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Viability Assessment of a Hybrid Microgrid System for Rural Electrification: A Case Study of Delta State, Nigeria

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Abstract: Energy poverty is a severe electrification challenge in Nigeria that has affected the country's economic development. The gap between electricity demand and supply continues to increase, and a large percentage of the populace affected are rural dwellers. With the prevailing electricity inaccessibility in rural, renewable energy sources (RES) present viable option for addressing rural electrification challenge. However, RES like solar have intermittency challenges since they are weather dependent. Thus, a hybrid microgrid system (HMS) comprising solar, hydropower and battery storage was sized as a feasible solution for electrifying rural areas in Nigeria. For the HMS sizing, a site was selected, whose residential load demand was estimated. The renewable energy generation potential for the selected resources at the site as well as grid reliability were assessed. Hybrid Optimisation Model for Multiple Energy Resources (HOMER) was used to size the HMS. An economic analysis was performed to determine the levelised cost of energy (LCOE) and net present cost (NPC). For the sized HMS, two scenarios were considered: off-grid and grid-connected HMS configurations. The results showed that the LCOE of the off-grid and grid-connected configurations are \$0.101/kWh and \$0.046/kWh, respectively. The NPC of the off-grid and grid-connected configurations are \$227,307 and \$145,282, respectively.

Keywords: hybrid microgrid system; renewable energy sources; energy storage; levelised cost of energy; rural electrification

1. Introduction

Conventional energy, particularly the fossil fuel-based is a major source of electricity production across the globe. In 2020, fossil fuel (coal and gas) based energy generation accounted for about 59% of global generation, while nuclear and renewable energy contributed the remaining share [1]. In Nigeria, fossil fuels dominate the country's energy mix, accounted for about 80% of the total installed capacity. Likewise, about 90% of the country's economy depends on crude oil. Nigeria is endowed with so many renewable energy sources (RES) such as wind, solar, biomass and hydropower, most of which are yet to be fully harnessed [2]. Due to poor maintenance of the grid infrastructure, Nigeria is only able to supply about 30% of the electricity generated for the 12,522 MW installed capacity [2–4]. Power loss in the country's grid is between 30-35%, which is significantly high. Overall, the rate of access to electricity in Nigeria is about 55% in urban areas and 36% in rural areas [2–4].

Nigeria's electricity generation is mainly from the fossil fuels based installed plants. The country's percentage mix of electricity generation is 39.8% natural gas, 35.6% hydro, 24.8% oil and 0.4% coal [5]. The gap between electricity demand and supply continues to increase as the maximum generation capacity which is less than 4,000 MW fails to match the electricity demand of the country. This challenge is caused by several factors such as the unpremeditated shut down of power plants for preservation, inadequate gas supply to thermal stations, and power equipment vandalisation [5].

The limited access to reliable and affordable electricity by the citizens is considered as one of the key causes of poverty in Nigeria and other Sub-Saharan Africa (SSA) countries. In SSA, about 585 million people do not have access to electricity [6,7]. According to the World Economic Forum, energy poverty is defined as the lack of access to sustainable energy services and products [8]. In Nigeria, the total populace that lacks access to electricity in rural areas is more than 80 million people [4,9]. Though some rural areas are connected to the grid, power outages still pose a problem in these regions as a result of constraints related to electricity generation, transmission and distribution [4,9]. In 2018, Nigeria had the highest average frequency of interruptions of about 304 interruptions per customer and the longest average duration of interruptions of 742 hours of interruption per customer [6]. Due to limited access and unreliability of the grid in the country, household electricity demand in rural areas is very low, though the desire to use electricity is very high [10]. Some households use kerosene and candles due to the absence of electricity, which can be harmful, causing respiratory infections as a result of soot emission. Lack of access to electricity also affects income and business productivity in rural areas [11].

Several reasons for these electricity challenges in rural areas have been identified. The primary reason is the location of rural settlements which are largely dispersed and very far from urban areas; hence, the grid extension to such areas is very expensive and almost impossible. Microgrid systems as an alternative to national grid system are crucial due to the disparity between low electricity demand and grid extension costs. However, though off-grid systems are beneficial, they cannot provide enough energy due to the intermittent nature of RES such a solar and wind [12].

This study aims to size an economically feasible hybrid microgrid system (HMS) for addressing the rural electrification challenges in Nigeria. This research focuses on energy storage which is an integral part of a microgrid system. The study considers improving the reliability of an off-grid system using battery storage and also the possibility of connecting to the grid. To achieve this, the study analyses two renewable energy sources in Nigeria, namely, solar energy and hydropower. To size the HMS, HOMER was used. This software is widely used and is considered the best and easiest tool for renewable energy sources' evaluation [13].

2. Addressing Electrification Challenges in Nigeria

A major drawback of RES like solar is their intermittent nature, due to their dependence on weather conditions. Hybrid systems using several RES that include energy storage systems such as batteries and diesel generators can help improve the reliability of RES [14]. Solar energy systems have a promising future since they can be used in various locations and are highly efficient. They are beneficial for many reasons especially in Sub-Saharan African countries that have a high solar resource potential [15]. Located north of the equator at coordinates 9.0830oN and 8.6753oE, Nigeria is one of the tropical countries that have a high solar potential and an even distribution of sunlight throughout the year. The average total daily solar irradiation is estimated to be around 3.5 kWh/m2/day in the South and 7.0 kWh/m2/day in the North [16]. Considering such an abundant energy resource across the country, the use of solar energy could be effective in providing electricity to rural settlements that are off the national grid in Nigeria.

In Nigeria, large-scale hydropower systems contribute about 30% of the total installed generation capacity and form one of the major electricity sources due to the presence of large rivers in different parts of the country [16]. The proper execution of project plans and the maintenance of hydropower already commissioned can play a major part in alleviating the electricity crisis in Nigeria as it can provide twice the amount of the present generation capacity. Small-scale hydropower systems, on the other hand, use streams, small rivers and waterfalls to generate electricity. These systems generate approximately 10 MW of electricity. Nigeria shows a very high resource potential for hydropower, which can be used for both off-grid and on-grid connections [16].

Small-scale hydropower is an appropriate scheme for rural electrification. Hydropower utilization would promote the conservation of petroleum resources, encourage economic diversification and cause a significant reduction in dangerous gas emissions [17]. Rivers such as Benue and Niger, including some smaller rivers, have a high potential for hydropower exploitation in Nigeria. Also, the mountains and high terrains in some regions are good sites for reservoirs and flow diversion for generating electricity [18,19].

Even though solar photovoltaic (PV) and hydropower systems are environmentally friendly, they both have some drawbacks; solar PV has an intermittent nature, and hydropower relies on the inflow of water. Consequently, solar PV cannot provide electricity reliably, except if equipped with energy storage systems [20]. Distributed energy systems like microgrids have autonomous characteristics that enable the development of an electrical generating infrastructure using renewable energy technologies. Microgrids are interconnected networks that can be standalone or grid-connected. The decentralised nature of microgrids makes them more beneficial than centralised systems. Some benefits include a sustainable environment, economic improvement, and regional equity relating to rural electrification and technical performance [21]. The microgrid is also advantageous due to its proximity to the load centre. Unlike the traditional standalone system, microgrids provide the flexibility of being integrated to the grid when there is an increase in electricity demand or grid expansion sometime in the future [21].

Several research works have been conducted regarding the reliability of microgrids and hybrid systems. When taking into consideration the Nigeria's energy sector and renewable energy features, the application of renewable energy technologies in a remote economic sector is more beneficial than conventional energy [2]. Study [22] emphasised that renewable energy supported microgrids could make a significant impact by providing a cost-effective solution to the rural electrification challenge in SSA countries compared to grid extension investments. The study presented a detailed review of the ongoing renewable energy supported technology for the SSA region's rural electrification. It also discussed energy poverty, challenges facing the development of renewable energy technology, and how it is directly related to these countries' lagging economy.

HOMER software has widely beeb used such as in studies [23–27] size hybrid energy systems as well as for techno-economic analysis. HOMER software is used for the design and analysis of the energy system. HOMER is preferred for hybrid system optimisation among other software tools because it allows multiple possible combinations of renewable energy systems [28]. It can easily perform sensitivity and optimisation analysis of many possible system configurations [28,29]. Many studies performed technical and economic feasibility of hybrid energy system worldwide using HOMER software [30–32]. Further description of HOMER software are covered in [33].

For instance, using HOMER, the feasibility of a grid-tied solar PV system considering a case study of Jos, Nigeria was investigated in [23]. The techno-economic performance of combining 80 kW solar PV and grid power of 100 kW was studied. At the cost of $2,400/kW for solar PV and at an average global solar radiation of 6.0 kWh/m2/day, the total annual electricity generated was 331,536 kWh, and the LCOE was found to be $0.103/kWh. The solar PV contributed about 40.4% of the total generated energy by the hybrid system [23]. Also, HOMER was used in [24] to investigate the possibility of generating electricity in rural and semi-urban areas by using a hybrid energy system in Jos, a northern part of Nigeria. The obtained results showed that considering diesel price of $1.1/L, the PV/generator/battery hybrid was the most suitable option for electricity generation in the study location. The obtained optimal simulation result showed that the LCOE varies between $0.348/kWh and $0.378/kWh. The LCOE value obtained was lower than the cost of using only diesel generator (without battery), ranging between $0.417 and $0.423/kWh.

Techno-economic study of PV/wind/diesel energy/battery sources that considered case study villages across the six geo-political zones in Nigeria was carried out in [25] using HOMER. The PV/diesel/battery system configuration results had the least net present cost (NPC) among other considered configurations investigated for the six case studies. Similarly, the study [27] analysed the technical and economic feasibility of employing hybrid energy system to supply electricity to a rural healthcare facility in six geo-political zones in Nigeria. The obtained results showed that PV/battery/diesel as the optimum configuration for Port Harcourt, while PV/battery/wind/diesel as the optimal configuration for Jos, Enugu and Maiduguri. The feasibility of energizing a remote mobile transceiver station in Nigeria was studied in [26]. PV/wind/ diesel/battery system and PV/diesel/battery system configurations were the two best system configurations obtained. However,

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when the two optimal hybrid systems were compared with the conventional standalone diesel generator, the PV/diesel/battery system was the most economically viable system with the least cost of electricity of $0.409/kWh and NPC of $69,811.

The research work in [12] conducted in Rwanda articulated the importance of microgrids for rural areas in SSA. The study highlighted the fact that extending the grid to rural areas where electricity demand is low can be a costly venture; therefore, harnessing the untapped renewable energy potentials of these rural communities can improve rural electrification. Various challenges of electrification in SSA, including lack of financial means, dispersed rural settlements, lack of energy policies, and lack of appropriate knowledge, were presented in the study. The improvement in renewable energy technologies and microgrid systems provided a viable rural electrification solution, which was modelled using HOMER. A microgrid system was designed for electrification in rural Rwanda which consisted of solar PV, batteries and micro-hydro. The installation of a microgrid based on solar PV, batteries and micro-hydro was more cost-effective than a grid extension [12].

Focusing on Nigeria, study [29] highlighted the fact that even with its diverse renewable energy sources, lack of experts in the field has prevented the country from harnessing these resources for electricity production. Most rural areas in Nigeria lack access to the grid but have close proximity to renewable energy sources like hydro and solar. The study analysed a hydro-based hybrid system as a solution to energy poverty in remote areas. The hybrid system consisted of solar PV and a pico-hydro scheme. The results showed that harnessing clean energy in Nigeria is important for economic development and is a solution to energy poverty [29].

3. Case Study Description

The selected site is a community village located at 5.3994o N and 6.3421o E in Ndokwa East local government area of Delta State, Nigeria. The potential for renewable energy technologies utilisation at the site was identified, solar irradiance data were obtained from NASA surface meteorology and applied in HOMER software.

3.1. Load Analysis

The residential load profile for the village considered in this study was obtained from the low-income demographic data of the Mapo region in study [34]. The low income data was selected because rural areas are largely populated by low-income earners with lower energy demand, as compared to the energy demand of middle- and high-income earners [10]. The total daily energy demand of all households in the selected village was estimated to be 476.36 kWh/day. Based on this energy demand, the typical hourly energy consumption curve was derived and is shown in Figure 1.

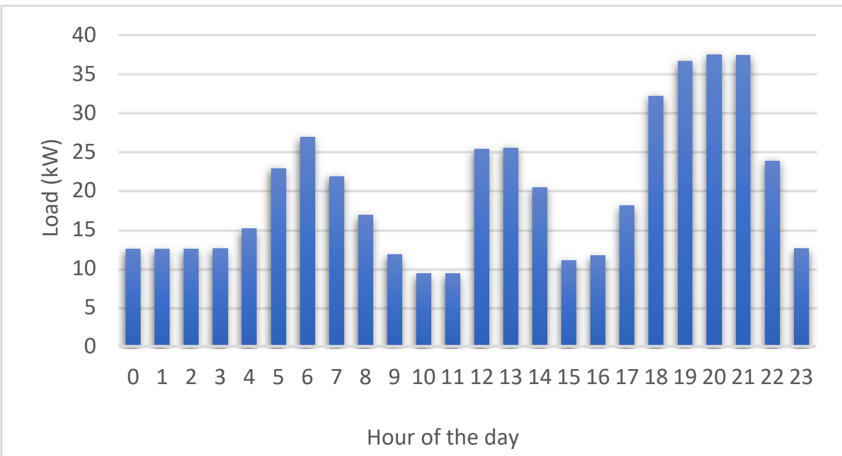

Figure 1. Load profile of Ase village.

3.2. Microgrid Technology Selection

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An important factor used in the selection of the system's renewable energy sources is the resource potential of the study area. The proposed microgrid is a hybrid system which comprises of solar PV and hydropower renewable energy sources. The River Asse as a major river located in Ase village, as shown in Figure 2, provides the States with high potential energy from hydro. The solar resource potential is almost unlimited in Nigeria and enough for rural electrification needs. The major sources of electricity generation for the HMS design are solar and hydropower; a battery is used as a backup energy storage system. The system configuration includes solar PV, micro-hydro and batteries.

Figure 2. Location of Asse river in Delta State [35].

3.3. Solar Resource Assessment.

The solar irradiation data for the study location, latitude 5.3994° N and longitude 6.3421° E was downloaded from the NASA surface meteorology and was used in HOMER. Figure 3 shows the monthly average daily radiation and clearness index data of all 12 months of the year. Clearness index is the ratio between the monthly average daily radiation on a surface (horizontal plane) and the location's extra-terrestrial radiation [36]. The average clearness index is 0.411, and the annual average daily solar radiation is 4.53 kWh/m²/day. The monthly average daily temperatures of Ase village is represented in Figure 4. The temperatures range from 24°C to 26°C throughout the year. The annual average temperature is 25.16°C.

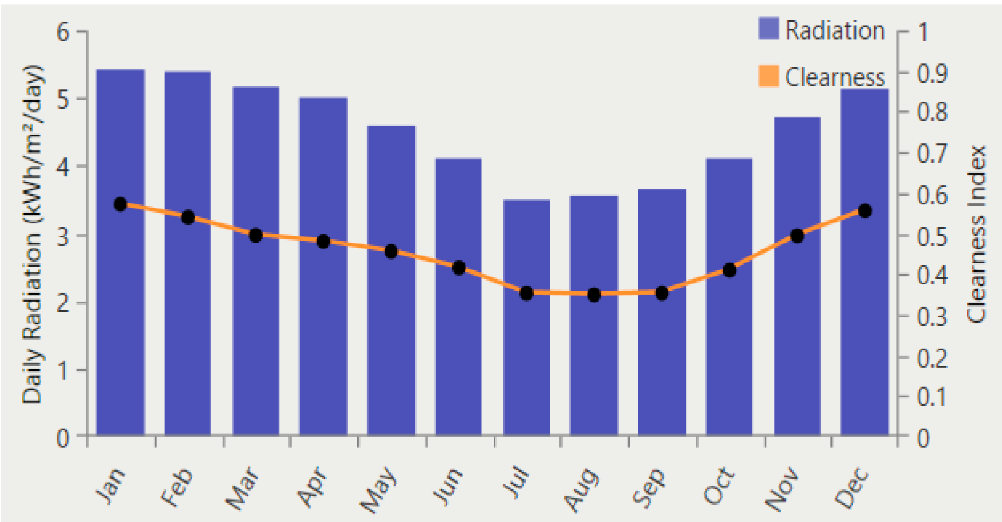

Figure 3. Monthly average daily radiation of Ase village.

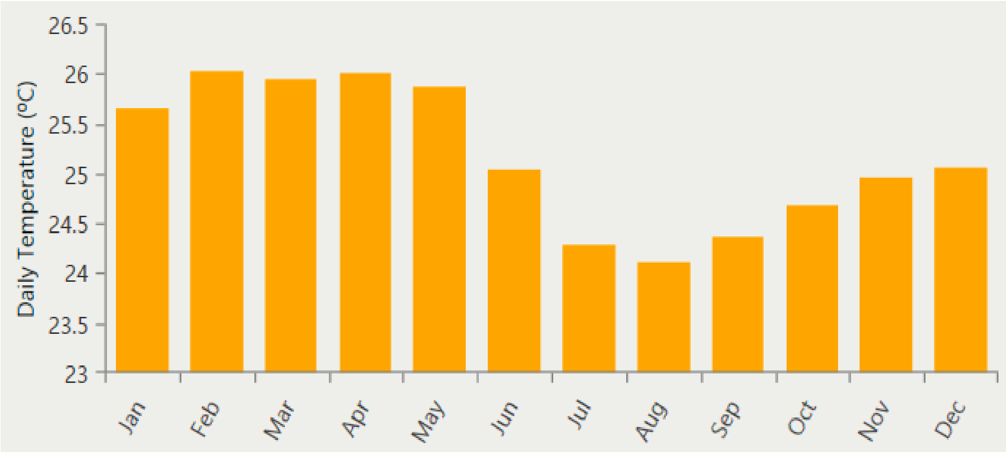

Figure 4. Monthly average daily temperature of Ase village.

3.4. Hydro Resource Assessment

Delta State as one of the nine States in the South-South geopolitical zone of Nigeria that borders the Atlantic Ocean is a region with several rivers. Asse river is marked in a red circle in Figure 2. The study was limited by the unavailability of stream discharge data in the literature for any of the rivers in Delta State and the inability to collect on-site data. Thus, the available stream discharge data for some rivers in another State was used to approximate the stream discharge for rivers in Delta State. The hydrological data was estimated by taking the average stream discharge of four rivers in Edo State, Nigeria: the Edion, Ovia, Ikpoba and Orlie rivers. Edo State is located in the South-South geopolitical zone of Nigeria and also, similar to Delta State, it borders the Atlantic Ocean. Since the stream discharges for some of the rivers in Edo State are approximately the same as for the rivers in Delta State, the average hydrological data for steam disharge in Edo State was used in this investigation. The stream discharge (flow) is defined as the water volume available from a river basin over a specific time [37]. As shown in Figure 5, the maximum average stream discharge is in September at a total of 214,680 litres per second (L/s). The minimum stream discharge is in April at a total of 3,320 L/s. The annual average stream discharge is 47,455 L/s. The residual flow is set to a range between 500 and 2,500 L/s. Residual flow is the water volume that must not be disturbed in the channel to support aquatic life [38].

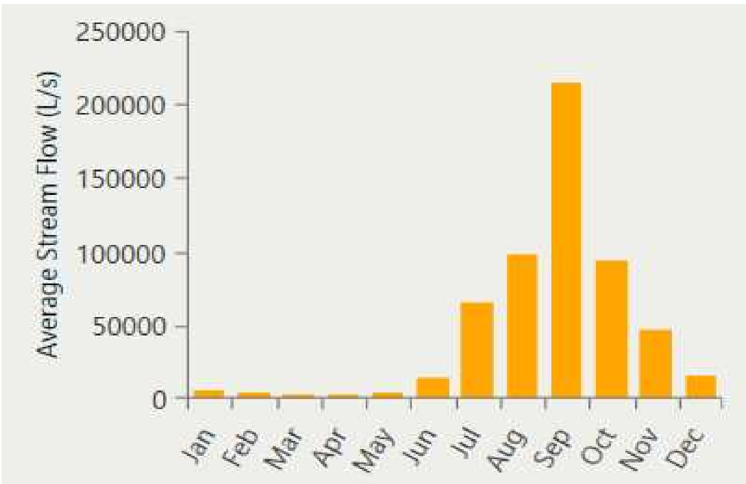

Figure 5. Monthly average stream discharge.

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4. System Design and Methodology

Figure 6 describes the methodology steps of the HMS design adopted for in this research. The HMS comprises of five components including solar PV, hydropower, batteries, converter, grid and residential load. The system design is made up of two parts, off-grid and grid-connected configurations as shown in Figure 7 and Figure 8, respectively.

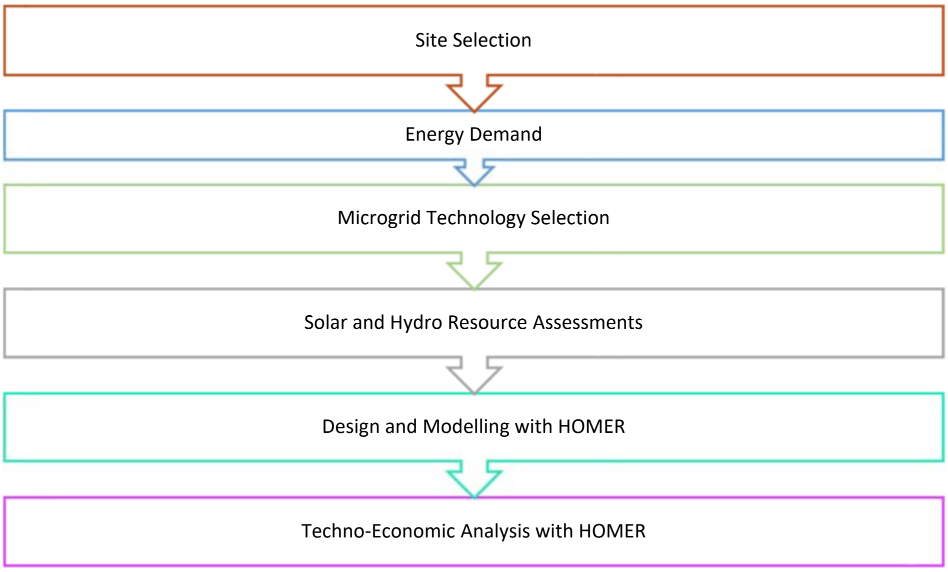

Figure 6. Methodology of the HMS design.

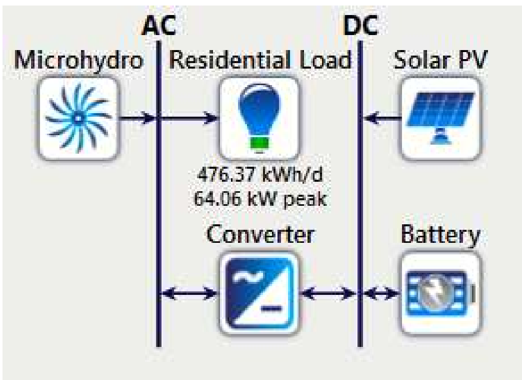

Figure 7. Schematic of the off-grid microgrid.

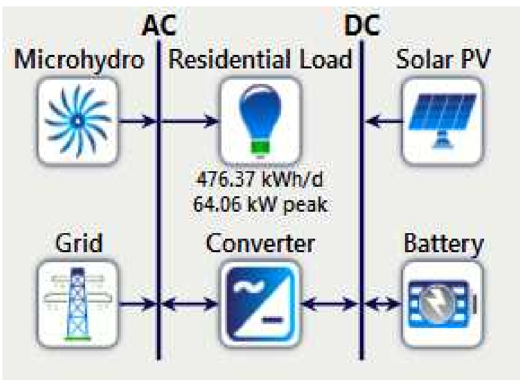

Figure 8. Schematic of the grid-connected microgrid.

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4.1. The Electric Grid

The reliability of the grid was considered in the system configuration. The random outages parameters were calculated. These parameters include the mean outage frequency, mean repair time and the repair time variability. The mean outage frequency is the number of times of grid failure per year; the mean repair time is the mean hourly duration of grid outages; the repair time variability is the standard deviation of the grid outage duration, usually expressed as a percentage of the mean. Due to the unreliability of the grid, with its frequent outages, it is only able to supply a minimal amount of power throughout the year.

4.2. Solar PV Module

The solar PV panels for the hybrid system configuration supply power to the load and simultaneously charge the battery system during daylight hours. A derating factor of 88% was applied to the configuration. This factor decreases the electricity production of the solar PV panels by 12%. The derating factor include factors such as panel soiling, shading, ageing and wiring losses. The temperature effect was excluded from the derating factor because it was explicitly considered when selecting the PV module. The monthly solar irradiance varies throughout the year, and the peak for each month is always in the twelfth hour (at noon). The solar PV module power output P_{pv} (kW) is a function of the cell temperature and solar irradiance, and is calculated by HOMER using Equation (1).

$$P_{pv} = P_{rated} * f_{pv} * \left(\frac{G_T}{G_{T,STC}}\right) * [1 + \propto_p (T_c - T_{c,STC})] \quad (1)$$

where, P_{rated} is the rated capacity of the PV array (kW); f_{pv} is the PV derating factor; G_T is the solar radiance incident on the PV array (kW/m^2); $G_{T,STC}$ is the incident radiation at standard test conditions (1 kW/m^2); $\propto_p$is the temperature coefficient of power; T_c is the cell temperature of PV; and $T_{c,STC}$ is the cell temperature of PV under standard test conditions (25^{o}C).

A Canadian solar PV module CS6X-325P, which is a polycrystalline type was selected from HOMER library for this model. The characteristics of the PV module were obtained from the manufacturer's datasheet and are shown in Table 1.

Table 1. Component specifications.

Components	Parameters	Specifications
PV panel	Model	CS6X-325P
	Nominal maximum power (P_{max})	325 W
	Module efficiency	16.94%
Microhydro Turbine/Generator	Model	XJ30-20SCTF4/6-Z / SF10-4
	Power output	20 kW
	Turbine efficiency	70%
Battery	Model	8CS25P
	Nominal voltage	8 V
	Nominal capacity	1156 Ah
Converter	Model	SUNSYS-PCS^2 IM 66TR
	Rated power	66 kW
	Efficiency	97%

4.3. Micro-hydropower System

The micro-hydro system is set to supply baseload in the system configuration. The excess energy generated by the micro-hydro at any hour of the day is used to charge the battery system. The microturbine parameters, head and flow rate, are selected to fit the nominal capacity required to supply the baseload.

HOMER uses the run of the river development, and this is better suited for a micro-hydro system. Suneco hydropower generation technology (comprising of a turbine and generator) was selected for the system configuration. The technology consists of a controller that regulates the output voltage. The turbine is an impulse-type turgo turbine; it was selected due to its compatibility with site characteristics of medium head and high flow rate. The turgo turbine can handle a very high flow rate.

4.4. Battery Storage System

A lead-acid battery was considered for the system configuration. The Surette 8CS25P battery of 1156 Ah (9.485 kWh) capacity was selected from HOMER library. The capacity curve of a Surette 8CS25P battery in Figure 9 shows that an increase in discharge current leads to a decrease in the capacity. In Figure 10, it can be seen that the discharge power rate of the battery occurs at night-time and in the early hours of the morning; this shows the time of battery usage in the system.

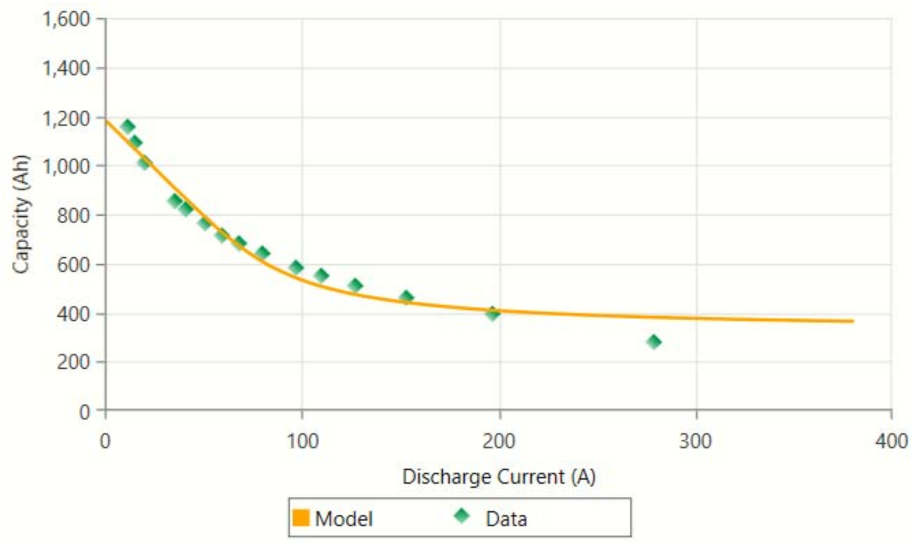

Figure 9. Capacity curve of Surette 8CS25P battery.

The lifetime of a battery bank is defined by the depth of discharge and cycles to failure. The depth of discharge is the fraction of the battery that has been discharged to the total capacity of the battery [38]. The battery lifetime R_B (years) is calculated by HOMER using Eq. (2).

$$R_B = \min\left(\frac{N_B \cdot Q_{lifetime}}{Q_{throughput}}, R_{B,f}\right). \quad (2)$$

where, N_B is the number of batteries, $Q_{lifetime}$ is the lifetime throughput of the battery (kWh), $Q_{throughput}$ is the annual battery throughput (kWh/year) and $R_{B,f}$ is the battery's float life.

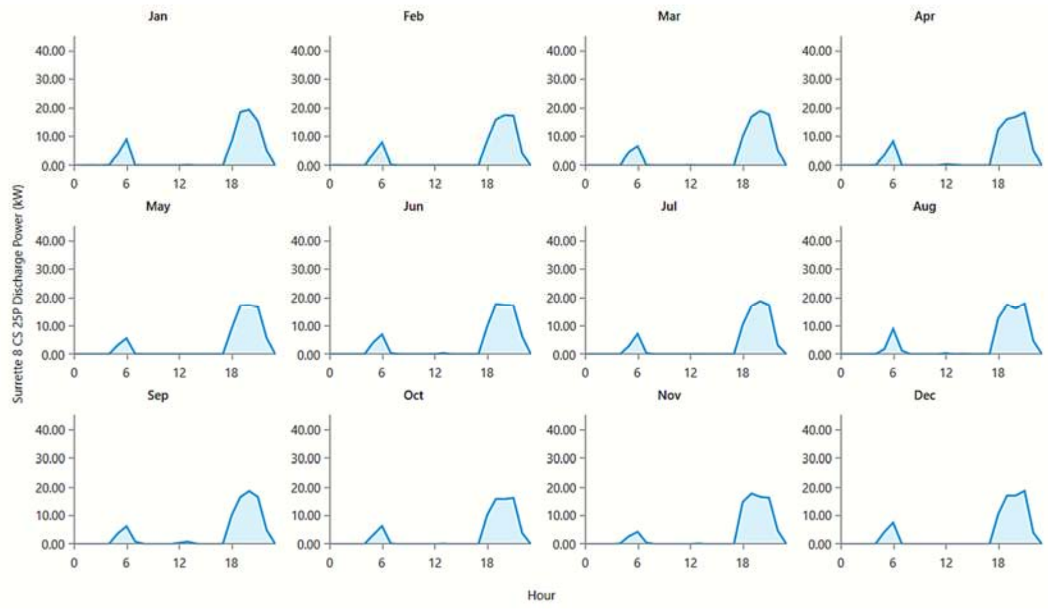

Figure 10. Average annual monthly discharge power of the battery.

The lifetime curve of the Surette 8CS25P battery, as indicated in Figure 11, shows the lifetime throughput of the battery. The yellow dots on the curve shows a decrease in the number of cycles to failure with an increase in the depth of discharge. The lifetime throughput is the total amount of energy storage cycles of the battery through its lifetime. The suggested throughput, 13,271 kWh, as calculated by HOMER, is specified by the horizontal line on the curve which is an average of the throughput values at each depth of discharge, indicated with black dots.

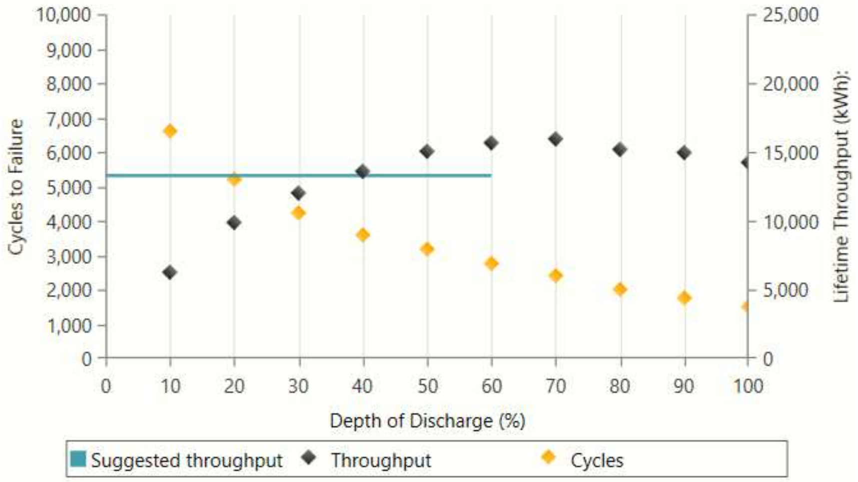

Figure 11. Lifetime curve of Surette 8CS25P battery.

4.5. Converter

The converter is required to convert the DC output from the battery bank into AC electricity to power the load, and be able to sell excess electricity to the grid. The power converter selected for this system configuration is a bidirectional string inverter, with an integrated transformer that regulates the voltage, and the specifications are shown in Table 1. The inverter was selected because it supports both on-grid and off-grid configurations, and it has a lower cost than a micro-inverter.

4.6. Economic Analysis and Modelling

HOMER Pro optimisation algorithms are based on the analysis of the LCOE. The LCOE is the average cost per kWh of the useful electrical energy generated by the system. In HOMER, it is the

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ratio of the annualised cost of generating electricity to the total annual electricity supplied to the load, for an off-grid system. For a grid-connected system, it is the ratio of the annualised cost of generating electricity to the total annual useful electricity generated (the sum of the annual electricity supplied to the load and the electricity sold to the grid). The off-grid and grid-connected system LCOE calculations are represented in Equations (3) and (4), respectively. Based on HOMER optimisation, the system configuration that has the least capital cost is the most economic and feasible option. Other economic parameters in HOMER include net present cost, O&M cost, and project lifetime. The system costs simulated in HOMER are based on US Dollar ($) values and then converted to Nigerian Naira (₦). At the time of writing, $1 was equivalent to ₦386.4. Table 2 shows the cost summary of the system components.

$$LCOE_{Off-grid} = \frac{C_{ann,total}}{E_{served}}. \quad (3)$$

where, $C_{ann,tot}$ is the total annualised cost of the system ($/year) and E_{served} is the total annual electricity supplied to the load (kWh/year).

$$LCOE_{On-grid} = \frac{C_{ann,total}}{E_{served} + E_{grid}}. \quad (4)$$

where, E_{grid} is the total annual electricity sold to the grid (kWh/year).

Table 2. Cost summary of components.

Component	Capacity/Quantity	Capital cost ($)	Replacement cost ($)	O&M cost ($/year)
Solar PV	30 kW	18000	15000	500
Micro-hydro	16 kW	30000	20000	3000
Battery	1	1000	800	50
Converter	66 kW	10750	3450	500

5. Results and Discussion

According to the optimisation results of the HMS design model, the analysis comprises two scenarios, namely off-grid and grid-connected microgrid configurations.

5.1. Off-grid Hybrid Microgrid Configuration

The system architecture of the off-grid microgrid configuration includes solar PV, micro-hydro, batteries and converter. From the optimisation results, a base case system architecture was automatically selected by HOMER as the most feasible configuration with the lowest capital cost. The base case system architecture comprises a solar PV module, a micro-hydro turbine, and a converter with the capacities of 78.6 kW, 20 kW and 45.8 kW, respectively, and a total of 45 batteries. The annual electricity generated by solar PV is 107,408 kWh and by micro-hydro is 178,782 kWh, making an annual total generated electricity of 286,190 kWh.

In Figure 12, the percentages of electricity generated by solar PV and micro-hydro are 37.5% and 62.5%, respectively. The electricity produced by solar PV is less than that of micro-hydro, given that the daily solar irradiance varies throughout the year. Micro-hydro can produce that much electricity as a result of the predominant flow rate because it is constant all year round, with 8,760 hours of operation.

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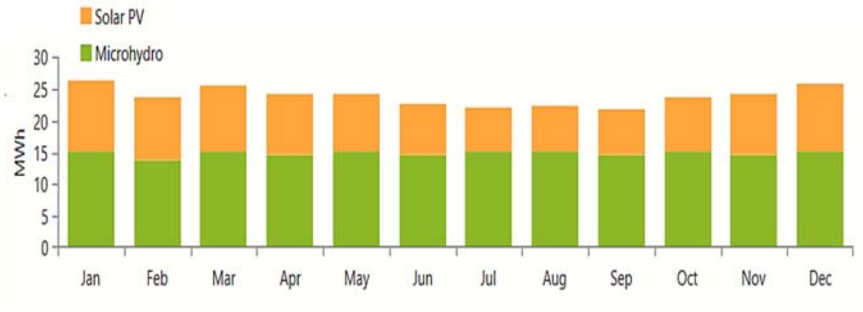

Figure 12. Average monthly electricity production of renewable energy sources.

The solar PV power output, battery system charge power, micro-hydro power output and total electrical load served by a combination of solar PV, micro-hydro and battery is presented in Figure 13**Error! Reference source not found.**. The top and bottom graphs show the yearly and weekly performance, respectively.

The PV system has a capacity factor of 15.6% and a total annual operation time of 4,422 hours, generating power between the hours of 08:00 and 18:00 daily. The solar PV module generates electricity during daytime and micro-hydro generates a constant 20 kW power, 24 hours a day. Both renewable sources cannot meet the demand at night-time; the battery stores energy during the day to use at night. The configuration of the storage is a lead-acid battery bank with a nominal ampere-hour and energy capacity values of 1,156 Ah and 427 kWh, respectively. The battery's state of charge is in the range of 40% and 100% in the yearly profile and between 60% and 100% in the first week, as shown in Figure 14. The battery autonomy is approximately 13 hours.

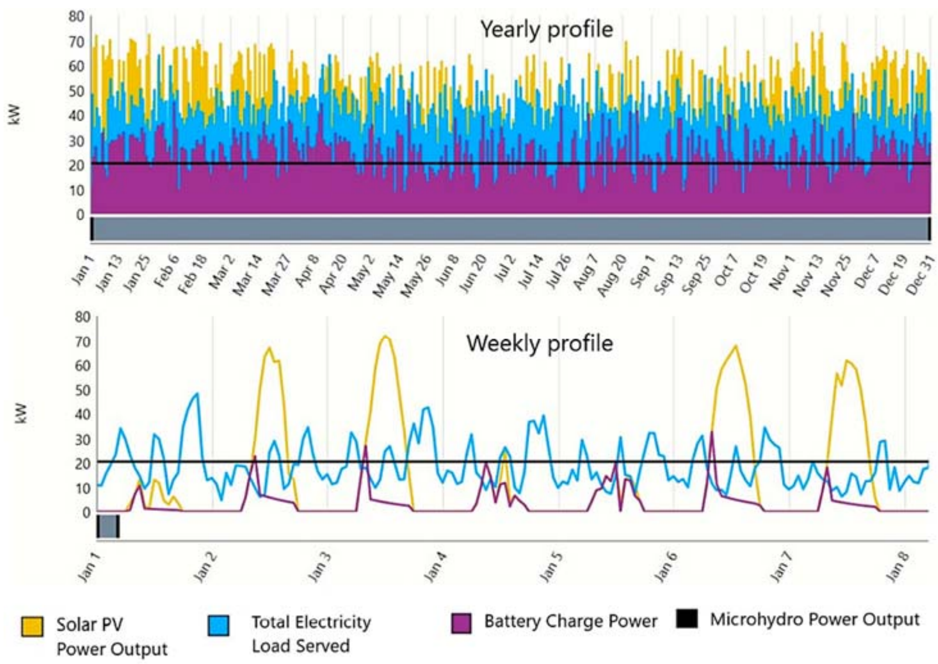

Figure 13. Electricity generation power output to load.

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Figure 14. Battery state of charge.

The configuration produces an annual excess of electricity of 104,420 kWh, 36.5% of the total electricity produced which is presented in Figure 15. This system was designed with about 20% oversizing to allow for the accomodation of any increment of energy demand in the future. Also, contrary to the assumed invariant household consumption used in the analysis, ideally some households may consume more energy than others. The excess energy generated could be used to accomodate for these disparities.

A grid-connected scenario is analysed in the next subsection. The selected site in this study is connected to the utility grid and the existence of the grid in the area was investigated for the possibility of integrating the proposed HMS to it.

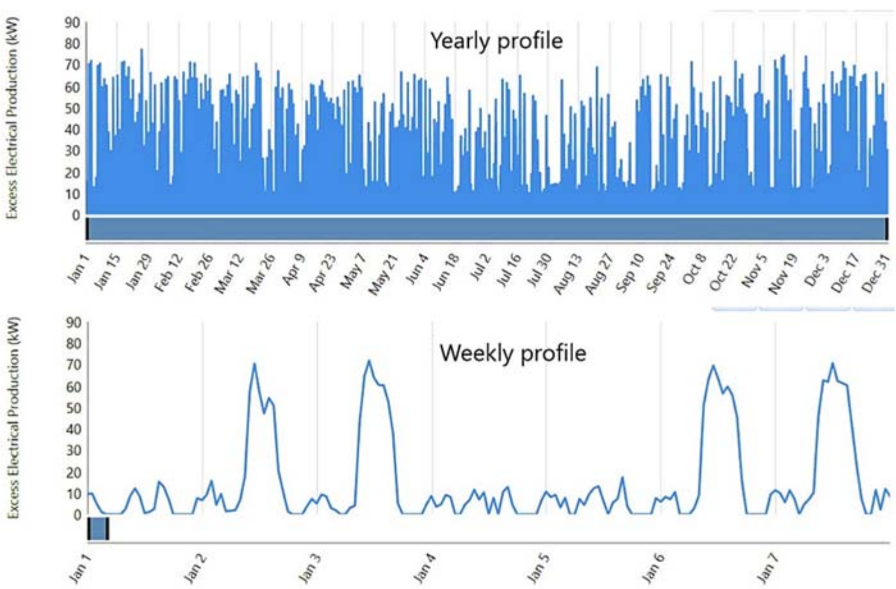

Figure 15. Excess electricity and the unmet load of the off-grid microgrid.

5.2. Grid-connected Microgrid Configuration

This microgrid configuration is connected to the utility grid. It consists of the grid, a solar PV, micro-hydro, battery, converter and the load. The nominal capacities of the solar PV, micro-hydro and converter components are 61.2 kW, 20 kW and 36.4 kW, respectively, and there is a total of 30 batteries. The grid supplies an annual average peak load of 32 kW. The total annual electricity

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production from all three sources is 264,196 kWh, with a production percentage of 67.7%, 31.7% and 0.672% for micro-hydro, solar PV and the grid, respectively. Electricity is consumed from the grid only when there is a shortfall in the microgrid system. Therefore, the grid electricity production is termed as grid purchases. The average annual monthly amounts of the electricity purchased from the grid, as well as the electricity production from solar PV and micro-hydro, are shown in Figure 16.

Figure 16. Average monthly electricity production.

The total annual load consumption is 173,791 kWh, which is approximately 66% of the total electricity produced, and the surplus energy of 70,466 kWh is sold to the grid. Because part of the surplus energy is sold to the grid, the annual excess electricity reduces to 11,260 kWh, which is 4.26% of the total electricity produced as shown in Fig. 17.

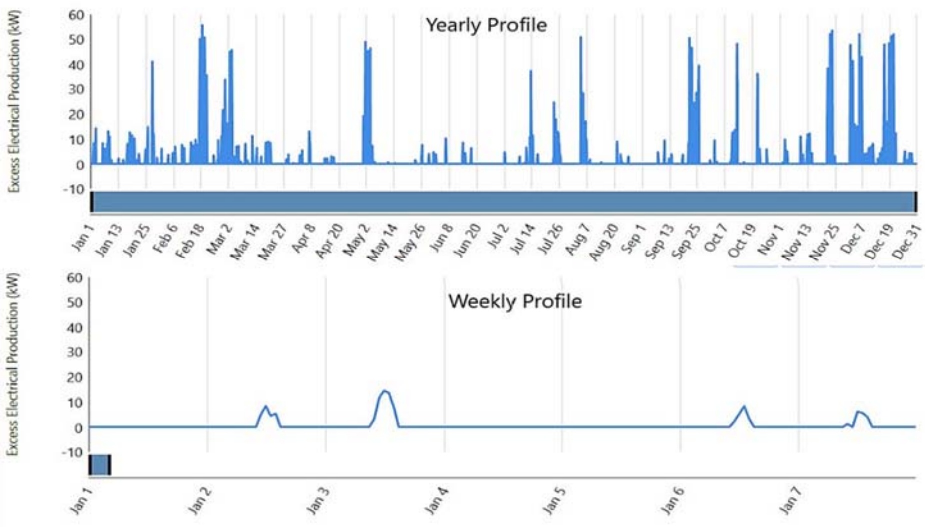

Figure 17. Excess electricity of grid-connected microgrid.

The micro-hydro generates a total of 178,782 kWh annually, operating 8,760 hours throughout the year. It generates a constant power of 20 kW. The solar PV generates annually a total of 83,638 kWh, a capacity factor of 15.6%, and its annual hours of operation is 4,422 hours. The demand for electricity during the daytime is lower than night-time. The PV generates electricity during the daytime, as the battery stores electricity from the PV.

The battery system nominal capacity is 285 kWh and annual consumption is 26,974 kWh. The average yearly/weekly state of charge is shown in Figure 18. The state of charge is within the range of 40% to 100%.

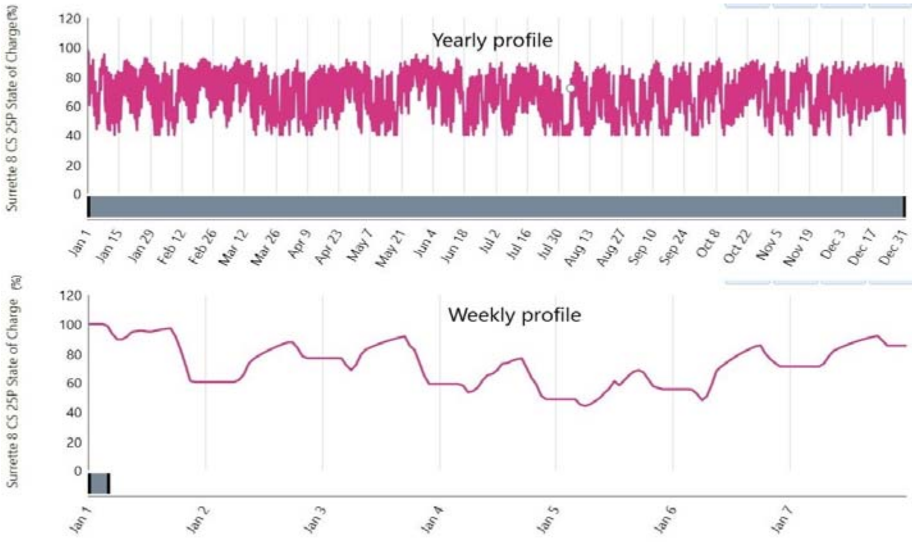

Figure 18. Battery state of charge.

5.3. Excess Electricity sold to the Grid

The configurations presented above are optimised to find the most cost effective and reliable electricity with the available resources, solar and hydro, for Ase village in Nigeria. The study aims to improve microgrid reliability using an energy storage system; therefore, a battery bank was included in the system's configuration. The number of households in the village is estimated to be 101; average daily load demand is 476.37 kWh/day, and a peak load of 64 kW occurs in the evening between the hours of 18:00 and 22:00.

The selected site is connected to the utility grid and, as such, two configurations were analysed. The off-grid microgrid configuration had an annual excess electricity of 104,420 kWh, 36.5% of the total annual electricity produced. In the grid-connected microgrid configuration, the annual excess electricity reduced to 11,260 kWh, 4.26% of the total annual electricity produced, because the bulk of the excess electricity could be sold to the grid. To encourage investments in renewable energy generation in Nigeria, the Nigerian Electricity Regulatory Commission (NERC) targeted electricity generation of about 2,000 MW from renewables by 2020. To achieve this, the commission's aim was to promote grid-connected renewable energy projects by approving schemes that were yet to be commissioned. These schemes such as net-metering and feed-in tariff, which aid the selling of surplus electricity back to the grid are considered [39].

According to the results, the LCOE of the off-grid and grid-connected configurations are $0.101/kWh and $0.046/kWh, respectively. As a comparison, Benin Electricity Distribution Company (BEDC) approved tariff rate for residential customers as ₦31.36/kWh ($0.081/kWh) [40]. Due to the unreliability of the grid, rural dwellers use diesel generators for electricity supply [41]. However, the fuel price required to operate these generators ranges from ₦121.50 ($0.314) to ₦123.50 ($0.320) per litre, which is expensive [42]. The LCOE of both system configurations, when compared to the electricity tariff rate of BEDC and fuel price, is relatively lower and affordable; the LCOE of the microgrid, when connected to the utility grid, is almost half the electricity tariff rate.

The configuration is a function of the load profile and the renewable energy resource potentials of the selected site. The results of the HMS configurations are shown in Table 3.

Table 3. Off-grid and Grid-connected HMS configuration.

Scenario 1		*Scenario 2*	
Component	**Description**	**Component**	**Description**
Micro-hydro system	20 kW	Micro-hydro system	20 kW
Solar PV module	78.6 kW	Solar PV module	61.2 kW

Battery bank	427 kWh (45 batteries)	Battery bank	285 kWh (30 batteries)
Inverter	45.8 kW	Inverter	36.4 kW

The system generates enough electricity to serve the load. When there is a shortfall in the system, the battery bank is used as a backup. The excess electricity that is not used up by the load is sold back to the grid; the sell-back price is $0.05/kWh. Because the energy generated by solar PV, micro-hydro and battery storage is almost sufficient, the energy purchased from the grid is minimal as shown in Table 4. It is notable from Table 4 that the monthly energy sold to the grid is extremely higher than the energy purchased from the grid. The grid-connected configuration can earn up to $3,434.50/year by selling electricity to the grid.

Table 4. Excess electricity sold to the grid.

Month	Energy purchased [kWh]	Energy sold [kWh]	Peak load [kW]	Energy charge [$]
January	39	8,006	10	398.39
February	89	6,171	17	304.13
March	68	6,375	22	315.33
April	112	6,886	24	338.70
May	152	6,166	24	300.66
June	199	5,823	21	281.18
July	122	4,763	22	232.03
August	375	4,437	32	203.08
September	423	4,314	27	194.54
October	6	5,845	4	291.94
November	164	6,492	20	316.38
December	26	5,189	21	258.14
Annual	**1,776**	**70,466**	**32**	**3,434.50**

5.4. Economic Viability

The economics of both scenarios, the off-grid microgrid configuration (scenario 1) and grid-connected microgrid configuration (scenario 2), are analysed in this section. The net present cost (NPC), capital cost, O&M cost, and LCOE are important parameters for determining the configuration of a microgrid system. The grid sell-back price and purchase price generally affect the system costs, total NPC and LCOE. The important parameters are compared between both scenarios as shown in Table 5. The NPC values of both off-grid and grid-connected configurations are illustrated in Figures 19 and 20, respectively. The capital and O&M costs of the grid-connected system is relatively cheaper compared to the off-grid system because of the reduced components' capacities for the grid-connected system.

Table 5. Cost summary and comparison.

Scenarios	LCOE [$/kWh]	NPC [$]	Initial capital cost [$]	O&M [$/year]	Replacement cost [$]
1	0.101	227,307	129,605	7,558	14,448.70
2	0.046	145,282	102,635	3,299	12,965.99

The cost analysis of the off-grid configuration as a function of each component is as follows:

- The capital cost of the PV is 36.37% of the initial capital cost of the system, with the battery constituting about 34.72%. The micro-hydro and converter contributed about 23.14% and 0.06% of the system capital cost, respectively. The total capital cost of the system is $129,605, with the solar PV as the most costly component in this scenario.
- The solar PV and micro-hydro have no replacement costs since the lifetime of both components, which is 25 years, is the same as the project lifetime. However, the replacement cost is made up

of the costs of the battery and converter, which contribute 85.3% and 14.7%, respectively. The expected lifetime of the battery is 18.7 years.

- The total operating cost and salvage value during the project lifetime are $89,286.50 and $6,032.74, respectively.

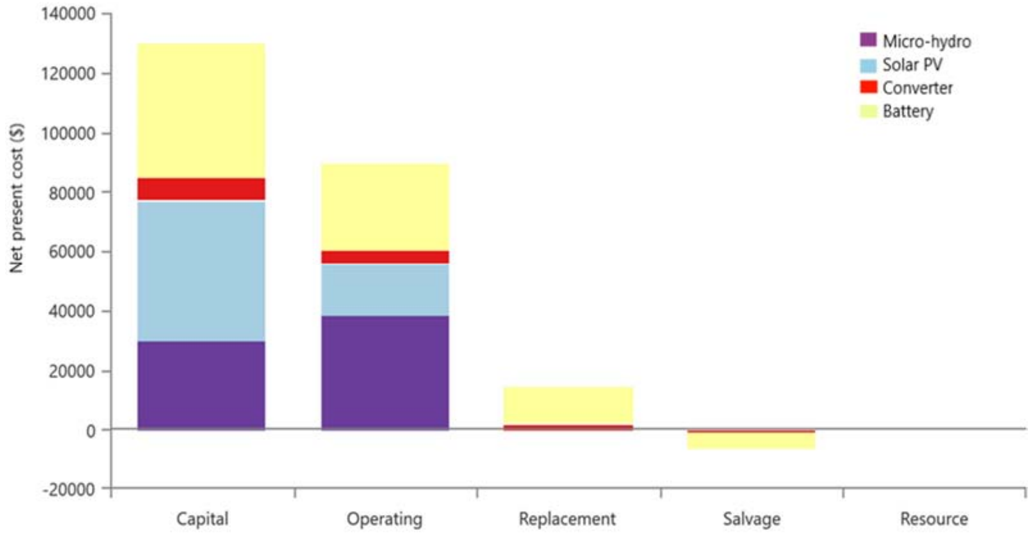

Figure 19. Off-grid net present cost summary by cost type.

The cost analysis of the grid-connected configuration as a function of each component is as follows:

- The capital costs of solar PV, micro-hydro, battery and converter are 35.76%, 29.23%, 29.23% and 5.78% of the total initial capital cost of the system, respectively. The grid is an existing one and therefore incurred no capital cost.
- Like scenario 1, the solar PV and micro-hydro have no replacement costs; the grid does not have a replacement cost either. The replacement costs of both battery and converter are 87% and 13% of the total replacement cost of the system, respectively. The expected lifetime of the battery is 13.2 years.
- The total operating cost and salvage value during the project lifetime are $30,520.31 and $839.16, respectively.

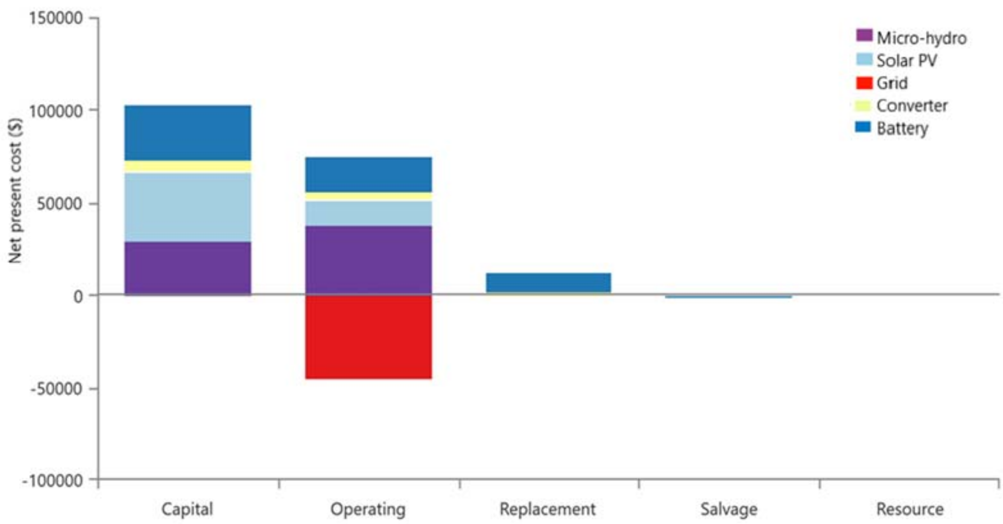

Figure 20. Grid-connected net present cost summary by cost type.

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5.5. Comparative Analysis of Studies' Findings

Table 6 shows a comparative techno-economic analysis results obtained in this study and that of similar studies in [23–26]. The proposed systems had better techno-economic feasibilities as compared to other studies with standalone PV, as well as hybrid systems. The LCOE of the grid-connected system in this study is relatively lower than that of study [23]. Also, the LCOE of this study's off-grid system is relatively lower than studies [24–26]. This could be as a result of the recent global reduction in the cost of components like solar PV panels and inverters, as well as the improved efficiency of these components.

Table 6. Comparing the results obtained from this study and previous relevant works.

Study	Location	System Components	LCOE [$/kWh]	Specific Energy yield [kWh/kW]	NPC [$]	Grid connected
This study	Delta, Nigeria	PV-microhydro-battery	0.101	1,367	$227,307	No
This study	Delta, Nigeria	PV-microhydro-battery	0.046	1,367	$145,282	Yes
Adaramola [23]	Jos, Nigeria	PV	0.103	1,674	$19,200	Yes
Adaramola et al [24]	Jos, Nigeria	PV-diesel generator-battery	0.364	1,491	$3,441,282	No
Olatomiwa et al [25]	Nigeria	PV-wind-diesel	0.540	----	$350,000	No
Olatomiwa et al [26]	A base transceiver station (BTS) in Kaduna state Nigeria	PV-wind-diesel-battery	0.445	1,616	$69,811	No

6. Conclusion and Future Works

The main objective of this paper was to design an economically feasible HMS that could solve the problem of rural electrification in Nigeria. The load profile of a village in Nigeria was estimated and the renewable energy sources were assessed by analysing the solar radiation and the stream discharge, as well as the reliability of the grid. Moreover, a battery bank was included in the system to ensure the continuous supply of electricity to the community, which will improve the power supply reliability.

The configuration of the off-grid HMS comprised of solar PV, micro-hydro and battery bank. The annual excess electricity generated was 104,420 kWh. A way to fully maximise the utilization of the excess electricity was analysed by modelling a grid-connected HMS. The grid-connected HMS configuration comprised of the grid, solar PV, micro-hydro and battery bank. The annual excess electricity reduced considerably to 11,260 kWh because most of the excess electricity was sold to the grid. In addition, this configuration could generate up to $3,434.50/year from the surplus energy sold to the grid.

The LCOE of the off-grid and grid-connected HMS configurations was $0.101/kWh and $0.046/kWh, respectively, which is relatively lower as compared to the grid tariff rate and generator fuel price. Furthermore, both configurations do not pose a threat to the environment because the renewable fraction is 100% and 99.3% for the off-grid HMS and grid-connected HMS, respectively.

Notably, the interest and adoption of grid-connected solar PV systems in Nigeria have recently increased. Thus, as future work, the impact of the penetration levels of intermittent renewable energy sources to the grid on the grid stability should be investigated. As a result, the regulatory authority will be able to safeguard the grid's stability as well as to establish appropriate policy frameworks to support renewable energy systems in the country.

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