Feasibility Study and Comparative Analysis of Hybrid Renewable Power System for off-Grid Rural Electrification in a Typical Remote Village Located in Nigeria

JAMIU O. OLADIGBOLU, (Member, IEEE), MAKBUL A. M. RAMLI, AND YUSUF A. AL-TURKI
Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
Corresponding author: Jamiu O. Oladigbolu (omotayooladigbolu@gmail.com)
This work was supported by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah, under grant no DG-028-135-1441.

ABSTRACT The introduction of a decentralized energy system in remote rural areas with limited or no access to power supply can improve the quality of life of people living in these areas. Renewable energy technology can play a key role in electricity generation, as grid expansion is not a cost-effective option. In this study, we focused on the techno-economic feasibility and optimal design of a hybrid micro-hydro-photovoltaic-diesel-battery-wind power system designed to electrify a typical remote village located in the southern part of Nigeria. We aimed at achieving the electrification at minimal cost while taking into cognizance the constraints of environmental pollutant emission. In this study, the technical details, as well as the economic feasibility of setting up such a power system, were determined using the hybrid optimization of multiple energy resources (HOMER) simulation tool. Different combinations of energy resources including solar, wind, hydro, and diesel were compared and analyzed. The system performance and economics using some determinant factors such as the cost of energy, operation, and maintenance cost, net present cost, excess electricity, capacity shortage, generator fuel consumption rates, and cost, load fulfillment, and CO₂ and other pollutant gas emission savings were determined. The experimental results and the comparative analysis revealed that a hybrid hydro/PV/wind/diesel/battery system was the most ideal and preferred option for off-grid rural electrification. The simulation results also indicated that the optimal system had a net present cost (NPC) and cost of energy (COE) of $1.01 m and $0.106/kWh, respectively, with a renewable fraction of 77.4% and environmental pollutant emission of 228,945 kg/year. This system was found to be environmentally friendly as it emitted the least pollutant gas among all the considered configurations. Bearing in mind the recent advocacy towards the actualization of Sustainable Development Goal (SDG) number 7, this work was found to be in alignment with the tenet of “Affordable and Clean Energy.”

INDEX TERMS Renewable energy, hybrid power system, net present cost, off-grid, techno-economic optimization, HOMER analysis tool.

I. INTRODUCTION
At the end of 2016, about 24% of electricity was generated globally from renewable energy sources (RESs). This was up by 2.5% (i.e. 26.5%) in 2017 [1]. Moreover, around 17% of the world population is out of the electricity coverage, out of which 85% are people living in rural areas; with Sub-Saharan Africa contributing the largest percentage [2]. RESs, especially wind, hydro and solar energy are primarily important for designing environmentally friendly and sustainable power systems [3], [4]. The availability and utilization of energy resources are among the key factors that determine the assets and growth of a country. In addition to its considerable amount of conventional energy resources (including those producing more than 2.5 million barrels of crude oil daily and 2.175 billion tons of coal and lignite, and 187 trillion ft³ of natural gas reserves [5]), Nigeria has the potential to integrate RESs for continuous power supply [5]. For instance, the study
reported in [6] revealed that there are about 277 potential sites for small-scale hydropower (SHP) application with an estimated total output of 734 MW while the value of solar energy per year is approximately 27 times that of the conventional energy sources in terms of the energy measurement [5] with an average of 6.5 h of sunshine per day [7]. The country’s wind speed on the other hand exceeded the cut-off value of 2.2 m/s for more than 35 stations (80% of the stations) at the 25-m level and a wind turbine of around 30% efficiency and 25-m diameter can produce as high as 97 MW per annum of electric power [8].

Non-access to reliable electricity is one of the major problems in Nigeria as a power crisis poses as an obstacle to the technological development and industrial prospect of the nation. This explains the rationale of why stakeholders seem to be paying more attention to power generation and a continuous supply of power. While most urban dwellers are moving with the tide of modernization, globalization, and amiable quality of life; the same cannot be said for many rural communities. Unavailability of electricity in many rural areas has widened the economic gap, fostered poverty, and made it increasingly difficult to upgrade their standard of living. In Nigeria, only around 22.6% of the rural populace has power supply connections [9]. This percentage of rural electrification rate is much lower than that of Algeria, Egypt, and Morocco whose rural areas are all covered under the electricity coverage.

A hybrid combination of renewable and conventional energy resources is more efficient and cost-effective than single-source power systems in addition to satisfying greater load for an extended period. At present, the country’s total renewable power capacity including hydropower is considerably lower than those of China, the United States, and Germany which as of 2017 were 647 GW, 241 GW, and 112 GW respectively [10]. The peak electricity generation ever attained in Nigeria as at the time of preparing this paper is 5,375 MW; this is about 28.1% of the peak national electricity demand forecast of 19,100 MW for the same period [11]. Following the Nigerian government’s partial deregulation of the power sector, the need has arisen to explore various options of electricity generation to improve power capacity as well as its availability and reliability in the country. One of the possible options is to reduce the dependency on centralized power generation by introducing a decentralized hybrid energy system (HES). The application of a standalone power generation concept in remote rural locations has been in existence globally. This concept serves as a good alternative for power supply in Sub-Saharan Africa and South-Asia since they have the largest percentage of power deficit rate and diesel generator (DG) systems in most cases are used for electricity supply. The addition of renewable energy systems to the existing DG plant can ensure a continuous electricity supply with low operational costs and minimal atmospheric pollution levels [4], [12]. On the other hand, the use of renewable energy sources alone to meet load demand often presents some drawbacks such as high initial cost (without financial incentives), the need for more storage devices which could increase the capital cost as well as the intermittent nature of these sources which often influence the power generation level. Also, the electricity regulatory body is aiming to diversify its power generation, which is mostly from conventional energy sources through the utilization of other alternative generation options to support the rising electricity demand. In this run, the hybrid integration of renewable power technologies like solar, wind, and hydro energy can be a viable alternative. By the end of 2020, a minimum of 2,000MW of electricity is expected to be produced from RESs [13], with a 30% share of total capacity in 2030 [14]. Furthermore, based on the forecast of energy demand conducted in Nigeria for an optimistic GDP of as high as 13% growth rate with a suppressed base demand of 5746 MW. It was established that the country needs to generate approximately 11,700 MW every year to meet the demand projection of 297,900 MW at the end of 2030 [15]. This implies that all the potential energy resources (solar, wind, hydropower, coal, and crude oil) in the country need to be adequately exploited to meet customer electricity needs. The appropriate design of a combination of energy sources can reduce maintenance costs as well as the environmental impact besides its cost-effectiveness.

II. RESEARCH BACKGROUND

Numerous researches have been carried out on the techno-economic and environmental feasibility of a renewable-based HES. The optimal sizing of a hydro based HES has been investigated in various studies [1], [16], [17]. The optimal design of renewable-based and combined renewable and conventional energy system have been examined in other studies. For instance, Aziz [18] analyzed the economic viability of different HES for power supply at a desert safari camp in UAE using HOMER. He concluded that HES of solar PV, wind, and battery storage is an optimum system with higher efficiency. The techno-economic sizing of a HES comprising of PV, wind, DG, and battery was probed in [19] for power supply at a rural community in Sri Lanka. Their results reveal that the optimized configuration could supply power at a cost of $0.34/kWh. Another study [20] investigated the economic feasibility of PV/diesel configuration at six different climate zones in Tamil Nadu, India. Their findings showed an arid interior climate as the best climate type for setting up a PV system with diesel plants. Likewise, they mentioned that government subsidy needed to be established to attract more investors to support large scale renewable-based hybrid systems in the area.

Similarly, HOMER was used in [21] to evaluate the techno-economic possibility of a HES for a residential house in China, while taking into account the effect of load variation, PV module tilt angle as well as the ambient temperature of the HES. Their findings reveal HES with PV and wind turbines as the optimal system; having an acceptable value for NPC when the load increases. The implementation of a hybrid
configuration comprising of wind, solar PV, and hydropower for powering remote villages at Makawanpur District, Nepal was discussed using two RESs integration techniques [22]. They stated that HES is the best option for power supply in remote areas in terms of cost, environmental sustainability, and lifestyle improvement. Kaldellis et al. [23] modeled an autonomous standalone PV system using the pay-back energy method. They analyzed two separate areas of high and medium solar potential with different PV-battery autonomous energy systems. The authors stated that the battery contribution is more than 27% of the system energy requirement in all scenarios investigated.

Also, various photovoltaic solar energy conversion systems have been set up in cities and rural areas in Nigeria for power supply; projects are listed in [5], [24]. Wind turbine system has seen considerable applications in rural areas of Bauchi, Kebbi, and the Sokoto States for mill grinding and water pumping [24], [25]. While few hydropower schemes have been installed in different locations, mostly in the northern region [5]. Due to the inherent variability nature of RESs, these projects experience fluctuations. Hence, the idea of introducing a system comprising of a suitably sized hydroelectric system, PV panel, wind generation unit, and a more stable power system (diesel plant) to provide reliable and sustainable power supply at a low cost and less environmental impact.

From the previous studies, electrifying rural areas using a decentralized HES can improve the standard of living of its residents, as well as delivering quality healthcare service. Mindful of the security challenges that Nigerians are facing, it was reported in [16] that rural electrification could improve the security level in rural areas up to 94.7% with 92% improvement in the standard of living. Moreover, Bekele and Tadesse [17] suggested a hybrid hydro/PV/wind/diesel system for clean energy development, expansion of electricity production as well as for improving the lives of rural dwellers in remote areas. This kind of hybrid energy system (HES) is superior to the fossil fuel-based system, as small money is spent on oil and pollutant emission rate is better managed with the help of RESs. The hydroelectric plant uses the flow of the water stream (river run-off) to produce electricity while the energy production from wind and solar systems depends on the wind velocity and solar irradiation level. The battery bank can be effectively utilized as storage equipment in a remote location with no grid access. Although, the cost of power generated could be seriously affected by this additional storage cost.

Besides battery degradation can affect the system lifespan [26], while the fast degradation of battery storage in a standalone system can also lead to a high energy cost due to frequent replacement [27], [28]. The DG, on the other hand, serves as an auxiliary energy system to ensure continuous operation. The integration of a battery and DG system with the abundance of RESs could support the country to realize its goal of meeting the energy need of its citizens, most especially the rural dwellers. However, adequate attention has not been focused on conducting a feasibility study and detailed investigation into the potentiality and suitable usability of solar, hydro, and wind with diesel systems for rural implementation in Nigeria. As per literature, no study has been performed to evaluate the performance of these three major RESs through techno-economic and environmental analysis in Nigeria. The previous study only concentrates on the optimal sizing of a system using RESs like solar and wind energy with diesel systems and storage devices for off-grid electrification [29]–[32]. This paper aims to fill that research gap, with details of the design and techno-economic and environmental feasibility of the hydro/PV/wind/diesel system using HOMER simulation software. A comparative study was performed to examine the validity of the proposed standalone energy scheme. The selected village has an electricity connection but it is unreliable as the power supply is available for only 4 hours daily and the diesel-powered plant has always been the alternative power system used to supplement the unstable grid power. This will serve as a guide and input data in the design and planning of RESs based rural electrification framework to assist the government and the other key investors in the Nigerian energy industry.

III. DEVELOPMENT AND SPECIFICATIONS OF THE CASE STUDY

A. SELECTED SITE

The Ekwe community located in the Isu local government area of the Imo state, the southeastern region of Nigeria, has been chosen for the present study. The community is approximately 378 km south of the country’s capital (Abuja). It lies on a wave plain, with a natural boundary created by the run of the Njaba river causing a separation with the other neighboring villages such as Okwudor on the west and Amucha on the north. The community is however situated at 5°40’44.76” N and 7°3’9” E. This community is a predominantly agrarian society, with most of its occupants earning a larger part of their living from the agricultural activities that they engage in during the wet season. There is grid power in this community, as electricity in the Imo state is supplied by Affam Genco and managed by Enugu Electricity Distribution Companies. The power supply is available for approximately 4 h daily, leading to many residents and healthcare workers facing difficulties in running their daily activities. DGs are the alternative power source commonly deployed to supplement the unstable power from the utility grid while some use lamps powered by kerosene. The cost of diesel fuel and kerosene used by the village dwellers is most expensive due to the poor state of the roads and the high cost of transportation. Additionally, the unstable grid power affects the education system as most students find it difficult to study without a stable supply of electricity. Though characterized by little infrastructure development, the territory is expected to be provided with off-grid electrification to improve the school’s electricity access which could make it possible for the students to learn under a conducive environment.
The daily energy demand of the selected houses and healthcare centers is presented in Figs. 1(a) and (b), respectively. The total annual average daily load demand was calculated based on the hourly aggregate load profile, provided in Fig. 1(c), of 3,853 kWh/day at a peak load and load factor of 421.89 kW and 0.38 respectively. The gross load demand of 3,853 kWh/day used in this study was estimated by considering the users power demand, the different appliances available as well as the daily operational hours of these appliances.

**IV. SYSTEM DESIGN SPECIFICATIONS**

The hydrological characteristics of the river considered in this study were taken from [35]. It was evident from the hydrological data shown in Fig. 2 that the selected location experienced a high-water discharge for the hydroelectric application. Furthermore, the stream flow rate varied between 6.14 m³/s and 8.48 m³/s for the hydrological year with annual average streamflow of 7.67 m³/s. The nominal power of 94.1 kW was estimated for the water turbine by using the available data, such as the available head and design flow rate.

The monthly mean global solar irradiation data presented in Fig. 3 were obtained from NASA and considered in HOMER as the solar resource input. The period from July to September reported a low value of solar irradiance and clearness index because of the peak of the wet periods leading to a low potential value for the PV electricity supply. However, the irradiation level in the other months was sufficiently high for considerable power generation. Furthermore, the ambient temperature influenced the PV performance as well as its energy production level. Therefore, it was necessary to consider the changes in the ambient temperature of the chosen site. The monthly mean ambient temperature is illustrated in Fig. 4. The average value of the temperature, however, exceeded 23°C in all the months with the peak temperature occurring in April. The average yearly temperature was approximately 25°C.

The wind speed data presented in Fig. 5 were obtained from the HOMER software via the NASA website at the height of 10 m [36]. On average, the annual wind speed was reported to be 2.7 m/s, with a minimum wind speed of 2.23 m/s in May and a peak speed of 3.37 m/s in August. Moreover, the high wind speed was observed between July and August, which could supplement the low potential of the PV application during this period. The fluctuation observed in the wind pattern was mostly due to the topographic characteristics and the water bodies [25]. Furthermore, other parameters considered for the wind resources during the simulation were a 1.00-h auto-correlation factor (taken as 0.85), the diurnal pattern strength (taken as 0.25), and the Weibull factor (taken as 2). Depending on the weather conditions available for a certain period (high sunshine hours or windy days or rainy season), renewable energy (solar, wind, and hydro) systems with a battery storage device were used to supply electricity to the whole load as well as for meeting the peak demand time. In contrast, the diesel generator was only operated in the
event of any shortfall in supply to ensure continuous operation and to charge the storage battery depending on the type of dispatch strategies used.

A. SYSTEM COMPONENT DATA

The cost and the sizing data of the main components used in this analysis are given in detail in Table 1. Different sizes of the system components were analyzed to determine the optimal size suitable for the selected location. The component pricing and technical details were obtained from [1], [2], [25]. Note that two different generator sizes (50 kW and 100 kW) were considered for meeting the lower and the higher load demand conditions, respectively, to optimize their efficiency as well as to regulate the fuel cost. The two generators operated at different times depending on the load demand. However, they could both be operated simultaneously.

**FIGURE 1.** Hourly load profile of (a) residential houses, (b) healthcare centers, and (c) aggregate load demand.
whenever the load demand was greater than 100 kW and the RESs and/or batteries were inefficient in supplying adequate energy to the load.

B. PROPOSED HYBRID SYSTEM CONFIGURATION

The HES proposed in this paper comprises a hydroelectric system, PV solar system and wind turbine system with battery, and a DG as illustrated in Fig. 6. The system components were interconnected together in HOMER, and their technical and economic specifications were provided for simulation purposes. Micro-hydro systems produce power in the range of 5–300 kW via the hydroelectric plant and are installed in an area with sufficient stream water (river run-off) all through the year [16], [22]. The southern part of the country is blessed with abundant energy sources required to implement such a hybrid system. Ekwe, a village located in the southeast geopolitical zone was chosen for the installation of the proposed system. The load-following dispatch strategy has been considered for energy management systems. In this control strategy, RESs are given priority to
provide the energy demand and to charge the storage unit. The diesel plant is only operated when RESs fails to satisfy the load demand and the battery state of charge falls to or below 40%. This strategy tends to reduce the total NPC as well as the excess energy generated. Moreover, the amount of CO₂ emissions produced is better managed under this strategy. The energy-producing units contained both AC and DC buses combined by a bi-directional converter to sustain the flow of power between the following components: PV panel, wind turbine and battery storage (DC bus), hydro turbine, and diesel generator (AC bus).

In this study, a feasibility study along with a comparative analysis of some other system models was conducted to obtain an optimal system as well as to check the validity of the proposed standalone scheme. The various system configurations simulated for the comparative analysis have been studied in past literature for different load, input settings as well as locations; only the design configuration ideas of these systems were considered in the present study.

C. MATHEMATICAL MODELING
1) WIND TURBINE MODELING
The electrical power from the wind turbine system is thus calculated as follows [38]:
\[ P_e = \frac{1}{2} \times \rho \times C_p \times A \times V^3 \times 10^{-3}, \]  
where \( C_p \) refers to the power coefficient of the wind turbine system, \( \rho \) represents the air density (1.22 kg/m³), \( A \) refers to the surface swept by the rotor (m²), and \( V \) denotes the wind speed (m/s).

2) HYDROELECTRIC PLANT MODELING
In HOMER, the following equation is used to compute the electrical power produced by the hydro turbine [1]:
\[ P_{\text{hyd}} = \eta_{\text{hyd}} \times h_{\text{net}} \times \rho_{\text{water}} \times Q_{\text{turbine}} \times g \times 1000 \left( \frac{W}{kW} \right), \]
where \( \eta_{\text{hyd}} \) refers to the efficiency of the hydro turbine (%), \( h_{\text{net}} \) denotes the effective head (m), \( \rho_{\text{water}} \) represents the water density (1000 kg/m³), \( Q_{\text{turbine}} \) is the hydro turbine flow rate (m³/s), and \( g \) is the gravitational acceleration (9.81 m/s²).

3) PV SYSTEM WITH TEMPERATURE MODELING
The following expression is utilized in HOMER to compute the PV output power [39]:
\[ P_{PV} = Y_{PV} f_{PV} \left( \frac{G_{T}}{G_{T, \text{STC}}} \right) [1 + \alpha_p (T_C - T_{C, \text{STC}})], \]
where \( Y_{PV} \) is the PV power output under standard test conditions (STC) (kW), \( \alpha_p \) is the temperature coefficient of power (%/°C), \( f_{PV} \) denotes the PV de-rating factor (%), \( G_{T, \text{STC}} \) refers to the incident radiation under STC (1 kW/m²), \( G_T \) refers to the solar irradiation striking the PV panel (kW/m²), \( T_C \) is the PV cell temperature (°C), and \( T_{C, \text{STC}} \) is the PV cell temperature under STC (25°C).
The following equation shows the relationship between the PV cell and ambient temperatures [40]:

\[ T_C = T_a + (0.0256 \times G) \]  

(4)

where G is the solar radiation (W/m²).

**TABLE 1.** Hybrid system component specifications.

| Reference(s) | Component parameter          | Specification           |
|--------------|------------------------------|-------------------------|
| [1], [2]     | PV module                    | Efficiency under standard test condition 13% |
|              | Temperature coefficient      | -0.48%/°C               |
|              | Capital cost                 | $3200/kW                |
|              | Cost of replacement          | $3000/kW                |
|              | O&M cost                     | $5/kW/year              |
|              | Deviation factor             | 80%                     |
|              | Ground reflection            | 20%                     |
|              | Lifetime                     | 25 years                |
| [25]         | Wind turbine                 | Capital cost            | $4000/kW |
|              |                              | Replacement cost        | $3200/kW |
|              |                              | O&M cost per year       | $200/kW  |
|              |                              | Lifetime                | 20 years |
| [1]          | Hydro system                 | Capital cost            | $1700/kW |
|              |                              | Replacement cost        | $500/kW  |
|              |                              | O&M cost per year       | $100     |
|              |                              | Efficiency              | 75%      |
|              |                              | Lifetime                | 25 years |
| [37]         | Batteries                    | Model                   | Surrette 6CS2SP |
|              |                              | Nominal voltage         | 6 V      |
|              |                              | Nominal capacity        | 6.94 kWh |
|              |                              | Capital cost            | $1100    |
|              |                              | Replacement cost        | $1100    |
|              |                              | O&M cost per year       | $10      |
|              |                              | Lifetime throughput     | 9645 kWh |
| [2]          | Converter                    | Capital cost            | $245/kW  |
|              |                              | Cost of replacement     | $245/kW  |
|              |                              | Efficiency              | 90%      |
|              |                              | O&M cost per year       | $10      |
|              |                              | Lifetime                | 10 years |
| [2]          | Diesel generator             | Capital cost            | $200/kW  |
|              |                              | Replacement cost        | $200/kW  |
|              |                              | Lifetime                | 15000 h  |
|              |                              | Maintenance cost        | $0.05/kWh |
|              |                              | Minimum load ratio      | 25%      |

**TABLE 2.** Summarized optimization results of the system.

| PV (kW) | Wind (kW) | DG1 (kW) | DG2 (kW) | Battery | Hydro (kW) | Converter (kW) | NPC ($) | COE ($/kWh) | Operating cost ($/year) | Renewable fraction (%) | CO₂ (kg/ye ar) | Diesel (L) |
|---------|-----------|----------|----------|---------|------------|----------------|---------|-------------|------------------------|------------------------|---------------|------------|
| 50      | -         | 100      | 50       | 16      | 94.1       | 50             | 1.00M   | 0.1055      | 91,339                 | 77.4                   | 226,39        | 86,538     |
| 50      | 1         | 100      | 50       | 16      | 94.1       | 50             | 1.01M   | 0.106      | 91,536                 | 77.4                   | 226,38        | 86,534     |
| 50      | -         | 100      | 100      | -       | 94.1       | 50             | 1.14M   | 0.119      | 112,686                | 73.3                   | 275,50        | 105,31     |
| 50      | -         | 100      | 200      | -       | -          | 50             | 2.58M   | 0.271      | 344,390                | 4.06                    | 951,15        | 363,42     |
| 300     | 830       | -        | -        | 920     | 94.1       | 300            | 8.70M   | 0.921      | 464,975                | 100                    | -             | -          |

**4) ECONOMIC MODELING**

Economic analysis is an important aspect of HOMER because of its core objective, which is cost minimization.

The net present cost (NPC) is calculated using the following expression [41]:

\[ C_{NPC} = \frac{TAC}{CRF(i, N)} \]  

(5)

where the total annualized cost ($/year) is denoted by TAC, N denotes the project lifetime (year), and i refers to the yearly real discount rate (%). The capital recovery factor (CRF) is defined in [42] as related to both N and i as given below:

\[ CRF(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1} \]  

(6)

The levelized cost of energy (COE) is defined in [43] as follows:

\[ COE = \frac{TAC}{E_{unloaderved}} \]  

(7)

where E_{unloaderved} represents the overall annual load (kWh) served by the system.

**V. SIMULATION RESULTS**

The simulation performed in this study considered the load profile as well as the available resources in the selected area. The HOMER simulation tool was used to find the optimum configuration in HESs based on a techno-economic and environmental analysis corresponding to the chosen site of the Ekwe village, Nigeria. A comparative analysis of various combinations of energy sources including a stand-alone DG was carried out. The various hybrid systems simulated for the comparative analysis have hitherto been analyzed and proposed by various researchers; only their design configuration ideas (i.e. the different ways of integrating various energy resources) were considered. The analysis was performed for a project lifetime of 20 years. The electrical and economic performance, in addition to the environmental aspect of the optimized system, was also considered.

**A. OPTIMIZATION RESULTS**

The simulation results presented in Table 2 showed the optimum configuration with the other feasible system
configuration to demonstrate that the chosen system performed better. It was evident from the sensitivity results that the levelized COE varied in the range of $0.1055–$0.921/kWh, while the production capacity of 0.6%–2.09% was observed to be the energy shortage. It was also clear from the table that PV/hydro/DG/battery scheme was the least expensive configuration with a 2.01% capacity shortage and consumed approximately 86,538 L of fuel, which led to a CO$_2$ emission of 226,398 kg/year. However, the hybrid system ranked as the second most cost-effective system had a capacity shortage of only 2.01% and emitted 226,386 kg/year of CO$_2$, which was slightly less, and the COE was only $0.0005/kWh more than that of the top-ranked configuration. Based on the associated environmental benefits and the maximized uptime, this system was suggested for implementation. Therefore, the proposed optimal system is hydro/PV/wind/DG/battery system configuration.

**B. PERFORMANCE EVALUATION OF THE OPTIMAL HYBRID SYSTEM**

1) TECHNICAL EVALUATION

The layout of this system was such that the load requirement was met via the combination of a micro-hydro turbine, wind generation unit, a PV system with a storage unit, and a DG system, as illustrated in Fig. 6.

Fig. 7 illustrates the monthly electricity produced by each component of the optimal standalone system as well as the percentage of energy consumption of the AC primary load. From this figure, we inferred that a large proportion of the electricity produced was harnessed from hydro turbines (75.7% of the total generation) because of the high streamflow experienced at this site. The second major contributor to electricity generation was the diesel plants, where DG1 contributed 15.3% of the total generation with a 4.89% share from DG2. This was closely followed by PV, which added a share of 4.05%, while the remaining share of 0.0034% (52.2 kWh/year) was supplied by the wind turbine.

Furthermore, the system relied mostly on renewable energy systems for its operation, showing a renewable fraction of 77.4%, while minimizing the use of conventional energy sources. This configuration proved to be effective in handling an electric load, as the quantity of energy wastage was small. Moreover, surplus electricity was produced at 9.4% (146,333 kWh/year) of the total generation capacity after completely meeting the load requirement. This percentage of excess power was acceptable, bearing in mind that it could be adequately utilized by connecting dump loads or as reserves. It is known that only an ideal system operates without producing any excess power, which was not the case in this study. Moreover, the system could not satisfy only approximately 0.86% of the electrical load. This showed that the system could fulfill most of its load requirements and had the maximum uptime, as the capacity shortage was only approximately 2% of the total production.

The sizes, hours of operation, as well as the electrical output and the capacity factor of each subunit of the optimal HES (hybrid hydro/PV/wind/diesel/battery system), are illustrated in Table 3. It is evident from this table that the hydro system operated for the whole hours of the year at 8,760 hrs./year with the highest maximum electrical output of 140 kW. This system had a high percentage of penetration of 83.8%, which shows its huge contribution to power generation as well as its positive impact in reducing the operating hours of the two generators and the number of pollutant emissions. The wind turbine had the least hours of operation per year (2,404 hrs./year) and maximum electrical output (0.443 kW).
due to the weak wind potential experience in some of the months. This resulted in having the least energy production from the wind system. The fuel consumption summary presented in Fig. 8 shows that the two generators consumed a combined fuel of 86,534 L at an average of 237 L/day and 9.88 L/hrs. to meet the load requirement of the system.

The battery autonomy, which represents the time (hours) during which the storage battery can sufficiently supply the load demand without the need to recharge, was determined to be 0.413 h for two strings of batteries, at a nominal capacity of 111 kWh. It was evident from the daily and monthly average state of charge (SOC) of the battery storage shown in Fig. 9 that April to June (or between 90 to 180 days) reported the least charging cycles because of the low water stream flow experienced during these months. Moreover, solar radiation and wind speed were not very high during this period. During the dry season, i.e., from November to February, when the energy demand was low, the battery had a higher charge capacity. This was attributed to the high level of RESs reported, except for the wind resource, which was not very high.

2) ECONOMIC EVALUATION

The total NPC of the optimal HES was calculated to be $1,007,995, while the COE and operating costs are $0.106/kWh and $91,536/year, respectively. Fig. 10 illustrates the system cost summary. We observed that the fuel cost ($371,741.9) and the initial capital cost ($383,820) were the costliest components. These fuel and capital costs were considered high; the capital cost was attributed to the considerable amount of money spent on the purchase of the PV and the hydro system, while the fuel cost was attributed to the working conditions of the two categories of generators.

The maintenance of the moving section of the two types of generators also led to high O&M costs. The replacement cost, however, was reported to be a low value of $73,687.8. This is because the hydro, wind, and PV systems have no replacement cost since the lifetime of these components ranges between 20-25 years, which either correspond to or higher than the project’s lifetime. The replacement cost is, however, the sum of the battery, DG1, DG2, and converter cost of replacement. The nominal cash flow of the optimal system and base case (PV/DG system) for 20 years (project lifetime) is presented in Fig. 11. The cash flow (nominal) sustained a continuous minimum value throughout the project lifetime for the optimal system as compared to the base case scenario where the cash flow kept a maximum constant value throughout the 20 years.

Also, the variation in renewable components costs can influence the system’s economy, for instance, when the
simulation was conducted for a varying wind turbine cost of $1000/kW and $8000/kW, the COE increases from $0.119/kWh to $0.12/kWh. The increment noticed in the COE is mainly due to the increase in the cost of the wind turbine which gives rise to higher total NPC. This shows that the optimal standalone renewable energy system is a viable and economically feasible power system for the selected area and other similar locations.

C. ENVIRONMENTAL IMPACT ASSESSMENT

Pollutants and greenhouse gases (GHGs) such as CO₂, CO, unburned hydrocarbons, particulate matter, SO₂, NOX are discharged during the combustion of fuels in power conversion. In this analysis, the release of harmful emissions is only attributed to the diesel fuel consumption level. The environmental results obtained from HOMER and as shown in Fig. 12 reveal that the base case generates the highest level of gross pollutant emissions with 963,925.7 kg/year, while the value of the optimal system configuration was far less at 228,945 kg/year. On the other hand, the PV/wind/hydro/battery scheme reports the best environmental impact of zero-emissions; this is because of the absence of the DG while the system completely depends on RESs. This shows that the configuration is the most
environmentally friendly system, but regrettably, the system presented one of the worst economic prospects with high NPC and COE values compared to the optimal HES. The optimal configuration is considered environmentally friendly as its emission is about 76.3% lower than the base case.

D. COMPARATIVE ANALYSIS OF DG AND HYBRID POWER SYSTEMS
The proposed optimal system can be compared with some other combination of energy resources (diesel-only, PV/diesel/battery, PV/wind/diesel/battery, and hydro/wind/diesel/battery systems) to examine its validity. The various energy systems simulated has been investigated in previous literature for different load demands, simulation input parameters, and settings and locations. In this analysis, only the design configuration ideas were taking into consideration. For a valid comparison, the load and other input parameters required during the simulation were kept the same and the outcomes were compared with the proposed standalone system. The details of the various energy systems analyzed for the comparative analysis are presented in the following subsections.

1) STAND-ALONE DG SYSTEM
The use of a diesel plant for electricity generation is very common in remote rural areas with no grid power supply or where the energy supply from the utility grid is unreliable. Fig. 13(a) presents a schematic representation of this configuration. The results of the analysis revealed that this system was the most cost-effective system with the lowest initial cost among all the configurations assessed. Its cost-effectiveness mainly depended on the price of diesel. Moreover, no renewable power resources with high installation costs were included in its setup, making the system less expensive to install. The best combination of the diesel-alone system was obtained with two diesel generators (DGs) having an individual rated capacity of 100 kW and 200 kW, respectively. The technical and economic characteristics of

![FIGURE 11. Nominal cash flow (Total) of the (a) optimal system and (b) base case.](image-url)
this system configuration along with other system models are presented in Table 4. This table shows that the total annual energy produced from the two generators when operated for a total of 11,835 hours per year was 1,398,601 kWh with DG1 contributing to the lower percentage (29.7%). This led to the total annual consumption of 378,292 L of fuel. The total NPC and the COE were approximately $2,486,535 and $0.261/kWh, respectively, at the diesel fuel price of $0.63 per liter. The initial capital and operating costs were $60,000 and $355,854/year, respectively. These values were on the high side, which could be attributed to the remote setting of the area considered, which increased the cost of diesel transportation and storage. Fig. 14 presents the average monthly electric production of the individual generators.

![Graph showing pollutant emissions](image1)

**FIGURE 12.** Results of the pollutant emissions produced.

| Systems                     | Diesel generator system | PV/DG/battery hybrid | PV/wind/DG/battery hybrid | Hydro/wind/DG hybrid | Proposed hydro/PV/wind/DG hybrid |
|-----------------------------|-------------------------|----------------------|----------------------------|----------------------|----------------------------------|
| Electric production (kWh/year) | 1,398,601               | 1,404,913            | 1,404,933                  | 1,510,904            | 1,556,584                        |
| Consumption (kWh/year)      | 1,398,601               | 1,398,620            | 1,398,624                  | 1,393,750            | 1,394,243                        |
| Excess energy (kWh/year)    | -                       | 4.31                 | 4.38                       | 99,164               | 146,333                          |
| Total fuel consumption (L)  | 378,292                 | 363,418              | 363,382                    | 91,290               | 86,534                           |
| Initial capital ($)         | 60,000                  | 241,050              | 253,050                    | 219,820              | 383,820                          |
| Unmet load (kWh/year)       | 7,744                   | 7,725                | 7,721                      | 12,595               | 12,102                           |
| NPC ($)                     | 2,486,535               | 2,606,767            | 2,622,661                  | 874,774              | 1,007,995                        |
| LCOE ($/kWh)                | 0.261                   | 0.273                | 0.275                      | 0.092                | 0.106                            |
| Operating cost ($/year)     | 355,854                 | 346,935              | 347,506                    | 96,050               | 91,536                           |
| Capacity shortage (kWh/year) | 20,907                  | 20,769               | 20,765                     | 29,231               | 28,225                           |
| Renewable fraction (%)      | -                       | 4.1                  | 4.1                        | 76.2                 | 77.4                             |

**TABLE 4.** Comparison of the technical and economic characteristics of the stand-alone DG and hybrid energy systems.
The detailed cost summary of the DG system as distributed among different cost types is depicted in Fig. 15. It was evident from the cost summary chart that most of the system costs accrued to fuel consumption ($1,625,108), followed by the O&M cost component ($648,000). Also, the total amount of emissions produced by this system was 1,003,403 kg/year. This was distributed between CO$_2$ and other harmful pollutants and greenhouse gases (GHGs),
as shown in Table 5. The total annual emissions value was considered very high, but this was because renewable resources were not included in the setup, thus causing the system to consume more fuel during its operation.

2) PV/DG/BATTERY SYSTEM

The second system analyzed in this study consisted of a combination of a PV system with a battery bank and DGs. Such a system was previously investigated by Kumar and Manoharan [20] and Adaramola et al. [29]. This configuration is illustrated in Fig. 13(b), solves some of the drawbacks associated with the diesel-only system, such as the number of emissions released, in addition to the money spent on the diesel fuel resources. The total amount of pollutants and GHGs released is 963,895.7 kg/year, which is considerably lower than that of the diesel-only system, as presented in Table 5. The percentage contribution of PV is comparatively small because the renewable fraction stands at a low rate (4.1%). It is evident from the cost summary graph illustrated in Fig. 16 that the money spent on fuel is 3.93% less than that of the diesel-only system. The simulation results also showed that 100% load was met with a total energy generation of 1,404,913 kWh/year, where PV contributed only approximately 63,112 kWh/year (4.49%), while the additional energy was supplied by the two generators at 95.5% of the total production. The monthly electricity generation of each component is illustrated in Fig. 17. A small amount of excess energy estimated at 4.31 kWh (0%) was found, and a capacity shortage of 20,769 kWh/year (1.48%) was reported in Table 4. The capacity shortage was however considered to be moderate because of the generator’s rated capacity, which showed that the system had the maximum uptime.

3) HYBRID PV/WIND/DG/BATTERY SYSTEM

The next hybrid configuration modeled in this study consisted of DGs with a wind turbine and PV integrated into a storage unit, as shown in Fig. 13(c). The technical feasibility, in addition to the economic and environmental aspects of such a hybrid configuration, was previously investigated by Hossain et al. [44] and Oladigbolu et al. [37]. This system generated an annual sum of 1,404,933 kWh of electricity. Fig. 18 shows the monthly power production of each subunit. The capacity shortage (20,765 kWh/year) was found to be 1.48% while the yearly excess energy and unmet electric load were estimated to be approximately 4.38 kWh and 7,721 kWh, respectively, as illustrated in Table 4. Fig. 19 presents the cost summary of this configuration. This figure clearly shows that the fuel cost accounted for the largest share ($1,561,058) of the total cost because of the presence of two DGs with large capacities. This was closely followed by the O&M cost component ($641,761), while the initial capital cost and replacement cost was found
to be around $253,050 and $173,038) respectively. The environmental effects of this system are significant, as it emits approximately 963,801 kg/year of pollutant emission (Table 5).

4) HYDRO/WIND/DG/BATTERY SYSTEM
The next system configuration analyzed here consisted of two RESs, namely the wind and hydro resources with DGs as back-up and a battery bank, as illustrated in Fig. 13(d). Bakos [45] suggested such a system for electric power generation at a low cost, while a comprehensive study of such a system was conducted by Canales et al. [46]. The NPC of the optimized configuration was found to be $874,774, while the COE was $0.092/kWh. The operating and salvage costs were estimated to be approximately $96,050/year and $1,709, respectively. Fig. 20 presents the cost summary of the system. Note that more money ($392,175) was expended on fuel resources because of the consumption and operation of the two generators, where DG1 operated for 3,516 h/year, which led to annual fuel consumption of 68,220 L at the rate of 0.271 L/kWh. As for DG2, it ran for 3,750 h/year to consume 23,071 L of fuel per annum at the rate of 0.286 L/kWh. The other large costs, according to Fig. 20, came from the initial capital cost ($219,820) and O&M cost ($188,986). The capital cost was high because of the initial investment cost of the hydroelectric system, while the O&M cost was simply due to the high cost incurred during the maintenance of the generator’s moving parts. The replacement costs were relatively small, as the hydro lifetime exceeded the system’s lifetime; hence, no money was spent on replacing the hydro system. The system gross emission was 241,529.82 kg/year as illustrated in Table 5. The system’s total annual generation was 1,510,904 kWh as illustrated in Table 4. The hydro turbine contributed the largest share of 78%, and 16.7% of
the total capacity came from DG1, while the remaining percentage (5.3%) was supplied by DG2. The monthly electric production of each component is depicted in Fig. 21.

E. RESULTS ANALYSIS AND DISCUSSION

The DG system performed better concerning the capital cost ($60,000) in addition to having an acceptable unmet load (7,744 kWh/year) and capacity shortage (20,907 kWh/year) but had the largest emission rate of 1,003,403 kg/year distributed between CO$_2$ and other greenhouse gases (GHGs). This system requires a considerable amount of money ($1,625,108) for fuel as well as high maintenance cost ($648,000) and operating cost ($355,854/year). The high emission rate coupled with having one of the worst economic prospects made the implementation of this system a non-viable option. According to [47], [48], the amount of pollutant gas emitted is directly related to global warming, and a trillion tons of carbon released can cause a peak warming of approximately 2°C.

The PV/DG/battery system on the other hand solves some of the drawbacks associated with the DG system, such as the number of emissions released, in addition to the money spent on the fuel resources. This system performed better in terms of fuel consumption as the money spent on fuel is 3.93% less than that of the DG system in addition to reducing the DG system pollutant emission by approximately 3.94% (Table 5). Also, its operating cost ($346,935/year) was found to be slightly lower than that of the DG system ($355,854/year) as well as had a tolerable NPC and COE values (Table 4). However, this system released large amounts of pollutants (963,895.7 kg/year) as compared to other feasible system models; this has made its implementation environmentally unsuitable.

Furthermore, the environmental effects of PV/wind/DG/battery system are significant, as it emits approximately 963,895.7 kg/year of pollutant emission (Table 5). This is because of the large amount (363,382 L) of fuel consumed at the rate of 0.268 L/kWh (DG1) and 0.272 L/kWh (DG2)
by its DGs. This system configuration had the worst financial prospect as it presented the highest NPC and COE values in addition to having a high initial capital cost (Table 4). Therefore, we concluded that the system performed better in terms of satisfying most of its load as its unmet load was at a low value of 7,721 kWh/year and there was approximately no wastage (0.0003%) of energy with little shortage (20,765 kWh/year) as compared to other system models (Table 4). However, this system failed from the environmental and economic aspects, as the emission rate, NPC, and COE values were high in addition to low renewable power penetration (4.1%). The limitation of carbon emission is key, as increasing its value above a certain point could significantly impact global warming, as suggested in [48].

Consequently, approximately 6.56% of excess energy was produced, while the capacity shortage was estimated to be around 2.08% of the production capacity (Table 4) and more money ($392,175) was expended on diesel fuel resources due to the consumption and operation of the two generators in the case of the hybrid hydro/wind/DG/battery system. This system’s total pollutant emission rate was found to be approximately 241,530 kg/year (Table 5), while the energy cost was estimated at $0.092/kWh. This system is the closest competitor of the proposed system configuration. According to Table 4, it shows greater economic prospects based on the outcome of its total net present cost and the energy cost as well as its initial cost, which was next in rank to the DG system but generated a large amount of CO₂ and other GHGs,
as depicted in Table 5; this value of emission could significantly impact the environment, besides causing considerable energy wastage.

However, the proposed hydro/PV/wind/DG/battery system showed better performance in terms of the fuel consumption reduction, operating cost, renewable penetration rate, and the fuel cost saving (Table 4). The proposed system also reduced the total NPC and COE by approximately 59.5% and 59.4%, respectively, as compared to the standalone DG system used under the current condition. The system operating cost was approximately $91,536/year which was also 74.3% cheaper than that of the DG system and the percentage of renewable penetration (77.4%), which was the highest among all the considered system models revealed that the system depended more on the renewable components to support the load [49].

Furthermore, the proposed HES reported only approximately 2% (28,225 kWh/year) of the energy shortage (which was lower than that of the hydro/wind/DG/battery system at 29,231 kWh/year) with excess electricity of around 9.4%, while the unfulfilled electric load was only approximately 0.861%. This result revealed the high capability of the system to satisfy most of its electrical loads in addition to having an acceptable surplus energy production with maximum uptime.

The annual emission produced by the various system models in Table 5 showed that the proposed system also released pollutant emissions, but their emission (228,945 kg/year) was the lowest among all the considered energy systems. They can reduce the total emissions of the DG system, hybrid PV/DG/battery system, hybrid PV/wind/DG/battery system, and that of the hybrid hydro/wind/DG/battery system by 77.18%, 76.25%, 76.24%, and 5.21%, respectively. The overall results reveal that the other energy systems simulated were not a suitable choice for implementation because of their relatively high pollutant emission rates and inadequate efficiency. Moreover, some of them had higher cost implications and consumed more fuel. This made the proposed system ideal and suitable for off-grid and rural electrification.

VI. CONCLUSION

In this study, we designed a system for deployment to power a typical remote community in the southern part of Nigeria taking into consideration the available renewable energy sources. The HOMER optimization tool was used in the simulation and analysis of such a system, which consisted of a hydroelectric system, PV array, and wind generation unit with a battery bank and a diesel plant system. Besides, several analyses were performed to compare and evaluate the proposed system’s performance with the performance of some other system configurations which include the stand-alone diesel generator system, PV/diesel/battery, PV/wind/diesel/battery, and hydro/wind/diesel/battery systems. From the obtained simulation results, it can be concluded that

- hydro/PV/wind/DG/battery system with an NPC and COE of $1.01 m and $0.106/kWh, respectively, was recommended for implementation based on the associated environmental benefits and for maximized uptime. This configuration has a renewable fraction of 77.4% and reported the least environmental impact of 228,945 kg/year emissions, which is about 76.3% lower than the PV/DG hybrid scheme.

- Among all the energy systems simulated for the comparative study, the hydro/wind/diesel/battery scheme presented the best economy in terms of the total NPC, initial capital cost, electricity cost, and operational maintenance cost while the proposed hydro/PV/wind/DG/battery hybrid scheme was more efficient and displayed better performance in terms of the fuel cost, fuel consumption savings, total operating cost, and emission reduction. The proposed configuration also reduces the total NPC and COE by approximately 59.5% and 59.4%, respectively, compared to the DG system.

- The DG system used under the present condition performed better concerning the capital cost but had the largest emission rate as well as having one of the worst economic prospects, which made its implementation a non-viable option.

- Due to the high investment cost required for the implementation of RES based system and because the location considered in this study is a rural village with local people earning below the minimum wage, tariff concession, government subsidies, as well as favorable policies, need to be established in Nigeria to encourage and speed up investment in the renewable power sector.

- The use of an off-grid renewable energy-based system to meet load demand often presents some drawbacks such as high initial cost (without financial incentives), the need for more storage and back-up devices which could increase the capital cost as well as the intermittent nature of these resources which often influence the power production level.

- This feasibility study of utilizing renewable power production for remote rural villages can be utilized in other developing countries in which a large percentage of their rural population faces unreliable and unstable grid electricity.

- The next stage from this analysis should be the setting up and performance evaluation of a functional/practical standalone hydro/PV/wind/DG/battery system in this site.

- Future work is to add more energy resources (Biomass, municipal solid waste, and geothermal) and investigate the techno-economic analysis potential to use the energy obtainable from these resources for the production of electricity as well as to conduct a detailed sensitivity analysis to evaluate the system behavior while changing some variables that influence system performance.

ACKNOWLEDGMENT

This work was supported by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah, under
grant no. (DG-028-135-1441). The authors, therefore, gratefully acknowledge the DSR technical and financial support.

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JAMU O. OLADIGBOLU (Member, IEEE) received an Ordinary National Diploma in electrical/electronic engineering from Federal Polytechnic Bauchi, Nigeria, in 2008, and the bachelor’s degree in electrical and computer engineering from the Federal University of Technology Minna, Nigeria, in 2014. He is currently pursuing the master’s degree with King Abdulaziz University (KAU). He is also working as a Research Assistant with the Electrical and Computer Engineering Department, KAU. His research interests include distributed generation, energy management systems, and renewable and alternative energy.

MAKBUL A. M. RAMLI received the B.Eng. degree in electrical engineering from the University of Tanjungpura, Indonesia, in 1995, the M.Eng. degree in electrical engineering from the Bandung Institute of Technology (ITB), Indonesia, in 2000, and the Dr.Eng. degree from the Nagaoka University of Technology (NUT), Japan, in 2005. He is currently a Professor with the Department of Electrical and Computer Engineering, King Abdulaziz University (KAU). His research interests include renewable and alternative energy, distributed generation, energy management systems, and smart grid.

YUSUF A. AL-TURKI received the Ph.D. degree in power systems from the University of Manchester, U.K., in 1985. Since 1999, he has been a Professor with the Department of Electrical and Computer Engineering, King Abdulaziz University (KAU), Saudi Arabia, where he is also the Vice President for Graduate Studies and Scientific Research. His research interests include system modeling, power system dynamics, renewable energy, and microgrids.