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Feasibility Study and Sustainability Analysis of Off-Grid PV/Wind/Battery/Small-Hydro/Diesel Hybrid Energy System for a Typical Remote Location

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ABSTRACT

The notion of hybrid renewable energy system (HRES) has been globally accepted as a means of electrifying remote or electricity-deficient regions based on their geographical locations. The techno-economic viability of photovoltaic (PV), wind turbines (WT), hydro, battery system (BS) and diesel generator (DG) HRES is proposed in this paper for an islanded power system by using HOMER. The sustainability of the HRES has been examined by using significant performance metrics such as net present cost (NPC), emissions, fuel consumption, cost of energy (COE), etc. The performance of the base system and HRES is carried out through technical, economic and environmental analysis; and the optimized solution is carefully chosen using minimum NPC and COE. The results obtained from the simulation demonstrate that scenario 2 has NPC of \$77,164 and COE of \$0.0925/kWh, which are 91.59% and 91.59% lower than the base system. The HRES is considered to be the most ecologically friendly configuration with fuel consumption of 453 L/yr, renewable fraction of 98%, CO_2 of 1,184kg/yr, SO_2 of 2.9 kg/yr and NO_x of 6.56 kg/yr. The outcomes of the research show that PV/DG/WT/hydro/BS HRES is the most viable solution and preferred choice for standalone rural electrification projects when compared to the base system.

1. INTRODUCTION

A significant fraction of the global population resides in isolated, thinly inhabited remote locations that have no connection to the utility grid due to topography terrain, political constraints and economics of scale

(Adefarati *et al.,* 2021). This has prompted independent power providers to utilize renewable energy sources in place of traditional electrical energy production methods to supply electricity to rural communities (Adefarati *et al.,* 2024). The inclusion of renewable energy resources in the conventional power system has made substantial progress in the improvement of access to electricity in recent years (Nsafon *et al.,* 2020). Access to electricity has become a global phenomenon because it alleviates abject poverty in society, promotes economic development and improves standards of living. Thus, estimating the share of the population that has access to electrical power is a crucial social and economic metric. The percentage of individuals who have access to electrical power worldwide increased from 87% in 2015 to 91% in 2021, benefited approximately about 800 million people (Ritchie *et al.,* 2024). Presently, 733 million individuals globally lack access to electricity; most of these people are living in remote communities. The population of sub-Saharan Africa (SSA) is growing faster than the region's energy infrastructure, resulting in a greater number of people living without power than in prior years. To achieve SAS 2030 target of providing affordable power to everybody, 90 million people must be connected annually to the utility or hybrid energy system in a threefold increase over previous years. About 600 million people or 43% of the SSA's total population do not have access to an electric power supply (IEA, 2022). The absence of electricity in remote communities of many African countries has adversely affected socio-economic development and standard of living. The standard of living of rural dwellers can be improved through standalone systems that are the most practical options for more than 80% of people without access to electricity in rural areas. The electricity access rate in Nigeria is very low where 40.8% of the entire population lack access to electricity and power interruption frequently affects those who do have access. The electricity access in urban and rural populations is estimated to be 89.2% and 26.3% (World Bank, 2023). The abovementioned challenge has a considerable adverse effect on commercial activities and the industrial sector in Nigeria. As a result, small and medium-sized businesses have been forced out of business. It has also hindered the ability of small enterprises to come up with creative ideas and generate employment.

The power deficit created by an imbalance between power demand and power supply has sporadically led to the utilization of fossil fuels for production of electricity, which would increase greenhouse gas emissions and contribute to global warming (Adefarati *et al.,* 2021b). Thus, to combat climate change caused by human activities, further improvement of renewable energy is required. It has been reported that there have been substantial increases in the application of green energy technologies to reduce electricity deficit in rural communities and isolated areas (Nsafon *et al*., 2020). Rural dwellers are subject to a lot of hardship associated with a lack of electricity owing to the non-connection of their communities to the utility grid, geographical barriers such as steep terrain, dense jungle and rivers. Access to electricity in the local community can be improved with the usage of green energy technologies such as hydropower, solar, wind, tide and biomass based on the following benefits: reduced carbon emissions, readily available, improved reliability and security of power system, reduced cost of energy, creation of job opportunities, improved cost savings, clean and affordable source of electricity, inexhaustible supply, low operation and maintenance costs and accessible and easy to obtain (Filho *et al.,* 2021). The embedded operation of multiple sources of energy inform of hybrid energy system (HES) can be utilized to increase the power supply's reliability at the load points (Adefarati *et al.,* 2019a). The HRES is a cost-effective and efficient way of meeting the load requirements by using localized green energy resources and DG as a standby unit or backup to supply uninterrupted power supply to rural dwellers. Access to electricity in rural communities through HRES can be used to improve the standard of living and boost commercial activities (Oladigbolu *et al.,* 2020). As a means of supplying isolated areas where the development of the distribution network is impractical, the usage of HRES running on a combination of energy sources is growing owing to the following benefits: optimal utilization of renewable energy resources, high efficiency, cost savings, continuous power supply, scalability and adaptability, energy storage and flexibility, environmental benefits, load management and increased energy independence. The security challenges that the Nigerian government is currently facing can be overcome by increasing the access to electricity in rural areas. The technical effects of intermittent nature or uncertainties of renewable energy sources on the sustainability of power supply can be reduced with the incorporation of fuel cells and battery systems into the conventional power system, to improve efficiency and remove flaws associated with power deficit at the load points (Agarwal *et al*., 2013). The geographical location and accessibility to local renewable energy sources as well as financial and technical limitations are the primary determinants that affect the sizing of HES components. The application of HES in a standalone power system has become a cost-effective and potential power solution to meet power demands when compared to fossil fuels-based conventional power sources (Sari *et al.,* 2022). The best way to design HRES and provide more efficient and economical outcomes is a key topic of discussion. The optimal planning and design of HRESs has become a major challenge from an economic and technical perspective based on irregularities of local renewable energy resources and their dependence on seasonal variation. The sizing of HES components to satisfy the required power demand is often either undersized or oversized. An undersized HES will not be able to provide enough electricity to the necessary loads. On the other hand, oversized systems produce excess power supply with considerable capital cost, operation and maintenance (O&M) costs, replacement cost, etc. The combination of optimal sizing of HRES components and strong power flow coordination among the components of the power system is necessary to fully reap the benefits of renewable energy in HES (Oladigbolu *et al.*, 2021).

Several studies have been examined performance and optimization aspects of the hybridization of traditional power system and renewable energy resources, as well as other important factors that are relevant to the operation of power systems. Hence, numerous studies have been conducted on this topic. Sofimieari *et al,* (2019) proposed HOMER for the analysis of a PV/WT/DG HES designed for a remote area electrification project in Kaduna, Nigeria. The PV/WT/DG HES presented in the study is found to be the most optimal configuration, financially viable and ecologically friendly owing to significant savings in the COE and reductions of emissions. He *et al.,* (2023) developed a genetic algorithm for the optimization of an islanded HES that comprises PV, a bio-generator, DG and BSS with the objective of reducing the annualized cost of the system (ACS). The outcomes of the study indicated that HES is a financially sensible way to satisfy the load demand while satisfying the system constraints. Dong *et al.,* (2016) proposed ant colony optimization method to improve the reliability and reduce the COE of a standalone PV/WT/BSS/FC HES. In another study, Aziz (2017) studied the financial feasibility of several HESs that are designed to supply electricity to a camp in the United Arab Emirates using HOMER. The author established from the outcomes of the study that combination of PV, WT and BS is the most efficient option. Kolhe *et al.,* (2015) implemented the techno-economic assessment and optimal sizing of HES that consists of WT, PV, BS and DG. The designed HES was meant to supply uninterrupted power to a remote area in Sri Lanka at minimal cost of energy ($ 0.34/kWh). Bukar *et al.,* (2019) applied the grasshopper optimization algorithm to ascertain the best architecture of a microgrid system that comprised DG, PV, WT and BS with minimum cost of energy. Diab *et al.,* (2019) applied meta-heuristic optimization methods to select the optimal configuration of HES that has the following components: PV, WT, DG and BS. According to the comparison analysis based on the four meta-heuristic optimization methods, the whale optimization method produced the best results in terms of the COE and reliability of the system. Suryoatmojo *et al.,* (2009) applied genetic algorithm for the optimization of DG/PV/BS HRES designed for isolated islands and remote communities. The optimization model minimized the ACS. Belfkira *et al.,* (2011) presented a direct algorithm to determine the optimal sizing of standalone DG/PV/WT HRES designed for satisfying the power demand of isolated islands and remote areas in Dakar, Senegal. The outcomes of the research indicate that WT/PV/DG HES is the most effective and environmentally friendly solution to satisfy electricity needs of the selected sites. In the related study, Askari *et al.,* (2012) examined the technological-economic viability of PV/WT HES by changing the WT's hub height and PV module sizes.

The viability and appropriate use of PV, hydro, WT, and BS in conjunction with DG for rural Nigerian deployment have not received enough consideration. The literature review presented above indicates that no research has been done to assess the performance of PV/WT/hydro/WDG/BS HES in Nigeria. The prior studies solely focused on the feasibility analysis and optimal sizing of HES components for rural electrification without considering hydro turbines. This work seeks to close the research gaps established in the previous studies by utilizing HOMER to design and carry out the environmental and techno-economic viability of PV/WT/hydro/DG/BS HES. The technical, financial and environmental performance of standalone PV/WT/hydro/BS/DG hybrid energy system has not been fully assessed in Nigeria, as far as the authors are aware. The chosen community does not have access to the grid due to the economics of scale and the only practical way to meet power demand has been the application of fossil fuels-based reciprocating engines. Based on the literature review and the research gap previously stated, the purpose of this work is to investigate the techno-economic and environmental performance of an islanded PV/WT/hydro/DG/BS HES providing power to a remote community. The objective of the study is to design an islanded HRES that can satisfy the load demand of desired rural dwellers at the low COE, NPC, low carbon footprint emissions, fuel consumption, operating cost and payback period and high internal rate of return (IRR), present worth, annual worth and return on investment (ROI). The outcomes of the research serve as input information for designing and planning of HES for rural areas and assist the stakeholders to make the best managerial decision in renewable energy projects.

2. METHODOLOGY

2.1. Hybrid Renewable Energy System

A HRES is a combination of various sources of electricity generation such as PV, WT, hydro, microturbines, DG, BS and biomass to enhance system efficiency and improve the balance in power supply (Kelly *et al.*, 2023). The proposed HRES is presented Figure 1. The HRES offers the following benefits: continuous power supply, flexibility and scalability, optimization of renewable sources, low maintenance cost, reduced risk of outages, improved cost savings, high efficiency, load management, environmental sustainability, cost-effectiveness, increased security and improved reliability of power supply (Adefarati *et al.,* 2019b). It is vital to understand the roles played by each of its components as well as the various configurations required to increase the efficiency, reliability and profitability of HRES. As a result, a brief description of every component of the system is provided below.

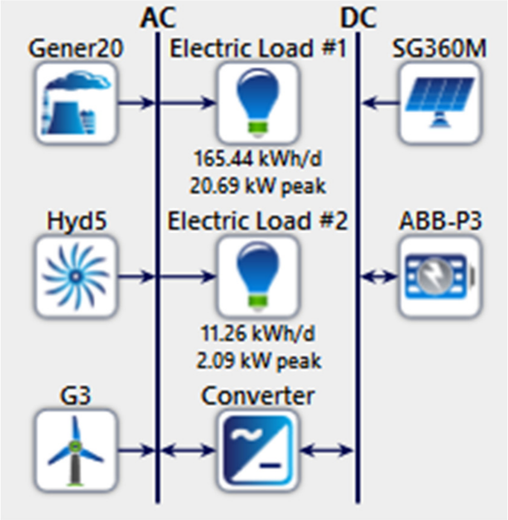

Figure 1: Schematic diagram of hybrid renewable energy system

2.1.1. Hydro turbines

A hydro turbine is a rotary machine used in hydroelectric generation plants for conversion of kinetic energy and potential energy of water to mechanical energy. A hydroelectric generator transforms the mechanical energy to electrical energy (Oladigbolu *et al.,* 2020). There are different types of hydro turbines that are suitable for particular applications. Each type of hydro turbine is designed to produce maximum power output for the application in which it is utilized. The selection of a hydro turbine for rural electrification projects depends on the net head, flow rate of water at the site, capital cost of hydro turbine and turbine efficiency. The Goronyo dam that captures the Rima River in Sokoto is considered in this paper as a case study. The power output of the hydro turbine can be estimated by utilizing Equation (1) (Aziz *et al.,* 2019).

$$P_{hyd} = \frac{Q_t \times h_{net} \times g \times \rho_{h20} \times \eta_{hyd}}{1000W/kW} \tag{1}$$

Where Q_t represents hydro turbine flow rate (m^3/s), h_{net} depicts the net head (m), g depicts acceleration due to gravity (m/s^2), ρ_{h20} represents density of water (1000 kg/m^3) and η_{hyd} depicts efficiency of hydro turbine (%).

The net head is the difference between the gross head and the head losses in all sections of the water conveyances. The net head is expressed in Equation (2) as (Oladigbolu *et al.,* 2020):

$$h_{net} = h(1 - f_h) \tag{2}$$

Where f_h is the pipe head loss (%) and h is the available head (m).

2.1.2. Photovoltaic system

The photovoltaic system consists of PV cells that absorb solar energy from the sun and convert it to electricity through photovoltaic effects (Owolabi *et al.,* 2019). The application of PV systems varies from residential to industrial-scale generation plants. The power generated by the PV panel can be estimated by utilizing Equation (3) (Nsafon *et al.*, 2020).

$$P_{pv} = \beta_{pv}\psi_{pv}\left(\frac{S_T}{S_{T,STC}}\right)\left[1 + \delta_p (T_c - T_{c,STC})\right] \tag{3}$$

Where ψ_{pv} is the derating factor of the PV (%), β_{pv} depicts the rated capacity of the PV panel (kW), S_T is the solar radiation that incidents on the PV panel (kW/m^2), $S_{T,STC}$ is the solar radiation that incidents on the PV panel at STC (1 kW/m^2), STC represents standard test conditions, δ_p depicts the temperature coefficient of power (%/^{o}C), T_c is the cell temperature of the PV panel (^{o}C) and $T_{c,STC}$ is the cell temperature of the PV panel at STC (^{o}C).

The average clearness index on the monthly basis is presented in Equation (4) as:

$$K_T = \frac{H_{ave}}{H_{o,ave}} \tag{4}$$

Where H_{ave} depicts the monthly average radiation on the horizontal surface of the earth (kWh/m^2/day) and $H_{o,ave}$ represents the extraterrestrial horizontal radiation (kWh/m^2/day).

2.1.3. Wind turbines

A WT is a device that transforms the kinetic energy of wind speed to electrical energy. The output power of the WT depends on the following factors: wind speed, air density, WT swept area, height of tower, weather temperature and conversion efficiency. The power produced by wind turbines can be presented in Equation (5) as (Adaramola *et al.,* 2014).

$$P_{WT} = \frac{1}{2} \times \rho \times A \times v^3 \tag{5}$$

Where A represents the swept area of the WT blades (m^2), ρ depicts the density of the air (kg/m^3) and v represents the velocity of the wind (m/s).

The hub height of wind speed can be estimated by using Equation (6) (El-Sattar *et al.* 2021).

$$V_{hub} = V_a \left(\frac{H_{hub}}{H_a} \right)^{\alpha} \tag{6}$$

Where V_{hub} represents the wind speed at the hub height of the wins speed (m/s), V_a is the wind speed at anemometer height (m/s), H_{hub} depicts the hub height of the wind turbine (m) H_a represents the anemometer height (m) and α is the power law exponent.

2.1.4. Diesel generator

A DG is a combination of alternator and prime mover (reciprocating engine) for the generation of electricity. It is designed to generate electricity by burning various fuels such as natural gas, compressed natural gas, diesel fuel and other liquid fuels. It can be used as a standby or backup unit to provide electrical power supply to residential, commercial and industrial facilities in the event of unscheduled power interruption (Kelly *et al.,* 2023). The fuel consumption of a DG depends on fuel quality, share of load demand on DG, capacity or size, ambient temperature and system maintenance. The fuel consumption of DG can be estimated by utilizing Equation (7) (Ouedraogo *et al.*, 2015).

$$DG_{fuel} = \delta^{o}{}_{fuel} \times \varphi_{DG} + \delta^{1}{}_{fuel} \times P_{DG} \tag{7}$$

Where $\delta^{o}{}_{fuel}$ is the diesel fuel curve intercept coefficient (units/hr/kW), φ_{DG} depicts the rated capacity of the DG (kW), $\delta^{1}{}_{fuel}$ represents fuel curve slope (units/hr/kW) and P_{DG} is the power output of the DG (kW).

2.1.5. Battery storage system

The battery storage system is a device that allows energy from green energy technologies to be stored and then released when needed at the load points (Oladigbolu *et al.,* 2021). It plays a substantial role in balancing the power supplies from green technologies and responding to power demands. The rapid substitution of renewable energy sources for fossil fuels will need the development of battery storage systems. The storage capacity of the battery system is given by Equation (8) Homer manual (2024).

$$P_{bss} = \frac{N_{bss} \times I_{\max} \times V_n}{1000} \tag{8}$$

Where N_{bss} depicts the number of battery systems in the battery bank, $I_{\max}$ is the maximum charge current of the battery bank (A) and V_n is the nominal voltage of the battery bank (V).

The state of charge (SOC) of the BS is the ratio of energy stored to its total installed capacity or full capacity. The SOC is a substantial parameter that reflects the performance of the BS. It can be used to increase the lifespan and ensure efficient operation of the entire power system.

2.2. Technical and Economic and Environmental Metrics of Hybrid Energy System

The economic, technical and environmental advantages that independent power providers and distribution network operators derive from using standalone HRES are assessed in this paper by using some key performance metrics (kPMs). This paper is focused on the optimal performance of HRES by utilizing some kPMs such as NPC, COE, annual worth, present worth, IRR, ROI, payback period (PBP), renewable fraction and emissions (Adefarati 2019b). The metrics can be used to investigate the investment feasibility of HRES and determine the most viable configuration.

2.2.1. Cost of energy

The COE is the ratio of total cost of the system to annual load served. It is expressed in Equation as (Oladigbolu *et al,* 2020):

$$COE = \frac{TAC}{TES} \text{ (\$/kWh)} \tag{9}$$

Where TAC is the total annualized cost of the system ($/yr) and TES is the total load served (kWh/yr).

2.2.2. Net present cost

The NPC is equal to the present value of all of the expenses it incurs when the system's lifetime costs are deducted from its lifetime revenue (Sawle *et al.,* 2018).

$$NPC = \frac{TAC}{CRF(i,n)} \tag{10}$$

where CRF is the capital recovery factor.

The capital recovery factor is expressed in Equation (11) as (Saliu *et al.* 2019):

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{11}$$

Where *i* represents the interest rate (%) and *n* is the life span of the project (yr).

2.2.3. Return on investment

The ROI can be utilized to measure the profitability of green energy project by comparing the yearly cost savings with its initial expenditure. It can be applied to assess the efficiency of an investment or compare the performance of numerous investments.

$$ROI = \left\{ \frac{\sum_{i=0}^{n} C_{i,base} - C_i}{n(C_c - C_{c,base})} \right\} \tag{12}$$

Where $C_{i,base}$ is the nominal annual cash flow for base system, C_i is nominal annual cash flow for current system, C_c is the capital cost of current system and $C_{c,base}$ is the capital cost of base system.

2.2.4. Internal rate of return

The IRR can be applied to determine the profitability of green energy projects. It can be used to assess the returns of a potential investment or whether a project is worth pursuing.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_o \tag{13}$$

Where *t* depicts the number of time periods, C_o represents the total investment costs and C_t is the net cash inflow during the period *t.*

2.2.5. Payback period

The PBP is the number of years needed for the initial investment's cost to be recouped by the cash flows generated by the green energy investment. It is the period it takes for an investment to become profitable (Adefarati *et al,* 2019b).

$$PBP = \frac{CI}{AAC_{flow}} \tag{14}$$

Where *CI* depicts the cost investment and AAC_{flow} is the annual cash flow

2.2.6. Present worth

The definition of present worth is the value of future total cash flow as of today. It is a fundamental comparison tool that can be used during the investment selection process. The present worth provides the investors with a summary of the future value of their investments. Business organizations and investors can derive a lot of benefits from using present worth when making investment and financial decisions. It can offer insightful information about whether to prioritize some investments over others. The present worth is expressed in Equation (15) as (Agarwal *et al.,* 2013):

$$P = F\left(\frac{1}{1+i}\right)^n \tag{15}$$

Where *F* is the future worth.

2.2.7. Annual worth

The annual worth is the annual cost of owning and running HRES throughout its lifetime. It is a product of present worth and CRF. The annual worth can be estimated by using Equation (16) (Agarwal *et al.,* 2013):

$$A = P\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \tag{16}$$

2.2.8. Renewable fraction

The renewable fraction (RF) is the portion of energy coming from green energy technology that is delivered to the load. A great share of energy from renewable energy sources lowers emissions from sources that produce fossil fuels, this improves society's health. The renewable fraction can be estimated using Equation (17) (Adefarati *et al.,* 2019b).

$$RF = \left(1 - \frac{E_{ff}}{E_s}\right) \tag{17}$$

Where E_s represents the total electrical load served (kWh/yr) and E_{ff} is the non-renewable or fossil fuel electrical production (kWh/yr).

2.2.9. Emission

The contaminated pollution produced by diesel generators owing to the combustion of fossil fuels is harmful to society. The emissions produced by the DG can be estimated by taking the product of the emission factor and power produced by the DG (Adefarati *et al.,* 2019a).

$$Emission = \sum_{i=1}^{n} P_{DG,i} E_{factor,i} \tag{18}$$

Where $E_{factor,i}$ is the emission factor of CO_2, UHC, PM. SO_2 and NO_x

2.2.10. Battery throughput

The battery throughput is the amount of energy that flows through the battery bank. It affects the battery's operational lifetime Homer manual (2024). The battery throughput is the amount of energy that flows through the battery bank before its replacement. The lifetime throughput is presented in Equation (12) as Homer manual (2024):

$$Q_{lifetine,i} = f_i d_i \left(\frac{V_n \times q_{\max}}{1000W / kW} \right) \text{ (kWh)} \tag{19}$$

Where f_i is the number of cycles to failure, d_i is the depth of discharge (%), $q_{\max}$ represents the maximum state charge of the BS (%) and V_n is the nominal voltage of a single BS (V).

The battery throughput is the amount of energy that flows through the battery storage system in a given year. The annual throughput is presented in Equation (20) as Homer manual (2024):

$$Q_{annaul,i} = \frac{Q_{lifetine,i}}{\lambda_{bs}} \text{ (kWh/yr)} \tag{20}$$

Where λ_{bs} is the expected life of the battery system.

2.2.11. Battery autonomy

The battery autonomy storage is the size of the battery system divided by the electric load. It is expressed in Equation (21) as (Oladigbolu *et al.*, 2021):

$$A_{bss} = \frac{N_{bs} \times V_n Q_n \left(1 - \frac{q_{\min}}{100} \right) (24h/d)}{L_a (1000Wh/kWh)} \tag{21}$$

Where N_{bs} depicts the number of BSs in the battery bank, Q_n is the nominal capacity of a single BS (Ah), $q_{\min}$ represents the minimum state charge of the BS (%) and L_a is the average primary load (kWh/d).

2.2.12. Wear cost of battery

The storage wear cost is the cost that associated with energy cycling through a battery system. It can be estimated by using Equation (22) Homer manual (2024):

$$BS_{wc} = \frac{BS_{rc}}{N_{bs} \times Q_{lifetime} \times \sqrt{\eta_{bs}}} \tag{22}$$

Where BS_{rc} represents the replacement cost of battery bank ($), η_{bs} is the efficiency of BS round-trip and $Q_{lifetime}$ is the life span throughput of a single BS (kWh)

2.3. Technical and Financial Details of the Proposed Hybrid Renewable Energy System

The technical, economic and environmental sustainability of HRES is evaluated in the study by taking into account the load profile of typical consumers in Sokoto, Nigeria. The technical and financial details of HRES used in the paper are presented in Table 1 to assess the viability of the system. The model developed in the present study and technical specifications and financial details are used to determine the best configuration and assess the operation of the proposed HRES (Adefarati *et al.,* 2021a).

Table 1: Technical and financial details of hybrid renewable energy system

Description	Capital cost	Replacement cost	O&M cost	Other operating parameters
Photovoltaic	$ 650	$650	$10 /yr	Installed Capacity = 90 kW Nominal rating = 1kW Temperature coefficient: – 0.352 Operating temperature: 25 °C Efficiency: 18.5 % Panel area = 1.951 m^2 Lifespan: 25 yrs
Diesel generator	$ 1521 /kW	$1141 /kW	$0.02 /kW h	Installed Capacity= 100 kW Diesel fuel price = $1/L Lifespan: 25,000 hrs
Battery system	$100	$80	$2.10 /yr	Nominal rating = 78 A h Nominal capacity: 0.289 kWh Nominal capacity: 78 Ah Lifespan: 10 yrs
Converter	$300	$300	$20/yr	Installed Capacity= 20 to 26 kW Lifespan: 15 yrs
Hydro turbine	$40,000	$20,000	$1200/yr	Available head = 20 m Design flow rate = 35 L/s Efficiency: 0.8 Lifespan: 25 yrs
Wind turbine	$1200	$1200	$50	Capacity: 3 kW Lifespan: 20 yrs

3. RESULTS AND DISCUSSION

The simulation findings of the research are presented in this section to determine the capability of the system to satisfy load demand and assess the technical, financial and environmental feasibility of proposed HRES. The optimization model for the standalone HRES is evaluated with the application of HOMER to reduce the NPC, COE, emissions, fuel consumption, running hours of DG and payback period and increase the present worth, annual worth, ROI and IRR. The viability of HRES can be carried out by using the following scenarios:

- Scenario 1: DG only (base system)
- Scenario 2: DG/PV/WT/DG/Hydro/BS

3.1. Scenario 1: DG only (base system)

This scenario is designed to assess the performance of a conventional power system that depends only on the DG as a sole power source to satisfy the power requirements. The load profile of the selected site is presented in Figure 2. The DG is utilized in this scenario to meet the power demand without the incorporation of renewable sources (PV, WT and hydro) and battery system. The DG of 100 kW has been used in this study to meet the primary load demand of 64,495 kWh/yr and the excess electricity of 154,505 kWhr/yr generated from the plant via DG is sold to a typical customer through a consented power purchase agreement (PPA). This shows that 100% of load demands are satisfied by diesel generator which depends on already depleted fossil fuels. The monthly electrical production of the diesel generator is presented in Figure 3. The consumption of fossil fuels by reciprocating engines has adverse effects on the environment and detrimental impacts on human health. It can be established that the power system with DG alone is considered to be the most unfriendly environmentally option with significant amount of CO_2 emission (203,424 kg/year), CO emission (1409 kg/year), UCH emission (56 kg/year), PM emission (6.22 kg/year), SO_2 emission (499 kg/year) and NOx emission (1,127 kg/year) when compared to other HES architectures. The annual fuel consumption of $905,054.40 which translated to 77,789 L/yr is recorded in this scenario owing to the absence of renewable energy technologies. This indicates that the operation of the diesel generator should be supplemented by green energy technologies as a measure to fulfill the electricity needs of the study area. The RF of the base system is 0%, this demonstrates that the DG consumed 77,789 L/yr of fuel at an average fuel per day of 213 L/day and average fuel per hour of 8.88 L/yr and run for 8760 hours to produce annual electrical production of 219,000 kWh/yr. The average fuel per hour of DG with a base system is presented in Figure 4. The share of load demand on DG can be reduced with the addition of distributed generation to the base system. The base system produced NPC of $917,008.60, COE of $1.10/kWh and operating cost of $70,816.97, which are 91.59%, 91.59% and 96.82% higher than the proposed HRES. These results can be interpreted not to be economically feasible based on the high values of NPC and COE. The breakdown of NPC obtained in this study is stated as follows: capital cost ($8,277.58), replacement cost ($1,521.00), O&M cost ($2,264.90), fuel cost ($905,054.40) and salvage (-$109.33). It can be seen that fuel cost is responsible for 98.7% of the NPC of the base system.

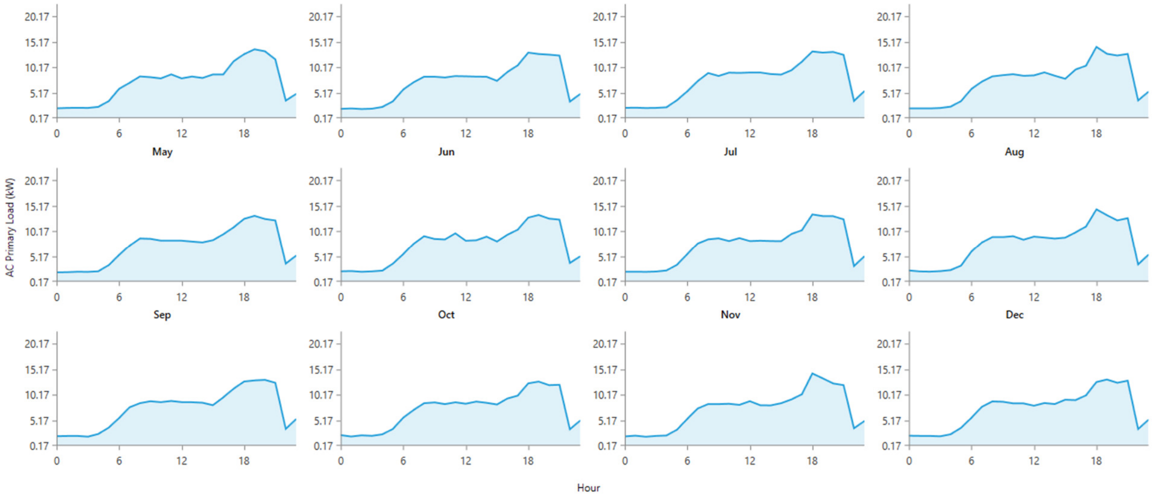

Figure 2: Daily load profile of the selected site

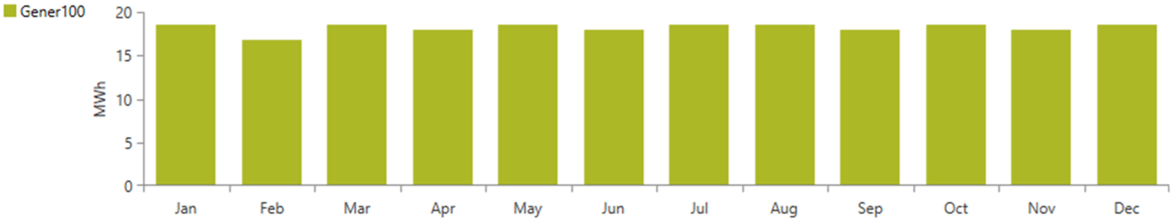

Figure 3: Monthly electrical production

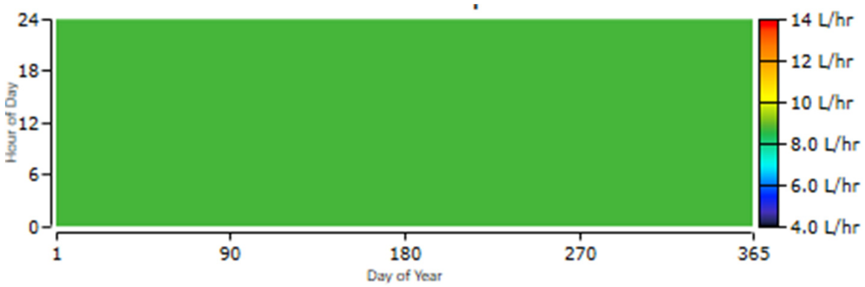

Figure 4: Average fuel per hour of DG with base system

3.2. Scenario 2: DG/PV/WT/Hydro/BS

The performance assessment in this scenario involves a hybrid energy system that allows the integration of PV, WT, DG, hydro and BSS into a single power system. The multiple components of HRES allow the strength of one component to be harnessed to overcome the weakness of other components. The DG can be used as a supplemental power source when local renewable resources are low or during peak periods when power demand exceeds power generation. The combination of different sources is a power solution that balances power demand and power supply and provides an uninterrupted power supply. The annual average radiation and annual average temperature of the selected site are 6.04 kWh/m^2/day and 26.36^{o}C. The daily radiation and temperature of the selected site are presented in Figures 5 and 6. The annual average wind speed of the site is 4.53 m/s as presented in Figure 7.

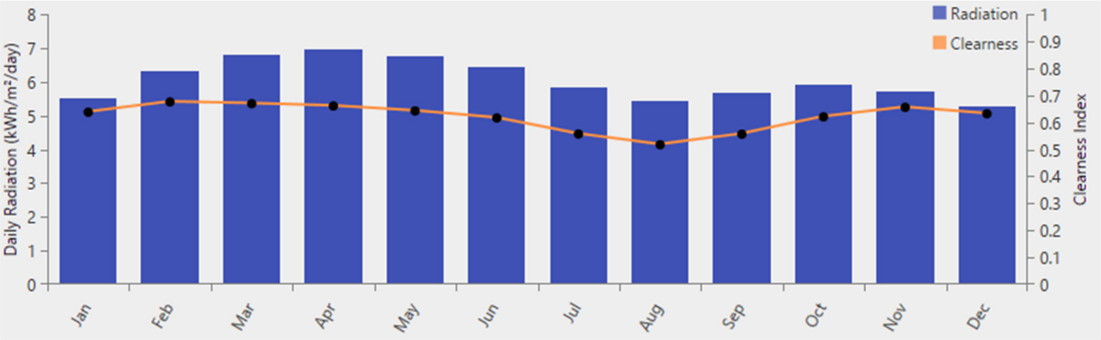

Figure 5: Daily radiation and clearness index of the site

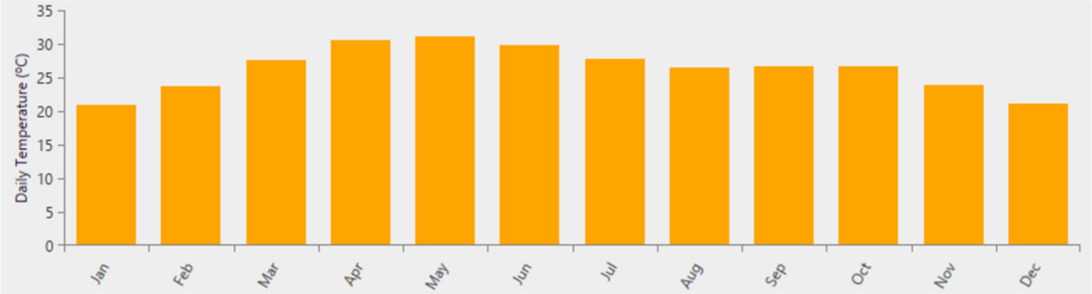

Figure 6: Daily temperature of the site

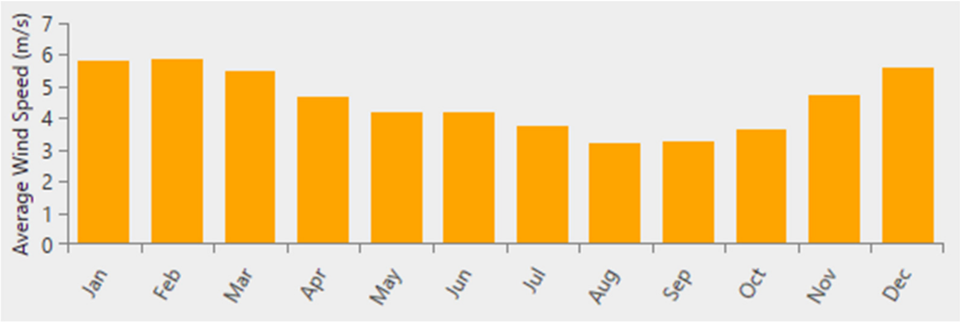

Figure 7: Average wind speed of selected site

The optimal combination of HRES is obtained under the load following control scheme that comprised PV of 9.49 kW PV, diesel generator of 100 kW, 198 batteries, 198 batteries string size and 1 string in parallel, hydro turbine of 5kW and converter of 15.5 kW. The daily and monthly SOC of the BS used in this scenario is presented in Figure 8 (a-b). The monthly electrical generation of all the components of HRES is presented in Figure 9. The annual electrical output of the HRES is 78,239 kWh/yr, where PV, WT, Hydro and DG produced 16,790 kWh/yr (21.5%), 6,361 kWh/yr (8.13%), 53,813 kWh/yr (68.8%) and 1,275 kWh/yr (1.63%). The proposed HRES satisfied the load demand of 64,495 kWh/year and also produced excess electricity of 11,799 kWh/yr that is sold to the typical customers at the consented PPA. The RF obtained in this scenario is 98%, this shows that renewable energy resources produced the largest proportion of electricity to satisfy the power requirements. The renewable fraction of 98% yields a fuel consumption of $5269.15 (453 L/yr), average fuel per day of 1.24 L/day and an average fuel per hour of 0.0517 L/hr as shown in Figure 10. The application of renewable energy resources in the base system has reduced fuel consumption by 77,336 L/yr (99.42%). The battery system that is a critical component of HRES that produced the autonomy, annual throughput, lifetime throughput and storage wear cost of 6.99 hr, 11,224 kWh/yr. 112,240 kWh and 0.0296 $/kWh.

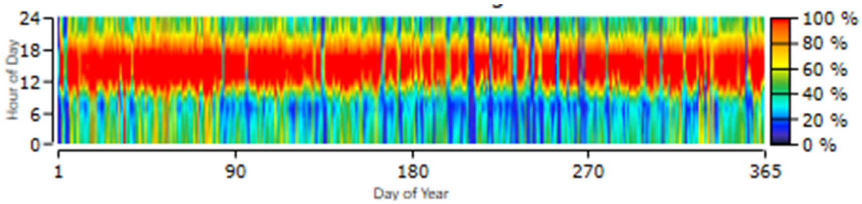

Figure 8a: Daily SOC of battery system

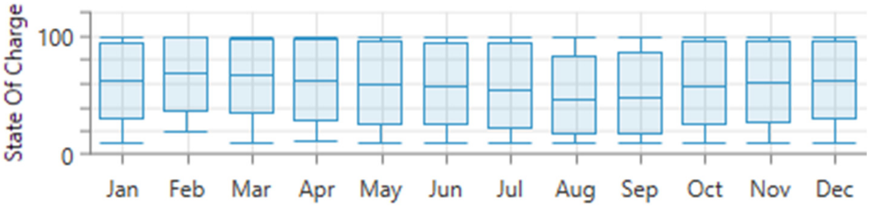

Figure 8b: Monthly SOC of battery system

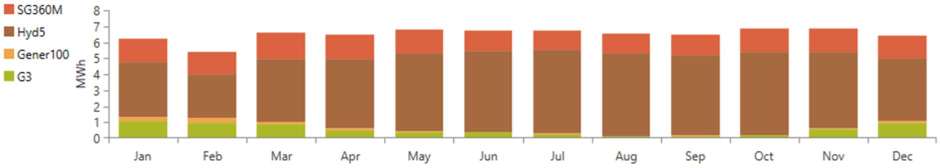

Figure 9: Monthly electrical production

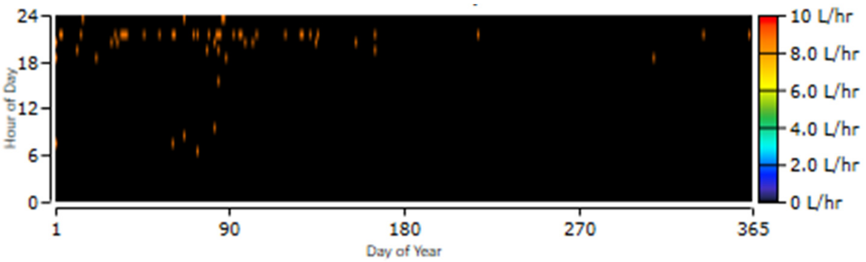

Figure 10: Average fuel per hour of DG with HRES

The findings of this scenario show that the use of green energy technologies has reduced the number of operation hours of DG to 51 hours. This has substantially reduced the annual emissions that emanated from DG. The annual emissions released to the atmosphere by the proposed HRES with different components have been compared with the base system from the environmental perspective. It can be seen that the proposed HRES is the most ecologically friendly solution with the least amount of the following emissions: CO_2 (1184 kg/yr), CO (8.20 kg/yr), UCH (0.326 kg/yr), PM (0.0362 kg/yr), SO_2 (2.90 kg/yr) and NOx (6.56 kg/yr). This shows that CO_2 of 202,240 kg/yr, CO of 1400.8 kg/yr, UCH of 55.674 kg/yr, PM of 6.1838 kg/yr, SO_2 of 496.1 kg/yr and NOx of 1120.44 kg/yr are prevented from being injected into the atmosphere. It is found that the fuel consumption of DG has reduced by 77,336 L/yr, this results in a drastic reduction in the amount of CO_2, CO, UCH, PM, SO_2 and NOx emissions that are estimated to be lower than the base system.

The HRES produced an NPC of $77,163.59, COE of $0.0925/kWh, operating cost (OC) of $2,250.97, present worth of $839,845, annual worth of $64,966/yr, ROI of 143.4%, IRR of 148.2% and PBP of 0.68 yr. The NPC, COE and OC obtained in this scenario are 91.59%, 91.59% and 96.82% lower than the base system. The breakdown of the NPC obtained from using HRES is as follows: capital cost ($48,064.09), replacement cost ($11,402.01), O&M costs ($14,854.82), fuel cost ($5,269.15) and salvage (-$2,426.49). It can be seen from Figure 12 that capital cost has the majority of NPC, followed by O&M cost, replacement cost, fuel cost and salvage value as shown in Figure 11. The capital cost carries about 62.29% of the total NPC of the system. The values of NPC and COE obtained in the scenario show that HRES is the most feasible solution to meet power demand from an economic performance perspective.

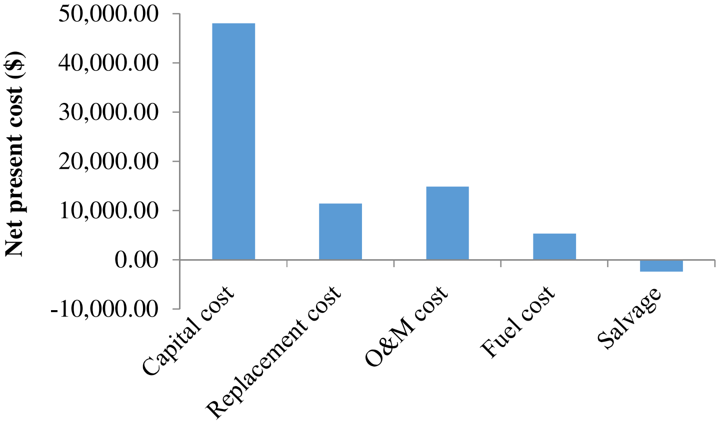

Figure 11: Breakdown of NPC obtained in HRES

4. CONCLUSION

A renewable energy-based HES is presented in this study to satisfy the electricity of rural areas that are mainly supplied by diesel generators. This is designed to curtail over dependence on already depleted fossil fuels and emissions associated with the combustion of crude oil, coal and natural gas and increase the usage of green energy technologies and the sustainability of power systems. The abovementioned objective is achieved in this paper by using an optimization tool that is substantial for the viability evaluation of HRES. The optimal operation of HRES is presented in this paper by carrying out a technical, economic and environmental assessment of PV/WT/Hydro/DG/BS HES for a remote area in Nigeria. HOMER was used in the study for simulation, modeling and optimization of standalone HRES designed to meet the electrical loads of rural dwellers. The economic analysis's findings show that hybridization of PV, DG, WT, BS, hydro turbines, DG and converter is the optimal power solution with COE of 0.0925 \$/kWh and NPC of \$77,968.02. This reveals that COE and NPC have been reduced by 91.59% and 91.59% in comparison to the base system. The minimum fuel consumption of 453 L/yr that is obtained in the second scenario by reducing the operation of operating hours of DG by 96.82%, this makes PV/WT/Hydro/DG/BS configuration to be the most environmentally friendly solution by reducing CO_2, CO, UCH, PM, SO_2 and NOx emissions to 1360 kg/yr, 9.26 kg/yr, 0.374 kg/yr, 0.0370 kg/yr, 3.33 kg/yr and 0.740 kg/yr, respectively. This shows that CO_2 of 207,717 kg/yr, CO of 1412.74 kg/yr, UCH of 57.226 kg/yr, PM of 5.653 kg/yr, SO_2 of 508. 67 kg/yr and NOx of 113.26 kg/yr are prevented from being injected into the atmosphere. The results of his study can be utilized by investors in the power sector for decision-making in the direction of better energy management schemes for the sustainability of power supply. The findings of this research could help investors and policymakers plan and execute the most practical and optimal solutions to boost global access to electricity, particularly in isolated and underdeveloped areas.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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