



DESIGN OF PHOTOVOLTAIC-WIND-DIESEL-BATTERY HYBRID ENERGY SYSTEM: PERSPECTIVE OF ENERGY MANAGEMENT SYSTEM FOR STAND ALONE POWER SOLUTION

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ABSTRACT

The use of renewable energy sources has increased significantly on global note as a result of the continued depletion of fossil fuel sources, removal of subsidies on petroleum products, growing environmental concerns, government policies and breakthroughs in power electronic technology.

The global energy industry has numerous difficulties, including balancing power supply and demand in the face of steady demand growth and unstable crude oil prices. The utilization of renewable energy sources in the conventional power systems has facilitated the establishment of self-sustaining hybrid energy system (HES) that consists of photovoltaic (PV), battery storage system (BSS), diesel generator (DG) and wind turbines (WT). The HESs that integrate multiple sources have become popular for power solutions due to their cost effectiveness and reliability when compared to conventional power systems. An effective energy management system is proposed in this paper to address the uncertainty problem and ensure the best operation of HES by using genetic algorithm. The study aims to reduce the fuel cost and usage of BSS and maximize the use of WT and PV. This article compares the relevant fuel costs and assesses the performance of the HES over a 24-hour horizon by considering the daily fluctuations in energy usage on weekdays and weekends. The simulation results demonstrate that fuel cost savings of 33.81% and 33.63% are achieved in the rainy season and 35.97% and 35.55% fuel cost savings in the dry season when compared to the DG alone. The proposed model can be utilized to reduce fuel cost by taking into account changes in the patterns of power consumption during dry and rainy seasons.

1.0 Introduction

The power sector on a global scale, the power sector is experiencing numerous problems, such as balancing ever-increasing load demand, limited power generation, reliability challenges and environmental issues. The rapid rise in the world's energy consumption has been linked to various factors such as industrialization, increased regional manufacturing, economic and industrial growth in developed and developing countries, population growth, high standards of living, and the establishment of retail outlets (Adefarati et al., 2023). The degree of poverty in any community is determined by the sustainability of the electricity supplied by the utility or

independent power producers to such areas. Access to electricity plays a pivotal role in alleviating poverty, boosting economic growth and commercial activities, and raising of living standards (Adefarati *et al.*, 2020). Currently, about 733 million people on a global scale lack access to electrical power supply owing to erratic power supplies, inconsistent government policies, aging generation, transmission and distribution infrastructures, limited access to the grid and incompetent work force of the utilities (World Bank, 2022 and Oluwatoyin *et al.*, 2015). According to the Energy Progress Report 2022 published by Tracking SDG 7, Nigeria is among the nations with the least amount of access to electricity globally, with approximately 92 million of the 220 million people living in the country lack access to electricity (Tracking SDG 7, 2022). The World Bank record shows that Nigeria's power outages cost the country over \$29 billion. This amount is equivalent to 2% of Nigeria's gross domestic product. The bank report also indicates that over 40% of Nigerians do not have to access to the utility power supply, and those who do have regular outages. The nation's industrial development, business enterprises' growth and profitability and the welfare of its citizens have all been hindered by the ongoing power crisis (World Bank, 2020). The epileptic electricity supply to the load points has hindered over 100 million people that should have been raised out of poverty with boom economic activities that associated with uninterrupted power supply.

The present installed capacity of the power stations in Nigeria does not match the country's population's energy demand because of inadequate policies and infrastructure (Oyedepo, 2012). The Nigerian government needs to invest \$10 billion per year for the next 20 years to achieve a continuous power supply for optimal industrial applications and human growth capacity. The amount of energy produced by Nigeria's electricity industry is far less than what is required to meet the country's industrial and domestic demands (Elinwa *et al.*, 2021). The industry worked so hard in 2012 to generate 5,000 MW, a significant amount that is less than the 40,000 MW required to meet the population's power demands. This shortfall ultimately led to unplanned load shedding and partial and complete system collapse. It has been projected that Nigeria needs nothing less than 40,000 MW to reach sufficiency by 2030 (Okoh *et al.*, 2023). The average electricity per capita in Nigeria is 14 W; this shows that Nigerians have been seriously depressed by the nature of power supply when compared to other countries (Wikipedia, 2023). The epileptic power supply in the country has compelled the industrial and commercial sectors to end up turning what should be a backup power source into a primary source without considering the costs involved. As a result, industries and retail outlets pass on the operation and maintenance costs of their generators to the general public through higher prices for goods and services. The current status of the country's transmission infrastructure is not reliable and weak, and has a limited coverage area. The TCN transmission network is made up of nearly 20,000km of transmission lines and a wheeling capacity of 7,500 MW (NERC, 2023). The total installed generation capacity of 12,522 MW is far greater than the existing transmission wheeling capacity of 5,300 MW, but it is more than the average power station generating capacity of 3,879 MW. There are inherent dependability problems because the entire system is essentially radial and lacks redundancy. The power loss across the transmission system is estimated to be about 7.4%; this value is substantial when compared to the benchmarks of emerging countries that fall within the range of 2 and 5%. The number of system collapses has decreased in recent years from 42 in 2010 to 25 in 2022. All of these highlight the vital infrastructure and practical problems facing the transmission subsector of Nigeria's power system (NERC, 2023).

Nigeria is not an exception to the worldwide trend that has seen the rise of solar and wind energy as a potential and sustainable substitute for traditional energy sources. The country has several energy-related issues, such as an excessive dependence on fossil fuels and restricted access to power (Adeyanju et al., 2020). With rising legislative efforts, technological improvements, and investment, renewable energy resources have a bright future in Nigeria. The domestic and foreign investment in solar and wind energy projects has increased in recent times owing to the government's initiatives to encourage investments in renewable energy, enactment of supportive laws and the creation of incentives. The federal government agency has developed policies that encourage the incorporation of solar power into the national grid through the Electricity Act of 2023 and the Renewable Energy Master Plan of 2005 (PSC Solar, 2023). One of the main issues in Nigeria's rural areas is the lack of access to electricity, which can be fixed by using renewable energy sources (RESs). Rural electrification projects with embedded solar and wind technologies can be utilized to expand access to electricity in remote areas and improve the well-being of the rural residents. The technological development coupled with reduction of the costs of HES components is responsible for making clean and sustainable energy more accessible and affordable. The aforementioned factors played an essential role in improving the efficiency of the power system. The application of RESs for power solutions reduces overdependence on fossil fuels, reduces the duration of power interruptions, stimulates economic growth, drives job creation, contributes to a cleaner and greener environment, stimulates socio-economic growth, reduces electricity bills, provides potential income for sales of excess power generated, and supports economic empowerment programs. Nigeria is endowed with an average daily solar radiation of 4.8 kWh/m to 5.4 kWh/m² and a landmass that covers 923,768 km² that can produce more than 1000 GW from solar resources (PSC Solar, 2023). The annual energy generated by the PV system is about 27 times that of the nation's total conventional energy resources (Energylopedia, 2022). The average wind speed of Nigeria on annual basis is estimated to be between 2 m/s and 9.5 m/s, while the annual power density varies between 3.40 kW/m² and 520 kW/m² (Adaramola et al., 2011). Southern Nigeria often has slower wind speeds, while wind speeds in the northern portion of the country are consistently higher. If the solar and wind potentials are fully harnessed, this would considerably contribute to satisfying the energy needs of the country and reducing power outages and their associated economic impacts.

The design of innovative power solutions to meet continuous power demand and enhance access to energy has been the subject of various studies in the literature. These studies produced a blueprint for the electrification projects that can be carried out to increase residential and industrial access to electricity, typically with a focus on boosting the use of RESs and minimizing the operation and maintenance costs of HES. The operational efficiency of HES and several optimization techniques are the focus of a large number of current studies. Khalilnejad et al. (2018) proposed the imperialist competitive algorithm for the optimization of PV/WT/electrolyzer HES and the production of hydrogen using real atmospheric data from Miami. Zhang et al. (2019) employed the hybrid optimization algorithm to determine the best configuration for a PV/WT/Hydrogen energy system by utilizing weather-predicting information. The benefits of the suggested algorithm with meteorological forecasts for a system that is not dependent on a grid are discovered. Zhang et al. (2021) applied a global dynamic harmony search algorithm to a standalone WT/PV/FC/hydrogen storage system to reduce the cost of the system. Meanwhile, Xu et al. (2021) carried out a technical and financial evaluation of PV/FC off-grid power system that is intended to provide electricity to a rural

community in China by using the amended water strider algorithm. Misra *et al.* (2017) emphasized the use of RESs in a microgrid system. According to the study, using renewable energy sources can cut operational costs, minimize greenhouse gas emissions and increase the flexibility of power supplies. Nazari-Heris *et al.* (2017) studied the short-term scheduling of a grid-connected microgrid system that comprises fuel cell, battery system, boiler and heat buffer tank for industrial heat and power solutions. In another study, Ahamad *et al.* (2018) looked into the best energy planning design and assessed the performance of the microgrid by taking into account a PV/WT/BSS grid-connected hybrid energy system designed for coastal ports. The outcomes of the study show that the microgrid system is a practical way to supply electrical power to the numerous customers. Mutarraf *et al.* (2020) looked into the usage of battery system and RESs in a microgrid system to supply the electrical power required for the operation of coastal ports. The system's ability to lower air pollutants and noise pollution is highlighted in the study. Chamandoust *et al.* (2019) employed demand-side management methods in their decision-making process for the islanded HES to meet power demand and improve the economic and technical assessment of the system. Nasser *et al.* (2022) carried out the technical and financial evaluation of the HES that comprises WT and PV for hydrogen generation under various climate conditions in five Egyptian scenarios.

Diverse renewable energy sources were utilized to optimize HES, according to the previously stated literature. However, there are not much research outputs on the optimal operation of HES considering the effects of load variation and seasonal changes on the performance of the system. Moreover, few studies have looked at the implementation of HES in the rural area facilities, despite the growing body of studies on these systems in Nigeria's rural areas. The majority of the research concentrated on a single objective function by using a simple optimization technique to carry out their simulation based on the energy management among the components of the system. Despite the many benefits of RESs, several studies failed to incorporate multi-resources into their systems, a vital component of energy management system that is significant in reducing the fuel cost of the HES. The aforementioned literature also failed to analyze the effects of maximizing renewable energy and minimizing the usage of DG and BS on the fuel costs without considering seasonal variation of load demand as well as solar and wind resources. The previous studies failed to account for the performance of microgrid systems or hybrid energy systems under unpredictable weather and unstable load demand, which limits their application to certain sectors of the economy. Moreover, some studies have not taken into account the viability of a remote or grid-connected microgrid system that includes a variety of energy resources and storage devices. In view of this, the abovementioned research gaps will be explored in this study by using a multi-objective metaheuristic algorithm. The current work uses an optimization technique termed the genetic algorithm to minimize the fuel cost and the power delivered by battery system and maximize the use of PV and WT while taking the proper power limits of the components and power demand constraints into account. As a result, a PV/BS/WT/DG hybrid energy system is designed taking into account the seasonal variations of some parameters, including wind speed, temperature, solar radiation and load demand. The ability and effectiveness of the suggested algorithm are demonstrated by comparing and evaluating its performance against fuel cost variations in rainy and dry seasons on weekdays and weekend. The outcomes of the research can be utilized by the government agencies to reduce over 746 million people who do not have access to electricity on a global scale. This will eventually alleviate the power crisis that many

nations are experiencing at the moment. The objectives of this paper are succinctly presented as follows:

- i. To design of a PV/BS/WT/DG hybrid energy system for a rural settlement that is located in North West of Nigeria.
- ii. To develop a model that can be used to minimize the operations of the DG and BSS and maximize the usage of PV and WT in the proposed hybrid energy system.
- iii. To improve the effectiveness of the energy management system and maximize the fuel cost savings of the proposed hybrid energy system by using a genetic algorithm.
- iv. To develop a model for assessment of the performance of the hybrid energy system based on the seasonal variations of wind speed and solar radiation and changes in load demand.
- v. To carry out performance analysis of the proposed HES by using solar radiation, wind speed and ambient temperature data obtained from NASA.
- vi. To control the energy flow among different components of a hybrid energy system.

I. Materials and Methods

I.1. Modelling of an Autonomous Photovoltaic/Wind/Battery System/Diesel Generator Hybrid Energy System

The HES is a combination of different generation technologies such as DG, BSS, WT, PV and load demand by sharing the same point of common coupling (Ashok, 2007). The combination of conventional and RESs in a single system can be used to increase the total benefits compared to a system that relies on a single source such as microturbine, diesel generator and gas generator. The application of renewable generation technologies with backing units such as DG, BSS and FC can be used to increase the usage of RESs and reduce overall costs, environmental impacts, and system disruptions (Bawonda et al., 2023). The dangers that are related to the vulnerability of the local RESs can be minimized with the deployment of the BSS in a microgrid system (Varaiya et al., 2011). To achieve a reliable electrical power supply at a reduced fuel cost, all the accessible RESs must be used for power generation solutions (Kumar et al., 2014). The financial advantages obtained from utilizing the HES have encouraged the development of numerous models for the utilization of WT and PV (Onalapo et al., 2023). The sum of power supplied by all the components of the proposed HES as shown in Figure 1 can satisfy the load demand.

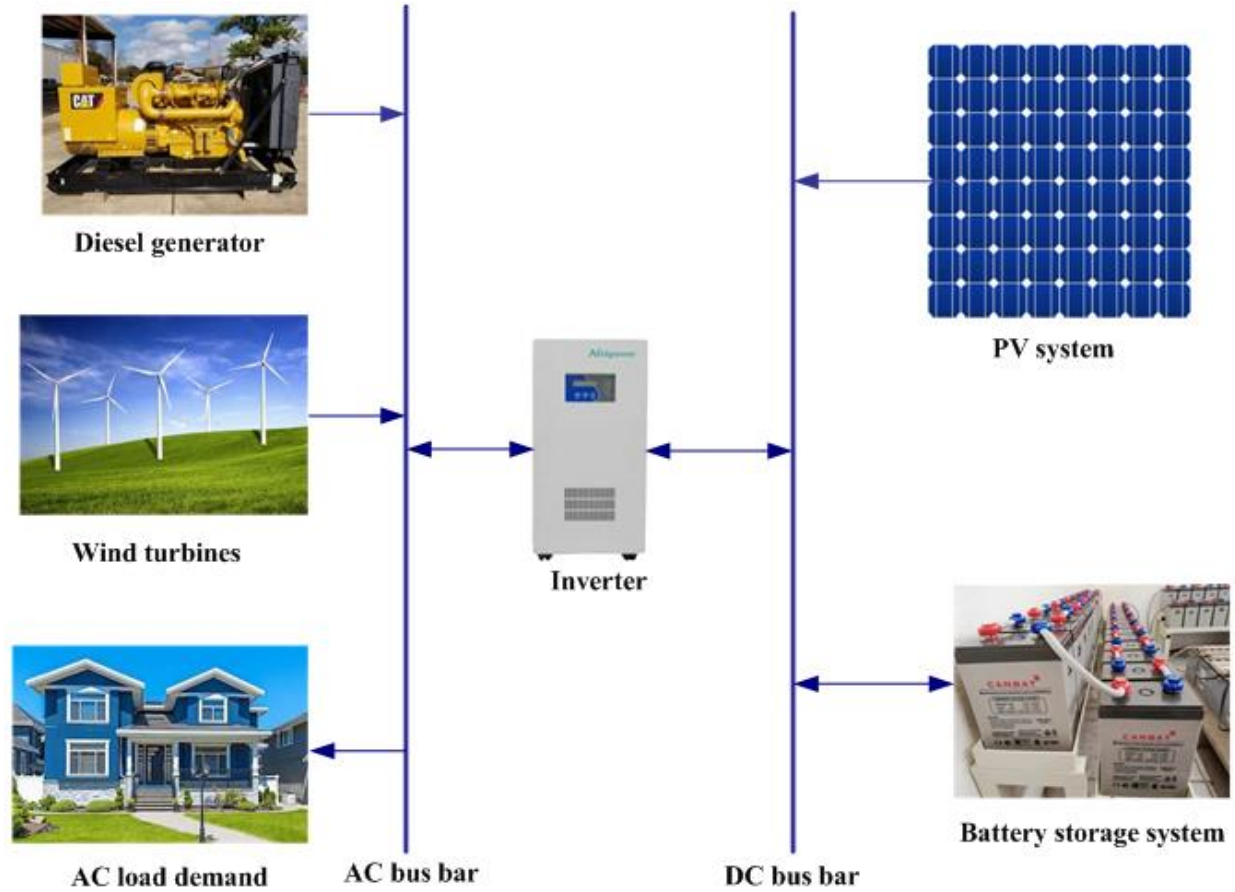


Figure 1: PV/WT/BSS/DG Hybrid energy system.

1.1.1. Photovoltaic System

A photovoltaic system is a device that converts sunlight directly into electricity using semiconducting materials such as silicon and gallium nitride that absorb energy from sunlight. The hourly power produced by the PV system can be calculated by using Eqn. (1) (Blaabjerg et al., 2015).

$$P_{pv} = I_{pv} \times A_{pv} \times \eta_{pv} \quad (1)$$

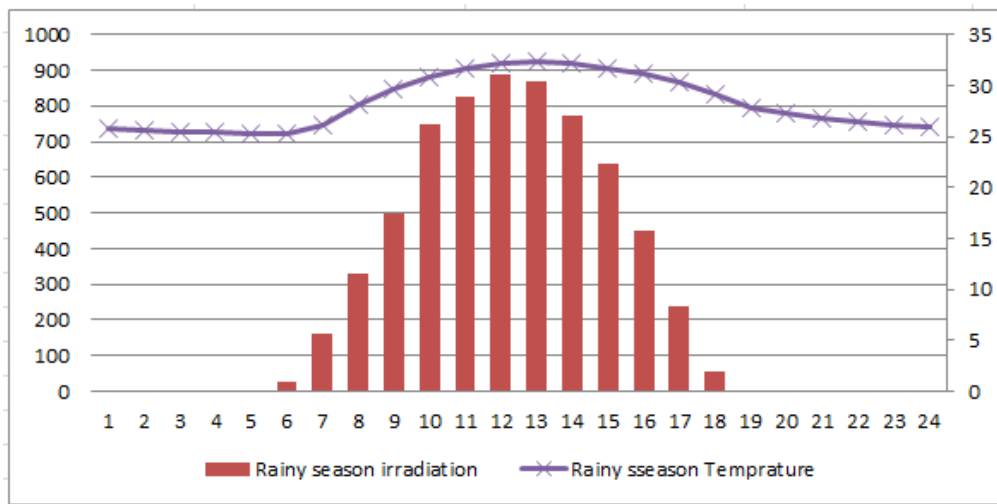
where I_{pv} is the solar irradiation (kWh/m^2), A_{pv} is the area of the PV panel (m^2) and η_{pv} is the efficiency of the PV system (%).

The efficiency of the PV system can be expressed in Eqn. (2) (Tazvinga et al., 2015):

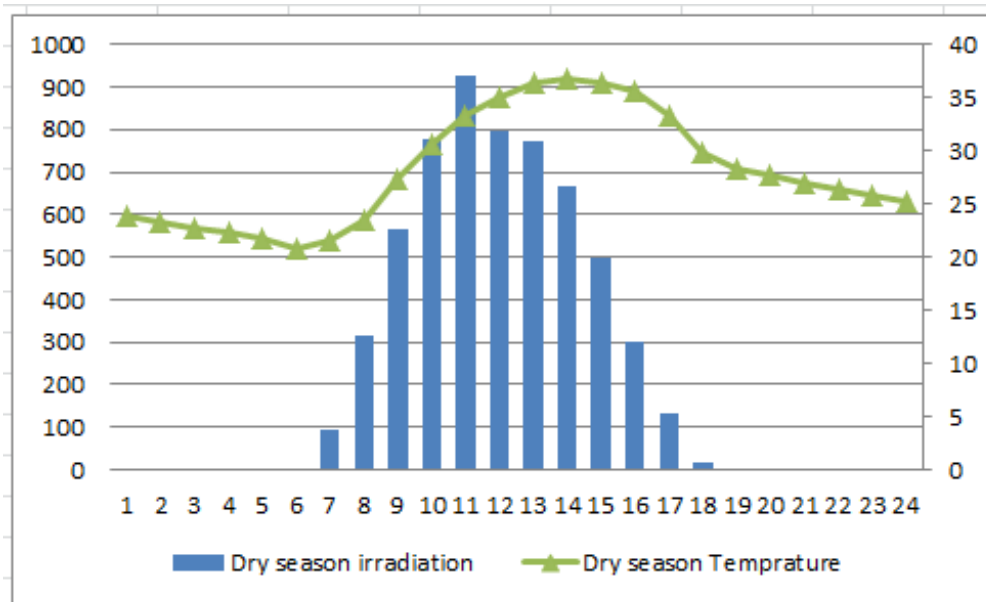
$$\eta_{pv} = \eta_r \left\{ 1 - 0.9\alpha \left(\frac{I_{pv}}{I_{pv,nt}} \right) (T_{c,nt} - T_{a,nt}) - \alpha(T_a - T_r) \right\} \quad (2)$$

where η_r is the efficiency of the PV system measured at reference cell temperature, α is the temperature coefficient of the PV cell, NT is the nominal cell operating temperature conditions, $I_{pv,nt}$ is the hourly solar irradiation on the PV panel at NT test conditions, T_r is cell temperature at reference point ($^{\circ}\text{C}$), $T_{c,nt}$ is the cell temperature at NT test conditions, $T_{a,nt}$ is the ambient temperature at NT test conditions and T_a is the ambient temperature ($^{\circ}\text{C}$).

The solar irradiation and temperature of the selected based on seasonal variation are presented in Figure 2.



(a)



(b)

Figure 2: Solar irradiation and temperature of the selected based on seasonal variation: (a) rainy season; (b) dry season (NASA, 2024).

1.1.2. Wind Turbine

The WT is a machine that uses the aerodynamic force of its rotor blades to transform wind energy into electrical energy, thereby harnessing the energy produced by wind speed. The air density, rotor diameter, pattern of wind speed at a particular location, efficiency of energy conversion, design characteristics of the WT and height of the tower affect the output power of the WT. The power output of the WT can be presented in Eqn. (3) as (Ashok, 2007):

$$P_{wt} = \frac{1}{2} \times \eta_{wt} \times C_p \times \eta_g \times \eta_b \times \rho \times A \times V^3 \tag{3}$$

where ρ is the density of the air (kg/m^3), A is the cross-sectional area of the wind turbine (m^2), v is the velocity of the wind (m/s), C_p is the performance coefficient, η_g is the generator efficiency and η_b is the gearbox.

The wind speed at a desired speed can be calculated by using Eqn. (4).

$$v_{hub} = v_{ref} \left(\frac{H_{hub}}{H_{ref}} \right)^\gamma \quad (4)$$

where v_{ref} is the wind speed at reference height is, H_{hub} is the hub height, H_{ref} is the reference height and γ is the power law exponent.

The wind speed of Sokoto that is corresponding to each season is presented in Figure 3.

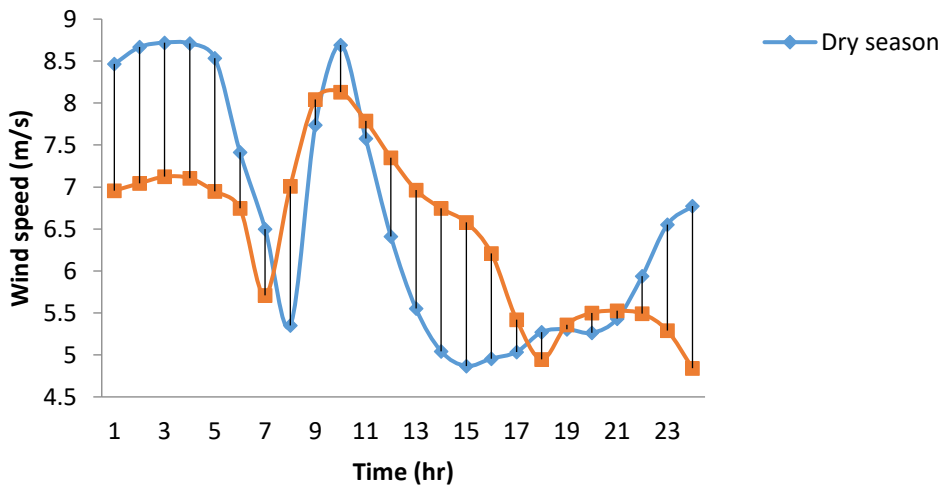


Figure 3: Wind speed of the selected area based on seasonal variation (NASA, 2024).

1.1.3. Diesel Generator

A diesel generator consists of an internal combustion engine, alternator and other electrical components to produce electrical energy. The DG can be used as a standby unit for an emergency operation to improve the availability of power supplies. The response time of the DG is satisfactory; it can start and supply the load in less than ten seconds (Sechilariu *et al.*, 2016). The fuel consumption of DG is assessed using Eqn. (5) (Adefarati *et al.*, 2021).

$$FC_{DG} = C_f (aP_{DG}^2 + bP_{DG} + c) \quad (5)$$

where P_{DG} is the hourly power output of the DG (kW), C_f is the cost of diesel per litre (₦/litre), and a , b and c are coefficients of fuel consumed by the DG

1.1.4. Battery storage system

The BSS is a technology that allows energy obtained from renewable energy sources to be stored and released to consumers when it is needed. The battery storage system plays a significant role between renewable energy supplies and corresponding energy demands at the load points. The battery storage systems encourage the adoption of

RESs, which lower greenhouse gas emissions and deliver electricity at a reduced cost of energy (Adefarati et al., 2017). The battery storage system mitigates the intermittent characteristics of renewable sources and ensures a consistent supply of electricity. The battery system is used for several applications. The battery system dynamic is expressed in Eqn. (6).

$$SOC(i) = SOC(O) + \Delta t \frac{\eta_c}{E_{nom}} \sum_{i=1}^n (P_4(i)) - \Delta t \frac{1}{\eta_d \times E_{nom}} \sum_{i=1}^n P_5(i) \quad (6)$$

where SOC is the state of charge of the BSS, η_c is the charge efficiency of the BSS, η_d is the discharge efficiency of the BSS, P_4 is the power entering the BSS, P_5 is the power leaving the BSS at sampling interval Δt , Δt is the sampling time interval and E_{nom} is the nominal energy of the BSS.

The BSS must operate based on the allowable minimum and maximum SOC (Seeling-Hochmuth, 1997) as presented in Eqns. (7-9).

$$SOC^{min}(i) \leq SOC(i) \leq SOC^{max}(i) \quad (7)$$

$$SOC^{min}(i) \leq \Delta t \frac{\eta_c}{E_{nom}} \sum_{i=1}^n (P_4(i)) - \Delta t \frac{1}{\eta_d \times E_{nom}} \sum_{i=1}^n P_5(i) \leq SOC^{max}(i) \quad (8)$$

where SOC^{min} and SOC^{max} are the minimum and maximum SOC of the BSS.

where $\mu_c = \Delta t \frac{\eta_c}{E_{nom}}$ and $\mu_d = \Delta t \frac{1}{\eta_d \times E_{nom}}$

Therefore,

$$SOC^{min}(i) \leq \mu_c \sum_{i=1}^n (P_4(i)) - \mu_d \sum_{i=1}^n P_5(i) \leq SOC^{max}(i) \quad (9)$$

1.2. Study Area

The study area is located at latitude of 12° 55' 21.34" N and longitude of 05° 28' 03.31" E in the North-West of Nigeria, as shown in Figure 4. The city is located near the confluence of the Rima River and the Sokoto River, with a population of over 709,000 and a landmass of about 25,972 km². Sokoto is one of the hottest places in Nigeria due to its vegetation, which lies between the Sudan and Sahel savannas. The city has an average annual temperature of 28.3 °C, a maximum daily temperature of less than 40 °C, an average relative humidity of 34.38 mm and an average relative humidity of 30.5%. The floodplains of the Rima and Sokoto Rivers, which are covered with rich alluvial soil, are used for irrigation systems and the cultivation of different types of crops such as maize, guinea corn, beans, millet, rice, onions, tomatoes, cabbage and lettuce. Despite being the nation's economic center and home to a wealth of energy resources, such as biomass, solar and wind, it suffers from epileptic power supply. The city currently relies heavily on the national grid and diesel generator sources, both of which have not been able to keep up with the city's energy needs. Many small-scale enterprises in Sokoto have closed down due to the high rate of power interruptions, and the few that are still open charge exorbitant fees for their services. This leads to a growing interest in the development of models and potential solutions to satisfy the electricity needs of the selected location.



Figure 4: Geographical location of the study area.

1.3. Formulation of Problem

The mathematical formulation of the problem is based on a model that can be utilized to optimize the operation of the proposed HES by considering the seasonal variation of the location. The optimization problem is formulated by using GA presented in Eqns. (10-11).

$$\min_x f(x) \tag{10}$$

subject to:

$$\begin{cases} Ax \leq b, \\ A_{eq} = b_{eq}, \\ C(x) \leq 0, \\ C_{eq}(x) \leq 0, \\ C_{eq}(x) = 0 \text{ and} \\ L_b \leq x \leq U_b \end{cases} \tag{11}$$

where A is the matrix for linear inequality constraints, b is vector for linear inequality constraints, A_{eq} is the matrix for linear equality constraints, b_{eq} is the vector for linear equality constraints, L_b is the lower bound on x and U_b is the upper bound on x .

1.3.1. Objective Function

The objective function of the formulated problem is focused on the optimal scheduling of generation at any time of the day, reduction of the fuel consumption cost and the power delivered by the battery system and maximization of the usage of PV and WT systems while meeting the load demand and other operating constraints of the power system. The objective functions are selected to optimize the system and ensure optimal operation of the HES at the lowest fuel cost. The optimal control technique that is utilized in this research coordinates the power flow among the components of the proposed HES based on the 24-hour horizon. The optimization of this dispatch problem can be carried out by taking into consideration a multi-objective function presented in Eqn. (12):

$$f = \min \sum_{k=1}^n (C_f (aP_1^2(k) + bP_1(k) + c) + P_5(k) - P_2(k) - P_3(k)) \quad (12)$$

The objective function is subject to the following constraints (Eqns. 13-17):

$$P_1(k) + P_2(k) + P_3(k) + P_5(k) = P_L(k) \quad (13)$$

$$P_2(k) + P_3(k) + P_4(k) \leq P_{pv}(k) + P_{wt}(k) \quad (14)$$

$$P_i(k) \geq 0, i = 1, 2, 3, 4, 5 \quad (15)$$

$$P_i^{\min} \leq P_i(k) \leq P_i^{\max}, i = 1, 2, 3, 4, 5 \quad (16)$$

$$SOC^{\min}(k) \leq \mu_c \sum_{k=1}^n (P_4(k)) - \mu_d \sum_{k=1}^n P_5(k) \leq SOC^{\max}(k) \quad (17)$$

1.4. Technical Parameters of the Proposed Hybrid Energy System

The method proposed in the study is used to carry out the assessment of the HES and to obtain the potential solution based on the best combination of the DG, PV, WT and BSS. The technical specifications of the components provided by the manufacturers are used to simulate the proposed HES. The technical details of the components of the HES as presented in Table 1 are used to evaluate the fuel cost of the HES based on the seasonal variation of the selected site. The performance of the HES is assessed by taking into consideration the load profile of the selected location in Sokoto, Nigeria.

Table 1: Technical specifications of all components of hybrid energy system (Generator set data sheet, 2022), (Able, 2022), (Amazon, 2022), (Power tech, 2020), (Powersync, 2018) and (Check Petrol Price, 2023).

Description	Technical specifications
Diesel generator	Capacity = 16 kW, Cummins, Model= C22 D5 (x-Series), a = 0.0031, b = 0.1775 and c = 1.55, Capacity = 12 kW, ABLE, a = 0.0028, b = 0.235 and c = 0.375 and Diesel fuel price = ₦1200/litre
PV system	Nominal power = 500W, Installed capacity = 8 kW, Open circuit voltage = 53.94 V, Short circuit current = 9.27 A, Module efficiency = 19.12%, maximum power point voltage = 35.9V, maximum power point current = 8.36A, dimension of the PV panel = 1996mm × 1310mm × 40mm, nominal cell operating temperature = 45°C ± 3%, current temperature coefficient = 0.032%/°C, voltage temperature coefficient = -0.308%/°C, power temperature coefficient = -0.42%/°C and operating module temperature = -40°C to 90°C.
Wind turbines	Nominal power = 500W, Installed capacity = 6KW, v_{ci} = 2 m/s, v_r = 10 m/s, v_{co} = 55 m/s, diameter = 1.35 m, wind energy utilize ratio = 0.48 and generator efficiency = 0.78.
Battery system	Nominal rating 250 Ah @ 12 V, Installed capacity = 3 kW, Stored energy = 3 kWh, Energy density = 125.41 Wh / L, Maximum continuous charge current = 150A, Continuous discharge current = 180A, Peak discharge current (< 30s) = 250A and Instant peak discharge current = 700A ± 50A.
Converter	Installed Capacity = 15 kW and Efficiency: 0.96

2. Results and Discussion

The results of the research are determined based on the daily load demand of a typical customer in Sokoto, Nigeria, as well as the seasonal variations of wind and solar resources in the study area. It is evident from the load profile that the seasonal variations in consumer daily activities correspond to the dry and rainy seasons. The highest peak load obtained from the study is 14 kW, which is recorded in rainy and dry seasons. The outcomes of the simulation are presented as follows:

2.1. The Pattern of Load Demand in the Rainy Season Weekday

The power demand during the 24-hour horizon of rainy season weekdays is presented in Figure 5a by using only the DG that has a weekday capacity of 16 kW. The highest peak load and least load demand recorded on weekdays of the rainy season are 14 kW and 7.84 kW, as shown in Figure 5a. It is obvious from the results presented in Figure 5b that DG produced all the power requirements at the load points with daily fuel consumption of ₦114810 and 95.68 L of diesel fuel.

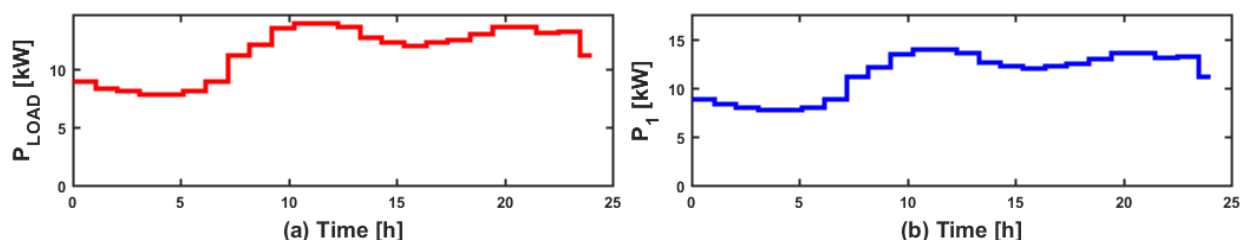


Figure 5: Weekday power flow by using DG alone during the rainy season: (a) Power demand; (b) Power output of the DG.

The application of only PV and WT in the HES will not offer a reliable electrical power supply due to seasonal changes and non-linear variation of wind and solar resources. For this reason, a reliable electricity supply can be achieved in a standalone HES with the deployment of multiple power sources such as DG (12 kW), PV (8 kW), WT (6 kW) and BSS (3 kW). This has ultimately enhanced the general performance of the HES. The power flow of all the components of the proposed HES is shown in Figure 6 (b-f). The nonlinear nature of power demand is established in Figure 6a where the load demand is lowest between 0 and 6 hours in the morning and has peak periods around 12 and 15 hours of the day. The inclusion of the RESs in the proposed HES has reduced the fuel cost, which has the highest proportion of the operation and maintenance costs of the DG. The corresponding fuel cost recorded with the application of HES is ₦75998. Due to the load management facility, the capacity of the DG has been reduced from 16 kW to 12 kW to fulfil the load requirement within the 24-hour horizon. This indicates that the DG is running at 44.5% of the rated capacity during this particular period. The seasonal variations in wind speed, solar radiation, temperature and load profiles affect the operation of the DG. This demonstrates that the corresponding power-generating capacity of the DG has decreased with the usage of PV and WT as shown in Figure 6b. The corresponding fuel cost recorded with the application of HES is ₦75998. This has resulted in a 33.81% reduction in the fuel cost of HES during the rainy season on weekdays, when compared to a scenario where diesel is utilized exclusively. The results show that ₦38812 cost savings that translate to 33.81% are achieved within a 24-hour horizon with the use of PV, BSS and WT as presented in Table 2.

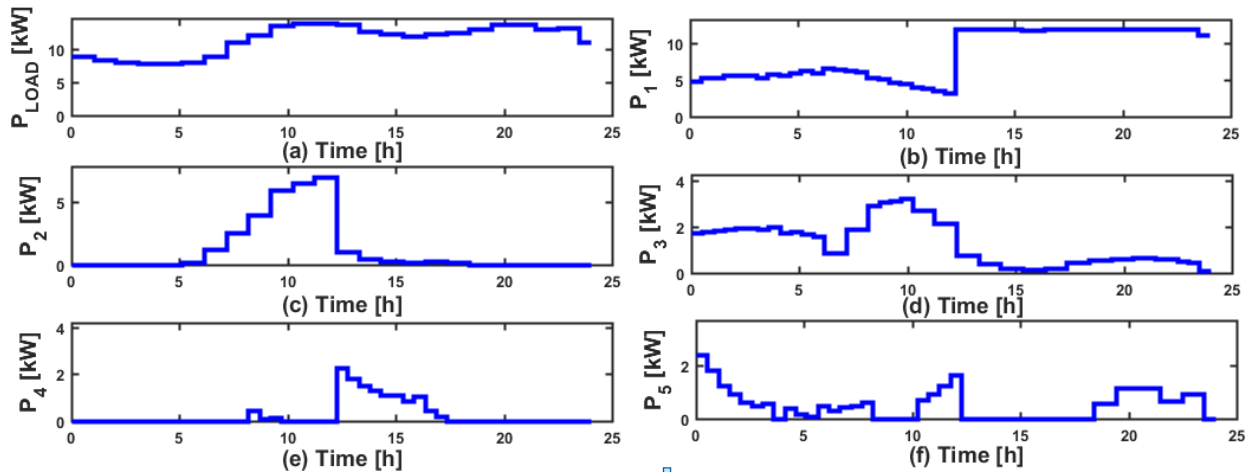


Figure 6: Weekday power flow by using HES during the rainy season: (a) Power demand; (b) Power output of the DG; (c) Power output of the PV system; (d) Power output of the WT; (e) Power charging the BSS and (f) Power leaving the BSS.

Table 2: Fuel cost savings with renewable energy resources.

Description	Rainy season		Dry season	
	Weekday	Weekend	Weekday	Weekend
Fuel cost with DG only (₦)	114810	114840	115220	115420
Fuel cost with hybrid energy system (₦)	75998	76217	73775	74391
Fuel cost savings (₦)	38812	38623	41445	41029
Fuel cost savings (%)	33.81	33.63	35.97	35.55

2.2. The Pattern of Load Demand in the Rainy Season Weekend

The power demand and power output of using the DG alone on a rainy-season weekend are presented in Figure 7 (a–b). It can be seen from findings shown in Figure 7b that the DG with a rated capacity of 16 kW has been overstressed, being the only source to meet the power demand with a daily fuel consumption of ₦114840 and 95.7L of diesel fuel. The operational efficiency of the conventional power system can be enhanced with the introduction of a strategically controlled power system that combines WT, PV, BSS and DG while reducing the need for the DG to operate and optimizing the use of wind and solar resources.

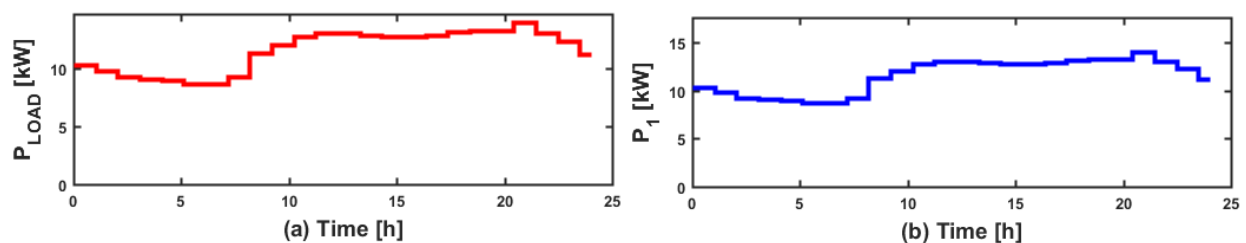


Figure 7: Weekend power flow by using DG alone during the rainy season: (a) Power demand; (b) Power output of the DG.

The generation capacity of the DG used in the HES has been reduced to 12 kW when compared with the DG alone. The power flow of all the components of the HES is shown in Figure 7(b-f) based on the seasonal variation and pattern of load demand profile during the rainy season weekend. The load demand pattern during the off-peak period between 0 and 6

and 22 and 24 hours is mostly fulfilled using the combined outputs of the DG, WT and BSS as indicated in Figure 7(b-d) since there is no power output from the PV at this particular period. This demonstrates that the DG and WT will run for many hours since the output of the PV is low between 0 and 6 and 22 and 24 hours of the day. The load demand between 10 and 15 hours of the day, as shown in Figure 7b, demonstrates that the power produced by the DG has reduced substantially owing to the contribution of the PV system and WT to the proposed HES. Thereafter, the power output of the DG increases since the PV does not supply the load during this period because of the non-availability of solar resources between 20 and 24 hours of the day. With the hybridization of some components such as DG, BSS, PV and PV, the fuel consumption of the DG is estimated to be ₦ 76217. The money expended on diesel fuel per day throughout the rainy season weekend is 33.63% less when compared to the diesel-only. Therefore, by implementing PV, WT, and BSS in the base system, ₦38623 in cost savings, or 33.63%, are realized within a 24-hour period. In addition to this, there is a substantial discrepancy in fuel consumption on weekdays and weekend. The consumer load pattern seen in Figures 6 and 8 is responsible for this. There is a noticeable increase in load demand because most people are at home on the weekends, utilizing various electronic devices. Moreover, many social activities are done at the weekends. The results presented in Table 2 demonstrate that the fuel cost on the rainy season weekend is ₦ 41029 higher than the fuel cost on the rainy season weekend, due to the seasonal variation of wind speed, solar radiation and temperature. Hence, more fuel is utilized on the weekend than on a weekday.

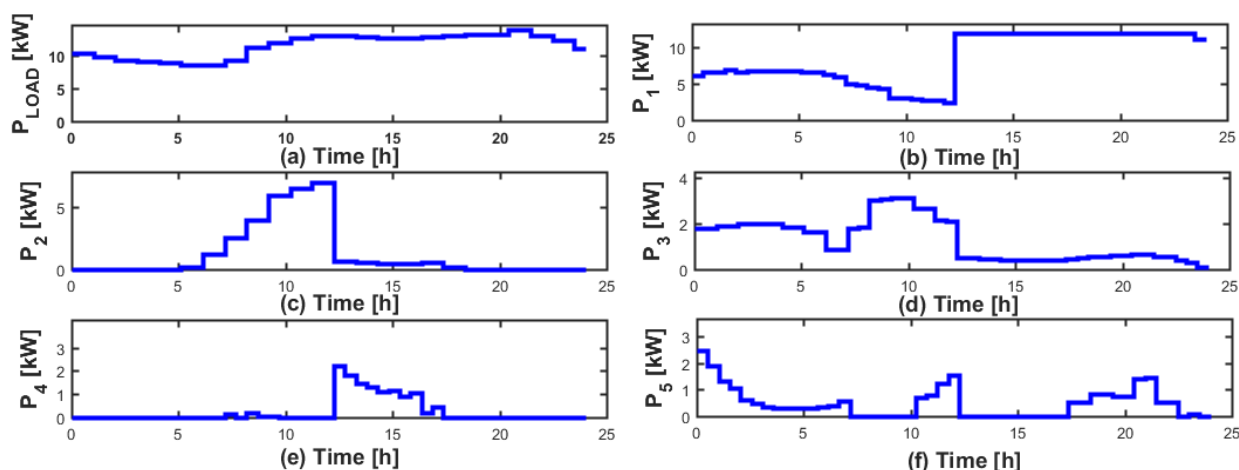


Figure 8: Weekend power flow by using HES during the rainy season: (a) Power demand; (b) Power output of the DG; (c) Power output of the PV system; (d) Power output of the WT; (e) Power charging the BSS and (f) Power leaving the BSS.

2.3. The Pattern of Load Demand in the Dry Season Weekday

The load demand and power output of the DG during the dry season are shown in Figure 9 (a-b). It is established from Figure 9b that DG is the only source of power during the weekday dry season. With the configuration presented in this study, a DG of 16 kW is employed to satisfy the electricity needs of consumers, with a corresponding daily fuel consumption of ₦115220 and 96.02 L of diesel fuel.

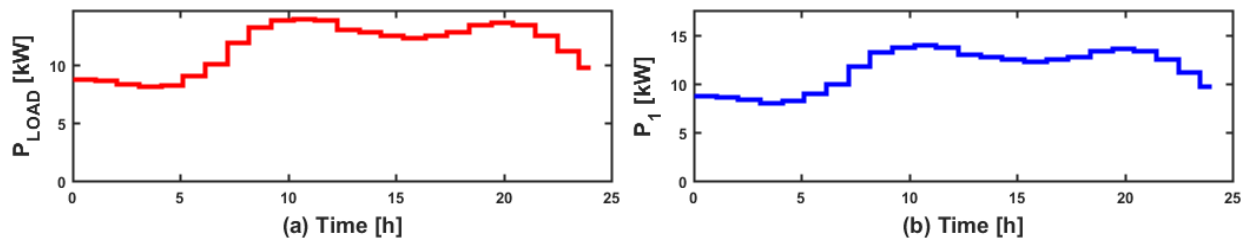


Figure 9: Weekday power flow by using DG alone during the dry season: (a) Power demand; (b) Power output of the DG.

The HES is meant to provide electricity for low-power applications in the current study. Therefore, HES is structured so that it will be able to respond to changes in power demand. The impacts of solar resources based on seasonal variation and load demand are assessed with the use of DG, BS, PV and WT. The configuration and design of the proposed HES allow maximum utilization of the power generated by the WT and PV system; and ensure that there is no dump power since the summation of the power outputs of all the components matches the power demand. The availability of solar radiation and wind speed at this particular time makes the PV and WT systems the major contributors of power to the required load demand. For the 7–18 hours of the day, the power demand is satisfied by the combination of the DG, PV, WT and BSS. At this particular period, the combined operation of DG, PV, WT and BSS has enough power to satisfy load demand, as presented in Figure 10 (a-f). The BSS is used in conjunction with the DG and WT to satisfy the power requirement that occurs during the peak load period at night and early in the morning. Figure 10 (b-f) shows that the power generated by the DG has decreased with the integration of BSS, PV and WT into the base system. The stored energy can be utilized during the peak period, as presented in Figure 10e based on the load demand. The daily fuel cost in the dry season weekday is ₦ 73775 with the deployment of the DG, PV, BSS and WT in the hybrid energy system. The fuel cost on weekdays has reduced to ₦ 73775 when the HES is optimally operated. This translates to a 35.97 % fuel cost saving, as shown in Table 2, which means customers can earn fuel cost savings of ₦ 41445 per day during the weekday. From the outcomes of the simulation obtained in this case study, it is established that the power demand on dry season weekdays is considerably greater than the power demand on rainy season weekdays. This suggests that during dry-season weekends, diesel fuel expenditure is ₦ 2442 more than it is on rainy-season weekdays.

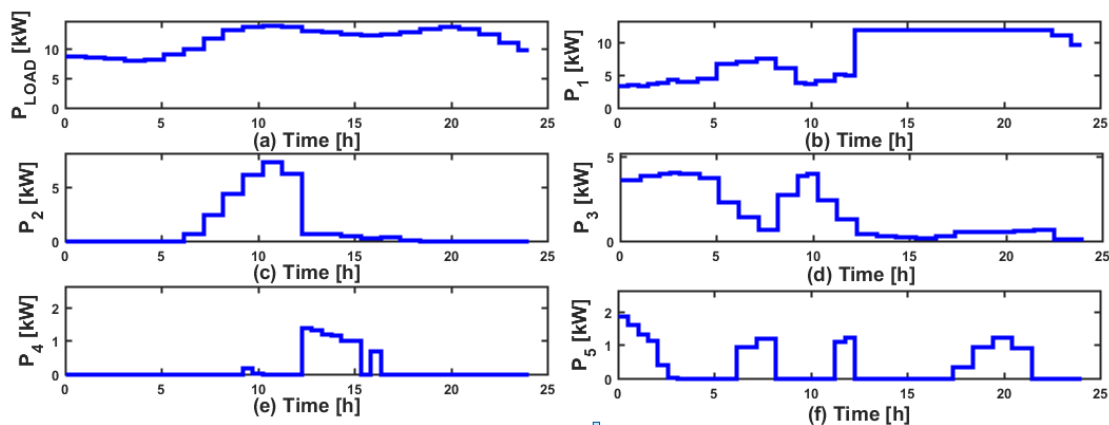


Figure 10: Weekday power flow by using HES during the dry season: (a) Power demand; (b) Power output of the DG; (c) Power output of the PV system; (d) Power output of the WT; (e) Power charging the BSS and (f) Power leaving the BSS.

2.4. The Pattern of Load Demand in the Dry Season Weekend

The power demand by consumers at the load points during 24 hours of a dry-season weekend is shown in Figure 11a. The DG of 16 kW is only utilized to satisfy the power demand throughout a rainy-season weekday. The results shown in Figure 11b make it clear that, with a daily fuel usage of ₦115420 and 96.18 L of diesel fuel, DG generated all the required power demand.

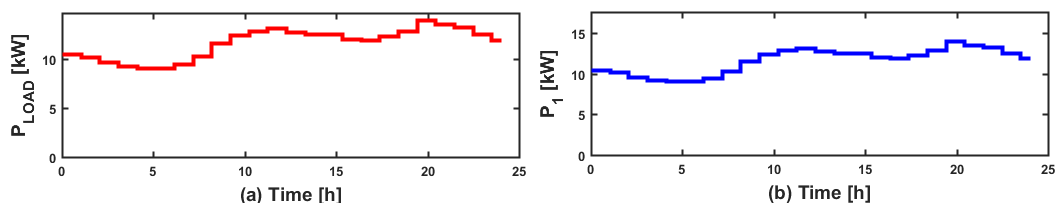


Figure 11: Weekend power flow by using DG alone during the dry season: (a) Power demand; (b) Power output of the DG.

The performance of the existing power system can be increased through an energy management system that strategically controls power flow among the components of HES, such as WT, PV, BSS and DG as shown in Figure 12 (a-f). This optimized the utilization of WT and PV while lowering the required generation capacity of the DG. There is relatively little power generated by the PV system during peak load periods in the morning and night because there is no solar radiation. Hence, the PV system does not operate during this period, as presented in Figure 10c. The load demand during the off-peak period between 12 and 16 hours of the day is very low owing to the load pattern at this particular time. The power produced by WT and PV system as shown in Figure 12 (b-c) is utilized to charge the BSS between 12 and 16 hours of the day when the load demand is low. During the peak periods that happen promptly towards the beginning of the day and later at night, the BSS supplied power to the load as depicted in Figure 12f. With the energy management system, the power output of the WT and PV must be utilized as a priority to satisfy the load demand, provided there is enough power from PV system and WT. The daily cost of fuel utilization for optimally operated HES is ₦74391 during the dry-season weekend. This shows that 35.55 % of fuel costs have been reduced with the use of WT and PV resulting in ₦41029 in fuel cost savings. Optimally operated HES can increase fuel cost savings by incorporating PV and WT into the DG-alone system. The fuel cost savings during the dry season weekend with the HES are significantly higher than during the rainy season weekend owing to periodic changes in load profile and seasonal variations.

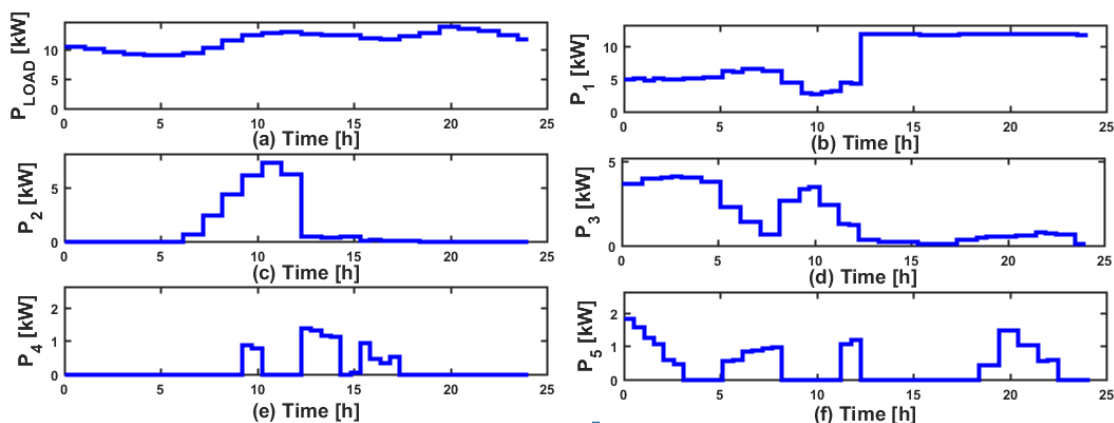


Figure 12: Weekend power flow by using HES during the dry season: (a) Power demand; (b) Power output of the DG; (c) Power output of the PV system; (d) Power output of the WT; (e) Power charging the BSS and (f) Power leaving the BSS.

3. Conclusion

There is a growing demand for hybrid energy systems that incorporate RESs and the establishment of an islanded power system with the penetration of local resources due to environmental concerns and the depletion of fossil fuels. The uncertainties of RESs that are prevalent in the distribution power system network, microgrid system, HES and smart grid systems are violations of operating constraints, optimal flow of power among the components of HES, optimal energy system and high operating costs. This research proposed a genetic algorithm to reduce the fuel cost, which accounted for more than 60% of the maintenance and operation costs of HES. The hybrid energy system that is aimed at providing a power control strategy with a minimum use of DG and BSS and a maximum utilization of WT and PV is presented in the current study. The total power produced is distributed across the components of the HES based on power output constraints and power demand requirements. The outcomes of the study demonstrate the impact of daily and seasonal fluctuations in demand and solar and wind resources on the proposed HES operational costs. It can be established from the results obtained from the study that rainy-season fuel costs are ₦2223 and ₦1826 higher than the dry season; this is attributed to low solar radiation and wind speed in the rainy season and higher power demand in the dry season. This indicates that the seasonal variation of load demand and seasonal variation of solar and wind resources have important consequences on the fuel cost and energy flow of the proposed power system. The optimized fuel cost accomplished by the established model has been demonstrated, and it can be used for the analysis of energy flows in any power system. As a measure to take advantage of the analysis of the results, it has been recommended to solve the problems related to the optimization of HES by using the load profile of a typical customer based on seasonal variations. The application of an optimal control strategy with a genetic algorithm in the present study can improve the performance and energy management of the proposed HES by allowing the optimization of RESs. The combined operation of multiple sources in this research improved the overall benefits of the HES when compared with a single-source system. The study's findings indicate that employing HES results in greater fuel cost savings of ₦38812, ₦38623, ₦41445 and ₦41029 than DG-only systems. This shows that fuel cost savings of 33.81%, 33.63%, 35.97% and 35.55% are achieved with the application of HES in rainy season (weekday and weekend) and dry season (weekday and weekend) when compared with DG alone. Therefore, it can be concluded from the outcomes of the study that the fuel cost is minimized and the usage of photovoltaic and wind turbines is maximized.

References

- Able, 2022. Diesel generator fuel consumption chart in litres. <https://www.ablesales.com.au/blog/diesel-generator-fuel-consumption-chart-in-litres.html> accessed on 10 December, 2023.
- Adaramola, MS. and Oyewola, OM. 2011. On wind speed pattern and energy potential in Nigeria. *Energy Policy*, 39 (5): 2501-2506.
- Adefarati, T., Bansal, RC. Shongwe, T. Naidoo, R. Bettayeb, M. and Onaolapo, AK. 2023. Optimal energy management, technical, economic, social, political and environmental benefit analysis of a grid-connected PV/WT/FC hybrid energy system. *Energy Conversion and Management*, 292:117390.

Adefarati, T., Bansal, RC. Naidoo, R. Potgieter, S. Rizzo, R. and Sanjeevikumar, P. 2020. Analysis and optimisation of a diesel-PV-wind-electric storage system for a standalone power solution. *IET Renewable Power Generation*, 14 (19): 4053-4062.

Adefarati, T., Bansal, RC. Bettayeb, M. and Naidoo, R. 2021. Optimal energy management of a PV-WTG-BSS-DG microgrid system, *Energy*, 217: 119358.

Adefarati, T. and Bansal, RC. 2017. Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources. *Applied Energy*, 206: 911-933.

Adeyanju., GC. Osobajo, OA. Otitoju, A. and Ajide, O. 2020. Exploring the potentials, barriers and option for support in the Nigeria renewable energy industry *Discover Sustainability*, 2020 1:7.

Amazon 2022.ATO 500W wind turbine, 12V/24V/48V, wind turbine generator for home, RV, and island (24V). <https://www.amazon.com/500W-Wind-Turbine-Generator-Island/dp/B08DTSQH9P?th=1> accessed on 2 January 2024.

Ashok, S. 2007. Optimised model for community-based hybrid energy system. *Renewable Energy*, 32 (7): 1155-1164.

Bawonda, FI. Adefarati, T. 2023. Evaluation of solar energy potential in six geopolitical regions of Nigeria using analytical and simulation techniques. *Energy Conversion and Management*, 290: 117193.

Blaabjerg, F. and Ionel, DM. 2015. Renewable energy devices and systems – state-of-the-art technology, research and development, challenges and future trends. *Electric Power Components and Systems*, vol. 43: 1319-1328.

Chamandoust, H., Derakhshan, G. Hakimi, SM and Bahramara. S. 2019. Tri-objective optimal scheduling of smart energy hub system with schedulable loads. *Journal of Cleaner Production*, 236: 117584.

Check petrol price, 2023. Nigeria diesel price. <https://www.checkpetrolprice.com/global-gasbuddy/Diesel-price-in-Nigeria.php> accessed on 20 December, 2023.

Elinwa, UK., Ogbaba, JE. and Agboola OP. 2021. Cleaner energy in Nigeria residential housing, *Results in Engineering*, 9: 100103.

Energypedia, 2022. Nigeria electricity sector. https://energypedia.info/wiki/Nigeria_Electricity_Sector accessed on 3 January, 2024.

Generator set data sheet, 2022. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://cdn.adepower.com/assets/pdf/generators/cummins/cummins-c22d5-data-sheet.pdf accessed on 12 December, 2023.

Khalilnejad, A., Sundararajan, A. and Sarwat, AI. 2018. Optimal design of hybrid wind/ photovoltaic electrolyzer for maximum hydrogen production using imperialist competitive algorithm, *J. Mod.Power Syst.Clean Energy* 6 (1): 40–49.

Kumar, S.; Bhattacharyya, B. and Gupta, V. 2014. Present and future energy scenario in India," Journal of The Institution of Engineers (India): Series B, 95 (3): 247-254.

Wikipedia. 2023. List of countries by electricity consumption, 2023. https://en.wikipedia.org/wiki/List_of_countries_by_electricity_consumption accessed on 5 January, 2024.

NASA. 2024. Power data access view. <https://power.larc.nasa.gov/data-access-viewer> accessed 10 November, 2023.

Nasser, M., Megahed, TF. Ookawara, S. and Hassan. H. 2022. Techno-economic assessment of clean hydrogen production and storage using hybrid renewable energy system of PV/wind under different climatic conditions. Sustainable Energy Technologies and Assessments, 52 (Part B): 102195.

NERC, 2023. Transmission Company of Nigeria. <https://nerc.gov.ng/index.php/home/nesi/404-transmission> accessed on 3 January, 2024.

Oluwatoyin, KK., Odunola, AM. and Alabi. AO. 2015. Ways of Achieving Stable and Uninterrupted Power Supply of Electricity in Nigeria, British Journal of Applied Science & Technology, 10(5): 1-15.

Okoh, AS. and Okpanachi, E. 2023. Transcending energy transition complexities in building a carbon-neutral economy: The case of Nigeria. Cleaner Energy Systems, 6: 100069.

Onaolapo, AK. Sharma, G. Bokoro, PN. Adefarati, T. Bansal, RC. 2023. A comprehensive review of the design and operations of a sustainable hybrid power system. Computers and Electrical Engineering, 111: 108954

Oyedepo, SO. 2012. Energy and sustainable development in Nigeria: the way forward. Energy, Sustainability and Society, 2 (15): 1-17.

Palatel, A. 2017. Isolated Hybrid Energy Systems for Remote Locations. Encyclopedia of Sustainable Technologies, 4: 205-216.

Powersync 2018. Powersync energy solution. <https://powersyncenergy.com/wp-content/uploads/2018/10/500-Watt-Monocrystalline-Module-Data-Sheet.pdf> accessed on 15 November, 2023.

Power tech 2020. Powertech advanced energy storage systems. <https://www.powertechsystems.eu/home/products/12v-lithium-battery-pack-powerbrick/250ah-12v-lithium-ion-battery-pack-powerbrick/> accessed on 15 December, 2023.

PSC Solar 2023. The Future of Solar Energy in Nigeria: Trends and Projections. <https://pscsolaruk.com/blog/the-future-of-solar-energy-in-nigeria-trends-and-projections/>, accessed on 2 January, 2024.

Sechilariu, M. and Locment, F. 2016. Backup power resources for microgrid. In Sechilariu, M. and Locment, F. (eds), Urban DC microgrid, intelligent control and power flow optimization, 93-132, Butterworth-Heinemann, Amsterdam.

Seeling-Hochmuth, G. 1997. A combined optimisation concept for the design and operation strategy of hybrid-PV energy systems. *Solar Energy*, 61 (2): 77-87.

Tazvinga, H. Xia, X. and Zhang, J. 2013. Minimum cost solution of photovoltaic-diesel battery hybrid power systems for remote consumers. *Solar Energy*, 96: 292-299.

Tracking SDG 7. The Energy Progress Report 2022, <https://www.worldbank.org/en/topic/energy/publication/tracking-sdg-7-the-energy-progress-report-2022> accessed on 2 January, 2024.

Varaiya, PP. Wu, FF. and Bialek, JW. 2011. Smart operation of smart grid: Risk-limiting dispatch," *Proceedings of the IEEE*, 99 (1): 40-57.

World bank, 2020. Nigeria to keep the lights on and power its economy. <https://www.worldbank.org/en/news/press-release/2020/06/23/nigeria-to-keep-the-lights-on-and-power-its-economy> accessed on 5 January, 2024.

World bank, 2022. Report: COVID-19 slows progress toward universal energy access. <https://www.worldbank.org/en/news/press-release/2022/06/01/report-covid-19-slows-progress-towards-universal-energy-access> accessed on 3 January, 2024.

Xu, YP., Ouyang, P. Xing, SM. Qi, LY. and Jafari, H. 2021. Optimal structure design of a PV/FC HRES using amended water strider algorithm, *Energy Rep.*, 7: 2057–2067.

Zhang, W. Maleki, A. Rosen, MA. and Liu, J. 2019. Sizing a stand-alone solar-wind-hydrogen energy system using weather forecasting and a hybrid search optimization algorithm, *Energy Convers. Manag.*, 180: 609–621.

Zhang, W. Maleki, A. Pourfayaz, F. and Shadloo. MS. 2021. An artificial intelligence approach to optimization of an off-grid hybrid wind/hydrogen system, *Int. J. Hydrog. Energy*, 46 (24): 12725–12738.