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Hydro Backed-up Hybrid Renewable System for Off-grid Power in Nigeria

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Abstract: This paper reports on a hydro backed-up (HPBU) hybrid renewable energy system (HRES) for a rural off-grid community in Kwara State Nigeria with an average demand load of 550.9 kWh (90.7 kW peak) per day. By using HOMER Pro software, the formulation and identification of the best reliable system architecture for attaining technical and economic viability while using nearby existing RE sources such as hydro, wind and solar energy are appropriately modelled and optimized based on the minimal net present cost (NPC) and cost of energy (COE). It was determined that the three best feasible configurations of a HPBU-HRES for the site have an annual output ranging from 1,642,979 – 1,749,272 kWh/yr and a cost of electricity (COE) in the range of 0.34 – 0.64 $/kWh. The best optimal HPBU-HRES (system 1) is a combination of 184 kW of solar PV (PV), 4,545 kWh of battery capacity (BB), 81.3 kW of converter (Conv) and 277 kW of hydro generation capacity (HPP). A comparison study undertaken to illustrate the economic benefits of the studied systems shows that about 288,116, 88,342 and 53, 88 kg/yr of CO_2 savings is possible against diesel only, grid extension and first best equivalent diesel engine backed-up (DEBU) system respectively. In furtherance of the study, a sensitivity analysis of the likely variation associated with the metrological parameters, load and cost of components was undertaken. The Outcomes show that system 1 (PV/HPP-BB) is the optimal system for small to medium loads (≤600 kWh/day), irrespective of the solar radiation. In addition, it is established that a decrease in the system's total initial cost by half will lead to a decline of COE to $0.177 per kWh at a corresponding NPC of $3,029.

Keywords: Wind Energy, Solar PV, Nigeria Energy Resources, Techno-economic Analysis, Rural Electrification

1. Introduction

Electricity has played a critical role in the development of human civilization. It has become a necessity in the lives of humans. Currently, about 80 million (40%) out of the over 200 million Nigerian population have no electricity access [1]. The transmission and distribution lines are old and Nigeria's national generation capacity is low (5,500MW of available grid capacity) [1]. This is a far cry from the national electricity demand which is projected conservatively to be about 40GW [1]. As a result of the depressing reliability of the grid, 86% of urban households connected to the grid only have access to intermittent and unreliable electricity, often receiving 6 – 12 hours per day of electricity supply nationally [1]. This has caused many urban dwellers with grid connections to use polluting diesel generators as backup. In the rural areas, only about 34% of the population has access to electricity through the national grid [2]. Despite significant renewable energy (RE) potential in Nigeria as shown in Table 1, the use of traditional biomass (such as firewood and charcoal) has dominated the energy sources in Nigeria making up about 70% of total fuels and technologies used for cooking [3] as shown in Figure 1.

Table 1. *Conventional and RE resource capacity in Nigeria [4, 5].*

Energy source	Estimated Quantities
Crude oil	37 Billion Barrels
Natural gas	187.44 Trillion cubic feet
Coal and lignite	40 billion tonnes
Large hydro-power	11.2 GW
Small hydro-power	3.5 GW
Animal waste	61 million tonnes/yr

Energy source	Estimated Quantities
Crop residue	83 million tonnes/yr
Solar radiation	3.5-7.5 kWh/m^2/day
Wind	2-8 m/s at 10m

In recent times, increased demands on the nation's electrical power systems and occurrences of electricity scarcities, power quality problems, rolling blackouts, electricity price increases and the need to cut back on emissions have caused many Nations across the globe to seek other sources of high-quality, reliable electricity [6]. Consequently, the Nigerian administration has prioritized the exploitation and development of local energy resource potential, particularly renewable energy (RE), as a way to improve the energy mix and warrant the steady and reliable accessibility of clean energy, especially in rural and remote areas. Based on the year 2030 energy mix projections for Nigeria, REs are expected to supply approximately 36% (68 GW) of the total energy supply by the source which is ~190 GW [7].

Distributed Generation (DG) based mini-grids have been tipped as an important route to supply electricity to areas not served by main grids. According to IEA, mini-grids are local power generation networks with own electricity generation capacity (0 –1 MW size) providing power to over one customer. In Nigeria, the grid's reliance on fossil fuels coupled with its prevalent poor service puts RE based mini-grids in a stronger position, both for rural and urban areas [2]. In recognising the importance of mini-grids to reliable electrification, the Nigeria Government has also issued a mini-grid regulatory policy encouraging the deployment of small-scale electricity generating technologies that are either stand-alone or interconnected to a distribution network [8]. The emphasis of this regulation is to empower local communities and encourage the development of local DG RE resources [8, 9].

Generating power through DG sources is a quicker, inexpensive option for the construction of big, central power plants and high-voltage transmission lines. They present to consumers the potential for high power quality, cheaper cost, greater service reliability, improved energy independence and efficiency [6, 10]. Amongst the DG technologies, the use of DG technologies based on RE sources such as wind, solar, geothermal, biomass, or hydro for mini-grids is favoured more because of their renewable nature [10, 11].

Renewable energy-based technologies are changing the situation for decentralized services. In the recent past, rapid advances in renewable technologies, especially solar and wind, coupled with ongoing drops in the manufacturing costs of photovoltaic (PV), Wind turbine (WT) and battery technologies, and information technology control packages have made renewable-based mini-grid systems to become a major government priority in Nigeria. These technologies provide both primary electricity to customers without grid access and backup to homes and businesses with unreliable grid connections [2].

However, mini-grids based on single renewable power sources alone like wind or solar is intermittent in output making it very difficult for only wind or solar-based mini-grid power system to respond to meet the electric load all the time leading to instability problems on the grid. One of the ways to solve this problem of mini-grid instability resulting from variability of wind or solar renewable power systems is to use an energy storage device or a hybrid renewable energy system (HRES) [11].

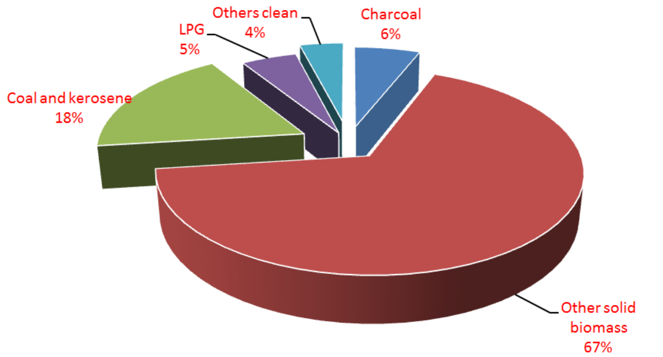


Figure 1. *Technologies and fuels used for cooking in Nigeria.*

Hybrid renewable energy systems (HRESs), characteristically consists of RE power sources as the main sources plus backup batteries and/or diesel generators. HRES can guarantee the availability of power when one of the constituent generation sources experiences intermittency. These systems may also lessen the costs, and optimize the size of the system components, thus decreasing operating costs and guaranteeing access to affordable, reliable, and sustainable forms of electricity [12].

Mini-hybrid system based on a hydropower plant (HPP) and other RE based power sources like wind turbine (WT) and solar photovoltaic (PV) plant represent a potential sustainable, viable and environmentally friendly electricity source that may endow local non-grid-connected households to generate their own power and reduce energy import. It performs a vital role in stabilizing the grid and alleviating the negative effects of intermittent generation from variable REs. Many locations in Nigeria have many untapped small hydropower (SHP) potential sites. There are currently more than 278 potential SHP sites with 734.3 MW potential capacity but only 37.0MW has been explored to date [13]. This makes mini-scale hydropower backed-up (HPBU) hybrid renewable energy system (HRES) one of the potential sources of electricity generation to increase energy access.

Techno-economic, reliability and energy return on investment analyses have been carried out for small, medium and large-scale off-grid and grid-connected, HRES systems for Nigerian locations [14–20]. The economic viability of hybrid system consisting of solar PV and diesel generator systems for different customer groups in different regions of Nigeria have been carried out in Refs. [14–16]. Their findings indicated that the available solar resources can be tapped to supply the power deficiencies of Nigerian consumers. In a related study, Sanni et al [17] reported on supplying an unreliable grid with a backup power supply using a hybrid solar PV/diesel/biogas system at a COE of \$0.164/kWh. Some studies reported on simulation, techno-economic analysis and optimization of various HRES configurations to obtain optimal configuration [18, 20]. Outside Nigeria, many studies have also been carried out on hydro based hybrid systems [21–24]. Nfah & Ngundam [22] reported on the feasibility of meeting the load of 73 kWh/day for remote villages in Cameroon using Pico-hydro (pH) and photovoltaic (PV) hybrid systems integrating a biogas generator. The authors [25] carried out a study comparing the net energy return on investment of mini-hydropower and solar PV systems for a mini-grid. The use of RE power system based on micro-hydro and solar photovoltaic for rural areas, using Yogyakarta, Indonesia as a case study was reported in [26].

The reviewed works of literature above revealed that all the studies on hybrid energy systems for Nigeria have focused on different HRES configurations such as PV/ Biomass/Diesel/Battery, Diesel/PV/Battery, Wind/PV/Battery, Wind/PV/Diesel/Battery and PV/Biogas/Wind/Diesel [14–20]. The results from all of them show that the supply, security and sustainability of power supply to users can be achieved through a hybrid combination of multiple RE power systems for use in the grid, off-grid or both applications. However, the full techno-economic performance of a medium hydro based HRES is yet to be sufficiently explored for Nigeria. The studies reviewed for Nigeria in Refs. [14–20] did not consider the hydropower plant option. Ref [27] included HPP generator for rural electrification in Neighboring Benin but did not consider WT but diesel generator as one of the power components.

In this study, these recognized gaps are filled by proposing small hydropower backed-up hybrid renewable energy system (HPBU-HRES) consisting of hybrid HPP, solar PV and wind turbine (PV/WT/HPP) system for unconnected rural communities in Kwara State Nigeria. The proposed systems target to completely serve the electric demand of the community with 100% use of RE based resources. Since the performance of a HRES is location-specific, a mixture of three factors forms the novelty of this work: (a) A wholly hydro based HRES that uses 100% of RE resources for rural electrification in Kwara state, Nigeria (b) a comparison of optimal proposed systems with diesel only and equivalent diesel-based hybrid alternatives under the same conditions. (c) Future load growth consideration.

Through HOMER software, the simulation, and techno-economic analysis of the most optimal combination of a HPBU-HRES that can best serve the electric load of the community for their sustainable energy self-sufficiency is implemented. The analysis offers an insight into how the available hydro, solar and wind RE sources in the study location can be optimally combined and harnessed to deliver 100% renewable-based high quality and uninterruptible electricity to the rural community. The outcomes of the research will be of great benefit to Nigerian Governments, other countries and any energy planner aiming to deliver electricity to many un-electrified populations in a developing country with similar unexploited RE resources and power supply access challenges. The results could help choose what type and size of hybrid micro-power architecture to deploy for diverse locations based on the magnitude of the demand load and average occurring hydro, solar radiation and wind speed of each community.

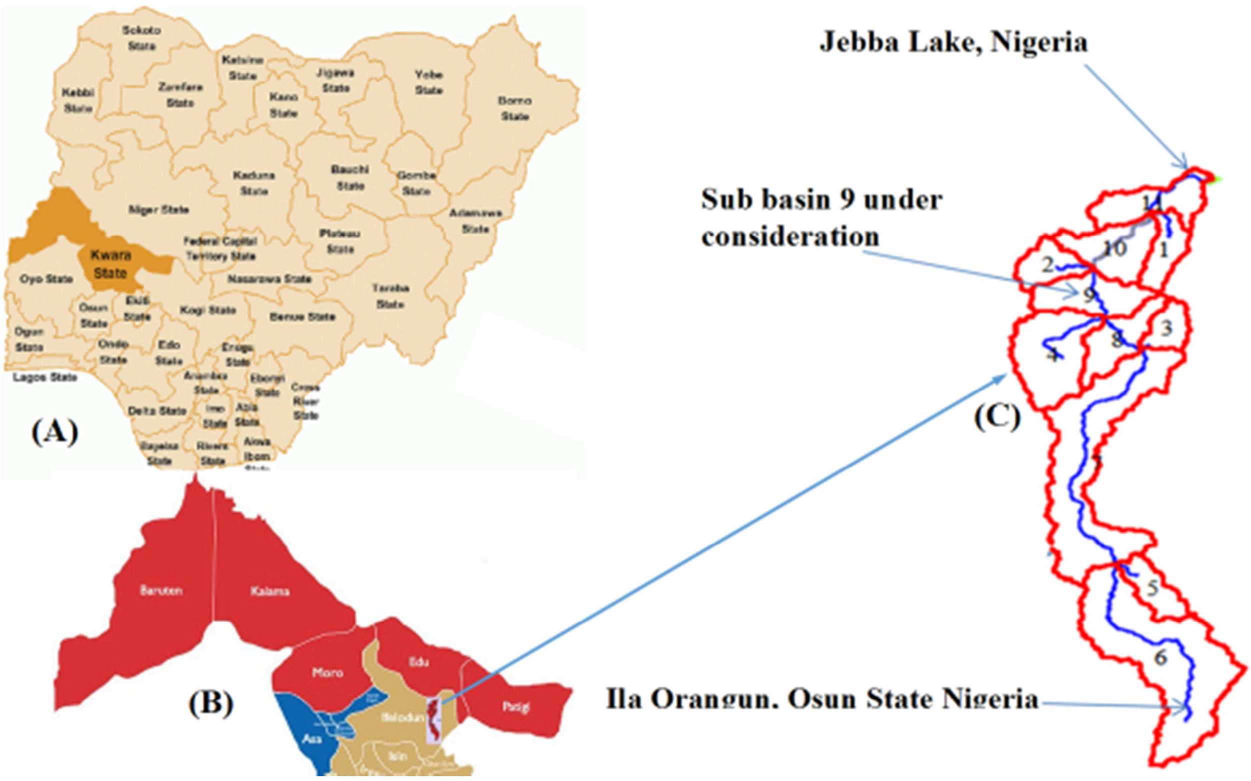


Figure 2. (A): Map of Nigeria showing Kwara state. (B): Map of Kwara state showing Ifelodun local government area and (C): River Oshin showing sub-basin under consideration [29].

2. Study Area and Resource Potential

2.1. Study Area

A group of three rural off-grid communities (Budo Umoru, Idi Isin and Sangotayo) having a total of 273 households and located geographically at 8°48.5′ N latitude and 4° 57.9′ E longitude in Ifelodun Local Government Area of Kwara State, Nigeria has been chosen as the site of study. This is because this area is rich in RE resources mostly solar, wind and hydro. River Oshin flows along these communities before finally discharging into River Niger. The characteristic of the rural community is shown in Table 2. This Community falls under the Ibadan Electricity Distribution Company (IBEDC) franchise area. The prevailing grid tariff in this region ranges from a minimum of 0.13 \$/kWh (55.76 N/kWh) for band D customers that receive a minimum supply of 8 hrs daily to 0.17 \$/kWh (69.2 N/kWh) for Band A customers that receive a minimum supply of 20 hrs daily [28].

Table 2. *Characteristics of the study area [29].*

Description	Sangotayo	Budo Umoru	Idi Isin
No of houses	14	63	9
No of shops	3	4	-
No of primary schools	1	1	1
No of mosques	1	3	-
No of Churches	-	-	2
No of households	70	158	45

The river under consideration in this paper is River Oshin which is located at Budo Umoru through Babaloma in Ifelodun local government area, Kwara State, North Central, Nigeria. The Map of Nigeria depicting the location of the case study river is presented in Figure 2. The river flows into Jebba Lake and has its source from Ila, Orangun in Osun State. The entire river has about 11 sub-basins as shown in Figure 2 and the sub-basin that is located near the three rural off-grid communities (hereafter referred to as the site) is sub-basin 9.

The potential hydropower in the site is assessed as 363.36 kW which lies in the classification of mini hydro-power plants (MHP) [29]. Figure 3 depicts the monthly hydro resource potential in the site. The net head and design flow rate were assessed as 7.62 m and 4.63 m^3/s respectively [29]. The site has a yearly mean stream flow rate of 4.63 m^3/s with the highest streamflow of 11.9 m^3/s occurring in September, while a low stream flow rate of 0.23 m^3/s occurs in April.

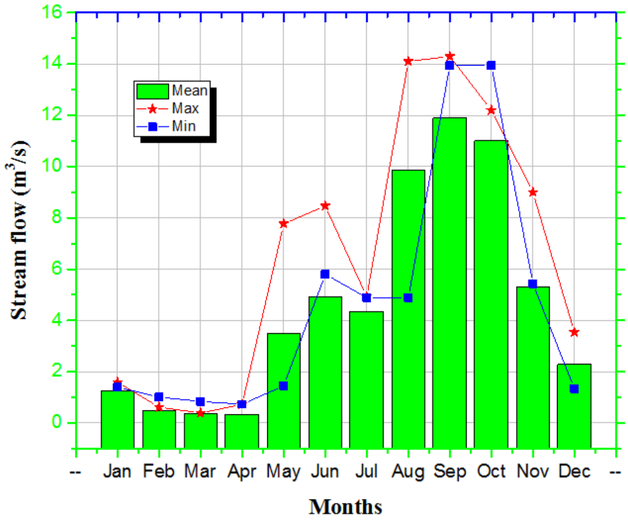
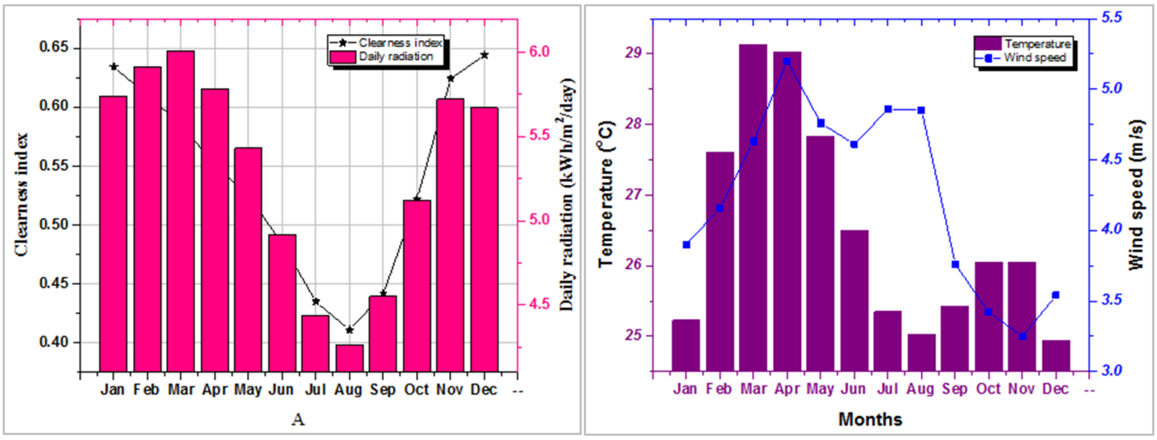


Figure 3. *Stream flow rate at the site [29].*

Apart from hydro resources, the site also has high solar energy and wind potential. The Solar radiation of the site downloaded from NASA surface meteorology data in HOMER shows that the area experiences an average daily solar radiation of 5.30 $kWh/m^2/day$ and a wind speed of 4.25 m/s at 10 meters height. Figure 4(a) shows the monthly occurring solar radiation and clearness index on the site.



(a) (b)

Figure 4. *Monthly occurring solar radiation (a) and wind speed (b) in the site.*

Figure 4(b) displays the wind speed and temperature occurring on the site. The Figures show that the clearness index, solar and wind resources in the site vary over the whole year. The clearness index ranges from a minimum of 0.41 in August to a maximum of 0.64 in December with an annual average of 0.54. This means that sky conditions in the location are barely cloudy. Maximum values of solar and wind potential are observed both in March while a minimum for solar is noted in August and that for wind occurs in December. It can be observed that solar and wind resource availability plots are almost opposite in shape to the hydro resource plot. Solar resource is available from January to May, but a drop in solar resource in other months is compensated by the hydro resource which is available from Jun to November.

2.2. Load Profile

The daily, monthly and yearly load profiles of the community under study are shown in Figure 5.

Since the details of the appliances used in each of the 273 households in the community are not available, the daily load profile of the community is obtained by scaling a representative hourly load profile of a low-income household in the same region as reported by Egbon [30]. Based on this, the community has a daily average load characterized by: hourly average load (22.94 kWh), daily average load (550.58 kWh/day) with a peak (90.67 kW), maximum load (54.24 kW) and minimum load (5.27 kW) at a load factor of 0.25.

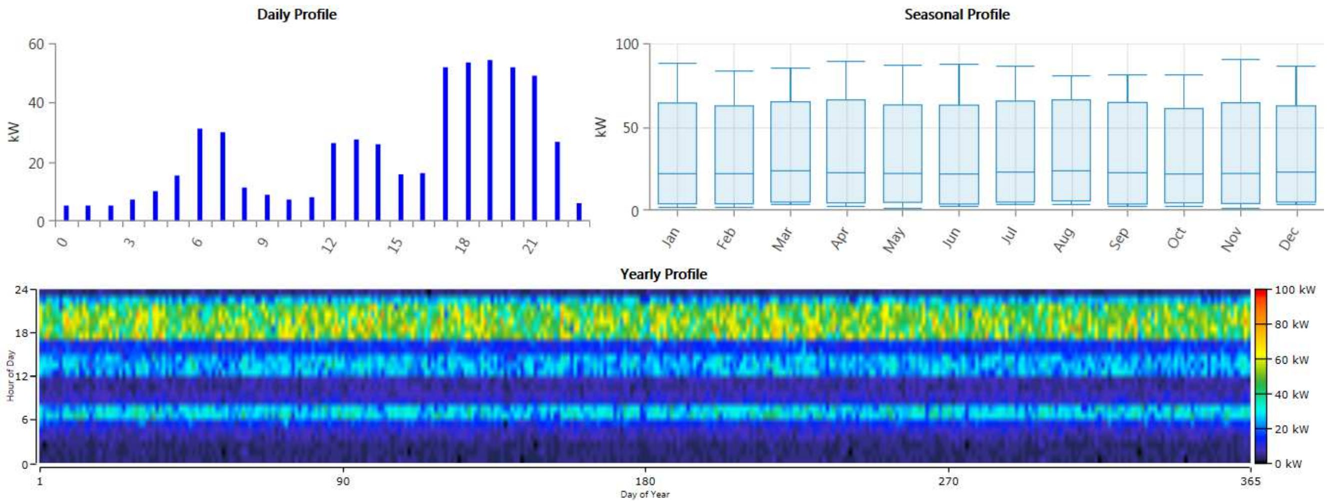


Figure 5. *Load profile of the community.*

3. System Description and Modelling

3.1. Description of HPBU-HRES

The general structure of the proposed hydropower backed-up HPBU- HRES for the site is shown in Figure 6. It consists of a hydropower plant (HPP), solar photovoltaic (PV) array, battery bank storage system (BSS), and power converter (PC). Although diesel generator is usually used as a backup solution, since it is associated with harmful emissions impact, and high operating and maintenance costs, it was not added as a backup source. To ensure the stability of the RE based hybrid system, an HPP is assumed present in all considered configurations as a backup plant to provide flexibility to deal with solar/wind variability. A battery storage system is included to sustain the power balance between generation and consumption and maximize the exploitation of renewable energy sources. Lastly, the power converter was added essentially to convert the PV DC output to the AC output required by the loads. The grid module existing in the architecture serves to help in modelling the breakeven grid extension distances.

3.2. System Technical Modelling

Comprehensive mathematical modelling of the hybrid system's different components can be found in the HOMER Pro user manual [31] or other previous research [15, 32, 33]. For every component of the system, a brief mathematical model describing the behavior of the component will be presented in the following subsections. Also, the financial modelling of the system will be presented.

3.2.1. Hydropower Plant (HPP)

The principle of electricity production from hydropower using a hydro turbine is founded on the conversion of the kinetic energy of moving water into mechanical power that is, then, transformed into electrical power by a generator. The equation used in HOMER to estimate the generated electrical power output by the hydro turbine is given as follows:

$$P_{e,HPP} = \eta_{HPP} \times \rho \times g \times Q \times H_{net} \quad (1)$$

Where η_{HPP}, ρ, g and Q represent the efficiency of the hydropower plant, the density of water, gravitational acceleration and streamflow rate respectively. An effective head and (H_{net}) can be calculated as follows:

$$P_{e,HPP} = H_{net} = H \times (1 - h_{loss}) \quad (2)$$

Where H symbolizes obtainable head and h_{loss} is the pipe head loss. For this study, design streamflow of 4630 m^3/s, a min and max flow ratio of 50 and 150% respectively. Efficiency and pipe head loss is set as 15 and 80% respectively.

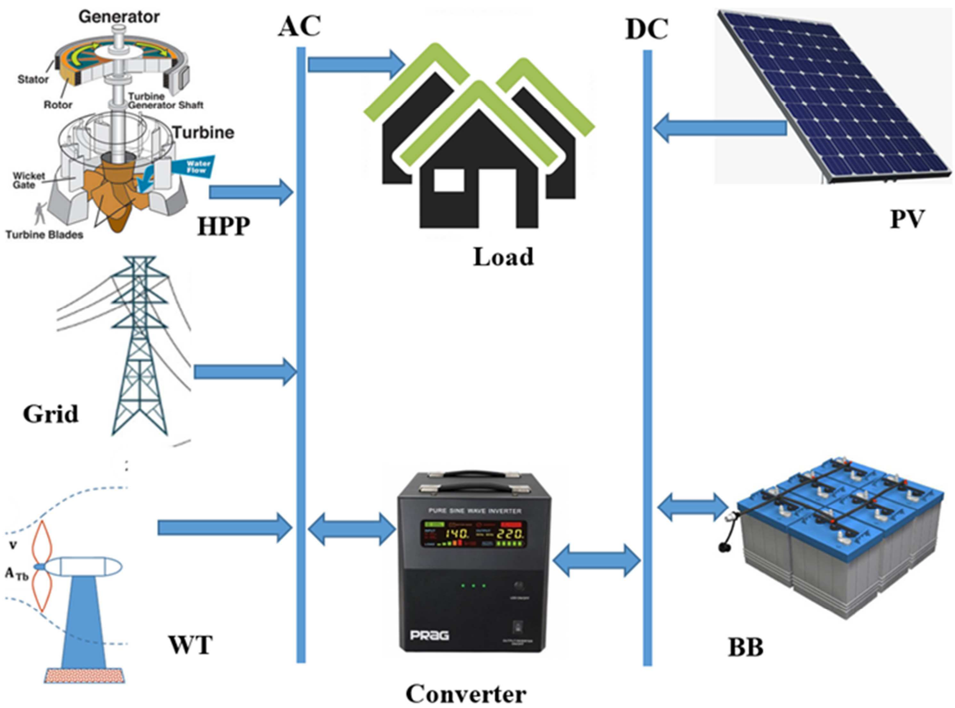


Figure 6. *Hydropower backed-up HRES.*

3.2.2. Solar PV

The generated power of PV modules depends on solar irradiance and environmental temperature. In HOMER, the following equation is used to calculate the PV output power [34]:

$$P_{PV-gen} = P_{PV} f_{PV} \times \left(\frac{G}{\bar{G}_{T,STC}}\right)\left[1 + \alpha_P (T_{cel} - T_{STC})\right] \quad (3)$$

Where P_{PV-gen}, P_{PV}, G, $\bar{G}_{T,STC}$, T_{STC} α_P and T_{cel} denote the power output by the PV module, the optimized PV panel capacity, solar irradiation on an inclined surface (W/m^2), the solar irradiation at the standard conditions (W/m^2), the cell temperature at standard conditions, the power temperature coefficient of the PV panel, and the cell temperature respectively [34]. The cell temperature can be calculated using the following:

$$T_{cel} = T_{amb} + ((((NOCT - 20)/800) \times G) \quad (4)$$

Where T_{amb} and NOCT denote the environment and the normal operating cell temperature in ℃ respectively.

3.2.3. Wind Turbine

The mechanical power output (P_{WT}) by a wind turbine varies directly with the swept area of the blades (A), the actual air density (ρ), the wind speed (v) and the power coefficient or rotor efficiency (Cp). When the speed of the wind is steady, the output power of the wind turbine (P_{WT}) is calculated as follows:

$$P_{WT} = \frac{C_p(\lambda,\beta)\rho A v^3}{2} \quad (5)$$

The power coefficient C_p, is not a static value as defined above; it varies non-linearly with the tip speed ratio, λ and blade tip angle θ of the turbine. For a given turbine, the coefficient $C_p(\lambda,\beta)$ is calculated using the following mathematical approximation [35]:

$$C_p(\lambda,\beta) = C_1(C_2/\lambda_i - C_3\beta - C_4)e^{-C_5/\lambda_i} + C_6\lambda \quad (6)$$

$$\lambda_i = \left(\frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta^3+1}\right)^{-1} \quad (7)$$

The constants C1 to C6 are; C1 = 0.5176, C2 = 116, C3 = 0.4, C4 = 5 and C6 = 0.0068.

Where $\lambda = v_b/v$, v_b is the blade tip speed (ωR), ω is the angular velocity and R is blade height. The Variation of power coefficient with tip speed ratio and blade angle for a typical turbine is shown in Figure 7.

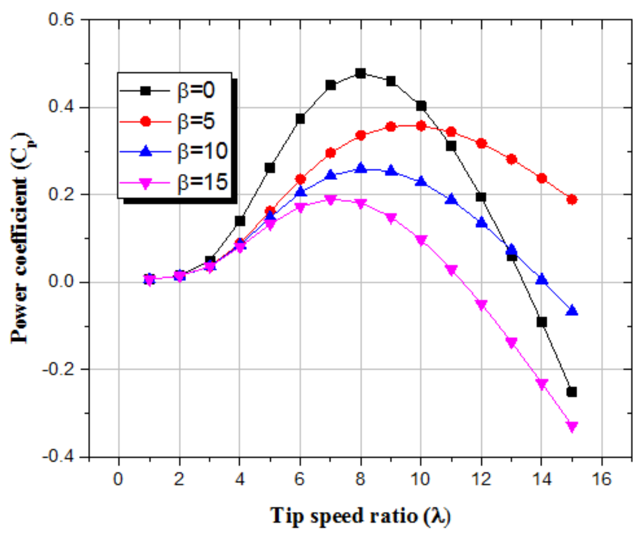


Figure 7. *The curve of power coefficient versus tip speed ratio.*

As can be observed, there is a value of λ and β, for which C_p is maximized, thus maximizing the power for a given wind speed. This maximum value of C_p (C_{pmax} = 0.48) is attained at β = 0 degrees and λ = 8.1 for the site. HOMER calculates the electrical power output of the WT based on the following equation [31]:

$$P_{WT} = \frac{\rho}{\rho_o} P_{WT,STP} \quad (8)$$

Where $P_{WT,STP}$, ρ and ρ_o denote the wind turbine power output at standard temperature, and pressure [kW], the actual air density [kg/m^3], and the air density at standard temperature and pressure (1.225 kg/m^3) respectively.

3.2.4. Battery System

The function of the battery bank is to ensure an uninterruptible supply of loads during periods of low power production. The size of the battery is primarily dependent on the everyday load demand (E_{load}) and the length of time (t) necessary for the battery to supply this load, in the lack of enough power from the HRES. The battery bank (BB) is charged by storing any excess power from the RE sources. It is discharged when the load demand is more than the total available power generated,

The obtainable BB size at a time (t) in the charging process can be described as follows [21]:

$$E_{BB}(t) = E_{BB}(t-1)(1-\varphi) + \left(E_{HRES}(t) - \frac{E_{load}(t)}{\eta_{inv}}\right)\eta_{BB} \quad (9)$$

In the discharging process, the BB size at any time (t) can be expressed as follows [21]:

$$E_{BB}(t) = E_{BB}(t-1)(1-\varphi) - \left(\frac{E_{load}(t)}{\eta_{inv}} - E_{HRES}(t)\right) \quad (10)$$

Where $E_{BB}(t)$ and $E_{BB}(t-1)$ is the available battery bank capacity (kWh) at periods t and t-1, correspondingly, $E_{HRES}(t)$ is the total power output by the HRES at time t, φ is the self-discharge rate of the battery, η_{BB} *and* η_{inv} are the efficiency of the battery bank and the inverter respectively.

3.2.5. The Converter (Conv)

The converter in the HRES architecture links both the DC and the AC bus. It operates as an inverter to transform voltage from DC to AC required by the building loads, and as a rectifier to change the voltage from the HPP from AC to DC to charge the BB. The required capacity of the inverter is calculated in HOMER based on the energy flow from the DC to AC as follows

$$E_{out}(t) = E_{in}(t) \times \eta_{inv} \quad (11)$$

Where E_{in} *and* E_{out} denote inverter input and output power respectively and η_{inv} is the inverter's efficiency (95%).

3.3. Economic Modelling

The optimal size of the hybrid system is determined based on the lowest net resent cost (NPC) and cost of electricity (COE) produced by the system. The total NPC of the HRES configuration is the difference between the present value of all the costs (capital costs, replacement costs, O & M costs, fuel) and revenue (salvage value and electricity sales revenue) over the useful life of the system [31]. In HOMER NPC is calculated as follows [31]:

$$NPC = \frac{TAC}{CRF(i,t)} \quad (12)$$

$$CRF(\$) = \frac{i \times (1+i)^N}{(1+i)^N - 1} \quad (13)$$

$$i = \frac{r-e}{r+e} \quad (14)$$

Where; *TAC* and *CRF* denote the total annualized cost ($) and capital recovery factor respectively; *i* is the annual real interest rate (%); *t* is the yearly project lifetime; *N* is the number of years; *e* is the annual inflation rate *and r is* the nominal interest rate.

3.3.1. Cost of Electricity (COE)

The COE by definition is the average cost of produced power from the HRES in $/kWh. It can be calculated using the following equation [34, 36]:

$$COE\left(\frac{\$}{kWh}\right) = \frac{TAC}{AEO} \quad (15)$$

where *AEO* is the total annual energy output in kWh/year. The economic analysis of the system was implemented by assuming a project life of 25 years, an inflation rate of 2% and a real discount rate of 12.75% (nominal discount rate of 15%).

3.3.2. Breakeven Grid Extension

Apart from standalone systems, another way of supplying electricity to remote communities is through grid extension. Grid extension analysis is performed to compare the values of NPC and COE for pure extension against the optimal stand-alone systems. The grid extension under the advanced grid module of HOMER, is used and the results are presented in form of breakeven grid extension distance (D_{grid}). The grid break-even extension distance is the distance from the grid that equalises the NPC of both grid extension and the stand-alone system [31]. HOMER calculates the break-even grid extension distance using the following equation:

$$D_{grid} = \frac{C_{NPC} \times CRF(i,t) - C_{e-G} \times AED}{C_{cap,Gex} \times CRF(i,t) + C_{O\&M-Gex}} \quad (16)$$

Where C_{NPC}, AED, C_{e-G}, $C_{cap,Gex}$ *and* $C_{O\&M-Gex}$ denote total net present cost of the stand-alone power system ($), total annual electrical demand (primary plus deferrable) (kWh/yr), grid electric tariff [$/kWh], capital cost of grid extension ($/km) and O&M cost of grid extension ($/yr/km). Table 3 displays the initial technical specification of the components before optimisation in HOMER while the corresponding cost of the various components is shown in Table 4.

Table 3. *Technical parameters of the system.*

Components	parameter	value
HPP	Generic capacity (kW)	100
	Available head (m)	7.62
	Design flow rate (m^3/s)	4.63
	Efficiency (%)	80
PV	Rated capacity (kW)	59.95
	Operating Temperature (°C)	45
	Efficiency (%)	17.3
WT	Rated capacity (kW)	90
	Rotor diameter (m)	26
	Cut in/cutout speed (m/s)	2.7/20
	Hub height (m)	38
Battery (BB)	Nominal capacity (kWh)	51.6
	Nominal voltage (V)	12
	Round trip efficiency (%)	97
	Capacity ratio	0.298
Diesel generator	Capacity (kW)	90
	Fuel curve intercept (L/hr)	5.25
	Fuel curve slope (L/hr/kW)	0.238

Table 4. *Cost parameters of the system.*

Components	Parameter	Value
HPP	Capital cost ($/kW)	1700
	Replacement cost ($/kW)	500
	O&M ($/yr)	100
PV [37]	Capital cost ($/kW)	1500
	Replacement cost ($/kW)	1500
	O&M ($/kW/yr)	10
WT [37]	Capital cost ($/kW)	4000
	Replacement cost ($/kW)	3200
	O&M ($/kW/yr)	20
Battery [37]	Capital cost ($/unit)	176
	Replacement cost ($/unit)	176
	O&M ($/yr)	8
Converter [37]	Capital cost ($/kW)	300
	Replacement cost ($/kW)	300
	O&M ($/yr)	0
Diesel generator [21]	Capital cost ($/kW)	370
	Replacement cost ($/kW)	296
	O&M ($/hr/yr)	0.05
	Fuel price ($/L)	0.693
Grid [27]	Capital cost ($/Km)	15500
	O&M ($/yr/Km)	310
	Tariff ($/kWh)	0.17

3.4. Sensitivity Analysis

Numerous parameters used in this study are variable. A parametric sensitivity analysis is implemented to examine and analyse the impact of the changes in the key project parameters on COE and NPC. The parameters considered are the solar, wind, load data and cost of the system components. The sensitivity variables considered for wind speed (m/s) and annual average solar radiation ($kWh/m^2/day$) are the minimum and maximum values of their monthly values. The nominal (real) discount rate (%) is varied from 8-18 (5.88 – 15.69) while the annual average stream flow (m^3/s) is varied from 926 to 3,704. To account for any possible increase or decline in the community load, a future daily community load (kWh/day) variation by $\pm 50\%$ is considered.

4. Result and Discussion

4.1. Optimal Systems Technical Results

The best optimal configuration of a hydropower backed-up (HPBU) hybrid renewable energy system (HRES) for meeting the load (550.58 kWh/day with a peak of 90.67 kW) of a rural off-grid community of 273 households in Kwara State Nigeria is conducted in this study. A Comparison of the feasible HPBU-HRES with each other and with a base case diesel only and equivalent diesel engine backed-up (DEBU) hybrid renewable energy system including grid extension was conducted to access the savings or otherwise, that could result from the systems. The results of the modelling, optimization and techno-economic study conducted with HOMER software using monthly annual values of both hydro, solar and wind resource at the study area shows that three feasible configurations of a hydro based HRES are possible for the site with an annual output ranging from 1,642,979 – 1,749,272 kWh/yr. The details of the electrical characteristics for all feasible configurations ranked based on minimum NPC and COE are presented in Table 5. It is observed that the best optimal system (System 1) for the community is a combination of 184 kW of solar PV capacity, 4,545 kWh of battery capacity and 277 kW of hydro turbine (HPP) capacity. The second system hereafter called system 2 is a combination of 161 kW of PV, 4,493 kWh of battery bank (BB) capacity, 90 kW of wind turbine (WT) capacity, 277 kW of hydropower plant (HPP) generation capacity and 85.6 kW converter (Conv). The third system (system 3) consists of 3,718 kWh of BB, 180 kW of WT capacity and 277 kW of HPP. All the systems have a renewable fraction of 100%.

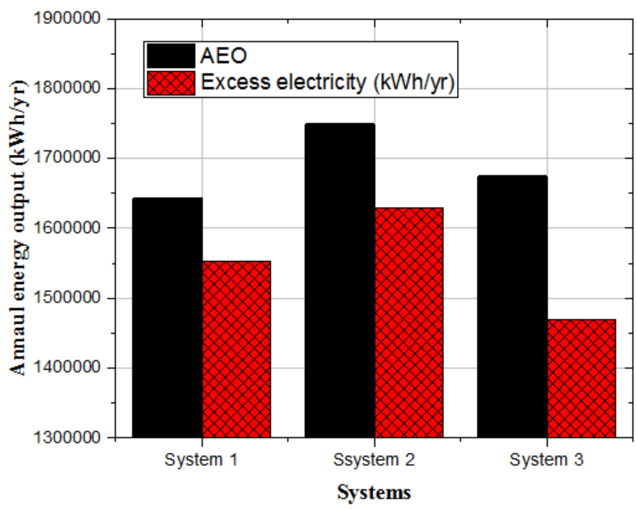


Figure 8. *Annual power output and excess energy by the optimal systems.*

Table 5. *Capacities and cost of the optimal architecture components.*

Architecture	Optimal Capacity of components (kW)	Dispatch	NPC ($)	COE ($/kWh)	Operating cost ($/yr)	Initial capital ($)	Unmet load (%)
PV/HPP/BB[a]/ Converter	183.7/276.9/88/81.3	LF	511012.9	0.34	3436.803	485391.1	0.017
PV WT/HPP/ BB[a]/ Converter	160.7/90/276.9/87/85.6	LF	847104.5	0.57	4700.458	812062	0.002
WT/HPP/ BB[a]/ Converter	0/180/276.9/72/74.3	LF	957268.8	0.64	4332.193	924971.8	0.029

[a] stated value for battery bank (BB) is quantity, not power rating.

System 1 produces a total power output of about 1,642,979 kWh per day with the HPP contributing about 1,447,022 kWh/day (88.1%) and the solar PV contributing 195,957 kWh/day representing 11.9% of the total annual output by the hybrid system. Figure 8 displays a comparison of the annual energy output (AEO) and excess energy (EE) by the three systems. It can be seen that the annual output by system 1 is less than that for systems 2 and 3 which are 1, 749,272 and 1, 674, 754 kWh/yr respectively. System 1 is the best system of the three systems despite producing the lowest annual output because the WT which has a high capital cost is not present in system 1 but in the systems 2 and 3, the presence of the WT increased the capital and operating costs which result to a higher NPC and COE than in system 1.

The WT contributes 6.5 and 13.6% of total power output in systems 2 and 3 respectively while for the HPP, the contribution is 13.6 and 86.4% of the total output for systems 2 and system 3 respectively. The excess electricity produced by the system stands at 1,533,414 kWh per year with an unmet electric load of 33.9 kWh/year representing a minimal 0.0169% and a capacity shortage of 170 kWh per year (0.084%). Figure 9 shows the time series plot of the total electric load served, total renewable power output and renewable fraction for system 1 in July. Observably, the total RE power output is more than the load most of the time accounting for the high excess energy of 1,533,414 kWh per year produced. The breakdown of the monthly contribution of the hybrid system components of systems 1, 2 and 3 in serving the electric load (peak of 91 kW) is shown in Figures 10-12. Observe that the HPP system did not output any power in all the systems in Jan-April and Dec because the HPP is acting as a backup power system and the output from the other power generation components (solar PV, WT or both) is enough to meet the load in those months.

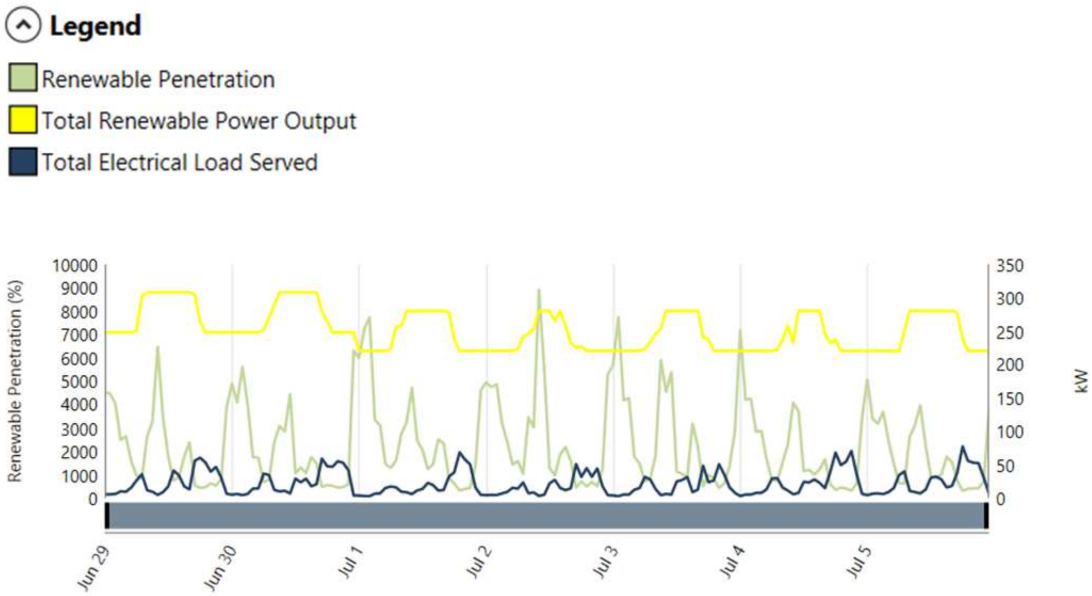


Figure 9. *The plot of RE output VS electric load.*

Table 6. *The technical performance of three optimal systems.*

Technical indicator	System1 PV/HPP/BB	System 2 PV/WT/HPP/BB	System 3 WT/HPP/BB
PV output (kWh/yr)	195,957	188,384	–
WT output (kWh/yr)	–	113,866	22,732
HPP output (kWh/yr)	1,447,022	1,447,022	1,447,022
Total output (kWh/yr)	1,642,979	1,749,272	1,674,754
Ac primary load served (kWh/yr)	200,928	200,959	200,954
Excess electricity (kWh/yr)	1,553,414	1,629,022	1,469,381
Unmet load (kWh/yr)	33.9 (0.02%)	3.13 (0.002%)	58.1 (0.03%)
Capacity shortage (kWh/yr)	170 (0.08%)	25.7 (0.01%)	197 (0.1%)

4.2. Three Optimal Systems Economic Results

The economic analysis results of the systems are summarized in Table 7. It can be seen the best system (system 1) has the lowest initial capital cost of $485, 391, NPC of $511,012.90 while COE stands at 0.3411 $/kWh at an operating cost of $3,436.80 per year. The COE of system 1 is higher than (almost twice) the prevailing fossil-based grid electric tariff in Kwara which ranges from 0.13 to 0.20 $ per kWh (55.76 – 69.2 N/kWh) [28] but lower than the COE for the use of only diesel generating set for meeting the load of the community which is about $0.473 per kWh for the study location. The COE of systems 2 and 3 are however higher than both the average grid tariff for Kwara in Ibadan DISCO (0.13 – 0.20 $/kWh) [28] and that for the use of only diesel generators for meeting the load of the study location.

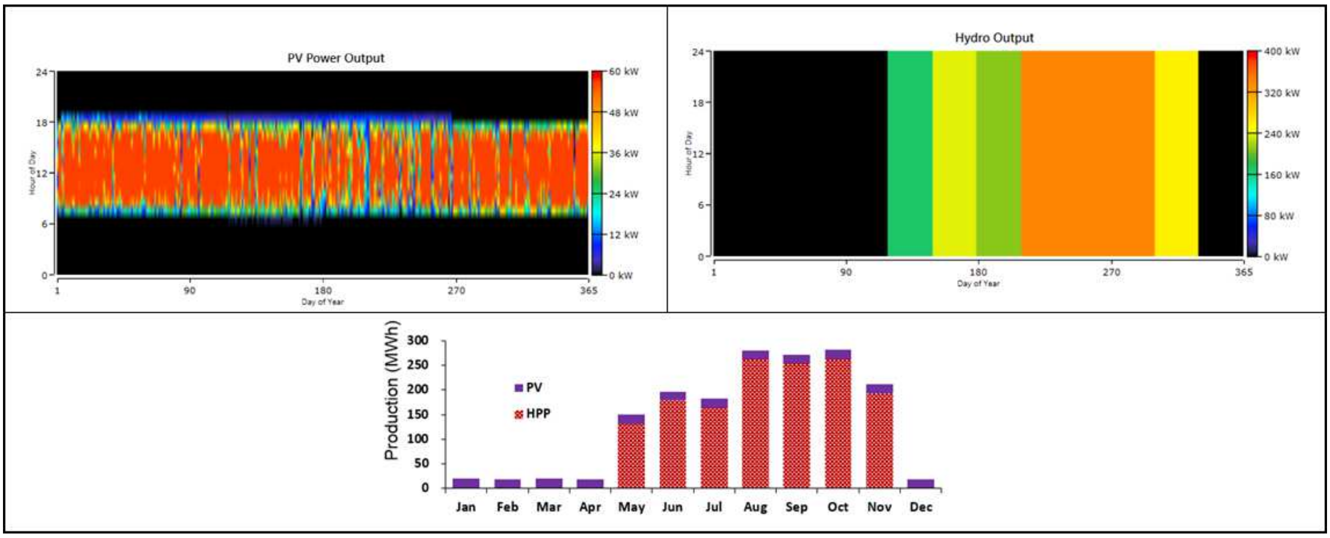


Figure 10. *The contribution of PV and HPP in serving the load of the community.*

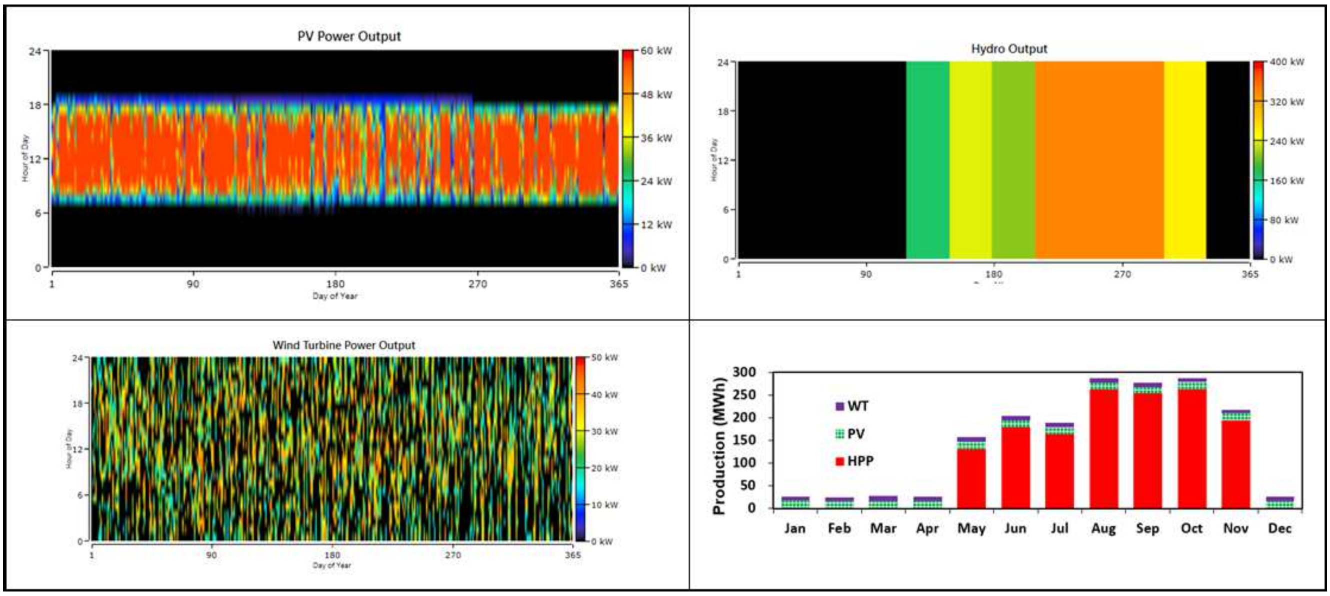


Figure 11. *The contribution of WT, PV and HPP in serving load of the community.*

When matched with system 1, it is observable that there is a 67 and 90% rise in the NPC of system 2 and system 3 respectively. This is because of the associated extra costs related to the presence of one and two WT components in systems 1 and 2 respectively which accumulated an operation and maintenance cost that is 59 and 62% more than that of system 1. The total initial cost (TIC) accounts for the highest percentage of the system's NPC followed by the O&M cost (see Table 7). The replacement cost is minimal because the lifetime of most of the system's components is within the operating life of the HRES.

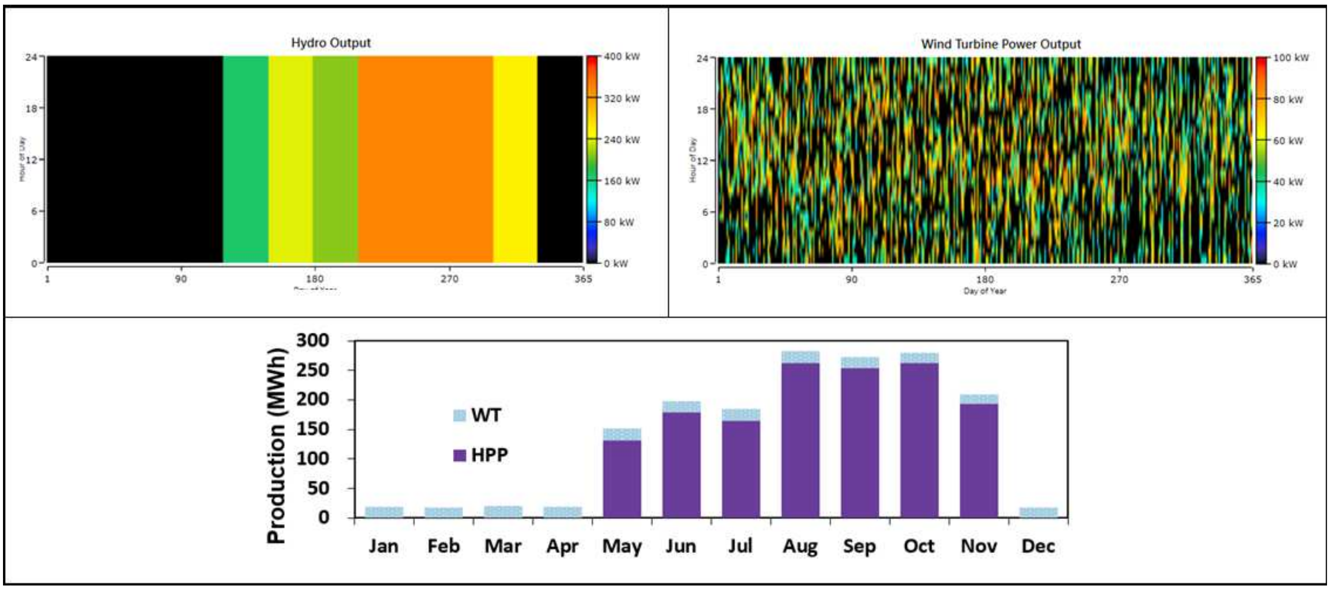


Figure 12. *The contribution of HPP and WT in serving load of the community.*

Table 7. *The technical performance of three optimal systems.*

Economic indicator	System1 PV/HPP/BB	System 2 PV/WT/HPP/BB	System 3 WT/HPP/BB
Total Initial cost ($)	485,391	812,062	924972
NPC ($)	511,013	847,105	957,269
COE ($/kWh)	0.341	0.565	0.639
Operating cost ($/yr)	3,437	4,700	4,332
O&M cost ($)	2,641	4,203	4,276

In system 1, the capital cost accounted for about 94% of the NPC. It is 96 and 97% for system 2 and system 3 respectively. The O&M cost accounted for 3.9, 3.7 and 3.3% for systems 1, 2 and 3 respectively. The configuration with the least O&M cost is as expected the hybrid PV/HPP/battery (BB) system with an O&M cost of $2,641. The next is the PV/WT/HPP/BB system with an O&M cost of $4,203. System 3 (WT/HPP/BB) has the highest O&M cost of 4,276 because of the high capital cost of WT. Also, system 1 has the highest replacement cost of $6,597.98 due to having the highest number of batteries (88). System 2 with 87 batteries has the next highest replacement cost ($6781.31) while system 3 with 72 batteries has the least replacement cost of $5,784.32. Notably, the system architecture having more number of batteries has the highest replacement cost owing to the high cost of batteries. Thus the quantity of batteries affects a system's cost. The percentage contribution of the various cost components (PV, WT, HPP, BB and Inverter (INV)) of the hybrid systems to the total initial capital, replacement and O&M costs of the systems (1-3) is depicted in Figure 13.

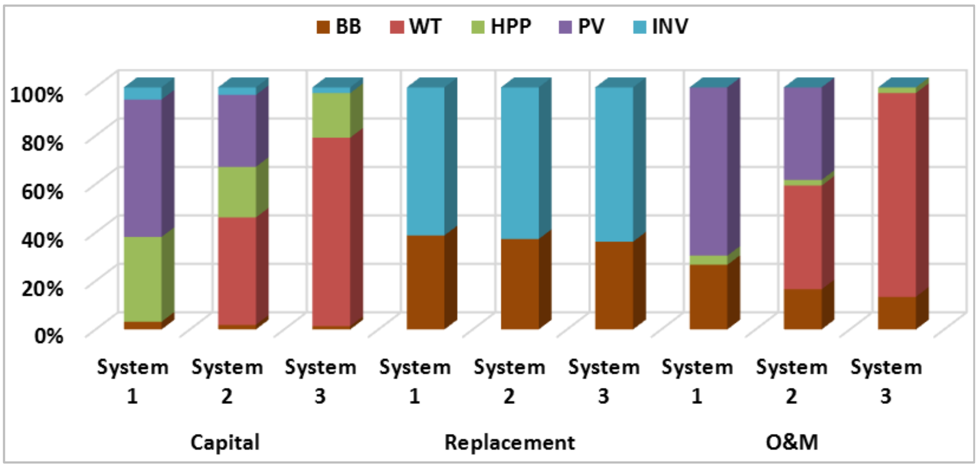


Figure 13. *Components contribution to system costs.*

Observably, the solar PV accounted for the highest (56%) of the TIC in system 1 whereas it is the WT in systems 2 and 3; accounting for 44 and 78% of the TIC respectively. The inverter accounted for the highest percentage (about 61%) of the total replacement cost in all the systems. The trend of the capital cost is replicated for the O&M cost, whereby the PV accounted for the highest percentage (70%) contribution of total O&M cost in system 1. The wind turbine has the highest percentage contribution of the O&M cost in systems 2 and 3 amounting to 43 and 84% respectively.

4.3. Comparison with Grid Extension

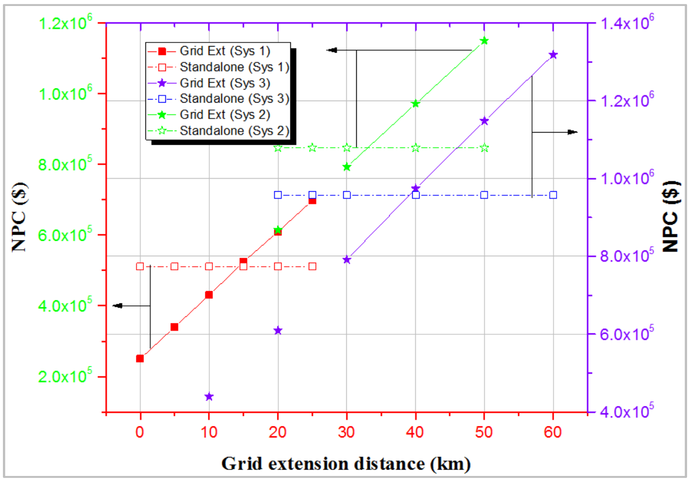


Figure 14. *Grid extension distance VS NPC.*

The COE of the HPBU mini-grid system analysed for this community is also matched with the average grid electric tariff in Nigeria to determine where the hybrid system can be a cost-optimal solutions in comparison with the grid extension. Based on a grid extension cost of $15,500 per km and O&M cost of $310/year/km [27], the break-even extension distances for systems 1, 2 and 3 were determined as 14.39, 29.06 and 30.24 km respectively as shown in Figure 14. This means that systems 1, 2 and 3 can be used for remote villages which are more than 10.2, 29.1 and 30.2 K km away from the existing grid respectively. On the other hand, if the community is presented with a choice between grid extension and any of the standalone systems, system 3 will better serve the community as a standalone system than grid extension since it is farthest away from the grid. According to HOMER [31], the closer to the grid, the grid extension is optimal. Far away from the grid, the standalone system is optimal.

4.4. Comparison with a Diesel-Only System

Since the study location has no access to grid electricity, a 90 kW diesel generator set to supply the electrical load requirement of the off-grid community was considered as the base case system. The plot of the time series data of the generator output is shown in Figure 15. The DEG which has an electrical efficiency of 24.7% produces an AEO of 264,544 kWh/yr at a mean output of 30.2 kW. The excess electricity stands at 63,583 kWh/day (24%) at a fuel consumption of 12.4 L/hour (298 L/day) and a capacity factor of 24.7%. Its NPC and COE are $708,859.10 and 0.4731 $/kWh respectively.

Comparing system 1 with the base case system (DEG system) with operating costs of US$90,617 per year indicates that the hybrid system would reduce the operating costs to US$3,437/yr which amounts to a savings of about $87,180 per year or $0.053 for every kWh of electricity produced. The return on investment of the project is 15.2% at the internal rate of return of 18.8% and simple (discounted) payback of 5.33 (8.93) years. Global warming (which results from the emission of CO_2 by fossil power plants) and its associated concerns have been recognized globally as an area of worry for sustainable electricity generation. The quantity of diesel fuel saved by the HRES is 108,893 litres. This gives rise to avoided emission of 288,116 kg of CO_2 and 714 kg/yr of Sulphur Dioxide into the air. Figure 16. Shows the comparison of the return on investment (ROI) and simple payback period (SPB) for the three systems. Notably. System 1 has the lowest SPB and highest ROI of the three systems followed by System 2 in that order.

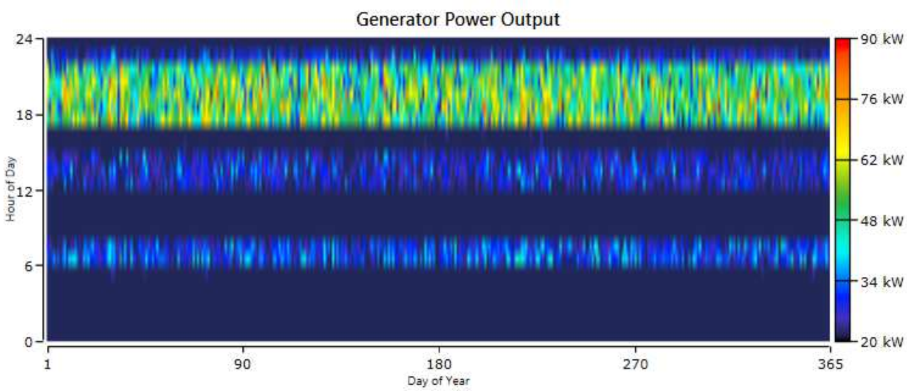


Figure 15. *Time series of DEG output.*

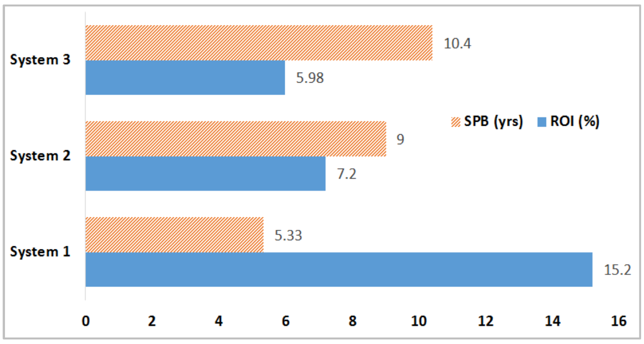


Figure 16. *The plot of SPB and ROI for all systems.*

4.5. Comparison with a Grid Electricity

The average grid electric tariff in Ibadan DISCO where the study location is cited ranges from 0.13-0.17 $/kWh. Thus it is seen that the proposed system's COE is more than the current grid electric tariff in the region. This is expected since the tariff in Nigeria is currently subsidized by Government and not cost-reflective. In the future, as the subsidy on tariffs is fully removed, the COE of the proposed system is expected to better that of the grid. In terms of environmental benefits, the three systems have 100% renewable fractions and thus have no operational emissions. To quantify the environmental benefits accruing from the use of the proposed systems, a comparison is made with the grid. Using a CO_2 grid emission factor of 0.4396 kg/kWh for grid electricity in Nigeria [39], the total CO_2 that will be produced by the grid to serve the total AC primary load demand of approximately 200,962 kWh is 88,342 kg/yr. It is observed that the configuration of HRES offered in this work is sustainable in comparison to grid electricity and will lead to a CO_2 savings of 88,342 kg/yr which will go a long way in helping Nigeria meet its target of unconditionally reducing GHG emissions by 20% in the year 2030.

4.6. Comparison with a Diesel Engine Backed-up-Hybrid RE System

A simulation and optimization study was carried out for an equivalent diesel engine backed-up (DEBU) hybrid renewable energy system (HRES) alternative to the HPBU-HRES simulated in this work based on the same conditions to compare their performances and emission savings. In the DEBU-HRES architecture, the HPP in the HPBU-HRES is replaced with a diesel engine generator (DEG). Table 8 shows the performance of the DEBU-HRES systems. The results of the simulation and optimization in HOMER Pro show that the first best Diesel backed-DEBU-HRES for the site is made of solar PV, Diesel engine generator (DEG), Battery bank (BB) and converter (Cov) with annual energy output (AEO) of 211.99 MWh at a COE of 0.24 $/kWh as shown in Table 8. This COE is less than the COE of all the optimal HPBU-HRES systems simulated in this study. The second and best DEBU-HRES for the site is PV/WT/DEG/ BB/ Conv with a COE of 0.38 $/kWh and WT/DEG/ BB/ Conv with a COE of 0.44 $/kWh. It is observed that the COE of the HPBU systems is generally higher than their equivalent DEBU-systems. However, the DEBU systems have substantially lower renewable fractions and thus emit significantly more emissions than those from the HPBU systems. Also, the annual energy output of all the HPBU systems is generally lower than their equivalent DEBU-systems as can be seen in Table 8.

Comparing the best DEBU systems with their equivalent HPBU systems, it can be observed from Table 8 that PV/DEG/BB/Conv system emits SO_2 and CO_2 emissions of 133 and 53, 88 kg per hour respectively while the PV/HPP/BB/ Conv has no operative emissions. Also the use of PV WT/HPP/ BB/ Conv and WT/HPP/ BB/ Conv in place of the equivalent HPBU systems results to environmental emission reduction of 27,004 and 107, 138 kg/hr of CO_2 respectively. The reason for the higher environmental emissions of the DEBU systems is because of the higher RFs of the HPBU systems (100%) compared to the DEBU systems which range from 52 to 88%. Among the first three optimal DEBU systems, the WT/DEG/ BB/ Conv produced the highest emissions followed by the PV/DEG/BB/Conv. This is because the WT/DEG/ BB/ Conv has the lowest renewable fraction (52.6%) followed by the PV/WT/DEG/ BB/Conv with a RF of 88.9%. From Table 8, It can be seen that the emissions of CO_2 by the latter stand at 107, 138 kg/yr, whereas for the former, the CO_2 emitted is 53, 88 kg/yr. The same similar tendencies are also observed for the SO_2 emissions. Thus, the execution of the proposed hydro backed-up hybrid RE systems brings about significant savings in CO_2 pollution against the diesel-only and diesel backed-up hybrid systems having battery bank storage systems.

Table 8. *Comparison of performance of DEBU-HRES with HPBU-HRES.*

Architecture	Optimal Capacity of components (kW)	COE	System output		Emissions	
		($/kWh)	Ren Frac (%)	Elec Prod (MWh/yr)	CO_2 (kg/yr)	SO_2 (kg/yr)
PV/DEG/BB[a]/Conv	116./90/233/54.8	0.24	77.3	211.99	53,808	133
PV/HPP/BB[a]/ Conv	183.7/276.9/88/81.3	0.34	100	164.3	—	—
PV/WT/DEG/ BB[a]/ Conv	50.5/90/90/19/56.0	0.38	88.9	222.10	27,004	67
PV WT/HPP/ BB[a]/ Conv	160.7/90/276.9/87/85.6	0.57	100	174.9	—	—
WT/DEG/ BB[a]/ Conv	0/90/90/8/35.1	0.44	52.6	209.09	107,138	266
WT/HPP/ BB[a]/ Conv	0/180/276.9/72/74.3	0.64	100	167.5	—	—

[a] stated value for battery bank (BB) is quantity, not power rating.

4.7. Sensitivity Analysis Results

Figure 17 displays the impact of solar radiation variation and future electrical load growth on optimal system type (PV/HPP, PV/WT/HPP, and WT/HPP) and COE at an average wind speed of 5.25 m/s. The diamonds in the diagram show the COE, and the colour of each diamond designates the system type that is optimal for that sensitivity case. As the mean solar radiation increases at an average load that is ≤601.38 kWh/day, the optimal system type remains system 1 (PV/HPP/battery). However, at an average load that is ≥670 kWh/day and the same range of solar radiation, the optimal system type becomes system 2 (PV/WT/HPP/battery). The COE changes at different load demands with both constant and varying solar irradiation. For instance, at 5.74 kWh/m^2/day of solar irradiation and an average annual wind speed of 4.25 m/s, the COEs vary from 0.359–0.471$/kWh when demand load varies from 305 kWh/day to 911kWh/day. A change in the solar radiation from 4.25 to 6.25 kWh/m^2/day resulted in a reduction in COE by about 13, 15 and 18% at different load demands of 305, 426.2 and 547.4 kWh/day respectively for system 1. Thus based on the assumptions used in this analysis, system 1 (PV/HPP-BB) is the optimal system for small to medium loads ($\leq 600\ kWh/day$), irrespective of the solar radiation. To a government or an energy planner intending to deliver electricity to various un-electrified populations in an emerging Nation, the analysis reported in this research could help choose what type and size of micro HRES to deploy for diverse sites based on the size of the load and average occurring wind, hydro and solar radiation of every location.

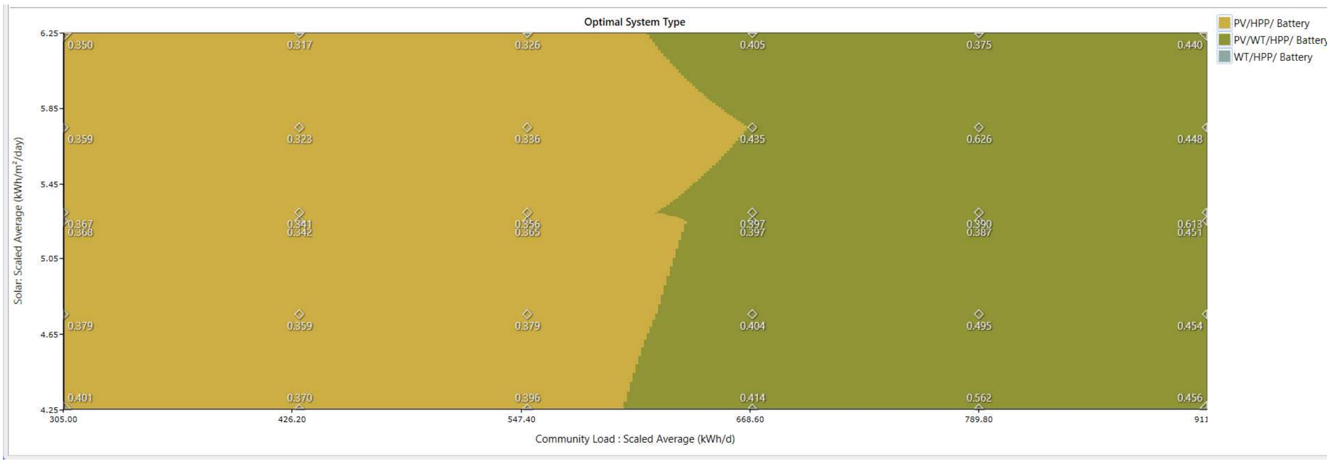


Figure 17. *Effect of solar irradiation and load demand.*

In addition to the load, wind speed and solar radiation, the sensitivity analysis is defined for capital cost, nominal discount rate and mean stream flow rate. The effect of change on project initial investment for system 1 reveals that a 50% decrease in the total initial price of the system will lead to a decline of COE to $0.177 per kWh at a corresponding NPC of $3,029. Also, the surface plot of the impact of change in the nominal discount rate (NDR) and PV capital cost on the COE superimposed with NPC is shown in Figure 18.

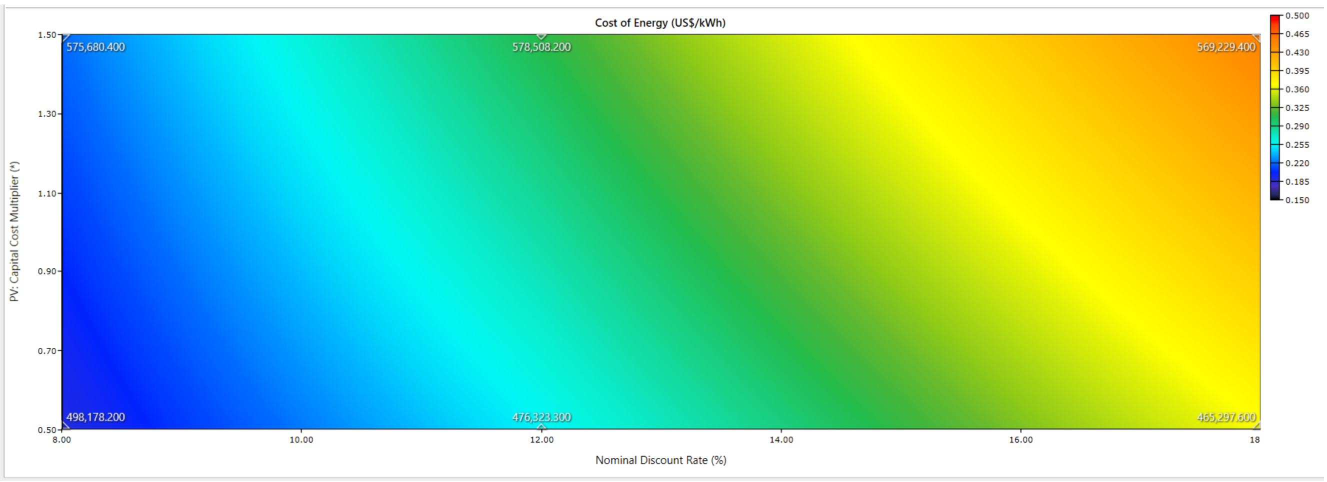


Figure 18. *Sensitivity of discount rate and PV cost on COE and TCC.*

The diamonds represent the NPC ($) while the colour codes represent the COE in $/kWh. Observe that the NDR and PV capital costs are proportionally related to the COE and NPC. A simultaneous reduction of the NDR by 46.6% to 8% and PV cost by 50% will result in a COE of about 0.18 $/kWh which is almost equal to the average grid electric tariff in Nigeria. Its corresponding NPC is $498,178.2. On the other hand, a simultaneous increase of the NDR by 20% to 0.18 and a reduction of PV cost by 50% results in a COE of about 0.4 $/kWh and NPC of $465,297.6. Thus the NDR has a greater effect on COE than PV capital cost.

5. Conclusion

In this paper, a design, optimization and economic analysis of a hydropower backed-up (HPBU) hybrid renewable energy system (HRES) with 100% renewable fraction for meeting the electrical load demand of 550 kWh/day and with a peak of 91 kW for a rural off-grid community located in Ifelodun Local Government Area of Kwara State Nigeria using HOMER Pro software have been carried out. The resources assessment study of this location reveals that the average annual wind speed, solar radiation and hydropower are 4.25 m/s at 10m height, 5.30 kWh/me/day and 4,629 L/s respectively.

Based on the average values of both hydro, solar and wind resource in this location and project life of 25 years at a real discount rate of 12.75% and inflation of 2%, it was determined that three feasible configurations of a HPBU-HRES is possible for the site with an annual output ranging from 1,642,979 – 1,749,272 kWh/yr at a cost of electricity (COE) ranging from 0.34 –.0.64 $/kWh. The best optimal HPBU-HRES (system 1) to meet the electric load of the rural community in terms of the lowest cost of electricity (COE) and net present cost (NPC) is a combination of 184 kW of solar PV (PV), 4,545 kWh of battery capacity (BB), 81.3 kW of converter (Conv) and 277 kW of hydro generation capacity (HPP). The second optical system (System 2: PV/WT/HPP/BB/Conv) is a combination of 161 kW of PV, 90 kW of wind generation capacity (WT), 277 kW of HPP, 4,493 kWh of BB and 85.6 kW of Conv whereas the third system (system 3: WT/HPP/BB/Conv) consists of 180 kW of WT capacity, 277 kW of HPP and 3,718 kWh of BB. These systems were analyzed, and the subsequent conclusions could be inferred

1) The COE of system 1 (0.341 $/kWh) is higher (almost twice) than the prevailing fossil-based grid electric tariff in Kwara in Ibadan DISCO which ranges from 0.13 to 0.17 $ per kWh but is lower than the COE for the use of only diesel generating set for, meeting the load of the community which is about $0.473 per kWh for the study location.
2) The COE of systems 2 and 3 are higher than both the average grid tariff for Ibadan DISCO and that for the use of only diesel generators for meeting the load of the study location.
3) Break-even extension distances analysis results show that systems 1, 2 and 3 can be used for remote villages which are at a minimum of 14.4, 29.1 and 30.2 K km away from the grid respectively.
4) The CO_2 emission savings from the proposed systems relative to a diesel-only, grid and an equivalent best diesel backed up hybrid renewable energy systems for the site are 288,116, 88,342 and 53, 88 kg/yr respectively.
5) Load scalability and solar radiation variation analysis results show that system 1 (PV/HPP-BB) is optimal for small to medium load ($\leq$ 600kWh/day), irrespective of the solar radiation in the site. While the system 2 option is found to be more economic at larger loads ($\geq$ 650 kWh/day).

Since solar, and hydropower resources are locally abundant in this rural off-grid location, the utilization of the proposed hydro based hybrid renewable energy system can be appropriate to power the remote rural community, delivering better resource utilization for energy production in a sustainable way. These results could be extended to so many areas where the conditions of the available energy resources are similar. Also, the implementation of the proposed system will help Nigeria to achieve its mission of unconditionally reducing GHG emissions by 20% by 2030. For a wide acceptance and use of the technology, the Nigerian Government should make available incentives or necessary supporting policies to interested investors that will lead to the overall reduction in investment costs and hence COE of the system.

The results of the present research on HRES have focused mainly on the optimal design and dispatch of HRES plant components to minimize total plant costs while satisfying the specified load demand. No attention has been given to the impact of the economic dispatch of HRES plants on system dynamic performance. In the future, this approach may violate system dynamic limits when a considerable number of integrated HRES plants dominate the power system. In this sense, strategies based on Artificial Intelligent Techniques and dynamic modelling of each unit in the HRES plants using detailed data may be required to find out the optimal configuration based on the perspective of both economy and system dynamic behaviour. Also, future research is needed to make the adoption of HRES technically feasible especially in the rural areas of developing countries. The improvement of the cost of the system and its output should form the key focus. To improve the energy access, duration, stability and efficiency at the nationwide and state level in Nigeria, off-grid and grid hybrid renewable energy technology systems should be promoted using different mechanisms including subsidy.

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