliance on fossil fuels (Adefarati et al., 2019). Among renewable energy sources, wind energy has gained prominence due to its clean and cost-effective nature, driven by technological advancements and increasing capacity per unit. Similarly, solar energy has emerged as a central player in renewable energy development, reducing fossil fuel consumption and greenhouse gas emissions. Solar energy is considered the fastest-growing renewable energy source, replacing conventional power plants while being cost-effective, reliable, and environmentally friendly. The operational and maintenance costs of solar modules are lower compared to other energy sources, and the technology continues to improve, enhancing panel efficiency, battery storage, and inverter capabilities (Adefarati et al., 2019). In Nigeria, unreliable electricity supply remains a significant constraint to economic growth. According to a 2016 World Bank report, nearly all businesses in Nigeria identified electricity as a major challenge, with some reporting losses of up to 30% of annual sales due to power outages. The dependence on diesel generators as backup power sources exacerbates environmental pollution through toxic emissions. This highlights the urgent need for alternative energy solutions, such as hybrid systems combining photovoltaic (PV), wind, and diesel generators.

Hybrid renewable energy systems are increasingly popular as standalone solutions for providing electricity in remote areas, particularly as fossil fuel prices rise and renewable technologies advance (Amir et al., 2021). The global shift toward renewable energy is driven by the depletion of fossil fuel reserves and the urgent need to mitigate greenhouse gas emissions. In 2018, the transition to renewable energy in the power sector avoided 215 million tons of carbon dioxide emissions. Countries like China and those in Europe played a significant role, contributing 66% to the global effort. Without these changes, emissions would have been 50% higher. The power sector's progress has resulted in a 10% reduction in CO_2 emissions per kilowatt-hour since 2010, a testament to the success of investments in renewable energy such as PV, wind, and bioenergy (Adefarati et al., 2019). The high levels of solar irradiance and sunshine duration in West Africa make solar energy a promising solution for the region's future energy needs. Harnessing renewable energy that is sustainable, economical, and environmentally friendly is essential to meet the rising demand for power. Photovoltaic (PV) systems, in particular, are seen as the most viable option due to their small size, ability to utilize unused spaces on buildings, and low ecological impact. In rural communities far from the national grid, PV systems offer a cost-effective solution, eliminating the challenges of transporting fuel or installing traditional generators in remote areas (Meysam, 2015). Optimization of renewable energy systems, such as standalone PV systems with energy storage batteries, has become a critical focus area. These systems are reliable, eco-friendly, and capable of meeting power demands in remote locations, including telecommunications base stations. The use of optimization algorithms, such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC), has enhanced the efficiency and performance of PV systems. These algorithms address the complexities associated with renewable energy systems, such as nonlinearities, uncertainties in power sources, and load demands. Their ability to adapt to incomplete meteorological data makes them indispensable for optimizing renewable energy systems (Adefarati et al., 2019). In conclusion, renewable energy sources, particularly solar and wind, are pivotal for addressing energy challenges in Nigeria and beyond. The integration of advanced optimization techniques ensures the efficient utilization of these resources, paving the way for a sustainable and low-carbon energy future.

Therefore, this paper aims to analyze the hybrid electrical power generation system in Gubio Local Government Area.

1.2 Material and Methods

This chapter presents the methods and procedures adopted to achieve the research objectives. It focuses on optimizing the sizing of an off-grid photovoltaic (PV) system using Differential Evolution (DE) algorithms implemented in MATLAB. PV arrays were modeled under ideal conditions, and mathematical models were derived to relate solar cell inputs to outputs as shown in figure 1 below.

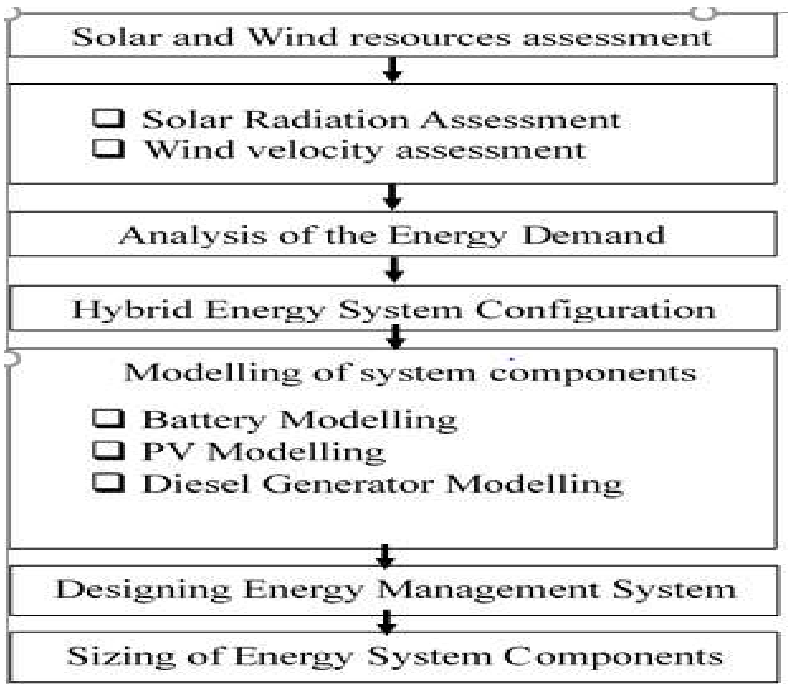

Figure 1:Flow chart of the over process

1.3 Solar Radiation

Gubio Village receives an average solar irradiation of 5.75 kWh/m²/day, with 7.5 hours of sunshine daily. Data from NASA's satellite database confirms the location's solar potential for sustainable power generation.

1.4 Wind Resources

Wind energy data, collected over 10 years at 10m above sea level, indicates wind speeds ranging from 2.41–5.63 m/s. Wind variations are influenced by topography, vegetation, and diurnal patterns, with a Weibull parameter (k) of 2.

1.5 Energy Demand Analysis

The energy demand for Gubio Village is estimated at 33.836 kWh/day, based on the study by Wale et al. (2019).

1.6 Hybrid PV-Wind-Diesel System Configuration

A hybrid PV-wind-diesel system with battery storage is proposed for reliable energy supply. Solar and wind energy complement each other, reducing storage requirements. The diesel generator acts as a backup during insufficient renewable energy supply, ensuring power reliability.

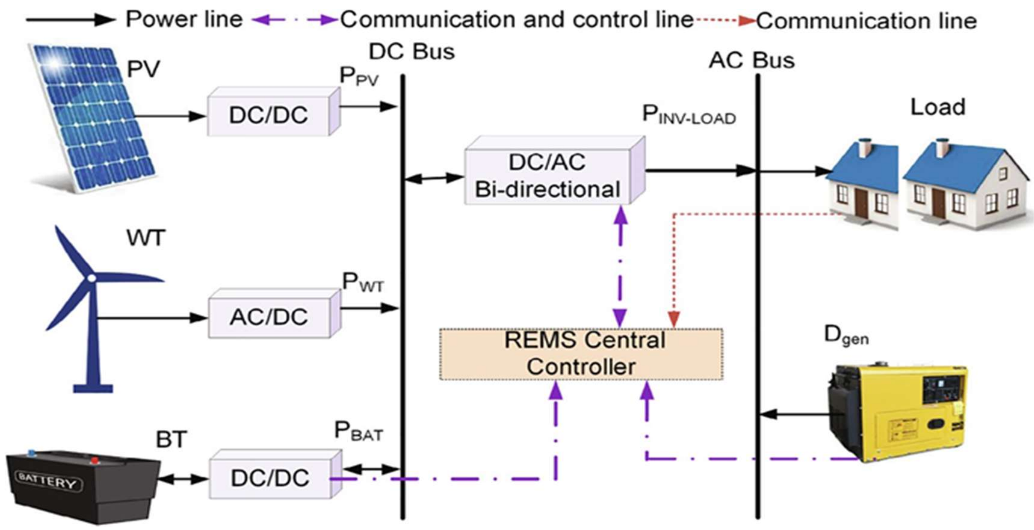

Figure 2: Hybrid PV-Wind-Diesel System Configuration

1.7 Modelling System Components

The component sizing was accomplished with three algorithms based on the following flow charts

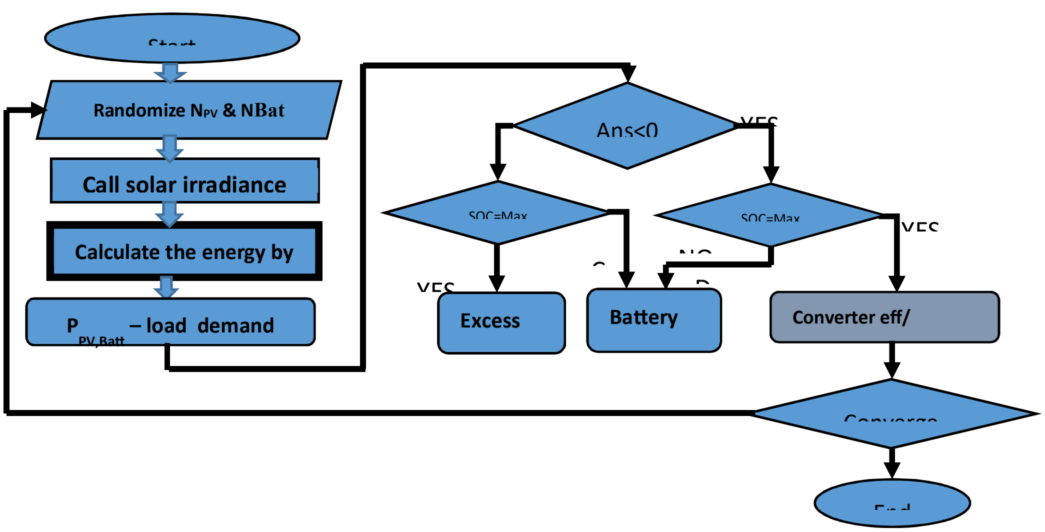

Figure 3: Flow chart for the sizing process.

1.7 Battery Modelling

Battery energy storage system Battery is a storage device essential for storing electrical energy for maximum utilization of the intermittent renewable resources. The lead-acid battery which is often used in HPS is a complex, nonlinear device controlling operational states of the system [50]. Modelling of lead-acid batteries for real time analysis of HPS must account for the dependence of battery parameters on: (i) state of charge, (ii) battery storage capacity, (iii) rate of charge/discharge, (iv) ambient temperature, (v) life and other internal phenomenon, such as gassing, double layer effect, self-discharge, heating loss and diffusion. As started earlier, the incorporation of BT to the grid-independent microgrid is inevitable. The BT is in charging mode in case the power generated by the RESs (POW^{wt} and POW^{pv}) is higher than the demand. The quantity of charge at time t is determined as in equation 1&2

$$E_{BT} = E_{BT}\ (t-1)(1-\sigma) + (POW^{wt}(t) + POW^{pv}).\eta_{inv} - \frac{P_t(t)}{\eta_{inv}}.\eta_{BT} \quad (1)$$

$$E_{BT} = E_{BT}\ (t-1)(1-\sigma) + (POW^{wt}(t) + POW^{pv}).\eta_{inv} - \frac{P_t(t)}{\eta_{inv}}.\eta_{BT}/\eta_{iBT} \quad (2)$$

The BT bank can supply the demand if the *SOC* (*t*) is greater than SOC minimum (*SOC*). Similarly, the BT bank can be charged by surplus power generated until SOC (t) reaches SOC maximum (SOC). The BT capacity in Ampere-hour (Ah) is evaluated in accordance with the desired autonomy day (AD) and the demand using the following formulae in equation 3.

$$B_{cap} = \frac{AD.E_L}{\eta_{inv} X \eta_B X\ DOD\ X\ V_s} \quad (3)$$

where *EL* denote the daily average demand and *Vs* is the system voltage taken to be 48 V. The number of BTs (*nBTss*)in a series string is determined using Equation 4.

$$nBT_{ss} = \frac{B_{cap}}{Max\_Ps} \quad (4)$$

where *Max_Ps* is the maximum number of parallel strings. Accordingly, the number of BT's in each series string (*nBTss*) , is computed using equation .5.

$$nBT_{ss} = \frac{V_B}{V_s} \quad (5)$$

where *VB* refers to BT bank voltage. The total number of BT required can be determined using equation 3.6.

$$TnB = nBT_{ss} x\ nBT_{ss} \quad (6)$$

1.8 Diesel Generator Modeling

Diesel generator fuel consumption and CO_2 emissions were modeled based on output power. Costs were analyzed considering varying diesel prices and cumulative present value.

1.9 PV Modeling

The PV system output was modeled as a function of ambient temperature and solar irradiance. Equations accounted for module characteristics, radiation levels, and cell temperatures. Gubio's high solar radiation was found suitable for sustainable electricity generation

2.0 RESULTS AND DISCUSSION

This research compares the optimization capabilities of Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) algorithms for sizing the components of an off-grid photovoltaic (PV) system, including PV panels, wind turbines, generators, and battery storage. Among the algorithms, DE demonstrated a faster convergence rate [25] and provided superior economic analysis. The study's objective is to design an off-grid PV system at an optimal cost while meeting load demand and adhering to constraints such as battery depth of discharge. Three years of solar irradiation, ambient temperature, and load profile data were analyzed. The study incorporates two key constraints: maintaining the battery's depth of discharge and ensuring the system can meet the maximum load during daytime and the defined autonomy period of three days. This autonomy period determined the required battery storage capacity.

2.1 System Description

The system's peak load is 64.8 kW, as illustrated in Figure 2.1. Energy demand is supplied by solar panels and battery storage. During the day, solar energy meets the load demand, while the battery storage system provides power during the night and is recharged during the daytime. This off-grid system combines solar PV and battery storage, with system components detailed in Table 2.1.

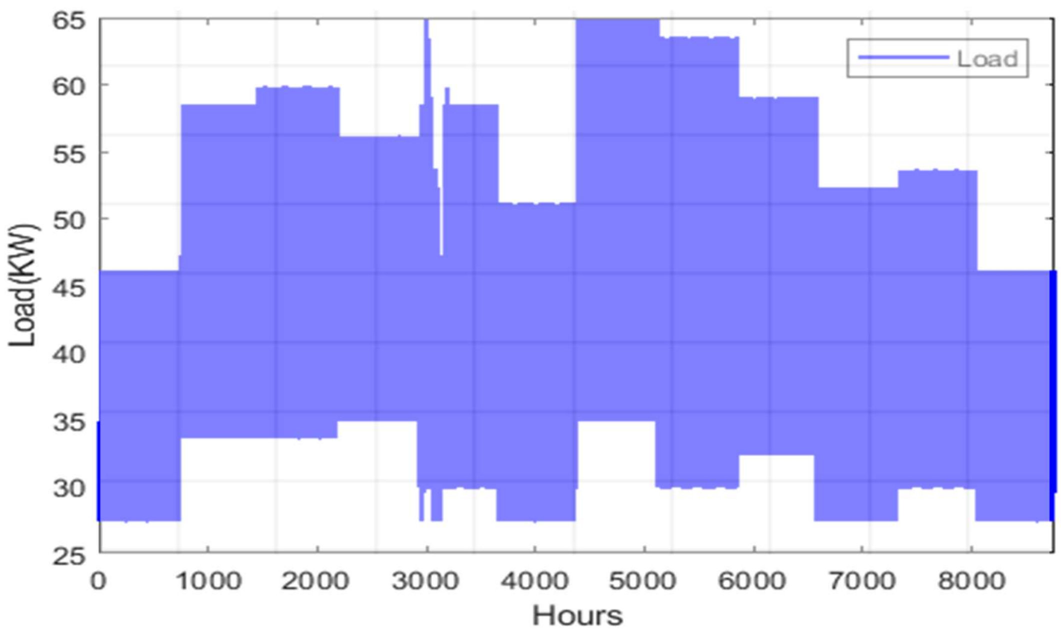

Figure 2.1:Annual load profile

Table 2.1: Technical Parameters and Economics of the System

Component	Parameter	Specification/Value
Solar Panel	Cell Type	Monocrystalline Cell
	STC Power Rating (Pmp)	315 W
	Open Circuit Voltage (Voc)	64.6 V
	Short Circuit Current (Isc)	6.14 A
	Nominal Operating Cell Temperature	46.0ºC
	Panel Efficiency	19.3%
	Fill Factor	79.4%
	Unit Price	$400.078
	Life Expectancy	25 years
Turbine	Blade Diameter	80 m
	Swept Area	4,978 m^2
	Rotational Speed	1.1–19.6 min^{-1}
	Material	Glass-fiber reinforced resin
	Unit Price	$500.665

Component	Parameter	Specification/Value
Bidirectional Inverter	Rated Power (at 25.0 ºC, CosΦ=1)	18 kVA
Battery	Nominal Voltage	24 VDC
	Maximum Charging Current	240 A
	Maximum Battery Current	460 A
	Efficiency	95%
	Output Frequency	50/60 Hz ± 3 Hz
	Life Expectancy	5 years
Generator	Fuel Consumption	200 liters/hour
	Generator Size	1,000 kW
	Dimensions	40' x 8.0' x 13.5'
	Price	$10,000.000
	Life Expectancy	10 years

The table presents the technical parameters and economic details of the components used in the optimization of an off-grid PV system. It includes specifications and performance metrics for the **solar panels**, **turbines**, **bidirectional inverters**, **batteries**, and **generators**. Key attributes such as power ratings, efficiency, material properties, operational characteristics, cost, and life expectancy are highlighted for each component. This detailed information supports the system design by ensuring that each element meets the functional requirements and cost-effectiveness of the overall system.

The photovoltaic panels used in this study are 315W SPR-315E-WHT-D monocrystalline cells with a nominal operating cell temperature (NOCT) of 46.0ºC. These panels were selected for their efficiency and performance characteristics, as specified in the algorithm for determining the optimal PV system size.

Similarly, the hourly load profile plot of the case study in Figure 2.2 shows a decline in energy demand starting around 8:30 PM, which continues on a downward trend until 7:00 AM. During this period, the load remains relatively stable until 10:00 AM, when it begins to rise steadily, peaking around 12:00 PM and staying consistent for approximately two hours. The decline in energy demand during the night corresponds to the time when most people have retired to bed, with household and lighting loads significantly reduced. In the morning, as many consumers leave for work or farms, energy usage remains low as most appliances are turned off to conserve electricity and reduce costs

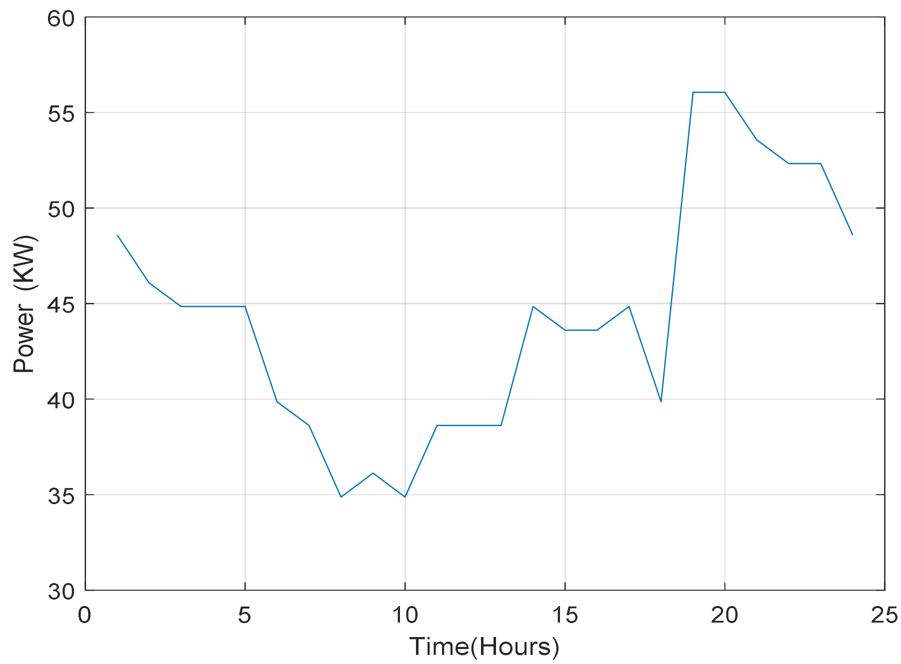

Figure 2.2 :Annual temperature location

Likewise, the annual solar irradiation data of the site for which the system is designed is shown in figure 2.3 below. The irradiance of location is at its peak during daytime and gradually decreases with time as the day goes down in the evening.

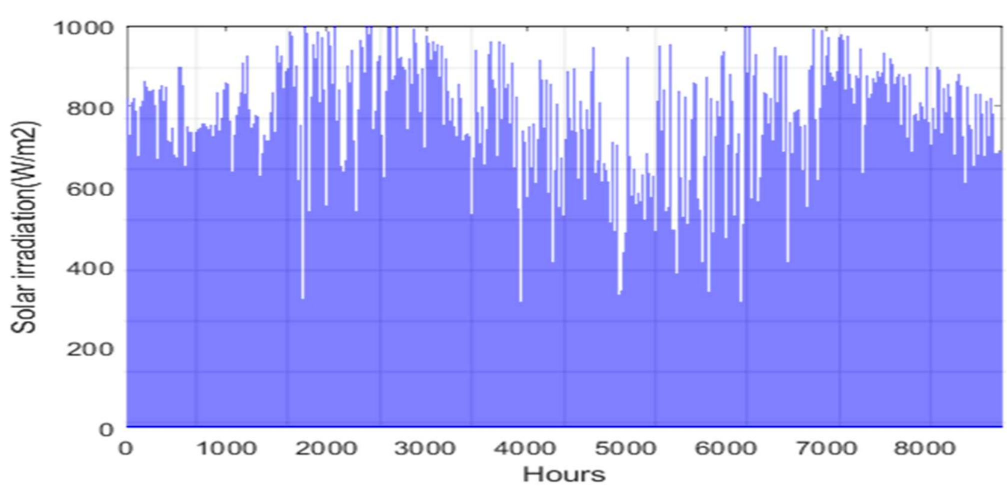

Figure 2.3: Hourly Solar irradiation of location

2.3 Results of the Optimization

The DE algorithm optimizes the size of PV and battery to reduce the overall cost of the system seeing the above two constraints and bounds. The annualized cost of the energy production of the system is chosen as an objective function. The system is analyzed on the three years' data and the results is based on the best fitness function. The results of the DE algorithm converged in less than 50 iterations. The DE optimization give optimal results of 1154 PV units of 315 W and 813 battery units each of 360Ah, so the peak power of the PV source will be 363.5KW. The result obtained for the optimum sizing of the Off-grid PV system with battery using the DE, PSO and GA is recorded in Table 2.1 The result shows significant reduction in the price of electricity using DE as compared to Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). Some savings are made in the number of PVs and batteries resulting in significant savings in the annual cost of energy as well as the Levelized cost of energy.

Table 2.2: Comparison of optimum sizing using DE, PSO and GA

Description	DE	PSO	GA
No. of PV modules	1155	1152	1160
No. of Battery units	844	824	825
Number turbines	30	27	27
Diesel generator (KWh	500	500	500
LPSP	0.015	0.012	0.017
Load served (KWh)	341.49	351.49	351.49
Annual cost of energy ($)	73403.0	73346.0	73470.0
LCOE ($/kWh)	0.3189	0.3564	0.3304

The number of hybrid system and batteries are estimated based on the modelling procedures outlined in chapter 3. The result in table 2.2 shows that the number of PVs and batteries required for DE is quite lower than that required for Genetic Algorithm and Particle Swarm Optimization. The percentage cost of energy per kilowatt is shown in figure 2.4 with uniform cost in percentage but there is some significant savings made in terms of numerical values over the life span of the system as can be seen in table 2.2.

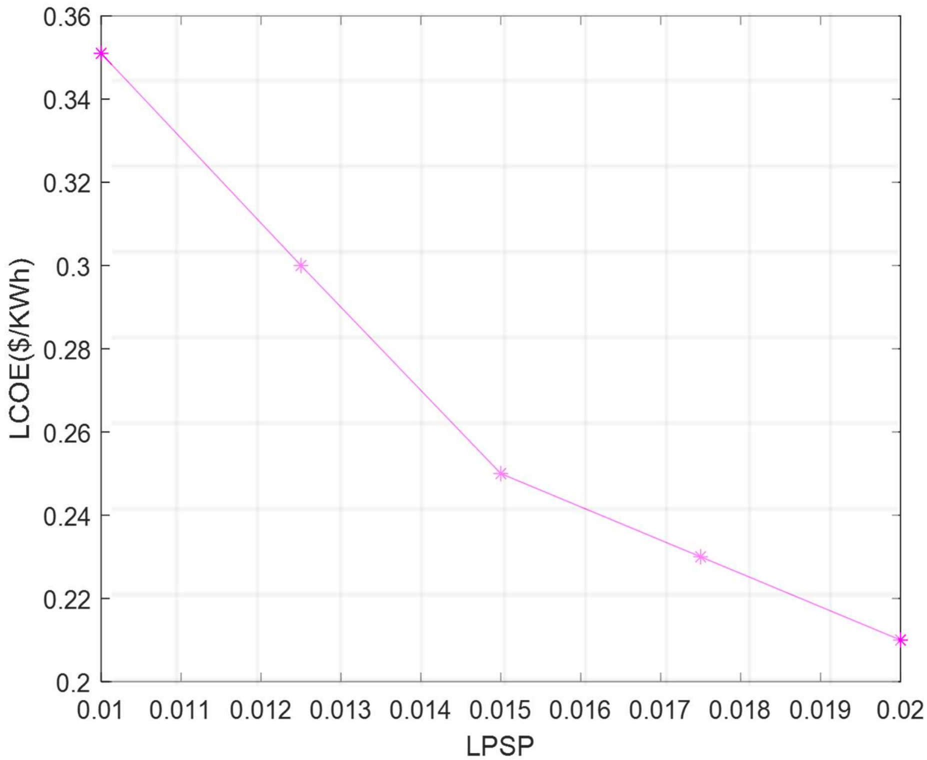

Figure 2.4: Percentage of LPSP with LCOE

Figure 2.4 illustrates the Loss of Power Supply Probability (LPSP) and Levelized Cost of Energy (LCOE). The LCOE is an evaluation metric representing the revenue required to construct and operate a power generation system over a predetermined cost recovery period. It also reflects the average income per unit of energy generated needed to cover the expenses incurred during the system's financial lifespan and debt cycle [60]. Among the optimization techniques evaluated, the PSO algorithm yielded the highest LCOE, indicating its ability to deliver optimal results. The LCOE is influenced by the efficiency of the battery bank and the converter. A decrease in converter efficiency leads to higher energy losses during conversion, necessitating a larger battery bank to compensate. This increase in battery bank size consequently raises the overall energy cost. A detailed analysis of how LCOE varies with changes in efficiency is presented later in this section. The annualized system cost is summarized in Table 4.2. Figure 4.5 highlights the rapid convergence of the DE algorithm, achieving the final solution within fewer than 50 iterations. The optimization results are based on the analysis of three years of data; however, the plotted results are displayed for a single week (168 hours) to enhance clarity and visibility. The convergence pattern demonstrates the robustness of the system under study

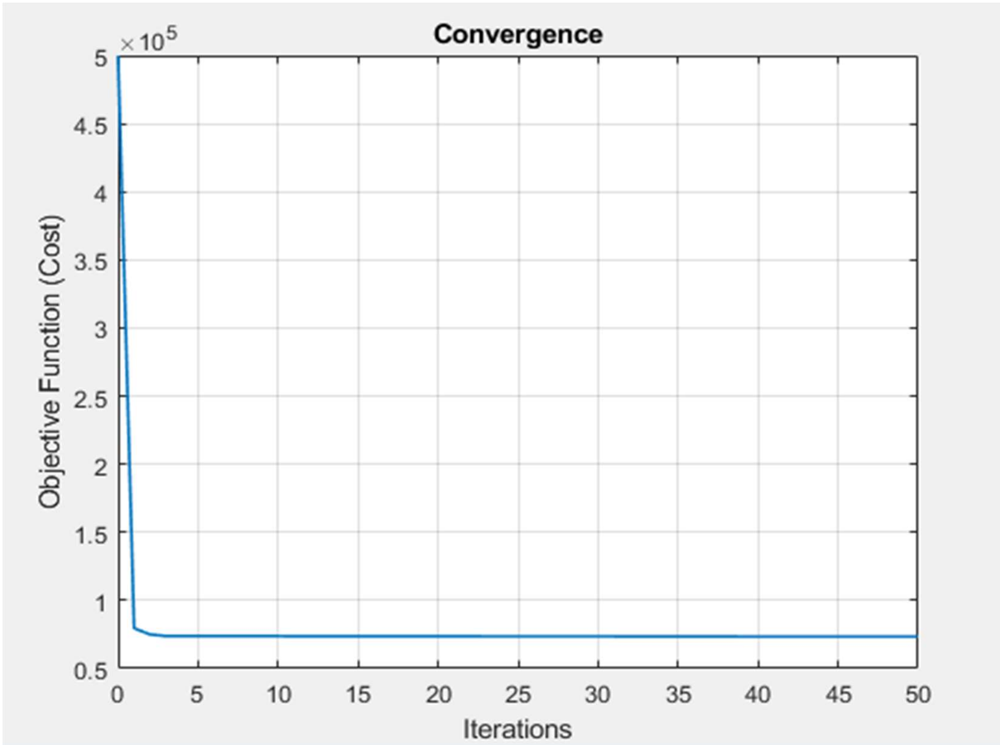

Figure 2.5 Convergence of the DE algorithm

The convergence of the system determines the robustness of the system under study. The figure 2.5 shows a convergence of GA as a means of comparison to the parent algorithm used in implementing the system under study. It could be seen that DE converges almost twice faster than GA. Through hereditary operations such crossover and mutation, GA will have the option to converge and create the fittest chromosome that have higher wellness esteem toward the finish of GA process. The he figure 2.6 shows a plot from one-week data of Load demand and generated power from the PV and battery which was analysed over 168-hour period**.** Total generated power, load profile and battery bank discharge is shown in figure 2.6. The battery discharge is labelled by 'Bout'. During the daytime solar array is meeting the load demand and charging the battery bank, while in off-day timing the load is met by the battery storage. In the analysed plot, the load curve is always below the solar curve in day timing, while in off-day timing it is below the battery discharge energy curve as the inverter is not 100% efficient. The efficiency of inverter is 90%, so load=0.9*(B_{out}).

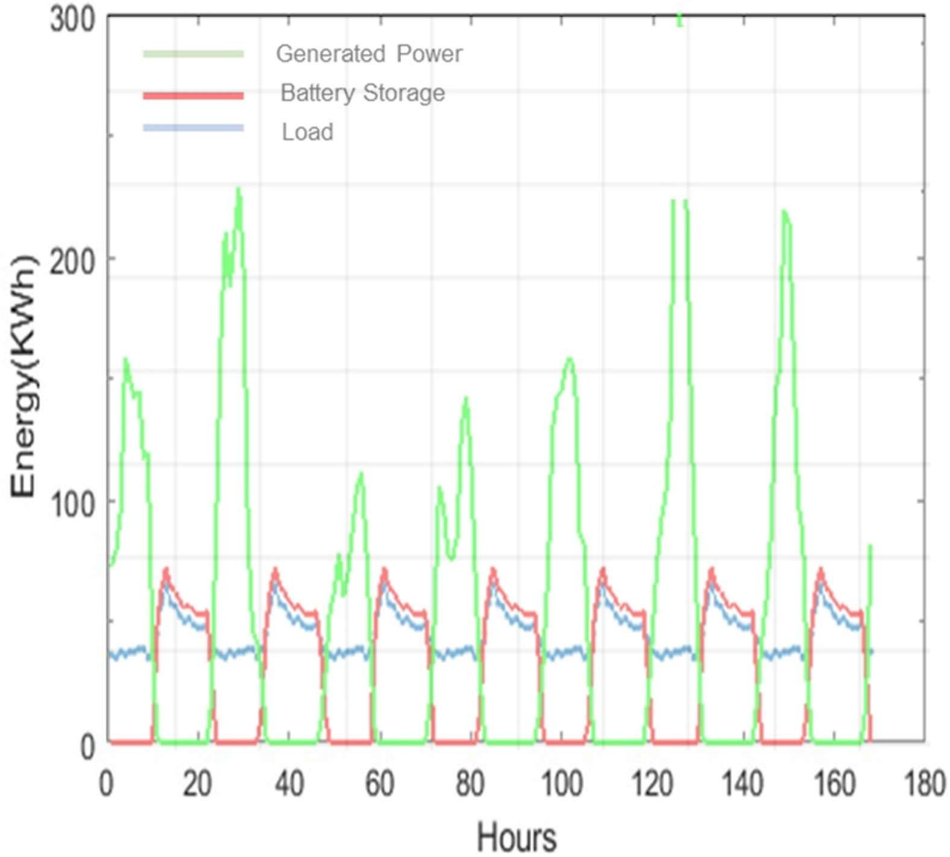

Figure 2.6: A week plot of Load profile and generated power

The charging of battery bank is shown below in figure 2.6 along with total generated power and battery discharging. In day timing when sufficient energy is available, after meeting load demand, the extra energy is used to charge the battery bank, the charging of the battery bank is visible in the plot during the solar peaks. The label 'Total generated power+ Bout' shows the combined plot of the generated power during day timing and battery discharge in off- timing.

2.4 Conclusion and Recommendations

This study, titled "Electrical Power Generation of Hybrid Power Wind Diesel Battery System for Gubio Village, Borno State", investigated the optimization of a hybrid power system using Differential Evolution (DE), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) techniques. The research focused on designing an off-grid hybrid system that integrates wind turbines, diesel generators, and battery storage to meet the energy demands of Gubio Village efficiently. The DE algorithm demonstrated superior performance by achieving optimal sizing of system components, faster convergence, and lower Levelized Cost of Energy (LCOE) compared to PSO and GA. The findings reveal that the DE algorithm effectively minimizes system costs while maintaining reliability, with results indicating significant savings in the number of PV modules and batteries required. Additionally, the hybrid system provides stable energy supply through efficient utilization of renewable and non-renewable resources, ensuring energy autonomy for three days during low-generation periods. The study underscores the importance of employing advanced optimization techniques and high-efficiency components in designing sustainable and cost-effective energy systems for remote areas like Gubio Village.

2.4.1 Recommendations

It is recommended to adopt the Differential Evolution (DE) algorithm for future hybrid power system designs, given its faster convergence and cost-saving benefits. Emphasis should be placed on investing in high-efficiency components such as wind turbines, battery banks, and converters to reduce energy losses and operational costs. To enhance energy security in Gubio Village, the system should be autonomous for at least three days to ensure uninterrupted power supply during low wind speeds or generator maintenance. Expanding the hybrid system by adding renewable energy sources like solar PV can stabilize the energy supply and reduce diesel dependency. Advanced real-time performance monitoring and predictive maintenance systems should be deployed to improve the system's reliability and efficiency. Government and community-level policies supporting renewable energy adoption, including financial incentives, are essential for hybrid energy systems in remote areas. Local capacity building, through training technicians and stakeholders in operation and maintenance, will ensure sustainability and minimize downtime. Long-term data analysis of environmental and load profiles should be utilized for optimizing the system's reliability under variable conditions. The system should be designed with scalability and adaptability in mind, allowing for future upgrades as energy demands grow. Finally, regular evaluations of the system's economic and environmental impacts will ensure it meets cost-effectiveness and sustainability goals.

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