Hindawi
International Journal of Photoenergy
Volume 2019, Article ID 6960191, 8 pages
https://doi.org/10.1155/2019/6960191

*Research Article*

# Optimal Sizing and Analysis of a Small Hybrid Power System for Umuokpo Amumara in Eastern Nigeria

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Received 1 October 2018; Revised 18 December 2018; Accepted 11 January 2019; Published 10 March 2019

Academic Editor: Senthilarasu Sundaram



Umuokpo Amumara is a village with an estimated population of 9,000 people and about 800 households located in the eastern region of Nigeria in West Africa. This village has no access to power grids for over a decade of existence. Umuokpo, by virtue of its location 5°27′35.9″N 7°19′60.0″E, on the average receives about 6 hours of sunlight with a daily average irradiance of 6.12 kWh/m$^2$. The solar energy can be tapped and harnessed to generate quality electricity for this small village. Since the wind speed is low (ranging between 3.0 m/s and 3.5 m/s), the wind resource cannot be incorporated into the design. The average load demand of the village is 9.422 MWh/day with a peak load of 1.3 MW. This paper is aimed at designing a small hybrid power system that can generate sustainable electricity for the village from renewable energy sources. The design also considers a backup diesel generator and an energy storage system. The designed system consists of a 2,750 kW solar photovoltaic (PV), a 21,600 kWh battery storage, a 1,500 kW power electronic converter, and a 1,000 kW diesel generator. The simulation suggests that the proposed system can adequately meet the electricity needs of the village. A sensitivity analysis is also carried out on the system to observe its behavior with varying levels of irradiation and load.

## 1. Introduction

Many rural areas in the world lack electrical supply due their remote locations and consequent high cost of electrical infrastructure. Worldwide, more than 1.5 billion people lack access to electricity [1]. These communities have therefore resorted to the use of local methods to meet their lighting, heating, and cooking needs, which to a very large extent have a detrimental effect on the surrounding environment, economic development, and quality of life. Most times, these areas have abundant renewable energy resources such as wind, solar, and hydro. In principle, these resources can provide electricity—at least in part.

Renewable resources are intermittent in nature, which creates significant system design challenges [2, 3]. To mitigate uncertainty caused by renewable energy sources, the combination of conventional and renewable power generation known as a hybrid power system appears to be effective [4]. Such systems can be either grid-connected or stand-alone and consist of conventional and renewable distributed generation, power conditioning equipment, and energy storage devices [5, 6].

This work focuses on the techno-economic feasibility of developing a hybrid power system to meet the electrical power needs of Umuokpo Amumara, a rural community in the eastern region of Nigeria. Till date, from literatures reviewed on the renewable energy possibilities in this geographical area, the energy system proposed in this paper has never been considered and as such can be considered to be novel with respect to the geographical zone. Specifically, the work contributes the following:

(i) Proposing a stand-alone hybrid renewable energy system to provide power to a rural village in Nigeria

(ii) Studying the feasibility of the proposed system to meet the electrical need of the community

The proposed system is chosen to combine solar, conventional diesel generator, and battery storage. The feasibility

Table 1: Electrical consumers in Umuokpo.

| Installations | Number in village |
|---|---|
| Houses | 800 |
| Schools | 2 |
| Churches | 3 |
| Town hall | 1 |
| Small shops | 20 |
| Village water pumping system | 1 |

simulation is carried out on HOMER (a tool developed by the National Renewable Energy Laboratory USA [7]) for optimum sizing and cost analysis of renewable energy systems. HOMER is chosen as the best optimizing tool for the research as it is renowned for its ability to give accurate optimization results as it already contains a lot of information on the geographical area of interest. These information include mainly the abundant renewable energy resources and an almost accurate cost of the employed components. HOMER can provide cost optimization of hybrid power systems based on the net present cost (NPC) method [8].

## 2. System Description

The proposed hybrid power system consists of (1) a solar photovoltaic (PV) array, (2) a diesel generator, and (3) a battery storage system. The diesel generator and the battery storage are intended to supply power when the solar power production is insufficient to meet the demand. The aim of the proposed system is to satisfy electricity needs of the Umuokpo community mainly by renewable energy sources with a very low dependence on the diesel generators.

*2.1. Description of Umuokpo and Load Profile.* Umuokpo is a remote settlement in Eastern Nigeria. It is one of the numerous rural areas in the world without any source of electricity due to its distance from the main cities, making grid connectivity cost-prohibitive. There are about 8,000 inhabitants, 800 households, and several community centers such as schools, churches, and town hall in the village. Most villagers leave the house in the morning and return in the evenings. Being located in Nigeria, Umuokpo only has two dominant seasons, rainy and dry seasons. Each season lasts about six months each. The cooking and heating energy demands are not dependent on electricity. Therefore, the load profile of the village effectively remains similar throughout the year. A breakdown of the various types of electrical loads is tabulated in Table 1.

In this study, it is assumed that each house consists of a living room, four bedrooms, a kitchen, a bathroom, and a balcony. Typical appliances and installations of a house are shown in Table 2. Each house has a peak load of 1.42 kW, which amounts to 1.136 MW for 800 houses. In addition to the houses, the village also has some public installations. The public installations include a central water pumping system, four churches, two schools, a town hall, and 20 shops. Considering these public installations, the peak load is about 7.3 kW. Further breakdown of the electrical loads for each installation is shown in Table 3.

Table 2: Electrical load of each house.

| Installation | Electrical features | Load rating (W) | Hours of operation | Energy (Wh/day) |
|---|---|---|---|---|
| 4 bedrooms | 4 ∗ 100 W bulbs | 400 | 6 | 2,400 |
| Sitting room | 2 ∗ 100 W bulbs | 200 | 6 | 1,200 |
| Kitchen | 100 W bulb | 100 | 6 | 600 |
| Bathroom | 100 W bulb | 100 | 6 | 600 |
| Balcony | 100 W bulb | 100 | 6 | 600 |
| Television | 150 W | 150 | 10 | 1,500 |
| Stereo | 50 W | 50 | 4 | 200 |
| Ceiling fan | 120 W | 120 | 5 | 600 |
| Refrigerator | 200 W | 200 | 20 | 4,000 |
| Total | | 1,420 | | 11,700 |

The total peak load of the village is a sum of the power from all the residential appliances and the public installations, which is calculated as follows:

$$\text{Peak load} = \text{House Peak} + \text{Community Peak}. \qquad (1)$$

For the considered Umuokpo village, the peak load is equal to 1,136 kW + 7.3 kW = 1,143 kW. Heating and cooking demands are met either through kerosene, propane gas, or firewood. Therefore, these are not considered in the load profile.

In a conventional Nigerian home, the peak usage of power occurs in the evenings from 1600-2200 hours—the morning and the afternoon power consumption being low. The village has a total energy consumption of 9.422 MWh/day. The daily, monthly, and seasonal load variations are shown in Figures 1–3, respectively.

*2.2. Evaluation of Renewable Energy Potentials.* The village of Umuokpo is situated down the hill with good exposure of solar irradiation and low wind speed. Both solar and wind power generation capacity is evaluated in this paper, the latter capacity being understandably low.

*2.2.1. Solar Potential.* The monthly solar radiation and clearness index of the village were obtained from the NASA surface meteorology and solar energy website [9] as shown in Table 4. From the table, the clearness index is higher in the dry season. The village has an average solar irradiation of 4.71 kWh/m$^2$/d, which indicates a high potential of electricity generation from solar.

*2.2.2. Wind Energy Potential.* Data obtained from NASA [9] states that Umuokpo has an average wind speed of 2.70 m/s at an anemometer height of 50 m. Wind speeds during a 12-month period based on NASA data are plotted in Figure 4.

From the wind data, it is observed that at a hub height of 50 m the wind speed in the village is very low owing to the valley-like location of the village. In this case, the

Table 3: Electrical load for public installations.

| Installation | Electrical features | Load rating (W) | Hours of operation | Energy (Wh/day) |
|---|---|---|---|---|
| Schools (2) | 2 * (10 * 60 W bulbs) + (2 * 80 W bulbs) | 1,360 | 6 | 8,160 |
| Churches (3) | 3 * (10 * 100 W bulbs) | 3,000 | 4 | 36,000 |
| Town hall | 4 * 60 W bulbs | 240 | 3 | 720 |
| Small shops (20) | 20 * 60 W bulbs | 1,200 | 12 | 14,400 |
| Village water pumping system (1) | 1,500 W | 1,500 | 2 | 3,000 |
| Total | | 7,300 | | 62,280 |

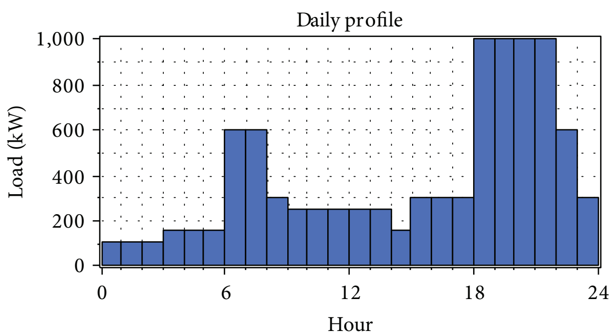


Figure 1: Umuokpo daily load profile.

following wind speed conversion between different heights can be used, which is also known as the power-law wind speed model [10]:

$$U_Z = U_{Zr}\left(\frac{Z}{Z_r}\right)^{\alpha}, \quad (2)$$

where $Z$ and $Z_r$ are the proposed height above the ground and reference height, respectively; $U_Z$ and $U_{Zr}$ are wind speed at the proposed height and known wind speed, respectively; and $\alpha$ is the wind shear coefficient (0.2).

Since only 3.0 m/s speed can be attained at an impractical height of 84 m, inclusion of wind turbines in the design is cost-prohibitive.

## 3. The Proposed Hybrid Power System Description

The considered hybrid system consisted of PV arrays, a diesel generator serving as backup, and a battery storage system as shown in Figure 5.

## 4. HOMER Optimization

The simulations to identify the most feasible system for the village electrification were carried out on HOMER. A total of 5,292 simulations were carried out. In Nigeria, the current prices of petroleum products are quite high. The diesel price used in this study is assumed to be $0.69 per liter. The influence of the diesel price variations is evaluated in the sensitivity study. Three system configurations are considered in this study: (1) diesel generator with the battery, (2) diesel generator alone, and (3) the proposed hybrid system.

*4.1. Configuration 1: Diesel Generator with the Battery.* This system has a 1,500 kW diesel generator unit and 2,500 units of battery storage (12 V, 200 Ah). The diesel generator is in operation for 2,292 hours of the entire year with a yearly production of 4.3 GWh/yr. Its surplus energy is used to charge the battery, which in turn supplies power during the generator shut-off time. Figure 6 shows a plot of the AC load, generator power, and the state of charge of the battery system in relation to the shut-off time of the generator.

Figure 6 shows that the generator meets the community load demand and at the same time charges the battery. The battery begins to discharge at the point the generator power falls at or below the load demand. This continuous cycle of the battery charging and discharging has a negative effect on the lifespan of the battery, which makes this system unattractive. The net present cost of this configuration is $156,293,424 with an operating cost of $12,019,834. The cost itself makes the system very uneconomic. The continuous operation of the generator also will reduce the lifespan of the system.

*4.2. Configuration 2: Diesel Generator Alone.* This configuration is solely made up of a 1,500 kW diesel generator unit, which runs for 8,760 hours in a year to meet the load demand of the community. This system has an excess energy production of 1.5 GWh/yr. Figure 7 shows the diesel generator power generation profile.

*4.3. Configuration 3: The Proposed Hybrid PV/Diesel/Battery System.* This configuration is the proposed hybrid system. It has an optimal configuration based on both cost and capacity to serve the load. The system consists of a 2,750 kW PV array, a 1,500 kW diesel generator as backup, and 15,000 units of battery system (12 V, 200 Ah) for energy storage. During the operation of the system, the PV is the main source of energy, while the generator and battery system are used to meet the power demand for the conditions without enough solar power. The configuration is shown in Figure 8 and the details of the proposed system components are shown in Table 5.

This system achieved 79% renewable energy fraction with the generated power of 3.6 GWh/yr from the PV array as shown in Figure 9. The diesel generator is in "on" state for just 959 hours in the whole year, which is equivalent to about 3 hours daily. The battery system is charged with the excess electricity produced during the PV operational hours. During the nights when the PV systems cannot produce power, the battery feeds the grid with the stored electricity. The battery system has a nominal capacity of

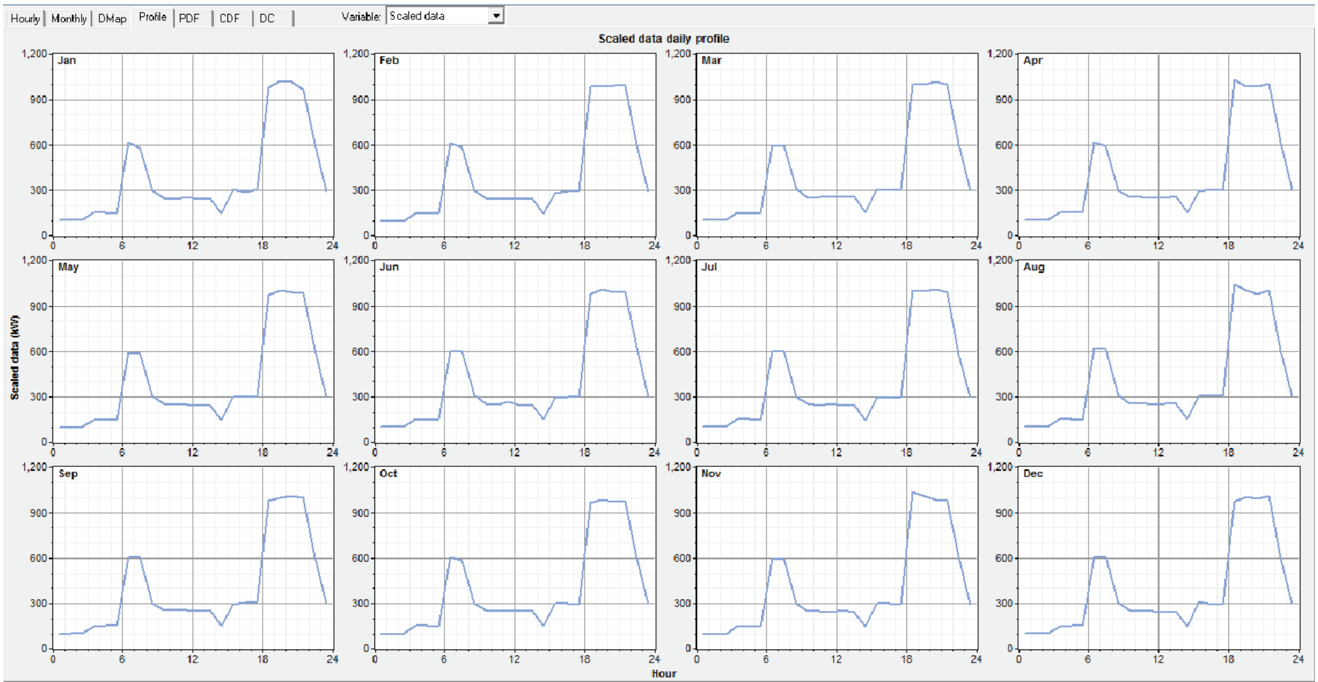


FIGURE 2: Umuokpo monthly load profile.

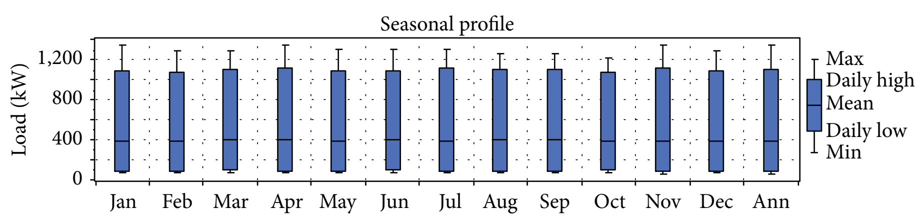


FIGURE 3: Umuokpo seasonal load variation.

TABLE 4: Monthly solar radiation and clearness index [9].

| Month | Clearness index | Daily radiation (kWh/m$^2$/d) |
|---|---|---|
| January | 0.533 | 5.035 |
| February | 0.506 | 5.047 |
| March | 0.480 | 4.991 |
| April | 0.446 | 4.647 |
| May | 0.434 | 4.390 |
| June | 0.397 | 3.917 |
| July | 0.366 | 3.633 |
| August | 0.398 | 4.072 |
| September | 0.410 | 4238 |
| October | 0.430 | 4.318 |
| November | 0.498 | 4.747 |
| December | 0.540 | 4.488 |
| Average | 0.452 | 4.699 |

36,000 kWh with an autonomy time of 55 hrs. This in turn means that the battery can meet the energy needs of the minigrid to a period of three days.

From Table 6, it is observed that the power from the PV system can adequately meet the load demand while the diesel

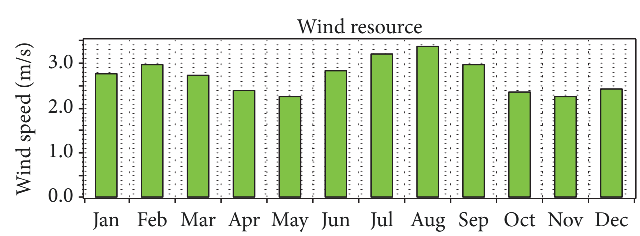


FIGURE 4: Plot of the monthly wind speed.

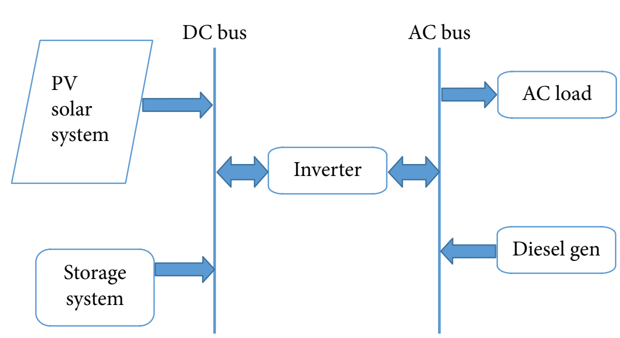


FIGURE 5: The proposed hybrid system configuration.

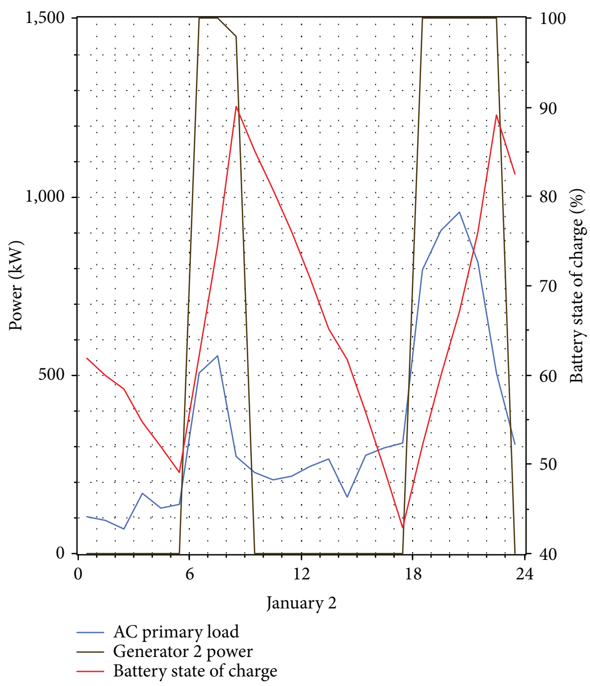


Figure 6: Battery state of charge meeting the load demand during the diesel generator off time.

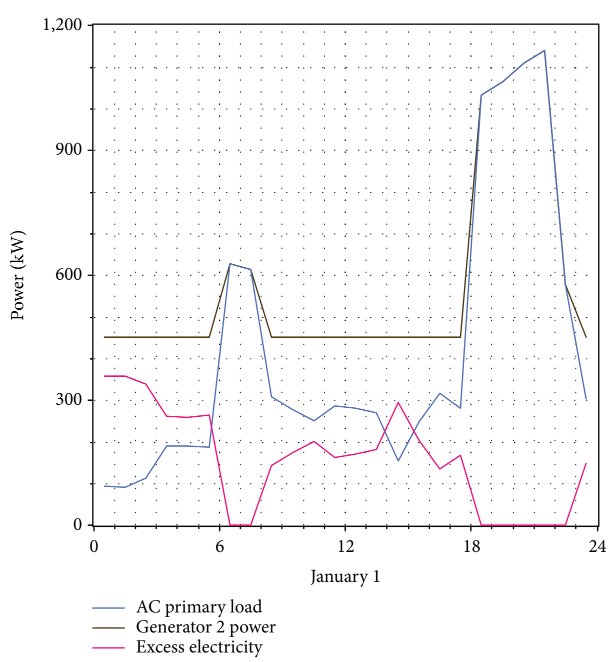


Figure 7: Plot of the electrical production and load demand of the diesel generator alone.

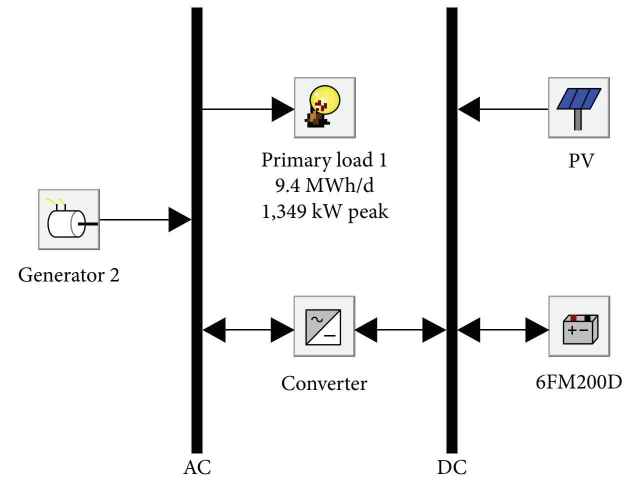


Figure 8: Configuration for the optimal proposed system.

Table 5: Electrical details of the components of the proposed hybrid system.

| | |
|---|---|
| *Battery* | |
| Nominal capacity | 36,000 kWh |
| Usable nominal capacity | 21,600 kWh |
| Autonomy | 55 hrs |
| Lifetime throughput | 13,755,000 kWh |
| String size | 50 |
| Strings in parallel | 300 |
| Total number of battery units | 15,000 |
| Energy in | 2,970,676 kWh/yr |
| Energy out | 2,391,040 kWh/yr |
| Expected life | 5.15 yrs |
| *Solar PV system* | |
| Rated capacity | 2,750 kW |
| Mean output | 415 kW |
| Mean output | 9,916 kWh/d |
| Capacity factor | 15.1% |
| Maximum output | 2,649 kW |
| PV penetration | 106% |
| Total production | 3,635,785 kWh/yr |
| *Diesel generator* | |
| Rated capacity | 1,000 kW |
| Mean electrical output | 1,000 kW |
| Operational life | 15.6 yrs |
| Capacity factor | 10.9% |

generator serves as the backup. Also, the excess energy is channeled to the charging of the battery system. Thus, an excess energy of 3.12% (of the generated energy) is achieved in a rather balanced system.

Figure 10 depicts the power generation and consumption of the system over a day. This shows that the PV system only generates power from 0900 hour and goes low at 1500 hour, which is evident from the area on the map when the power from the PV is greater than the load curve. During the hours of low PV power, the battery begins to discharge, which indicates that the battery system supports the PV system to meet the load requirements. At night between 1800 and 0600 hours, the battery system alone meets the power requirements of the load, hence the drop in battery's state

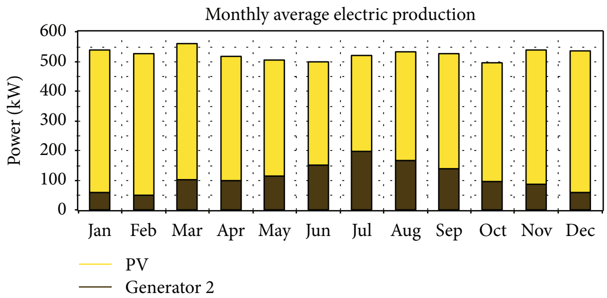


FIGURE 9: Electrical power production of the optimal configuration.

TABLE 6: Summary of energy production and consumption of the system.

| *Production* | *kWh/yr* | *% production* |
|---|---|---|
| PV array | 3,635,785 | 79 |
| Generator 2 | 959,000 | 21 |
| Total | 4,594,785 | 100 |
| *Consumption* | *kWh/yr* | *% consumption* |
| AC primary load | 3,439,031 | 100 |
| *Quantity* | *kWh/yr* | *%* |
| Excess electricity | 143,164 | 3.12 |
| Unmet electric load | 0.00237 | 0 |
| Capacity shortage | 42.2 | 0 |
| Renewable fraction | | 79 |

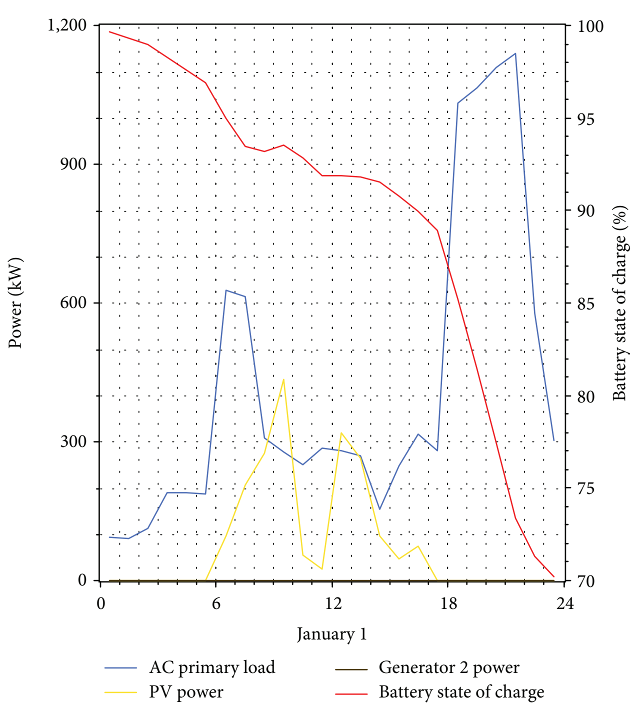


FIGURE 10: Plot of daily electrical power production.

of charge showing battery discharge. The power characteristics of the system for a period of three days are displayed in Figure 11.

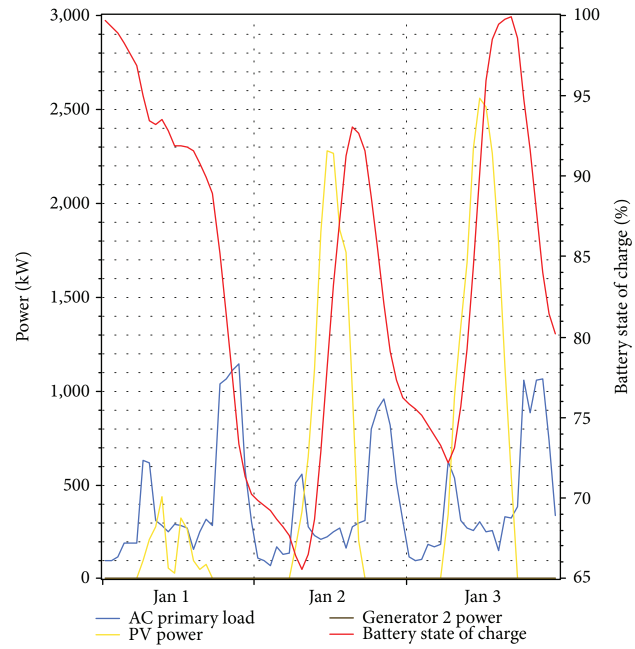


FIGURE 11: Plot of system electrical characteristics for three days.

In Figure 11, with special reference to Jan. 2, the battery state-of-charge curve begins to rise in the same graph with excess PV power. This means that during the day when there is good supply of sunlight, the PV system provides power for use to the load and at the same time charges the battery system. Recall that the aim of the battery system is to store energy when there is good sunlight supply and then supply energy to the load in periods of low sunlight when the PV system is not able to supply enough power. Also, it is noted that the generator production during this period is on the zero line depicting that the PV array together with the battery system can meet the load demand with low dependence on the diesel generator.

*4.4. Sensitivity Analysis.* A sensitivity analysis is carried out for the system to evaluate the influence of the parameter variations. The parameters considered are the community load and the renewable energy resources. The load is varied between 10,000 kWh and 11,000 kWh to observe the behavior of the system for an increased load demand. Since the solar irradiation varies significantly, a variability of 3.0 kWh/m$^2$/d to 5.0 kWh/m$^2$/d is considered for low- and high-irradiation conditions, respectively. The sensitivity results are shown in Figure 12.

It is observed in Figure 12 that even in the events of variation in load and renewable energy resources, the system is capable of meeting the load demands of the community. However, the plot shows that for solar irradiations less than 4.5 kWh/m$^2$/d and load variations above 10,000 kWh/d the load demands will not be met.

*4.5. Cost Summary.* The cost aspects of the proposed system are discussed in this section. With 959 annual hours of operation for the diesel generator, the proposed system has low operational cost for running the diesel generator. The net

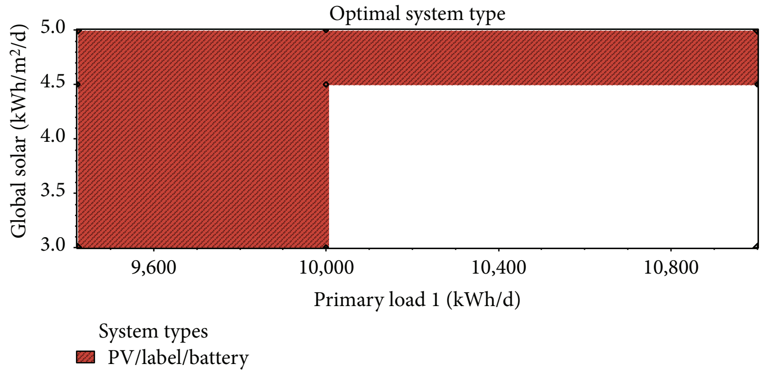


Figure 12: Plot of system sensitivity analysis.

Table 7: Cost breakdown of the proposed system.

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 3,492,064 | 952,738 | 111,601 | 0 | -533,956 | 4,022,445 |
| Diesel gen. | 220,000 | 72,353 | 29,422,188 | 2,427,331 | -16,846 | 32,125,024 |
| Battery | 7,200,000 | 8,991,780 | 287,626 | 0 | -148,153 | 16,331,256 |
| Converter | 1,664,400 | 434,123 | 0 | 0 | -80,804 | 2,017,719 |
| System | 12,576,464 | 10,450,994 | 29,821,416 | 2,427,331 | -7,7975,954 | 54,496,452 |

present cost of the system from HOMER is $54,496,420 with an annual operating cost of $3,279,261. The cost breakdown of the system is shown in Table 7.

The cost of the proposed hybrid system is low compared to Configurations 1 and 2. Configuration 1 with the generator and battery system has a net present cost (NPC) of $156,293,424 and an operating cost of $12,019,834 annually. Configuration 2 with the diesel generator only has the highest NPC value of $422,842,368 and an annual operation cost of $33,051,756.

The proposed system has the lowest Cost of Energy (COE) with a value of $1.240/kWh while the others have $3.56/kWh for Configuration 1 and $9.618/kWh for Configuration 2. The COE of the proposed system is on the high side, but with critical look on the fact that the community has been off the grid for a long while, it is a critical investment to improve the quality of life for the community. The summary of the comparison between the cost of the optimal hybrid system configuration and the other configurations is shown in Table 8.

Table 8: Comparison of the optimal and nonoptimal systems from HOMER.

| Item | Optimal system | Configuration 2 | Configuration 1 |
|---|---|---|---|
| PV capacity (kW) | 2,750 | — | — |
| Diesel gen. capacity | 1,000 | 1,500 | 1,500 |
| Number of batteries | 15,000 | — | 2,500 |
| Gen. operating hours | 959 | 8,760 | 2,929 |
| Inverter capacity | 1,500 | — | 1,000 |
| Total cost $ | 54,496,420 | 422,842,560 | 156,293,280 |

## 5. Conclusion

The main objective of the paper is to evaluate the feasibility of a hybrid renewable energy system design with solar and battery as energy storage. Also, the system had a diesel generator which was used as backup. The cost optimization method in HOMER, the NPC method, is used to obtain the optimal case of the system design, where the total system cost is minimized.

A case study is conducted using the proposed hybrid system assuming to be implemented in Umuokpo Amumara, south eastern Nigeria. Heating needs of the community were not considered in the study because due to its tropical location, heating is not considered a very important need of the community. Two additional configurations for power supply to the community were analyzed in the work.

The proposed renewable system fully met the power needs of the community. Solar resource was considered in this area as it is more abundant than the wind resource. The proposed system achieved 79% renewable fraction and produced a total energy of 4,594,785 kWh/yr which comfortably meets the total energy need of the community of 3,439,031 kWh/yr. It can therefore be deduced that the system will be self-sufficient as a stand-alone system. The proposed system also depicted good energy storage as the stored power in the batteries was observed to supply the community with power over a good period of time with low power from the PV system. The proposed system is also the cheapest with a COE of $1.240/kWh.

From the results obtained from the study, the proposed stand-alone hybrid power system is suitable for use in rural settlements with good renewable energy resources.

## Data Availability

The data used in this work is available on request. I can be contacted on cindukwe@mun.ca.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

I strongly acknowledge the support of my research supervisors Prof. Tariq Iqbal, Dr. X. Liang, and Dr. J. Khan for their guidance and support during the production of this work.

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