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Techno-economic Evaluation of Grid-connected Hybrid Energy System Based on Run-of-River and Solar Energy Plants for Sustainable Electrification of a Rural Community

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Abstract: *The connection between energy access and greenhouse gas emissions is an issue that continues to garner attention. Presently, hundreds of millions of people globally do not have access to sufficient electricity, and those who do, rely on expensive fossil resources characterized by greenhouse gases. A viable solution is to explore renewable energy (RE) sources to satisfy the electricity demand and curtail the effect of greenhouse gases. This study performed a techno-economic analysis of a grid-connected hybrid RE system that included micro-hydro and solar photovoltaic power plants for a Nigerian rural community. The optimal system, according to the analysis done with HOMER software tool, has an overall NPC, operating cost, and LCOE of \$3,202,139.00, \$37,515.81, and \$0.06053/kWh, respectively. A 98.1 kW micro-hydro turbine, a 150 kW converter, 100 kW solar panels, and 704 battery strings constitute the system components. An annual emission of 4,483 kg of CO_2, 0.356 kg of CO, 22.5 kg of SO_2, 4.86 kg of NO, and 1.66 kg of particulate matter will be released into the atmosphere. The implementation of this hybrid power system will not only increase access to energy but also help lessen greenhouse gas emissions.*

Keywords: *Clean Energy, Economic Analysis, HOMER, Hybrid Renewable Energy Systems, Micro-hydropower, Net Present Cost*

1. INTRODUCTION

The electricity industry is a major source of pollution and greenhouse gas emissions notwithstanding its recognition as the heartbeat of every socio-economic development [1]. There is broad consensus over the dire repercussions of climate change and global warming from the exploitation of fossil resources to meet the global energy demand. As a result, significant short-term initiatives are essential to decarbonize the environment. This task is made even more pressing by the fact that the world's energy demand will almost certainly keep rising. According to 2018 figures, a 25% increase in overall energy demand is predicted for 2040 [2]. Therefore, innovative and aggressive efforts must be made to reduce carbon footprints in all human activities and productive sectors to save future generations. In the electricity industry, this can be accomplished by switching from fossil fuel-based production to an ingenious use of renewable energy (RE) sources.

The Nigerian electricity sector confronts many obstacles, such as insufficient power generation, inadequate transmission and distribution infrastructure, and limited access, especially in rural regions, which results in frequent power interruptions and poor-quality power supply. Several policies have been inaugurated to boost generation capacity and improve the country's overall energy supply [3]. Despite these efforts, more than 50% of the population completely lacks grid access. More so, the interruptions are frequent where there are grid reticulations.

RE is considered a clean and abundant source of energy that can be leveraged to boost electricity supply [4]. They include geothermal, solar, biomass, wind, and hydro. Recent years have seen notable advancements in this area, to the point that RE sources now contribute significantly to energy generation. In Europe, the share of RE output increased from 14% to 29% annually between 2005 and 2017 [2]. Meanwhile, massive advancements in the development and application of RE technologies are necessary, particularly in developing nations where coal and natural gas are still mostly used in the electricity sector.

The major downsides of RE sources are their volatility, fluctuation, and randomness. Thus, relying on a single source for electricity generation is generally uneconomical, unreliable, and not sustainable [5]. Hence, a feasible solution is to amass diverse energy sources to form a hybrid RE system for either an off-grid or on-grid operation [6]. Hybrid RE systems comprising solar and diesel energy systems or solar, wind, and diesel energy systems have shown significant prospects and, hence, have been well-researched by the energy community. For instance, in [7], the performance of hybrid PV-fuel cell (FC)-battery (BAT) was examined for residential buildings requiring 69342W. In [8], computational algorithms were used to analyze hybrid PV-WT-DG-BAT based on LCOE, LPSP, and energy consumption by the dummy load. The optimal system has an LCOE of \$0.09138/kWh.

Roy et al. [9] used MATLAB Simulink for modeling HRES comprising Wave-Li-ion BAT-supercapacitor-Grid for six sea areas in the United States. The study applied the dispatching technique for a slider-crank wave energy converter. There is no environmental impact assessment and the LCOE associated with the system was also not stated. Canales et al. [10] used a multi-objective Grey Wolf Optimizer (MOGWO) to analyze hybrid WT-PV-PS H-BAT for Ometepe Island in Nicaragua. The cost of energy obtained ranged from €0.047/kWh and €0.095/kWh, based on the system that achieved a level of 95% LPSP. The effects of the highly variable metrological resources system's optimal sizing were ignored. No sensitivity analysis was performed. No idea about emission footprints. Oladigbolu et al. [11] used HOMER to perform techno-economic and environmental analyses of four distinct hybrid systems comprising hybrid PV/hydro/DG/BAT. The optimum system was found as PV/hydro/DG at LCOE of $0.112/kWh and prevented also 77.1% of CO_2 compared to PV/DG. Similarly, Mukhtar et al. [12] utilized HOMER to identify the most efficient and cost-effective hybrid energy system for a location in Pakistan. The ideal system comprised 91.4 kWp PV modules, a 19.6 kW hydropower plant, a 50 kW BG, 36 strings of batteries, and a 60.6 kW converter. The possibility of a grid connection was not considered. Meanwhile, the study did not also consider grid integration into the systems. Luta & Raji [13] employed HOMER to model PV-FC-SC for Cape Town, South Africa. The objective was to find the most economical solution for a commercial load by designing, modeling, and simulating HES with a fuel cell and supercapacitor. The cost of H_2 storage was taken as a sensitivity variable. The optimal system had an NPC of US$26.6 million and an LCOE of US$4.78/kWh. The cost of implementing such a hybrid storage system for a commercial load is high even though that price is anticipated to decline over the next few years. In Chamout et al. [14], hydrogen was considered as an energy carrier in a hybrid PV-WT-BAT system for a location in the Netherlands. Similarly, in Salisu et al. [15], wind turbines were excluded in the design of a hybrid PV-DG energy system for a location in Abuja due to a low wind speed. This resulted in reliance on diesel energy plant that emits poisonous gases. In Hussain Alhamami et al.[16], hybrid nature-inspired optimization algorithms were utilized to model an off-grid hybrid PV-WT-BAT for the Kano, Abuja, Niger, and Lagos states of Nigeria. The system excluded diesel generators and, hence, may not be able to satisfy the energy demand in the event the RE sources fluctuate.

From the literature surveyed, several studies focus on the design and analysis of RE systems utilizing solar, wind, and diesel resources. Meanwhile, little has been done to exploit hydro resources as a complementary source of energy [5], [11]. Furthermore, most of the examined systems are off-grid and a few ones that considered grid integration ignored instances of grid interruptions. Power failures, low voltage scenarios, load shedding, and system collapses are common in developing nations like Nigeria. From 2014 to 2018, for example, Nigeria's 132 kV and 330 kV transmission networks were plagued with 14,945 and 5,581 outages, respectively. Similarly, Nigeria, the largest economy in Africa, despite being located at a high solar radiation belt and endowed with enormous hydro resources, has more than 50% of its population lacking grid access. Thus, given the extensive network of rivers that traverse the majority of the states and the enormous solar radiation in Nigeria, a hybrid of solar and small hydropower plants would be a practical way to address the power crisis that affects a substantial part of the country [3]. Before reasonable financing and implementation of any power project, it is crucial to conduct its feasibility studies in terms of economy, technology, and greenhouse gas emissions.

Therefore, this study aimed to perform the techno-economic evaluation of hybrid solar-run-of-river power plants to complement the operation of an unreliable grid. The notable aspects of this study are the exclusion of the expensive and ecologically harmful diesel generators and the consideration of the grid failure scenario. The main points of emphasis of the technical analysis include the annual electricity generation profiles, unmet loads, excess electricity generation, and component sizes. The net present cost (NPC), replacement cost, operating cost, levelized cost of energy (LCOE), and salvage cost were considered in the economic assessments. If the models under investigation were deployed at the proposed project site, the environmental evaluations focus on the degree of penetration of renewable resources as well as the amount of carbon, sulphur, nitrogen oxides, and carbon monoxide emissions. To further appreciate the dynamics of the proposed HRES, a sensitivity analysis was performed to visualize how certain variables influence the optimal operation of the proposed energy system. The utilization of run-of-river to supply electricity for the complementary operation of erratic grid is envisaged to attract the attention of the energy community to the potential of incorporating hydro resources into the energy mix.

The rest of the paper is organized as follows: Section 2: Materials and Methods. Section 3: Results and Discussion. Section 4: Conclusion.

2. MATERIALS AND METHODS

A hybrid optimization of multiple energy resources (HOMER) was employed for the simulation and operational analysis of the proposed hybrid power system. The study methodology is represented in Figure 1.

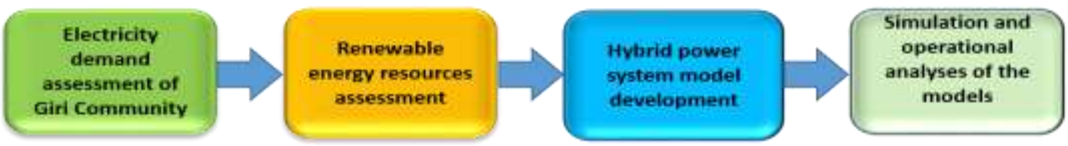


Figure 1: Study methodology

2.1 Project Site

The location considered for this project is Giri Community in Gwagwalada Area Council of the Federal Capital Territory of Nigeria. Sited on Latitude 9.008° N and Longitude 7.1548° E. Giri village aside from being a host to different agricultural and commercial activities serves as an off-campus to several students of the University of Abuja. The electricity supply to the community is epileptic. As a result, the level of insecurity especially at night has risen. More so, the students rely on paraffin wax to study especially during exams while essential health care services cannot be rendered. Meanwhile, the village is endowed with run-of-river (River Wuye) resources that can be exploited for the production of electricity [17]. Hence, it is essential to leverage the River Wuye, solar resources, and grid reticulation for a cost-effective and viable electricity supply to the community.

2.2 Proposed Hybrid Power System

The proposed hybrid power system for the Giri community of FCT is shown in Figure 2. The grid provides backup services in the event the solar radiation and hydro resources are unfavourable, and the state of charge of the battery is below the minimum threshold. The electricity exchange between the DC and AC buses is ensured by the power converter. Thus, it rectifies AC power from the generator for storage in the battery and inverts DC power from PV panels, and batteries for utilization by the community loads.

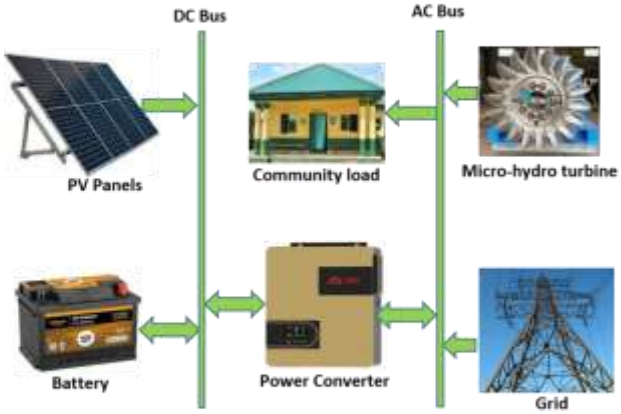


Figure 2: Proposed hybrid power system

2.3 Electricity Demand Assessment

The electricity demand of the community was assessed by taking the inventories of the appliances (quantity, power rating, and operational hours per day) in the community following the approaches in [15], [18]. A total of 250 households, two eateries, 2 barbershops, one primary school, 2 hair salons, one clinic, two worship centres, and a community water supply scheme were considered. The total calculated demand put in the HOMER software tool is 1,890.31 kWh/day. The daily and seasonal load profiles of the community are shown in Figure 3. The electricity demand is high from 7:00 pm to 7:00 am when most of the community dwellers have returned home from their various places of work. Similarly, more energy is consumed in February and March when the dry season is at its peak.

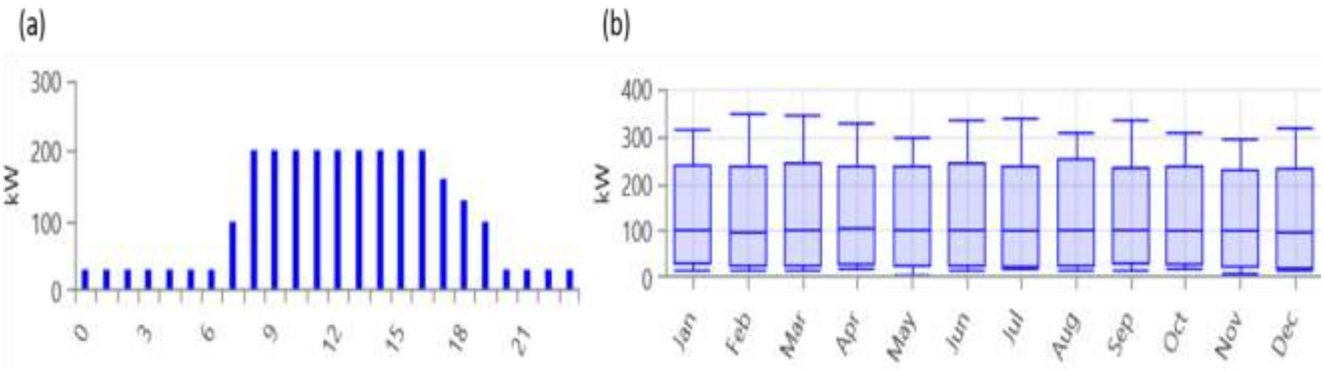


Figure 3: Electricity demand of Giri Community (a) Daily load (b) seasonal load

2.4 Renewable Resources Assessment

The Giri meteorological resource profiles (solar radiation and clearness index) shown in Figure 4 (a)were collected via the NASA Database in HOMER software. The solar radiation and clearness index reached their zeniths in March and February respectively. An annual average of 5.45 kWh/m^2/day of solar radiation was considered for the simulation. Furthermore, the hydrological profiles of River Wuye (flow rate of 14.5 m^3/s and gross head of 11 m) were utilized [17]. River Wuye is used predominantly for fishing and irrigation. It navigates the main Campus of the University of Abuja at

Giri and discharges into the Usuma River, which is a tributary of the Gurara River in Niger State, Nigeria. River Wuye at the proposed project sites experiences minimal flow in the dry season from November to April and peak flow from July to October each year as shown in Figure 4(b).

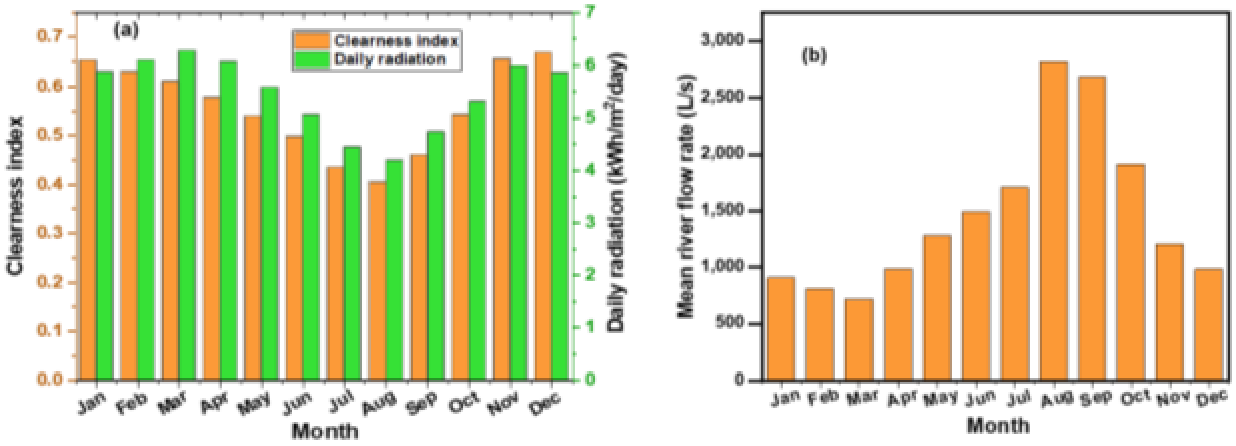


Figure 4: Giri community solar and hydro resources (a) Solar radiation and Clearness index (b) River Wuye Flow rates [4], [17].

2.5 Modelling of the System Components

2.5.1 Solar photovoltaic panel

The solar PV system functions primarily in the presence of the sun. It transforms solar radiation into DC electricity for evacuation to the load via an inverter or battery for storage purposes. The total energy $E_{pv}(t)$ generated by the solar PV array is expressed in equation (1)

$$E_{pv}(t) = \frac{\left(N_{p,pv} \times V_{pv}(t) \times I_{pv}(t) \times \Delta t\right)}{1000} \tag{1}$$

Where, $I_{pv}(t)$, $V_{pv}(t)$, $N_{p,pv}$ represents the solar PV module current, voltage, and number of PV modules required for electrification. A flat plate SunPower module having a capital cost, operation, and maintenance cost, and replacement cost of \$700/kW, \$15/year, and \$600/kW [1] respectively were chosen for analysis.

2.5.2 Battery bank

The battery serves as a backup storage device for the hybrid power system. They are deployed to meet the electricity demand whenever there is grid failure, or deficient or complete dearth of electricity generation from RE sources. The rating of the battery, commonly indicated in watt-hour (C_{Wh}) and ampere-hour (C_{Ah}) is essential in analyzing the reliability of the battery. The C_{Wh} of the BESS can be expressed as [6]:

$$C_{wh} = \frac{(AD \times E_L)}{(DoD \times n_{bat})} \tag{2}$$

Where DoD is the discharge depth of the battery, E_L is the average daily load (kWh/day), AD represents the daily autonomy of the battery, η_{bat} represents the battery efficiency. Similar to Dodo et al. [1], a modified kinetic battery model having the capital cost, replacement cost, and operation and maintenance costs of \$700, \$645, and \$16/year were considered in this research.

2.5.3 Micro hydropower plant

Hydropower plants convert the energy of moving and elevated water into electricity. The amount of electricity that can be generated principally depends on the water density, net head, and flow rate. HOMER uses equation (3) to evaluate the electrical power generation by the hydro turbine [4]:

$$P_h = \eta_h \times \rho_w \times h_{net} \times Q_t \times g \times 10^{-3} \tag{3}$$

Where η_h is the efficiency of the hydro turbine system (%), ρ_w is the water density (1000kg/m^3), Q_t refers to hydro turbine stream flow rate in m^3/s, g is the gravitational acceleration, and h_{net} is the effective head in meters.

2.5.4 Converter

A converter is an assembly of a rectifier and an inverter. It ensures electricity flow between AC and DC buses. Thus, it rectifies AC electricity from the grid and hydropower plants for storage by the battery bank and inverts DC electricity from the battery and solar PV for utilization by the community. The output power of the converter is expressed in the equation (4) [19].

$$P_0(t) = P_i(t) \times \eta_{conv} \tag{4}$$

Where $P_{i(t)}$, $P_{0(t)}$, and η_{conv}, respectively, are designated as power supplied to the converter, converter output power, and the converter efficiency. Leonics MTP-413F converter model having a capital cost of \$600/kW, replacement costs of \$500/kW and operation and operation and maintenance cost of \$10/year were considered for analysis [4].

2.5.5 Grid

The grid was modelled in HOMER as unreliable to reflect the characteristics of Nigeria’s national grid. Although there was no available data on grid outages of the study location, an assumption of a 2-hour daily grid outage with a mean repair time of 6 hours and a repair time variable of 90% was made. The Dmap created by HOMER under this grid condition is shown in Figure 5. The dark spots in the Figure indicate when the grid is interrupted, whereas the green colour denotes when it is operating normally. The emission characteristics of the grid are based on Nigeria's energy mix, which contains 378 g/kWh of CO_2, 0.41 g/kWh of NOx, 1.9 g/kWh of SO_2, 0.03 g/kWh of CO, and 0.14 g/kWh of particulate matters [1], [20]. The community is supplied by a 33 kV feeder categorized under Band A with a tariff of \$0.13/kWh (\$1 = ₦1,650).

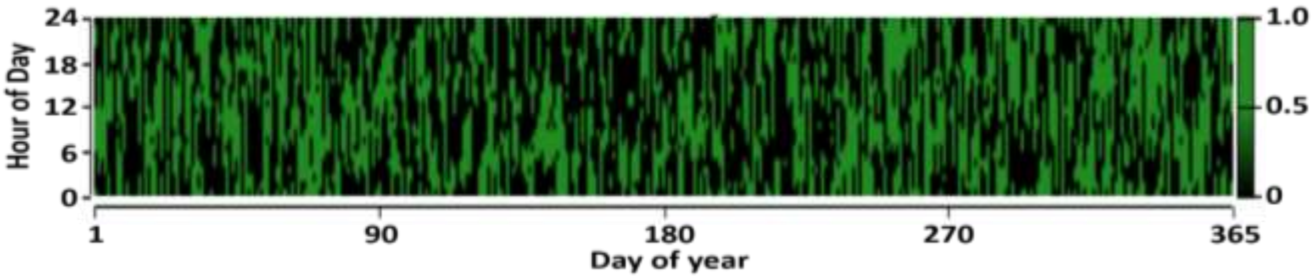


Figure 5: Giri grid characteristics

Equation (5) can be used to determine the yearly cost of purchasing electricity from the grid (5) [1].

$$C_g = \sum_{t=1}^{T} P_{g,t} \times \beta \tag{5}$$

Where C_g is the price of grid power (\$/kWh), $P_{g,t,}$ = Power purchased from the grid at hour t (kW), and T = Total time for study interval (1 to 8760 h for a year).

2.6 Economics of the System

HOMER was used for the simulation and optimization in order to minimize the levelized cost of energy (LCOE) and net present cost (NPC).

NPC covers all the costs incurred throughout the project lifetime excluding the salvage value as shown in equation (6) [21]:

$$NPC = \sum_{P_L=1}^{P_L=25} R_d \left(C_{rep} + C_{cap} + C_{OM} - C_{sv} \right) \tag{6}$$

Where C_{cap} is the components' capital cost, C_{rep} is the cost of replacement of the components, C_{OM} is the cost of operation and maintenance of the components, and C_{sv} represents the salvage value. The project lifetime is taken as 25 years.

The LCOE is defined as the ratio of total annualized cost (TAC) and total annual electrical energy (E_{tot}) supplied to the load, expressed in equation (7) [16]:

$$LCOE = \frac{TAC}{E_{tot}} \tag{7}$$

2.7 Sensitivity Analysis

Sensitivity analysis, sometimes referred to as “what-if” analysis, is a technique for examining how changes in a system's inputs impact its outputs. It is used to determine which inputs have the greatest influence on the output and to assist in long-term decision-making. Sensitivity analysis is a helpful technique for both model construction and model evaluation since it illustrates how the model behavior reacts to changes in parameter values. In this study, three variables, namely, seasonal flow rate (500 L/s, 700 L/s, 900 L/s, 1,100 L/s, 1,452 L/s, 1500 L/s, 1600 L/s), load demand (1890.31kWh/day, 1984.83 kWh/day, 2079.34 kWh/day, 2173.86 kWh/day, 2268.37 kWh/day, and 2362.89 kWh/day) and inflation rates (18%, 23%, 28%, 33%, 38%, and 43%) were chosen as sensitivity variables. The choice of these variables stemmed from their significance in the operation of the proposed hybrid power system.

3. RESULTS AND DISCUSSION

3.1 System Technical Characteristics

The capacities of the optimal system components include a 98.1 kW micro-hydro turbine, 150 kW converter, and 100 kW solar panels. A total of 704 strings of battery in parallel will serve as a backup to supply the required electricity when the river flow rate and solar insolation are poor and the grid is unavailable. The annual energy input and output of the batteries are 16,847 kWh/yr and 14,074 kWh/yr. The battery bank storage depletion, annual throughput, and losses respectively are 9.64 kWh/yr, 15,428 kWh/yr, and 2,782 kWh/yr. The projected lifespan of the battery bank is 16.7 years.

Figure 6 shows the electricity generation profile of the proposed hybrid power system. The system is capable of producing a total of 1,269,540 kWh per year of which 85.9% is a contribution by the hydropower plant, 13.2% by the solar PV panel and a mere 0.934% will be imported from the grid. This system has taken advantage of the river traversing the community to meet the substantial demand of the community while making the grid a source that will rarely be depended upon. Similarly, only 13.2% equivalent to 167,076 kWh of the electricity will be supplied by solar PV per annum. The monthly power output of the micro-hydro turbine, PV panels, and the power import from the grid is shown in Figure 6. The PV panels' highest share of electricity occurs in December (16,273.34 kW) while the lowest contribution occurs in August (10,621.95 kW). This low production in August is augmented by the grid's highest share of electricity of 1,769.41 kW. The microhydro turbine's output ranges from 84,052.08 kW and 93,057.66 kW with the lowest and highest generation occurring during the dry season (February) and rainy season (August) respectively.

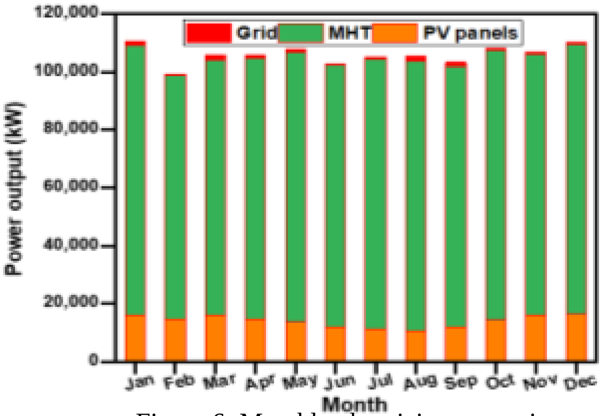


Figure 6: Monthly electricity generation

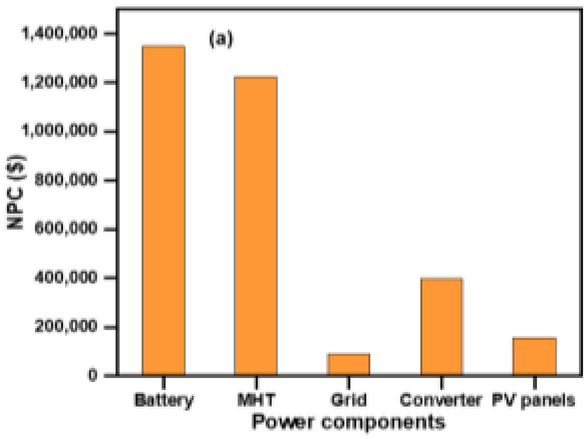
The monthly distribution of grid import and export of electricity is shown in Table 1. On an annual basis, about 266,957 kWh of electricity will be available for export to the national grid, while approximately 11,859.23 kWh will be imported to the Giri community from the grid. The low purchase from the grid is attributable to its unreliable nature which makes the system accord preference to renewable resources, particularly hydro. Furthermore, an excess electricity of 304,228 kWh/year and unmet electrical loads of 246 kWh/year will characterize this system.

Table 1: Grid energy import and export

Month	Energy purchased (kWh)	Energy sold (kWh)
January	1,053.25	22,596.98
February	517.82	22,009.52
March	1,664.76	21,926.80
April	930.94	20,268.58
May	837.33	23,121.45
June	585.87	16,669.98
July	916.65	20,875.51
August	1,769.41	18,901.16
September	1,372.40	24,064.45
October	701.24	23,303.17
November	821.85	25,867.29
December	687.72	27,352.08

3.2 System Economics

The proposed hybrid power system has a total NPC, operating cost, and LCOE of $3,202,139.00, $37,515.81, and $0.06053/kWh respectively. The bulk of the NPC amounting to $1,636,815.70 comes from the operation and maintenance cost followed by the operating cost of $1,497,478.14 and the capital cost of $1,127,645.00 respectively. The salvage cost of the components is $1,059,799.90. The cost of the system as per the components is shown in Figure 7 (a). From the Figure, the battery bank has the highest cost of $1,346,162.36 followed by the hydropower plant ($1,222,660.48), the converter ($395,120.66), and the solar PV panels ($152,944.78). The high cost of the battery is attributable to its high replacement cost of $1,141,659.99. The components that will still be useful at the end of the project lifespan are the battery and converter as evidenced in their salvage costs of $911,157.63 and $148,642.27 respectively. In Figure 7 (b), the NPC is expressed based on the cost type. The capital cost, replacement cost, operation and maintenance cost, and salvage costs, respectively are $1,127,645.00, $1,497,478.14, $1,636,815.70, and $1,059,799.90. This suggests that more funds will be expended on operating and maintaining the power components.



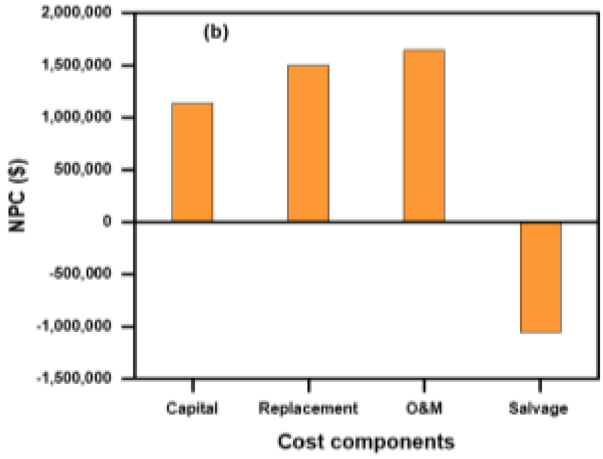


Figure 7: System cost distribution (a) Based on power components (b) Cost type

Although the optimal system of this study presents a higher NPC, it offers a lower LCOE and environmental impacts compared to [5], [15], [18] for similar locations in Abuja, Nigeria. The low carbon footprint is due to the exclusion of diesel-generating plants and waste-to-energy plants which utilize fossil resources and biomass respectively. There is also a consensus that hydropower plant offers a cheaper per unit cost of electricity compared to other RE sources.

3.3 System Emission Profiles

The optimal system has a renewable fraction of 98.8% implying a low greenhouse gas emission. On an annual basis, deployment of the proposed power system will result in the emission of 4,483kg of CO_2, 0.356 kg of CO, 22.5 kg of SO_2, 4.86 kg of NO, and 1.66 kg of particulate matter. Due to the exclusion of biogas gensets and diesel plants from the architecture, this system has no unburned hydrocarbons.

3.4 Sensitivity Analyses

Sensitivity analysis, sometimes known as "what-if" analysis, is a method for analyzing the effects of altering a system's inputs on its outputs. It helps with long-term decision-making because it shows how the model behavior responds to changes in parameter values. Three factors were selected as sensitivity variables in this study: inflation rate, load demand, and seasonal flow rate. They were chosen because of their importance to the functioning of the proposed hybrid power system.

3.4.1 Seasonal flow rate

The flow rate of the Rive Wuye significantly impacted the system economics as shown in Figure 8. An increase in flow rates results in a decrease in the total NPC, LCOE, operating cost, and salvage cost. For instance, when the flow rate was 500 L/s, the total NPC, LCOE, operating cost, and salvage cost, respectively are $9,770,876.00, $0.2245/kWh, $117,747.60 per year, and $4,956,613.32. Meanwhile, a significant decline was achieved at 1600 L/s having presented a total NPC of $3,168,749, LCOE of $0.05976/kWh, operating cost of $37,114.52, and the salvage cost of $1,039,091.77. This implies that a more economical hybrid power system can be achieved with a higher river flow rate.

The seasonal flow rate of the river has less influence on the hybrid power system capacity. As seen in the Table 2. The capacities of the PV panels, converters, and hydro turbines were not influenced by the flow rate, unlike the battery banks. The strings of the batteries required decrease with increasing flow rate. As shown in Table 2, strings of battery for a flow rate of 1500 L/s are 688, almost three times the requirements for a 500 L/s flow rate. This implies that the requirements for energy storage are less for a hydropower plant having a high flow rate and this will translate into huge financial savings.

The share of electricity supply by the PV panels, hydropower plants, and grid is presented in Table 3. Similarly, river flow rate has no impact on the PV output compared to hydropower plant output, and grid supply. Thus, the solar PV panels were 167,076 kW/year regardless of the seasonal flow rate, while the hydropower plants production and grid supply, respectively increase with increasing flow rates resulting in the corresponding increase in the excess electricity by the system.

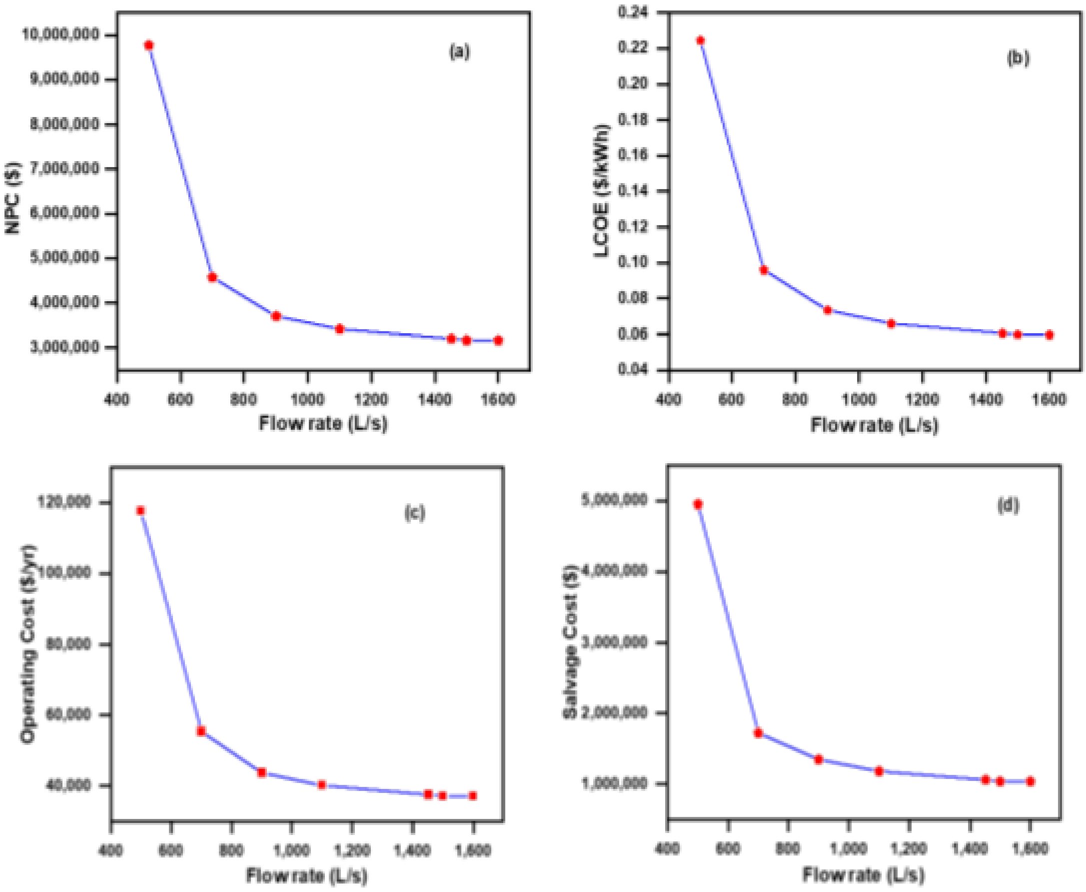


Figure 8: System economics using river flow rate as a sensitivity variable (a) NPC (b) LCOE (c) Operating cost (d) Salvage cost

Table 2: Capacities of the system components

Flow rate (L/s)	500	700	900	1,100	1,452	1,500	1,600
PV (kW)	100	100	100	100	100	100	100
BAT (strings)	3,600	1,104	928	800	704	688	688
Hydro (kW)	98.1	98.1	98.1	98.1	98.1	98.1	98.1
Conv (kW)	300	300	150	150	150	150	150

Table 3: Energy production

Flow rate (L/s)	500	700	900	1100	1452	1500	1600
Solar PV (kWh/yr)	167,076	167,076	167,076	167,076	167,076	167,076	167,076
Hydro (kWh/yr)	659,939	863,689	986,986	1,044,766	1,090,579	1,093,498	1,095,679
Grid Purchases (kWh/yr)	100,332	41,434	21,907	15,892	11,861	11,632	11,470
Excess Electricity (kWh/yr)	112,289	194,237	252,964	281,828	304,215	305,620	306,685

The emission profiles resulting from the sensitivity analyses on seasonal flow rates of the river are shown in Table 4. The higher the flow rates the lesser the system impacts on the environment. The system has no unburned hydrocarbons throughout the variation of the flow rates. The quantum of carbon dioxide emission dominates other gases. For instance, at a flow rate of 500 L/s, carbon dioxide emission is 37,926 kg/year while the carbon monoxide, sulfur dioxide, nitrogen oxides, and particulate matter, respectively are 3.01 kg/year, 191 kg/year, 41.1 kg/year, and 14.0 kg/year. Meanwhile, these values decrease almost ten-fold for a seasonal flow rate of 1600 L/s.

3.4.2 Inflation rate

The influence of inflation rates on the total NPC, LCOE, operating costs, and salvage costs is presented in Figure 9. These four economic variables exhibit divergent features with an increasing inflation rate. The total NPC and the salvage costs have similar patterns of impact on the inflation rate. Thus, they both increase with an increase in the inflation rate. Meanwhile, the LCOE and the operating cost decrease significantly with increasing inflation rates. The NPC, LCOE, operating costs, and salvage costs for an 18% inflation rate are $1,613,125, $0.1446/kWh, $42,467.76 per year, and $48,516.44 respectively, while for 43% inflation rates, the NPC, LCOE, operating costs, and the salvage costs respectively, are $5,246,291, $0.04139/kWh, $21,988.43 per year, and $6,845,490.66.

Table 4: Emissions into the atmosphere

Flow rate (L/s)	**500**	**700**	**900**	**1100**	**1452**	**1500**	**1600**
Carbon dioxide (kg/yr)	37,926	15,662	8,281	6,007	4,484	4,397	4,336
Carbon monoxide (kg/yr)	3.01	1.24	0.657	0.477	0.356	0.349	0.344
Unburned hydrocarbons (kg/yr)	0	0	0	0	0	0	0
Particulate matter (kg/yr)	14.0	5.80	3.07	2.22	1.66	1.63	1.61
Sulfur dioxide (kg/yr)	191	78.7	41.6	30.2	22.5	22.1	21.8
Nitrogen oxides (kg/yr)	41.1	17.0	8.98	6.52	4.86	4.77	4.70

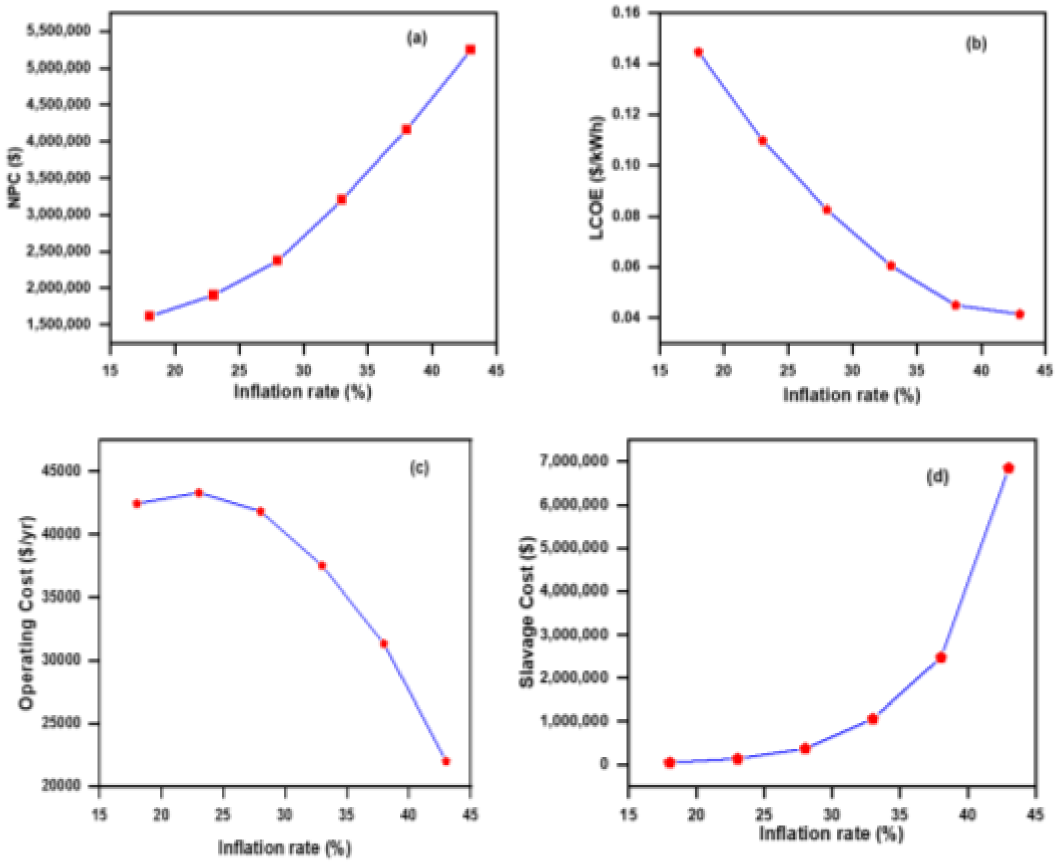


Figure 9: System economics using inflation rate as a sensitivity variable (a) NPC (b) LCOE (c) Operating cost (d) Salvage cost

As shown in Table 5, the hybrid power system components ratings are rarely influenced by the inflation rates. Thus, the capacities of the PV panels, hydro turbines, and converters remained unchanged regardless of the inflation rates. Battery is the only component in the system that is slightly influenced by the inflation rates. The strings in the battery bank are the same for 18%, 23%, and 28% inflation rates with a little increase to 704 strings for 33% and 38% respectively. For an inflation rate of 43%, the battery strings required are 816.

Table 5: Capacities of the system components

Inflation rate (%)	**18**	**23**	**28**	**33**	**38**	**43**
PV (kW)	100	100	100	100	100	100
BAT (strings)	690	690	690	704	704	816
Hydro (kW)	98.1	98.1	98.1	98.1	98.1	98.1
Conv (kW)	150	150	150	150	150	150

The electricity supply by the components is also not influenced by the inflation rates, although the system completely seized importing electricity from the grid for an inflation rate of 43% as depicted in Table 6. This implies that the system is better operated as an off-grid for high inflation rates. The suppression of the grid supply for RE sources resulted in a substantial increase in the amount of excess electricity generation from 304,215 kWh/year to 557,722 kWh/year by the system.

Table 6: Energy production

Inflation rate (%)	**18**	**23**	**28**	**33**	**38**	**43**
Solar PV (kWh/yr)	167,076	167,076	167,076	167,076	167,076	167,076
Hydro (kWh/yr)	1,090,579	1,090,579	1,090,579	1,090,579	1,090,579	1,090,579
Grid purchases (kWh/yr)	11,861	11,861	11,861	11,861	11,861	0
Excess electricity (kWh/yr)	304,211	304,211	304,211	304,215	304,215	557,722

Similarly, the inflation rates have no impacts on the emissions associated with the optimal systems as shown in Table 7. Meanwhile, for an inflation rate of 43% in which the grid was completely not supplying electricity, the system has no negative environmental impacts. This is attributed to the lack of grid emission profiles that could have influenced the release of these gases into the atmosphere [5].

Table 7: Emissions into the atmosphere

Inflation rate (%)	**18**	**23**	**28**	**33**	**38**	**43**
Carbon dioxide (kg/yr)	4,484	4,484	4,484	4,484	4,484	0
Carbon monoxide (kg/yr)	0.356	0.356	0.356	0.356	0.356	0
Unburned hydrocarbons (kg/yr)	0	0	0	0	0	0
Particulate matter (kg/yr)	1.66	1.66	1.66	1.66	1.66	0
Sulfur dioxide (kg/yr)	22.5	22.5	22.5	22.5	22.5	0
Nitrogen oxides (kg/yr)	4.86	4.86	4.86	4.86	4.86	0

3.4.3 Load demand

As shown in Figure 10 sensitivity analyses show that in the event the electricity demand of the proposed study location increases, the NPC, LCOE, operating costs, and salvage costs will increase. Thus these economic indices respectively have a positive correlation with the community load demands. When the load demand is at the peak of 2268.37 kWh/day, the NPC, LCOE, operating cost, and salvage cost respectively are $4,868,052, $0.08487/kWh, $58,477.58, and $1,951,346.26.

Similar to the inflation rates and seasonal flow rates, the load demand has little influence on the capacities of the optimal system components. As shown in Table 8, the capacities of the components remained the same despite the variation in load demand except for the strings of the battery that increased proportionally. The PV panels, and hydro turbines ratings are 100 kW, and 98.1 kW, respectively while the converter ratings double from 150 kW for the load demands of 1890.31 kWh/day and 1984.83 kWh/day to 300 kW for 2079.34 kWh/day. The increase in the capacities of the converter can be attributed to the corresponding increase in the sizes of the battery.

Table 8: Capacities of the system components

Load demand (kWh/d)	**1890.31**	**1984.83**	**2079.34**	**2173.86**	**2268.37**	**2362.89**
PV (kW)	100	100	100	100	100	100
BAT (strings)	690	903	957	1120	1278	1460
Hydro (kW)	98.1	98.1	98.1	98.1	98.1	98.1
Conv (kW)	150	150	300	300	300	300

As shown in Table 9, more electricity will be imported from the grid if the load demand of the community increases. This, however, does not translate to more electricity generation from hydropower turbines and solar PV panels. The PV panels and hydro turbines outputs respectively are 167,076 kW/year and 1,090,579 kWh/year. The optimal system's excess electricity generation declines as the demand for more electricity increases. Thus, for base loads of 1890.31 kWh/day, and 2362.89 kWh/day, the difference in the excess electricity generation by the system is 81,230 kWh/year. This excess electricity can be used for powering pimps for irrigation or serving dummy loads.

Table 9: Energy production

Load demand (kWh/d)	**1890.31**	**1984.83**	**2079.34**	**2173.86**	**2268.37**	**2362.89**
Solar PV (kWh/yr)	167,076	167,076	167,076	167,076	167,076	167,076
Hydro (kWh/yr)	1,090,579	1,090,579	1,090,579	1,090,579	1,090,579	1,090,579
Grid purchases (kWh/yr)	11,861	16,572	22,189	28,727	35,955	43,894
Excess electricity (kWh/yr)	304,211	287,144	270,540	254,333	238,468	222,981

The optimal system is influenced by the load demand as shown in Table 10. The higher the demand for electricity by the community the more the environment is negatively impacted. The carbon dioxides, carbon monoxides, nitrogen oxides, sulfur dioxides, and particulate matter increase proportionally with the load demands. With the base loads of 1890.31

kWh/day and 2362.89 kWh/day, the annual carbon dioxides emissions are 4,484 kg and 16,592 kg respectively while the annual emissions of sulfur dioxides are 22.5 kg and 83.4 kg respectively.

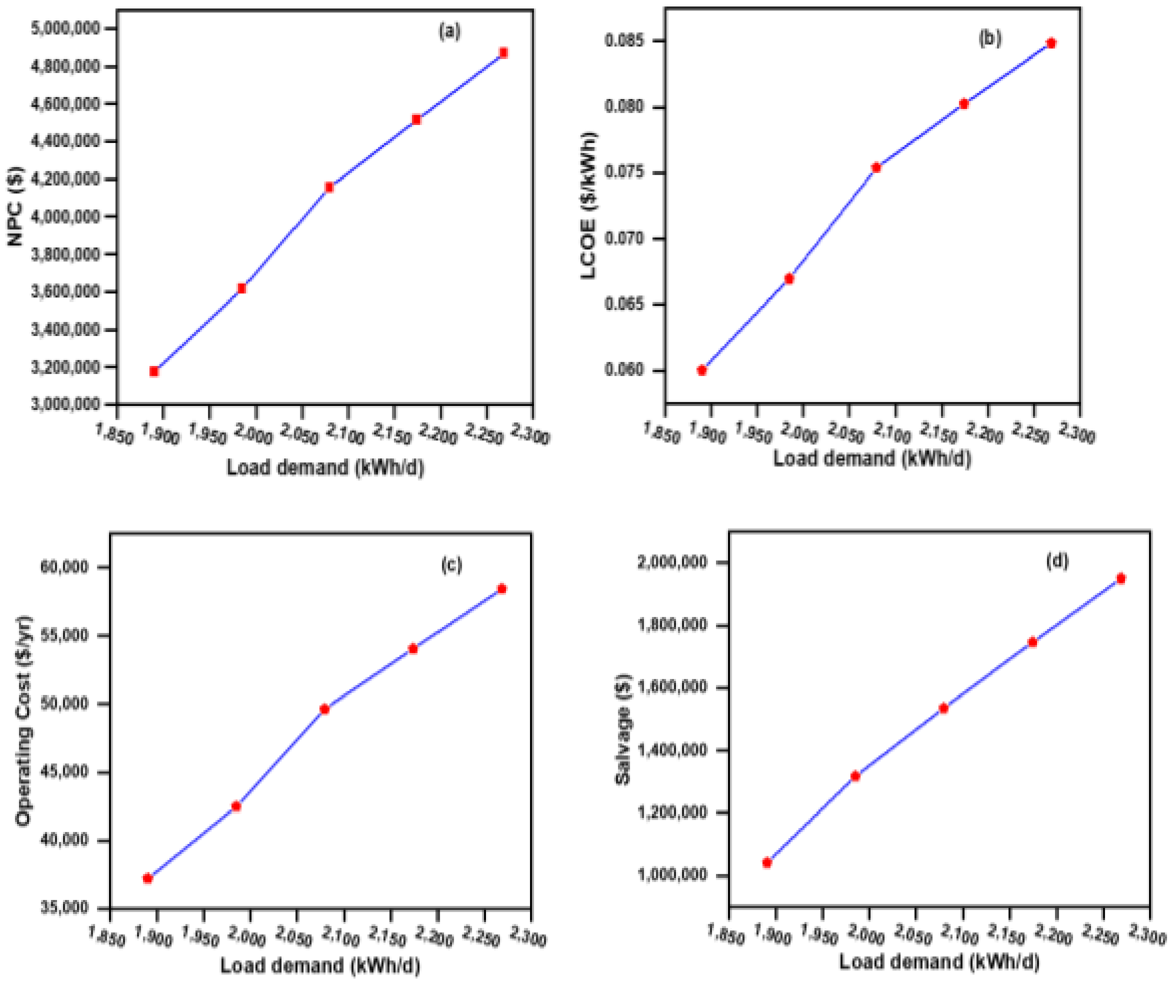


Figure 10: System economics using load demand as sensitivity variables (a) NPC (b) LCOE (c) Operating cost (d) Salvage cost

Table 10: Emissions into the atmosphere

Load demand (kwh/d)	**1890.31**	**1984.83**	**2079.34**	**2173.86**	**2268.37**	**2362.89**
Carbon dioxide (kg/yr)	4,484	6,264	8,387	10,859	13,591	16,592
Carbon monoxide (kg/yr)	0.356	0.497	0.666	0.862	1.08	1.32
Unburned hydrocarbons (kg/yr)	0	0	0	0	0	0
Particulate matter (kg/yr)	1.66	2.32	3.11	4.02	5.03	6.15
Sulfur dioxide (kg/yr)	22.5	31.5	42.2	54.6	68.3	83.4
Nitrogen oxides (kg/yr)	4.86	6.79	9.1	11.8	14.7	18

3.5 Comparison with Relevant Studies

The complexity of system topologies, capacities of the power components, load requirements, and RE sources accessible at different locations may make it difficult to compare the current study to the relevant literature. However, the results of this study can be compared to those of other research in the literature using several economic indices such as the LCOE. Thus, LCOE, which is calculated by dividing the total amount of power supplied by the annualised cost of producing electricity, can be a helpful indicator for evaluating the cost-effectiveness of hybrid energy systems. Table 11 shows the comparison of the LCOE with some findings in the literature. The LCOE varies by location, as the Table illustrates. As a result, the LCOE is not reliant on the whole amount of energy that is required; rather, it is dependent on the resources that are available at the project site, the type of fuel and components chosen, the economics of the fuel, interest, and inflation rates, and the limitations imposed by the hybrid power systems planner. It is obvious from the Table that the present study which focuses on Grid-PV-MHT is the most cost-effective energy solution compared to other studies. This can be attributed to the inclusion of the hydropower plant into the energy mix.

Table 11: HRES comparison with other studies

System topology	Study location	LCOE ($/kWh)	Reference
PV-BG-MHT	Pakistan	0.0728	[12]
PV-WT-DG	Algeria	0.24862	[8]
PV-WT		$0.284/kWh	
PV-WT-DG	Pakistan	$0.295/kWh	[22]
PV-Wind-FC		$0.409/kWh	
Grid-WT-PV-DG	Nigeria	0.0722	[1]
WT-PV-FC	India	0.232	[21]
Grid-WT-PV-BG	Nigeria	0.148	[6]
Grid-PV-MHT	Nigeria	0.06053	**Present study**

4. CONCLUSION

This study performed a techno-economic evaluation of a grid-connected hybrid RE system consisting of solar PV and micro-hydro power plants for a rural community in Nigeria. Results of the analysis performed using the HOMER software tool present the optimal system to have a total NPC, operating cost, and LCOE of $3,202,139.00, $37,515.81, and $0.06053/kWh respectively. The capacities of the optimal system components include a 98.1 kW micro-hydro turbine, 150 kW converter, 100 kW solar panels, and 704 strings of battery. In addition to enhancing access to electricity, the deployment of this hybrid power system will aid in reducing greenhouse gas emissions because hydro and solar resources are carbon-free. Future studies may consider other RE sources such as wind and biomass for complementary operation with an erratic utility grid.

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