# An Optimal Sizing Algorithm for a Hybrid Renewable Energy System

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**Abstract-** This paper proposed an optimal sizing algorithm to obtain the capacity sizes of several components of a hybrid renewable energy system. The recommended algorithm takes into account the maximum power generated by the Hybrid components and the minimum cost of operation, by considering the proposed energy storage systems. In this system, the techno-economic analysis of a hybrid renewable system was accomplished. A case study is conducted to analyze a hybrid project for critical loads in Nigeria which is used to supply a district hospital with geographical coordinates of 12.0022° N, 8.5920° E at an altitude of 472 m. Finally, the invariance nature of the battery storage system has been verified.

**Keywords:** Photovoltaic, wind, renewable energy

## 1. Introduction

Renewable energy (RE) sources are the likely option that can serve as a mechanism to confront climatic change and minimize greenhouse discharge emissions from conventional power generation [1]. In particular, they can be converted into electrical energy by suitable photovoltaic (PV) modules and wind turbines. Over the years enhanced electronics techniques are being applied to support RE sources to produce electrical power for extensive range applications frugally [2]. Solar and the wind have been found to be the prominent. Electrical energy can be easily generated either by the wind or solar or in combination as a hybrid system depending on their potentials and the load demand. The hybrid system, solar and the wind inclusive, in the right mix, can solve some of the problems associated with their random nature and over dependence on climatic conditions [3,4]. Consequently, it is appropriate to develop a power generating system consisting of PV array, wind turbine, and battery storage to satisfy particular load requirement.

To utilize solar and the wind resources efficiently and economically, optimum sizing of the hybrid system with the lowest possible cost need to be investigated. Several researchers have developed algorithms to design an excellent hybrid renewable energy system with great success. Li et al [4] developed a simple sizing algorithm for standalone PV/Wind/Battery hybrid microgrids. The studies are based on the fact that the state of the battery charge should be invariant and the efficiency of the system have been tested with great success, and the number of PV panels were computed based on the number of wind turbines. Another solar/wind optimization algorithm as developed by Yang et.al [5] chooses the optimum configuration using battery bank and economic index of loss of power supply probability (LPSP) through changing the number of PV arrays and wind turbines and the battery capacity. The LPSP is the likelihood that refers to a situation whereby inadequate power supply occurs when the hybrid system is not able to fulfil certain load requirements [6]. This technique determines the best PV modules, wind turbines and the number of batteries according to certain reliability index based on the theory of the cost and the loss energy probability [7]. Based on the literature, there are four hybrid optimization techniques developed namely graphic construction, iterative, probabilistic and artificial intelligence. The probabilistic method designed an optimal system based on the wind and solar variations of a particular area. Sinha et.al [8] developed an algorithm by considering the battery storage as a random walk. The increment and decrement of the battery storage was considered as either two or three event probability distribution. The graphic construction technique configures PV/Wind system based on long-term data resources for each hour of the data based on many years [9]. The iterative method chooses the optimum configuration based precise iterative technique. Fadaee et.al [10] developed an iterative technique by choosing wind turbines and the number of PV modules based on the certain iterative procedure to reduce the difference between generated and consumed power as small as possible. One advantage of this iterative approach is that many PV/Wind configurations were obtained. The artificial intelligence technique is another method to optimize the hybrid system using the neural network, generic algorithm, and the fuzzy logic, etc. Bourouni et.al [11] proposed an algorithm based on generic systems by using the solar and the wind data while the LPSP with the lowest cost maintained. Karen [12] compared all the three techniques based on their accuracy, complexity and the consumption time. Based on the mean square error, the iterative and artificial intelligence technique are better while the probabilistic and graphic technique produces the lowest mean square error.

This paper develops a meek algorithm for optimum PV/Wind system using the iterative method by considering certain simple iterative scheme. Specifically, the system with least cost and higher generated power will be determined. The battery was chosen based on its capability to store energy and provide adequate power when there is a shortage. It is also the aim of this work to verify the invariant nature of the battery. To test the proposed algorithm, certain critical load requirement for a region in Nigeria will be considered.

## 2. The Hybrid RE System

The proposed system of power generation through the RE sources comprises of three fundamental parts namely, the PV, wind and the battery bank as shown in Fig. 1. The battery helps as a storage device whenever there is surplus load from the PV or the wind and be able to supply the load when there is little power supply from the RE sources. Subject to the existing battery charging system technology employed, the maximum obtainable power can be obtained from the PV/Wind energy sources. Typically, an inverter can be used to convert the DC voltage from the battery for feeding consumer load terminals.

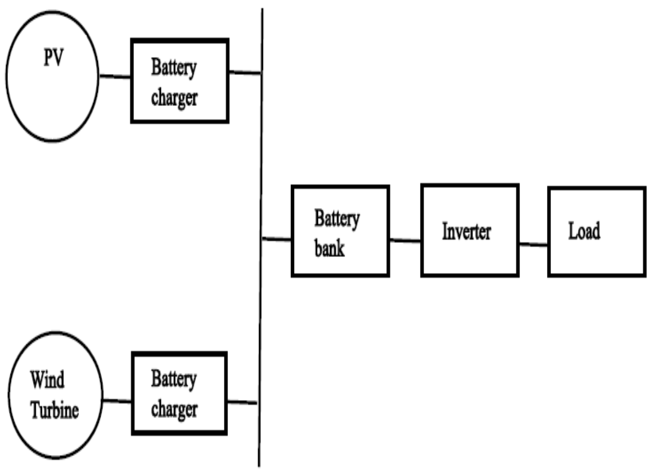


**Fig. 1:** Schematic diagram of a typical hybrid RE system

### *2.1. The PV generator power*

The power generated from the PV modules is strongly dependent on the temperature and the solar radiation [13,14,15]. To choose the appropriate solar module for a particular location, it is necessary to understand the temperature over the whole year to ensure the efficiency of the PV module. The maximum power obtained from PV modules based on solar irradiance and temperature is as follows:

$$P_P = \eta_V A_P G_r (1 - T_C \delta_T) \tag{1}$$

Where $\eta_V$ is the power generation efficiency of the PV. $A_p$ refers to the complete area of the PV modules. $G_r$ is the solar irradiance while $T_C$ represents the temperature coefficient. $\delta_T$ is the temperature error based on the reference cell temperature.

However based on the solar irradiance variation and temperature, the average obtainable power from the PV array is given by [3].

$$P_{av} = \int_0^{G_m} P_P . f .dG_r \tag{2}$$

Where $G_m$ is the maximum solar irradiance and $f$ is a beta distribution that correctly describes the solar irradiance as a random variable [16].

### *2.2. The Wind turbine generator power*

The power output characteristics of a wind turbine is strongly dependent on the wind speed distribution. The Weibull distribution based on a scale factor ($\alpha$) and shape factor ($n$) is usually applied to describe the wind speed data [17].

The simplified model for the output power of the wind turbine is as follows [18]:

$$P_w = \begin{cases} P_r \dfrac{(V_w^n - V_i^n)}{(V_i^n - V_r^n)} & if \quad V_i \le V_w \le V_r \\ P_r & if \quad V_r \le V_w \le V_o \\ 0 & otherwise \end{cases} \tag{3}$$

Where $P_r$ represents the rated power of the turbine, $V_w$ and $V_r$ are the wind speed and the rated wind speed of the turbine. $V_i$ and $V_o$ are the cut-in and cut-out speed of the turbines. The average power of the wind turbine based on certain manufacturer terms is given as follows:

$$P_{wav} = \int_0^{\infty} P_W . f_w dV_w \tag{4}$$

Where $f_w$ is the general representation of the Weibull distribution [17], in terms of the Weibull parameters and the wind speed. In other words, the wind profile can also be adjusted to consider the height using the power law as follows [19]:

$$\frac{V_H}{V_{Hr}} = \left(\frac{h}{h_r}\right)^{\beta} \tag{5}$$

Where $V_H$ and $V_{Hr}$ represent the wind speed at certain hub height $h$ and reference height $h_r$ respectively. β is the component of the power law.

*2.3. The battery bank*

The battery bank storage is chosen to satisfy the load demand requirement during periods of insufficient power from the renewable energy sources. Many factors affect the battery sizing i.e. temperature, battery life, and capacity, depth of discharge (DOD) [20,21,22]. In this paper, the capacity will be determined based on certain adopted sizing algorithm.

However, depending on the sizing algorithm or PV /wind power production and the load requirement, the battery state of the charge is as follows:

$$SOC(t) = SOC(t-1) + \frac{(E_g - E_L)}{V_{bat} C_{bat}} \quad (6)$$

$SOC(t)$ and $SOC(t-1)$ are the state of the battery bank at given time *t* and *t-1* respectively $E_g$ the generated power from the PV/Wind system is, $E_L$ is the load power, $V_{bat}$ is the battery voltage and $C_{bat}$ is the battery capacity.

The battery charging occurs when $E_g > E_L$;

while the discharging of the battery occurs when $E_L < E_g$;

The state of the charge of a battery at time (t) is greater than the minimum value and less than the maximum value of the situation of the charge. The highest state of the charge value is primarily the capacity of the battery bank ($C_{bat}$) and the minimum condition of the charge of the battery depends on the maximum DOD [23].

The power flow in and out of the battery if given by;

$$P_{bat} = E_g - E_L \quad (7)$$

while the average energy capacity of the battery is computed as follows:

$$A_E = A_{E0} + \sum_{t_1}^{t_2} \frac{P_{bat}}{V_{bat}} \quad (8)$$

where $A_{E0}$ is the initial condition of the battery state. The maximum and minimum value of $A_E$ and the number of batteries used are applied to determine the DOD of the battery [23].

*2.4. The overall system cost calculation*

Economic analysis is a crucial issue regarding the optimization of the integrated hybrid renewable energy system. Since it is important to design a reliable renewable energy system, efficiency and cost-effectiveness should not be compromised. Several ways have been applied to calculate the system cost [23,24,25]. The total cost of the system, which indicates the economic profitability of the scheme depends on the initial capital cost ($I_c$), replacement cost ($L_c$) and the overall maintenance cost ($M_c$) as follows:

$$T_c = I_c + L_c + M_c \quad (9)$$

The initial capital cost comprises of the cost of the components, installation, connections and the overall labour as follows:

$$I_c = C_P . N_P + C_W N_W + C_B N_B + C_O \quad (10)$$

Where $C_P$ and $N_P$ represent the unit cost of the PV and the number of PV arrays used. $C_W$ and $N_W$ represent the unit cost of the wind turbine and the number of wind turbines. $C_B$ and $N_B$ represent the cost of the battery and the number of batteries, while $C_0$ is the overall labor cost.

The replacement cost is also an important factor in the analysis since each component of the system has its own lifetime and computed as follows:

$$L_C = L_S . C_{per} \quad (11)$$

where $L_S$ is the complete lifetime of the whole system by considering the component with the highest lifetime while $C_{per}$ is a specified percentage of the initial capital cost of the system.

The last one is the operation and maintenance cost, calculated by the following equation:

$$M_C = N_B T_{Bat} + N_W T_{wind} + N_P T_{PV} \quad (12)$$

Where $T_{Bat}$, $T_{Wind}$ and $T_{PV}$ are the operation and maintenance cost of battery, wind turbine and the PV panels based on certain chosen interest rate using equations in the literature [13,26, 27].

## 3. Description of the Proposed Algorithm

The proposed algorithm for the feasible hybrid system configurations as developed in MATLAB can be described in Figure 2. The optimum feasible system is the one with the maximum injected power into the system and the most available minimum cost. For each iteration, the number of PV modules are computed based on the number of wind turbines, until maximum possible wind turbines reached ($N_{max}$).

## 4. A Case Study of Kano Nigeria

In this paper, Kano is taken as a case study to apply the proposed the algorithm. It had abundant solar radiation and located in the southern sahara region. It is usually hot in the summer and cold in the winter. March is the hottest and December is the coldest. It has geographical coordinates of 12.0022° N, 8.5920° E at an altitude of 472 m. The average temperature of Kano is 35°C in the summer and 23°C in the winter. The average sunshine hrs per day is 8, and the average monthly irradiation level is 953.7593W/m$^2$. The wind speed distribution of Kano can be assumed weibull or normally distributed with 5% significance level based on 95% confidence level [1]. This paper evaluates the daily solar irradiance and wind speed data for specific periods of summer and winter respectively. For the winter, three-month data of December, January, and February are considered while for the summer season June, July, and August data were averaged. Nine set of data for both wind and solar irradiance are collected for investigation.

*4.1 Evaluation of the wind and solar data for Kano*

Fig. 3 shows the solar irradiation for Kano at different periods of summer and winter respectively. For maximum power extraction from the PV, maximum power point tracker is utilized. Similarly, Fig. 4 shows the average daily wind speed for the aforementioned periods. The weillbull or normal distribution are usually applied to describe the wind speed data. By comparing Figs 3 and 4, it is obvious that both wind speed and solar radiation are at their peak during the day time from 8:00 am to 6 pm. This show that there is more than enough power to supply the load during the day and the surplus can be used to charge the battery to be used for lean period of solar and wind resources.

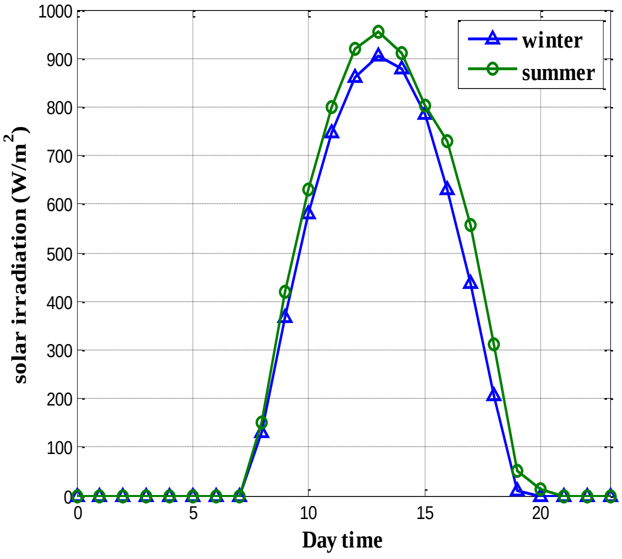


**Fig. 3:** Average solar radiation levels

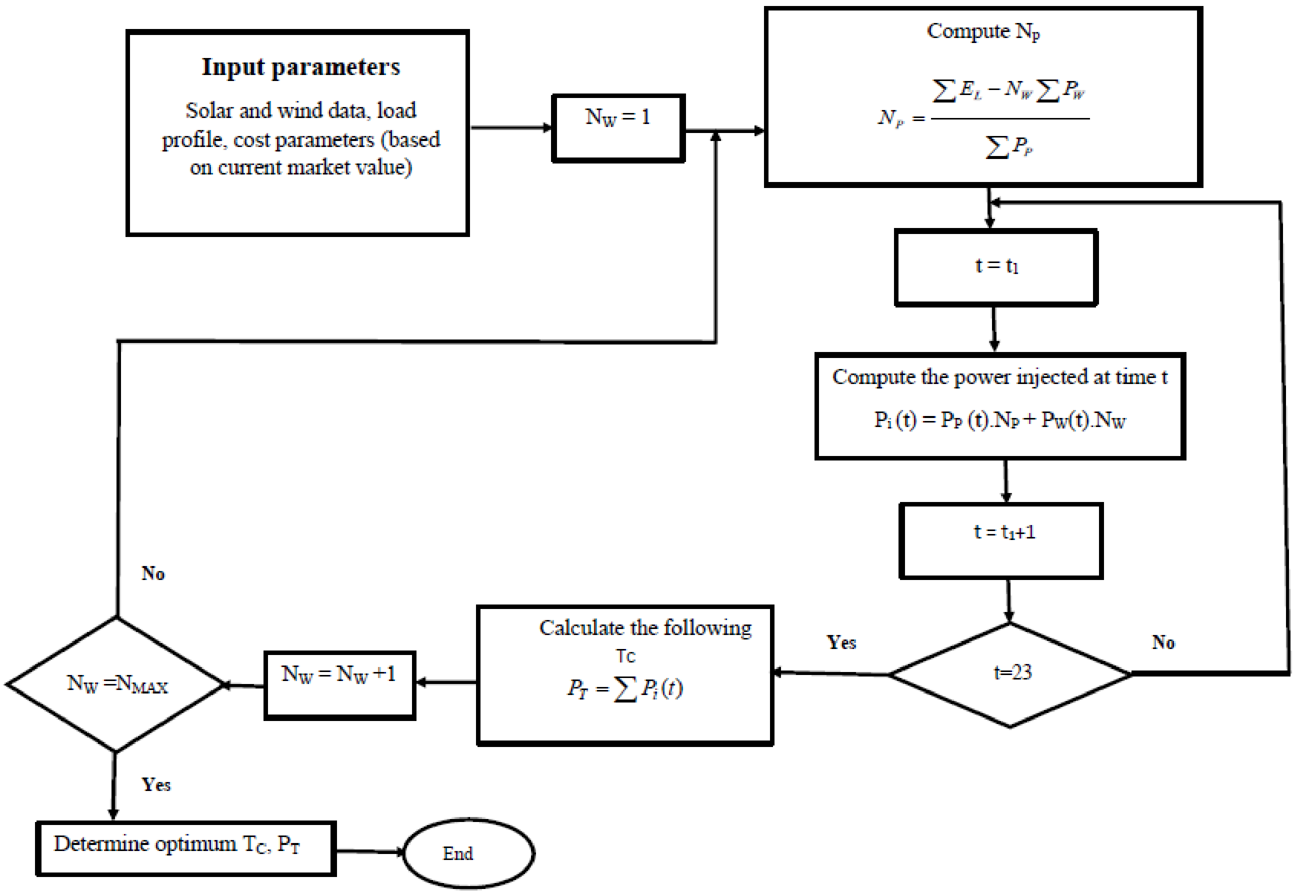


**Fig. 2.** Flow chart for the optimum RE algorithm

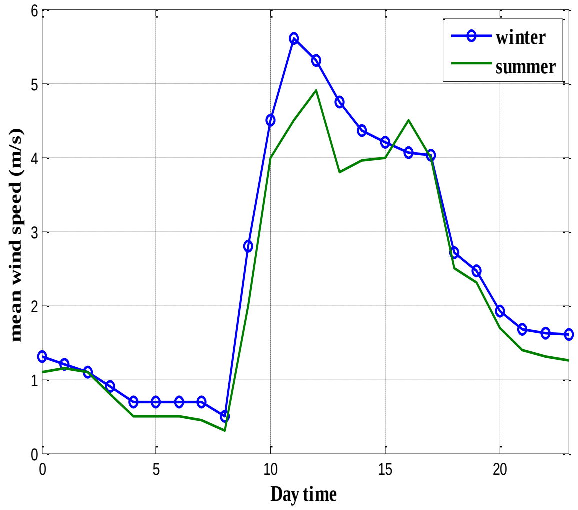


**Fig.4:** Average wind speed

*4.2 Load power*

In this paper, a district hospital in Kano is taken as a case study. The regions infirmary is chosen for this study because it is regarded as a critical load where most equipment's need to be operating all the time to serve emergency patients. Additionally, certain drugs need refrigeration to be bacteria free and available for use when needed. The load curve for the hospital is presented in Figure 5. It is obvious that the base load is around 2kW and the load never reaches zero. The peak load is 11kW and occurs at around 12 pm because most facilities will be operational. Other than that period, most of the power is utilized for lightning, and therefore the load power will be around 60%. Since the peak load appears during the day, a hybrid PV/Wind system is the most appropriate solution together with a storage system to supply period of low wind and solar resources.

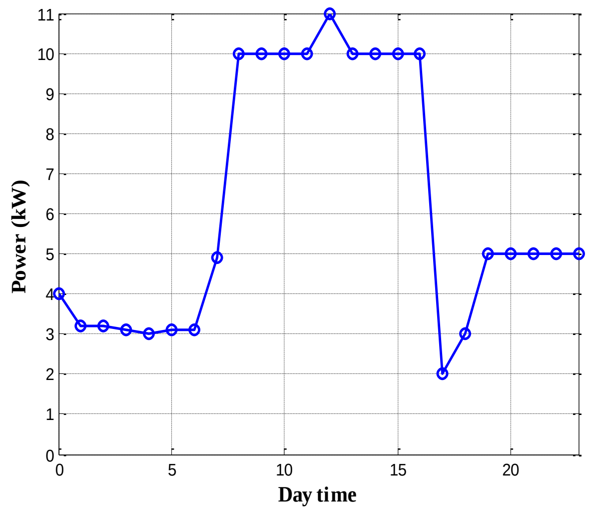


**Fig.5:** Average load variation for a District hospital in Kano

## 5. Results and Analysis

A sizing algorithm has been applied to determine the components of a hybrid system for a hospital environment in Kano, Nigeria. Both hourly wind speed and hourly solar radiation data were utilized to calculate the generated power for the system. The average hourly daily wind speed and solar radiation are obtained from the Nigerian Meteorological Society. Based on the sizing algorithm and calculations of the wind and solar power, the components of the hybrid RE system are chosen as follows:

*5.1 Wind turbine*

The wind power was calculated based on specific considerations such as the hub heights etc. The wind turbine selected is Fuhrländer FL 30 with a rotor diameter of 12.8m and sweep of 13m$^2$. The manufacturer of the FL 30 is Dorstener and it has a gear ratio of 1:22. The power curve characteristics of the FL 30 is shown in Fig. 6. The FL 30 has technologically simple design and generates clean energy, maintenance free. Table 1 shows the specifications of the wind turbine. The cost of one FL 30 wind turbine is $58,564.79 with a replacement cost of $34553.226 and lifespan of between 20-25 years.

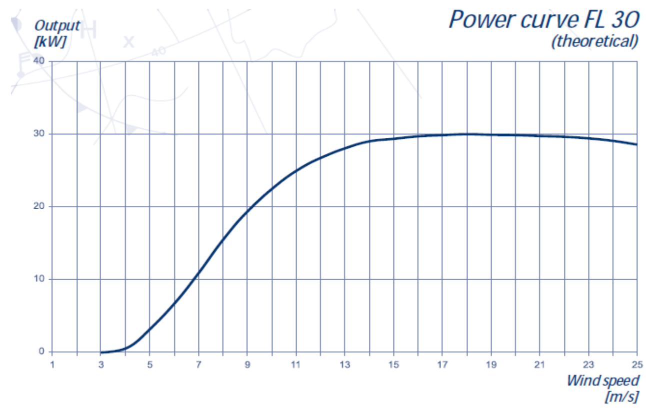


**Fig. 6:** Power curve characteristics of the FL 30 wind turbine

**Table 1:** Specifications for the suitable wind turbine

| Cut-in wind speed (m/s) | Cut-out wind speed (m/s) | Rated wind speed (m/s) | Rated power (kW) | Survival wind speed (m/s) |
|---|---|---|---|---|
| 2.5 | 25 | 12 | 30 | 67 |

*5.2 Solar PV*

For the PV system, the available generated energy was calculated based on the solar irradiation and the chosen PV model. The solar PV module chosen for this investigation is the PV-MLT260HC and its electrical performance shown in Figure 7. It is made up of monocrystalline silicon of size 76mm by 156mm. This module has nominal temperature of

47° and therefore make it suitable for kano with a yearly average temperature of 38°. Table 2 shows the solar PV characteristics. The PV panel has a lifetime of 25 years when operated at 80% maximum power and cost around $112.

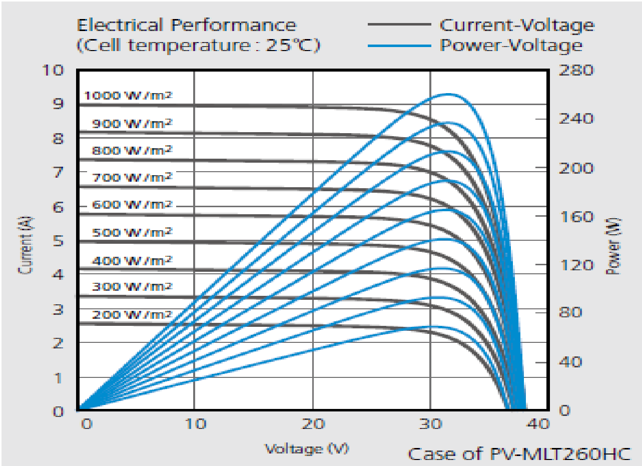


**Fig.7.** Electrical performance curve of the chosen PV.

**Table 2:** Solar PV Characteristics

| Module size | Coefficient of temperature | Module efficiency | Nominal temperature | Max. power (W) |
|---|---|---|---|---|
| 162x 1019m m | 0.45% | 15.7% | 47° | 260 |

*5.3 Battery Bank*

The type of battery that is used for this research is the RS lead acid battery 12V (50Ah) and specifications shown in Table 3. It has efficiency of 86%, DOD of 0.8 and lifetime of 10years. The cost of one battery is $146.50 with replacement cost of $102.55. Table 3 shows the specifications for the battery bank.

**Table 3:** Battery specifications

| Dimensions | Operating temperatu re range | weight | Internal resistance | Maximum discharge current |
|---|---|---|---|---|
| M | 0°C to 40°C | 16.5kg | <=6mΩ | 750A |

*5.4 Analysis of the optimum hybrid system results*

Based on the developed sizing algorithm in the previous section, a sequence of likely sizing results can be obtained for the hospital critical load case. Using Fig. 1, the number of PV arrays can be calculated based on the possible number of wind turbines and the results shown in Table 4. For this load, as expected the number of PV panels decreases with the increase of wind turbines. However, it is determined that the maximum wind turbines for the hybrid system possible are three because when the number of turbines extended to four, the PV panels will be zero to satisfy the load requirements. By this algorithm, one turbine with one hundred and nine PV panels is the optimal solution based on maximum power generation and the life cycle cost of the system. An additional advantage of the scheme is that employing many wind turbines may be noisy for this type of load as certain patients require noise-free environment for rehabilitation. Therefore the total cost of the optimal system consisting of one turbine, one hundred and nine PV panels and 50 battery banks is $239836.

**Table 4:** Number of PV panels with the corresponding wind turbines

| $N_W$ | $N_P$ |
|---|---|
| 1 | 109 |
| 2 | 70 |
| 3 | 32 |

In arriving at the best configuration for the system, the power generated by the PV and the wind is compared to the load demand of the critical load and based on this analysis the battery will be available for service (see Fig 8). Figs 9 and 10 illustrates the power in and out of the storage system and its effect on the average energy production of the battery. It was noted that there are periods when the available energy capacity of the battery is less than the demand, but this can be overcome by chosen appropriate Ah capacity for the system. Assume that the battery has original *SOC* of 78%, then the *SOC* can be better represented in Fig 11. It can be seen that the smallest *SOC* occurs at 9:00 am when the wind and solar power start to rise and reaches its peak around 6 pm when the solar irradiance drastically decreases. However, because of the similar weather conditions for the summer and the winter, the battery charging may have many variations. But, this may be an issue when there are even slight variations or in situations of inconsistent wind or solar irradiance conditions.

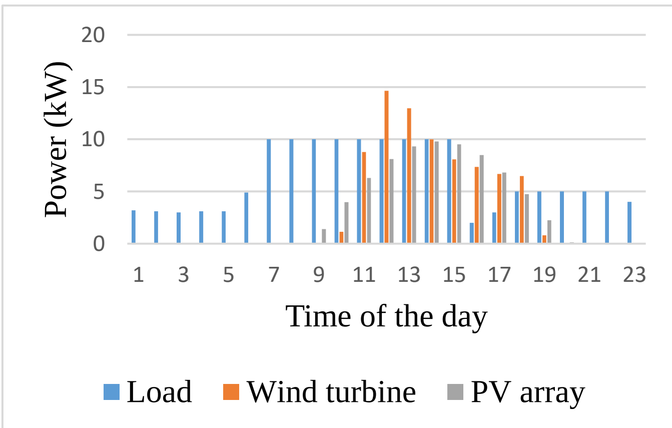


**Fig.8:** Average hourly output of the turbine/ PV array and the load demand for three cases considered for 1 turbine 109 PV panels.

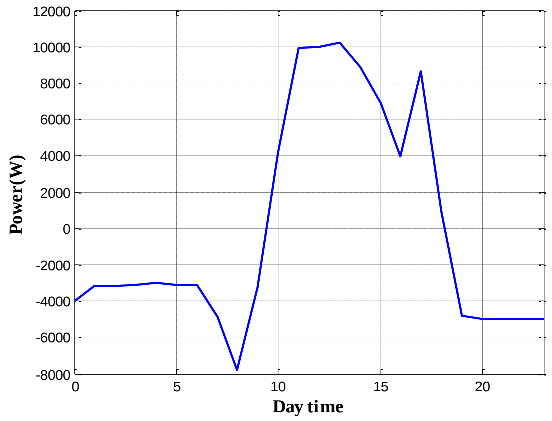


**Fig.9:** Power flowing in and out of the battery for 1 turbine and 109 PV panels.

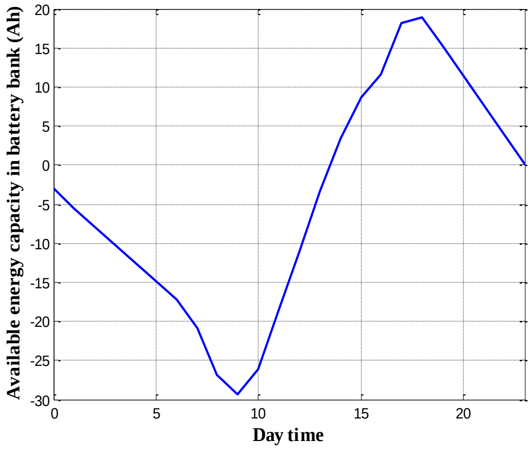


**Fig.10:** The mean Energy capacity of the battery

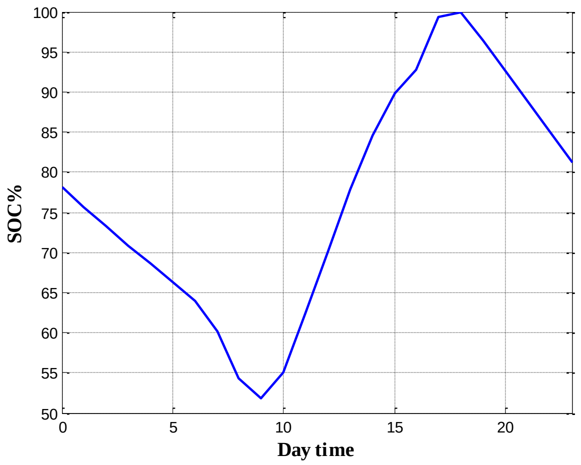


**Fig 11:** Battery state of the charge expressed as a percentage

## Conclusion

In this paper, a novel algorithm has been developed for a hybrid renewable system based on the PV system, wind turbines, and the related battery storage system. This system is based upon the maximum power injected into the system and the cost of the scheme. The number of turbines and the battery storage system are applied to obtain the number of PV panels. This paper has developed for the first time a hybrid renewable system for a critical load in the northern part of Nigeria with irregular weather conditions and high population. Lastly, the invariance nature of the battery system has been tested and verified. This work will be useful to the policy makers of kano, nigeria to consider implementing hybrid system as a solution to the reduce overdependance on hydropower system.

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