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Sizing application for the development of an integrated PV/wind/hydro-battery energy system for sustainable power supply

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Abstract

This paper presents an algorithm for the study, sizing, simulation, and data analysis of complete integrated PV/wind/hydro-battery systems. It is a computer program developed for determining and sizing renewable-based energy systems that can be used for electric power supply at any given time. This tool is used in sizing the integrated PV/wind/hydro-battery for sustainable power supply at Nkanu-West local government secretariat. The proposed sizing tool is verified with HOMER software. The program calculates the best configuration of the system according to the period of operation of solar cells as well as the weather data, and the structural analysis of the program is described in detail through data flow diagrams. From the simulation results, it was shown that the source and load attributes are effectively sized and the supplied energy is efficiently utilized. The developed program could be used during the process of design and analysis of the electrical power process in the integrated system (PV/wind/hydro-battery) for sustainable power supply for daily needs in any area.

Keywords: Renewable energy sources, Solar-PV, Hydro, Wind, Nkanu-West Local Government, Nigeria

1. Introduction

Local governments are structures created in Nigeria to perform specific functions that will help bring the government closer to the people. They are aimed at delivering quality service in a timely, satisfactory, honest, effective, and transparent manner, and all of these cannot be performed satisfactorily without a reliable power supply. A power supply is a major impediment to the management of the local government secretariat. Between 2013 and 2016, Nigeria generated between 3000-4500MW (megawatts) of electricity, far less than the estimated demand of 10,000-12,000 megawatts [1]. This has resulted in frequent and unpredictable load shedding which has affected many local governments and their communities, forcing them to rely on diesel generators as their primary source of electricity. The Nkanu West Local Government Area of Enugu state is among the many Local Governments affected by the country's energy crisis. Nkanu West Local Government secretariat has been experiencing worsening power outages in the past several years, with power outages lasting from several hours to several days. Many of the functions in this local government depend on a reliable supply of electricity to keep the local government moving and effective. Due to the unreliable power supply, the local government secretariat now relies on a diesel-powered solution. The power situation is so unreliable that the generator runs in the morning and afternoon and that consumes a lot of diesel, and negatively impacts workers and the environment [2].

Therefore, there is a need for alternative renewable energy to be explored and exploited for the LGs in Nigeria. Renewable energy sources (RESs) are abundant and freely available, virtually pollution-free, and are therefore a strategy for sustainable growth. RESs enhance the value of the overall resource base of a country by using the country's indigenous resources for electricity generation to power LGs. An integrated renewable energy source is the most effective solution for a sustainable energy supply system. An integrated solar/wind/hydro power generation system consists of PV arrays, wind turbines, hydro turbines, battery banks, an inverter, a controller, cables, and other accessory devices. Due to the unpredictable nature of the power produced by renewable systems (PV and the wind generator), an analysis of reliability plays a vital role in an integrated system design [3]. To predict the integrated system performance, each component needs to be modelled and then the generation system can be evaluated to meet the load demand [4]. Renewable integrated system component sizing is based on the climatic data and the maximum capacity and plays a significant role in the determination of the reliability of the system [5]. To assess the need and adequacy of a renewable energy system (RES), it is necessary to carry out technical analyses. It involves a study of the energy sources and load characteristics, as well as load sizing (energy source(s) and load characteristics should be effectively matched) and system design. This requires the development of a computer program for sizing. This paper aims to introduce an algorithm-based stand-alone application for load sizing and renewable energy system development. This algorithm will be used in the sizing of integrated renewable energy sources that will supply the load demand and satisfy a defined reliability index.

2. Literature review

Research has been done on the sizing of renewable energy systems and the effectiveness of energy storage for improving the variability of the renewable energy system. Elbaset [6] presented a computer program to size a PV/fuel cell power generation system component to match the load, for high operational reliability concerning the objective loss of power supply probability (LPSP). Kellogg et al. [7] presented an iterative optimization method to select the wind turbine size and PV module number using an iterative procedure to make the difference between the generated and demanded power as close to zero as possible over some time. Diaf et al. [8] found that to obtain a total renewable contribution of an autonomous integrated PV/wind system for a Loss of Power Supply Probability of 0, more than 30% of the energy production was unused unless the battery capacity was very large. Reviews of the methods based on the reliability of supply can be found in Daming et al [9] and Gupta et al [10]. In this study, the technical sizing model for the integrated PV/wind/hydro-battery system is developed according to the concept of LPSP to evaluate the reliability of integrated systems.

3. Research method

3.1. Location of study

Nkanu-West Local Government Area (N-WLGA) is the study area of this research work, which is located in the south-eastern part of the Enugu metropolis.

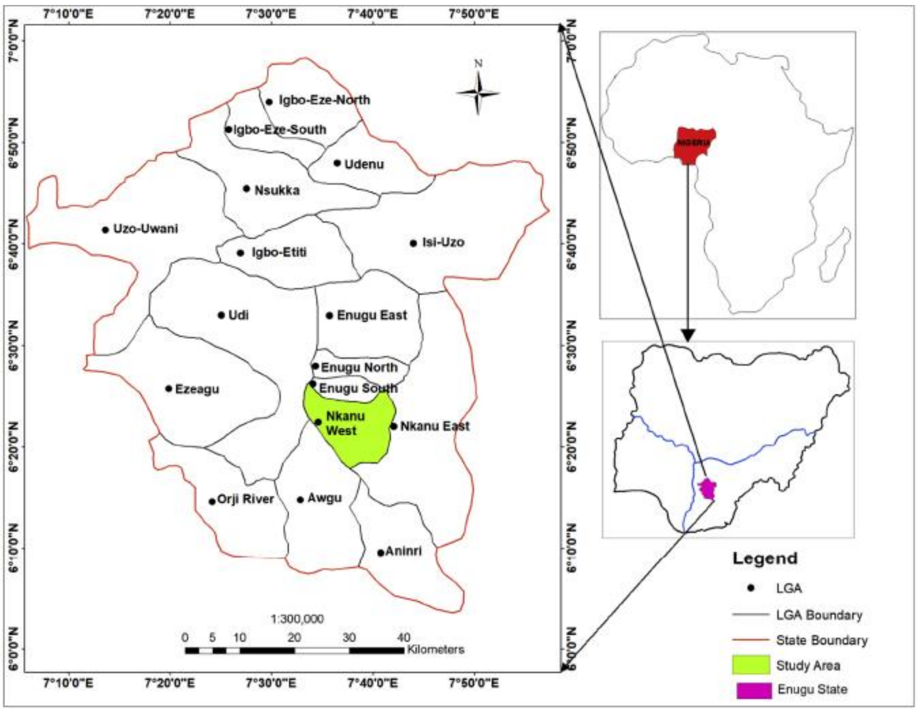

Figure 1. Location of the study area adapted from Ibuot, et al. [11]

It is bordered to the north by Enugu-south LGA, while to the northwest and west by Udi LGA. To the southwest, it is bordered by Awgu LGA and to the northeast, east and south, by Nkanu-East LGA as shown in figure 1 below. Nkanu-West LGA lies between longitudes 7.47° and 7.93° East and latitudes 6.20° and 6.60° North, and comprises Agbani, Akpugo, Amodu, Amuri, Ugboauka, Nara, Obe, Obuoffia, Ozalla, Mburumbu, Ubahu, Akegbe-Ugwu, Umueze, Nkerefi. Nkanu west local government headquarters is located at Agbani.

3.2. Prefeasibility analysis of the research location

Nkanu-West Local Government Secretariat is located in Agbani, and according to the National Aeronautic Space Administration (NASA) at a specific geographical location of 6° 18' 40" N latitude and 7° 30' 32" E longitude [12] with an annual average solar (clearness index and daily radiation) of 4.95kWh/m²/d whereas its annual average wind is 2.1m/s as shown in Table 1.

Table 1. Wind and solar resource for Agbani in Nkanu-West (Enugu State)

Month	**Clearness Index**	**Average Radiation** ($kWh/m^2/day$)	**Wind Speed** (m/s)
Jan	0.605	5.680	2.100
Feb	0.578	5.740	2.200
Mar	0.537	5.570	2.100
Apr	0.503	5.250	2.000
May	0.487	4.940	1.900
Jun	0.458	4.540	2.100
Jul	0.415	4.140	2.400
Aug	0.382	3.910	2.500
Sep	0.406	4.190	2.300
Oct	0.457	4.570	1.700
Nov	0.539	5.110	2.000
Dec	0.595	5.460	1.800
Scaled annual average		**4.950**	**2.1**

The river used for the study is Nneche stream which has its source at the embedded sedimentary strata in Agbani central in Nkanu-West Local Government Area of Enugu State. In carrying out the flow measurement of the stream, the length, width, and depth of the stream were measured (Length of the stream – 7.5m; Width of the stream – 7.5m; Depth of the stream – 2.6m; Constant factor of the stream – 0.16). The result analysis obtained from the Nneche stream is shown in Table (2) below.

Table 2. The readings and the result analysis obtained from the Nneche stream

Months	Time taken for the float to move from point A to B (sec)	Surface speed (m/s)	Average speed (m/s)	Stream Discharge (Q)	
				M^3/s	L/s
January	1200.0	0.0063	0.00100	0.0195	19.5
February	1170.0	0.0064	0.00102	0.0200	20.0
March	1170.0	0.0064	0.00102	0.0200	20.0
April	1170.0	0.0064	0.00102	0.0200	20.0
May	1231.5	0.0061	0.00097	0.0190	19.0
June	1300.0	0.0058	0.00092	0.0180	18.0
July	1462.5	0.0051	0.00082	0.0160	16.0
August	1799.9	0.0042	0.00067	0.0130	13.0
September	1733.3	0.0043	0.00069	0.0135	13.5
October	1613.8	0.0046	0.00074	0.0145	14.5
November	1462.5	0.0051	0.00082	0.0160	16.0
December	1264.9	0.0059	0.00095	0.0185	18.5

3.3. Resource variation

In the solar radiation variation, February was the sunniest month of the year. In this month (February), solar energy resource is 5.7kWh/m²/day while in August it is only 3.9kWh/m²/day as shown in table 3. In this month of August, the wind turbine system can compensate. In the months of September, October, November, December, January, and February, the solar radiation increases with differences, whereas in the months of March, April, May, June, July, and August, the solar radiation decreases with differences. In these months, the hydro system and battery can compensate. Whereas in the wind speed variation, August is the windiest month of the year. In this month (August), wind energy resource is 2.5m/s while in October it is only 1.7m/s as shown also in table 3. Meanwhile, wind speed in this location is very poor and insufficient to generate electricity on a sustainable basis.

Streamflow, on the other hand, has the highest and most steady flow in February, March, and April. In these months (February, March, and April), hydro energy resource is 20.0L/s while in August it is only 13.0L/s as shown also in table 3. In the months of September, October, November, December, January, February, March, and April, the streamflow increases with differences from month to month as (0.5), (1.0), (1.5), (2.5), (1.0), (0.5), (0), and (0), respectively. In the months of May, June, July, and August, the streamflow decreases with differences from month to month as (1.0), (1.0), (2.0), and (3.0), respectively. Table 3 shows the solar, wind, and hydro resource for Nkanu-West Local Government Secretariat, Agbani (Enugu State), Nigeria, used for the simulation.

Table 3. Wind, solar, and hydro resource for Nkanu-West Local Government Secretariat

Month	**Clearness Index**	**Average Radiation** (kWh/m^2/day)	**Wind Speed** (m/s)	**Stream Flow** (L/s)
Jan	0.605	5.68	2.1	19.5
Feb	0.578	5.74	2.2	20.0
Mar	0.537	5.57	2.1	20.0
Apr	0.503	5.25	2.0	20.0
May	0.487	4.94	1.9	19.0
Jun	0.458	4.54	2.1	18.0
Jul	0.415	4.14	2.4	16.0
Aug	0.382	3.91	2.5	13.0
Sep	0.406	4.19	2.3	13.5
Oct	0.457	4.57	1.7	14.5
Nov	0.539	5.11	2.0	16.0
Dec	0.595	5.46	1.8	18.5
Scaled annual average		**4.95**	**2.1**	**17.3**

3.4. Load required for the Local Government Secretariat

Nkanu West Local Government Secretariat consists of six departments and each of these departments has many electrical loads, but the critical load to be modelled for each of the six departments are desktop computers, printers, air conditioners, ceiling fans, and lighting bulbs (a lighting bulb at the general office; a lighting bulb at the passage leading to the department; a lighting bulb or two at the department main office, depending on how big is the department); out of the six departments, Agricultural department is the only department that its printer and the air conditioner was not included in the critical load that is modelled, as shown in table 4. The Chairman's office has various subunits under it and one of them is the security unit, which is critical to the local government and its communities. *The Chairman's office* has in the waiting room, a fan and a lighting bulb; at the general office, a ceiling fan and two (2) lighting bulbs; at the passage leading to the office of the chairman, a lighting bulb; and at the Chairman's main office, a desktop computer, printer, air conditioner, ceiling fan, refrigerator, CCTV camera, a lighting bulb, and internet connectivity. *The security unit* has at the security's main office, a desktop computer, ceiling fan, two (2) lighting bulbs, and a CCTV camera.

The items to be powered by the proposed integrated PV/Wind/Hydro-Battery Energy System are shown in table 5. All the critical load demands (desktop computers, printers, air conditioners, ceiling fans, refrigerator, and lighting bulbs) at the local government are all on for 11hrs (07:00h – 18:00h) except the CCTV cameras and internet connectivity that are always on for 24hrs (00:00h – 23:00h). The security lighting of the Streets of Agbani and the dual road that link the LG to Enugu comes on only for 13hrs (18:00h – 7:00h) as shown in table 6. It is assumed that it is identical for every day of the year. The annual peak load of 10.66kW was observed between 18:00h and 07:00h, with 254kWh/day energy consumption. The daily average load variation for the Local Government (LG) critical load and lighting of the Streets of Agbani with the dual road lighting that links the LG to Enugu is shown in table 6.

Table 4. Nkanu-West Local Government Secretariats' critical load demand

Department/Unit	Desktop Computer	Printer	Air Conditioning	Ceiling Fan	Office Lighting	Refrigerator	CCTV Camera	Internet Connectivity
Chairman's Office	1	1	1	2	5	1	1	1
Personnel Management	1	1	1	1	4			
Education	1	1	1	1	4			
Health	1	1	1	1	3			
Finance	1	1	1	1	4			
Works	1	1	1	1	3			
Agriculture	1			1	3			
Security Unit	1			1	2		1	
Total	**8**	**6**	**6**	**9**	**28**	**1**	**2**	**1**

Table 5. Items to be powered by the integrated PV/wind/hydro-battery energy system

Items	Wattage	Unit	Wattage x unit
Desktop Computer	495	8	3960
All-In-One Printer	24	6	144
Split Air Conditioner	900	6	5400
Ceiling Fan	65	9	585
Office Lighting	6	28	168
Refrigerator	110	1	110
CCTV Camera	30	2	60
Security Lighting	10	1056	10560
Internet Connectivity	40	1	40

3.5. Load variation

From 7:00 hr to 18:00 hr, load demand is at a minimum (10467 W) although solar starts to generate energy between 8:00hr and 18:00hr, most of the solar energy generated at these times is stored in the battery for use at night along with wind and hydro energy. Late-in-the-day and early morning hours (18:00 hr and 7:00 hr), the load demand is at a maximum (10660 W) as shown in table 6. Since the wind blows more at night rather than during the day, it is assumed that wind energy, hydro energy, and the stored energy in the battery can compensate at these hours until daytime when solar energy increases.

Table 6. Electrical load (daily load demands) data for the Local Government (LG) and lighting of streets of Agbani and the dual road lighting that links the LG to Enugu

Time	Daily load demands									Total/Hr.
	Desktop Computer	Internet connectivity	Printer	Office Lighting	Air Conditioning	Ceiling Fan	CCTV Camera	Refrigerator	Security Lighting	
00-01		40					60		10560	10660
01-02		40					60		10560	10660
02-03		40					60		10560	10660
03-04		40					60		10560	10660
04-05		40					60		10560	10660
05-06		40					60		10560	10660
06-07		40					60		10560	10660
07-08	3960	40	144	168	5400	585	60	110		10467
08-09	3960	40	144	168	5400	585	60	110		10467
09-10	3960	40	144	168	5400	585	60	110		10467
10-11	3960	40	144	168	5400	585	60	110		10467
11-12	3960	40	144	168	5400	585	60	110		10467
12-13	3960	40	144	168	5400	585	60	110		10467
13-14	3960	40	144	168	5400	585	60	110		10467
14-15	3960	40	144	168	5400	585	60	110		10467
15-16	3960	40	144	168	5400	585	60	110		10467
16-17	3960	40	144	168	5400	585	60	110		10467
17-18	3960	40	144	168	5400	585	60	110		10467
18-19		40					60		10560	10660
19-20		40					60		10560	10660
20-21		40					60		10560	10660
21-22		40					60		10560	10660
22-23		40					60		10560	10660
23-00		40					60		10560	10660
Total	**43560**	**960**	**1584**	**1848**	**59400**	**6435**	**1440**	**1210**	**137280**	**253717**

3.6. Integrated PV/wind/hydro-battery systems sizing

Sizing is one of the most important tasks during the design of an Integrated PV/Wind/Hydro-Battery System. Integrated renewable energy systems' optimal design depends on the technical parameters criteria such as system efficiency, and reliability to fulfill the load demand at higher efficiency [13]. The PV panels, wind turbines, hydro turbines, and batteries need to be examined as to how to be represented in this sizing in terms of the power that they generate for the systems. The sizing procedure here will determine the power rating of the PV array, wind turbine, hydro turbine, and the battery storage capacity needed to power the required load while ensuring the reliability of power delivered to the load is appropriate for a given application.

In this research, the design of optimal integrated renewable energy which has higher reliability and appropriate consideration of technical objectives is needed. There are various technical objectives used by many researchers such as Loss-of-Power Supply Probability [14], and Loss-of-Load Probability [15]. But in this paper, Loss-of-Power Supply Probability is considered and used as the technical objective. LPSP is a probability technique introduced by AbouZahr and Ramakumar [16] and is widely used in the design and optimization of renewable energy generation systems. It is based on the information on the variability of resources and their correlation with the load, that LPSP can be calculated. This method is particularly useful in assessing the behavior of energy storage, as can be seen in this study.

3.7. Model development for system sizing

Optimal sizing of renewable energy sources plays a significant role in the energy reliability of the system [17]. The equations used in the program, are based on equations used by Ani [18] and HOMER [19] to derive the power supplied by renewable energies. The system sizing of each of the three renewable energy sources (PV solar, wind, and hydro) and the battery was evaluated using the following model equations:

3.8. Solar photovoltaic panel sizing

Using the solar radiation available, the hourly energy output of the PV generator (E_{PVG}) can be calculated according to the following equation [18]:

$$E_{PVG} = G(t) \times A \times P \times \eta_{PVG} \text{ ---------------------------(1)}$$

An assumption was made that the temperature effects (on PV cells) will be ignored.

where, $G(t)$ is the hourly solar irradiance in kWh/m^2
A is the panel surface area in m^2
P is the PV penetration level factor
η_{PVG} is the efficiency of the PV generator

3.9. Wind turbine sizing

Hourly energy generated by wind generator (E_{WEG}) with rated power output (P_{WEG}) is defined by the following expression [18]:

$$P_{WEG} = \frac{1}{2}\rho_{wind} A v^3 C_p(\lambda, \beta) \times \eta_t \times \eta_g \text{ ----------------------(2)}$$

$$E_{WEG}(t) = P_{WEG} \times t \text{ ---------------------------------(3)}$$

where, ρ_{wind} is the density of air at $1.22 kg/m^3$
A is the swept area (m^2)
v is the wind speed (m/s)
C_p is the performance coefficient of the turbine
λ is the tip speed ratio of the rotor blade tip speed to wind speed
β is the blade pitch angle (deg) as 0^o
η_t is the wind turbine efficiency
η_g is the generator efficiency

3.10. Hydro turbine sizing

The sub-system is considered as a run of a river with a small pond. The available power will be dependent on the seasonal variation of the resources. The electrical power generated by a small hydropower generator is given by [18]:

$$P_{MHP}(t) = \eta_{hydro} \frac{9.81 \times Q \times \rho_{water} \times h}{1000} -------------------(4)$$

and the total energy in kWh is given by

$$E_{MHP}(t) = P_{MHP}(t) \times t ---------------------------(5)$$

where, $P_{MHP}(t)$ is the electrical power generated by micro hydropower generator
η_{hydro} is the hydro efficiency
3.10.1. Q is the flow rate in m^3/s
ρ_{water} is the density of water
h is the falling height, head (m)
$E_{MHP}(t)$ is the electrical energy generated by a micro hydropower generator
t is time in Hour

3.11. Battery sizing

A battery serves as an energy source entity when discharging and a load when charging. Energy is stored in batteries when the generated power by the PV array, wind turbine, and a hydro turbine is greater than the load. When the power generated is less than the load, the energy is taken from the batteries. The state of charge of the batteries is used as a decision variable for the control of the overcharge and discharge. In a case when the state of charge of the batteries reaches the maximum value B_{max} the control system intervenes and stops the charging process. On the other hand, if the state of charge decreases to a minimum level B_{min} the control system disconnects the load. Batteries have two different applications in an integrated renewable system: Storing the extra power generated by the system and providing additional energy requested by the load [20]. In terms of the state of charge of batteries, the loss of Power Supply Probability can be therefore defined as the probability of the state of charge at any accumulative time t, within the time T, to be less or equal to the minimum level E_{Bmin}. This can be defined mathematically as:

$$LPSP = P_r(E_B(t) \leq E_{Bmin};\ for\ t \leq T) --------------------(6)$$

3.12. Sizing procedure based on the reliability of supply

The reliability of the power supply is an important factor in Integrated PV/Wind/Hydro-Battery System design, and this is also reflected in some sizing procedures. Reliability of power supply to the load is the probability that it operates properly for a specific period under operating conditions without failure. In this study, to optimize the sizing components of the integrated energy power system (PV/wind/hydro-Battery), a program for calculating generation adequacy is developed using a reliability index which quantifies the system reliability; and one way to quantify the reliability of supply is by a parameter known as the Loss-of-Power Supply Probability (LPSP).

3.13. Sizing development program

In this study, a program for calculating the total available energy generated by PV array, wind turbine, hydro turbine, and the number of batteries for the desired LPSP is developed, which the flow chart diagram is shown in Figure 2.

In this paper, the battery charge efficiency is set equal to the roundtrip efficiency, and the discharge efficiency is set equal to 1, while the inverter is rated in terms of the peak load demand, and a constant value of inverter efficiency was used based on the average load demand.

The total available energy generated $E_G(t)$ by PV array, wind turbine, and hydro turbine for hour t, can be expressed as follows:

$$E_G(t) = \left(N_{PV} \times E_{PV}(t)\right) + E_W(t) + E_H(t) ---------------------- (7)$$

Where N_{PV} is the number of PV modules in a PV array, $E_{PV}(t)$ is the energy generated by a PV module (kW) for hour t, $E_W(t)$ is the energy generated by wind turbine (kW) for hour t, $E_H(t)$ is the energy generated by the hydro turbine at time t.

The generated power is subjected to the following constraint:

$$E_G(t) \geq \frac{E_L(t)}{\eta_{inv}} ---------------------------------(8)$$

Since the battery charge efficiency is set equal to the round-trip efficiency and the discharge efficiency is set equal to 1, two cases were considered in expressing the current energy stored in the batteries for hour *t*.

(1). The batteries will be charged with the round-trip efficiency only if the generated energy from the power sources (PV array, wind turbine, and hydro turbine) exceeds that of the load demand. It can be expressed as follows:

$$E_B(t) = E_B(t-1) \cdot (1-\sigma) + \left(E_G(t) - \frac{E_L(t)}{\eta_{inv}}\right) \cdot \eta_{batt,inv} ---------------(9)$$

(2). But when the load demand is greater than the available energy generated from PV array, wind turbine, and hydro turbine, the batteries will be discharged by the amount that is needed to cover the deficit. It can be expressed as follows:

$$E_B(t) = E_B(t-1) \cdot (1-\sigma) - \left(\frac{E_L(t)}{\eta_{inv}} - E_G(t)\right) -----------------(10)$$

Where $E_B(t)$ is the energy stored in batteries in hour t (kW), $E_B(t-1)$ is the energy stored in the previous hour (kW), σ is the hourly self-discharge rate of the battery bank, $E_L(t)$ is the load demand in hour t (kW), η_{inv} is the efficiency of the inverter, and $\eta_{batt,inv}$ is the round-trip efficiency of the batteries.

The energy stored in batteries at any hour t is subject to the following constraint:

$$E_{Bmin} \leq E_B(t) \leq E_{Bmax} -----------------------------(11)$$

Where E_{Bmin} is the battery minimum allowable energy (Wh), and E_{Bmax} is the battery maximum allowable energy (Wh).

When the available energy generated and stored in batteries is insufficient to satisfy the load demand for hour t, that deficit is called Loss of Power Supply for hour t and can be expressed as:

$$LPS(t) = E_L(t) - (E_G(t) + E_B(t-1) - E_{Bmin}) \cdot \eta_{inv} -------------- (12)$$

In an ideal system where the load is always met by the supply, $LPS(t) = 0$, and in a system where the load is never met, $LPS(t) = 1$. In this system sizing program, the desired $LPS(t)$ is set to zero.

The Loss of Power Supply Probability for a considered time T is the ratio of summation of all $LPS(t)$ at a specific time (t) over the summation of load demand, E_L(t) at the same time (t). This can be defined mathematically as:

$$LPSP = \frac{\sum LPS(t)}{\sum E_L(t)} \ (for\ t \leq T) ------------------------- (13)$$

Once the solar, wind, and hydro resource of the site and available energy generated from a PV module, a wind turbine, and a hydro turbine is known, a simulation will be run to determine for every hour of a day in each month of the whole year, the number of PV modules, number of a wind turbine, number of a hydro turbine, and the number of batteries.

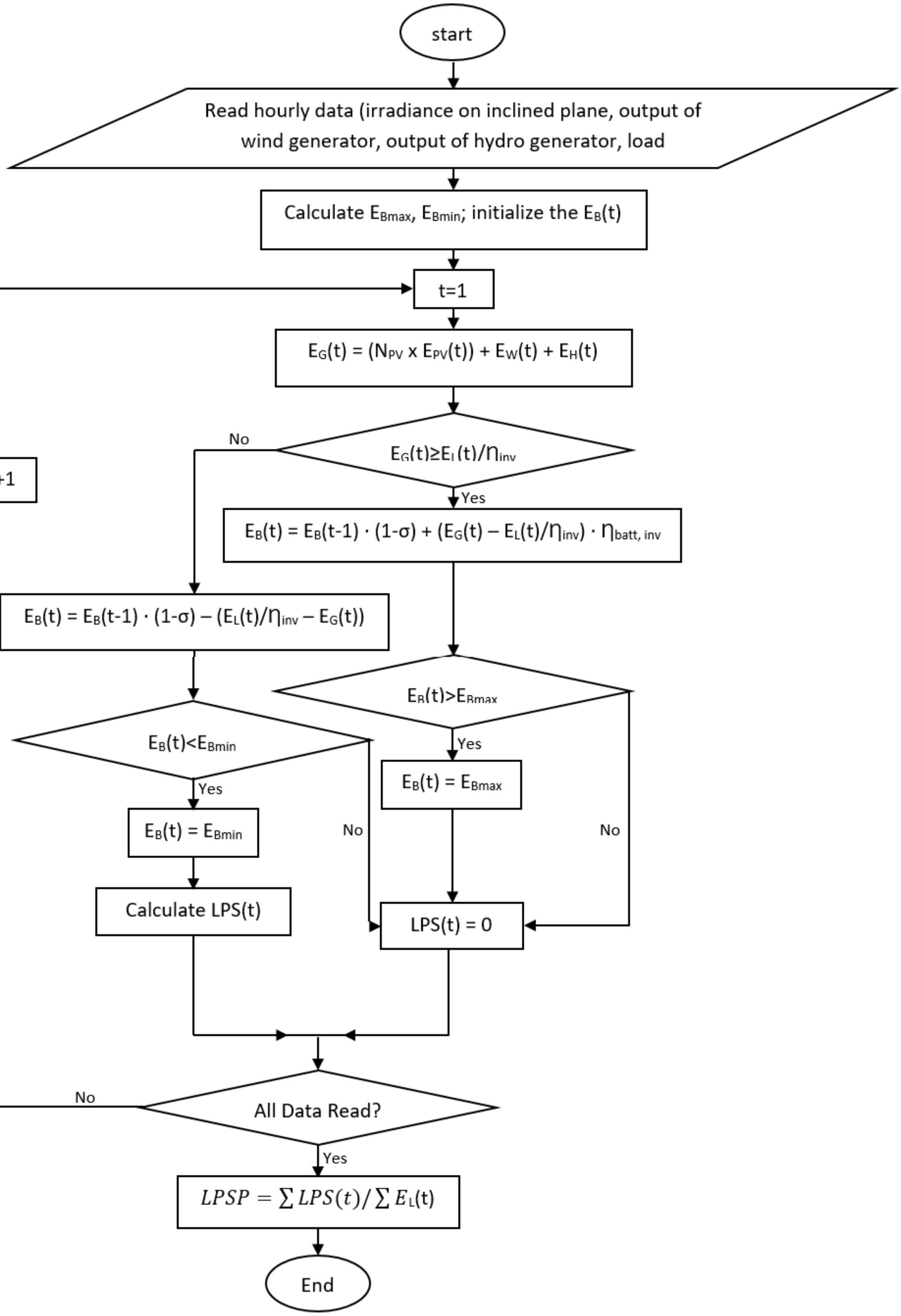

Figure 2. Flowchart diagram for calculation of the integrated PV/wind/hydro-battery system according to the reliability of power supply to a load

3.14. Description of the program

The proposed sizing application is a computer-assisted sizing tool for integrated battery-based PV/Wind/Hydro systems; the program flow chart is shown in Figure 3.

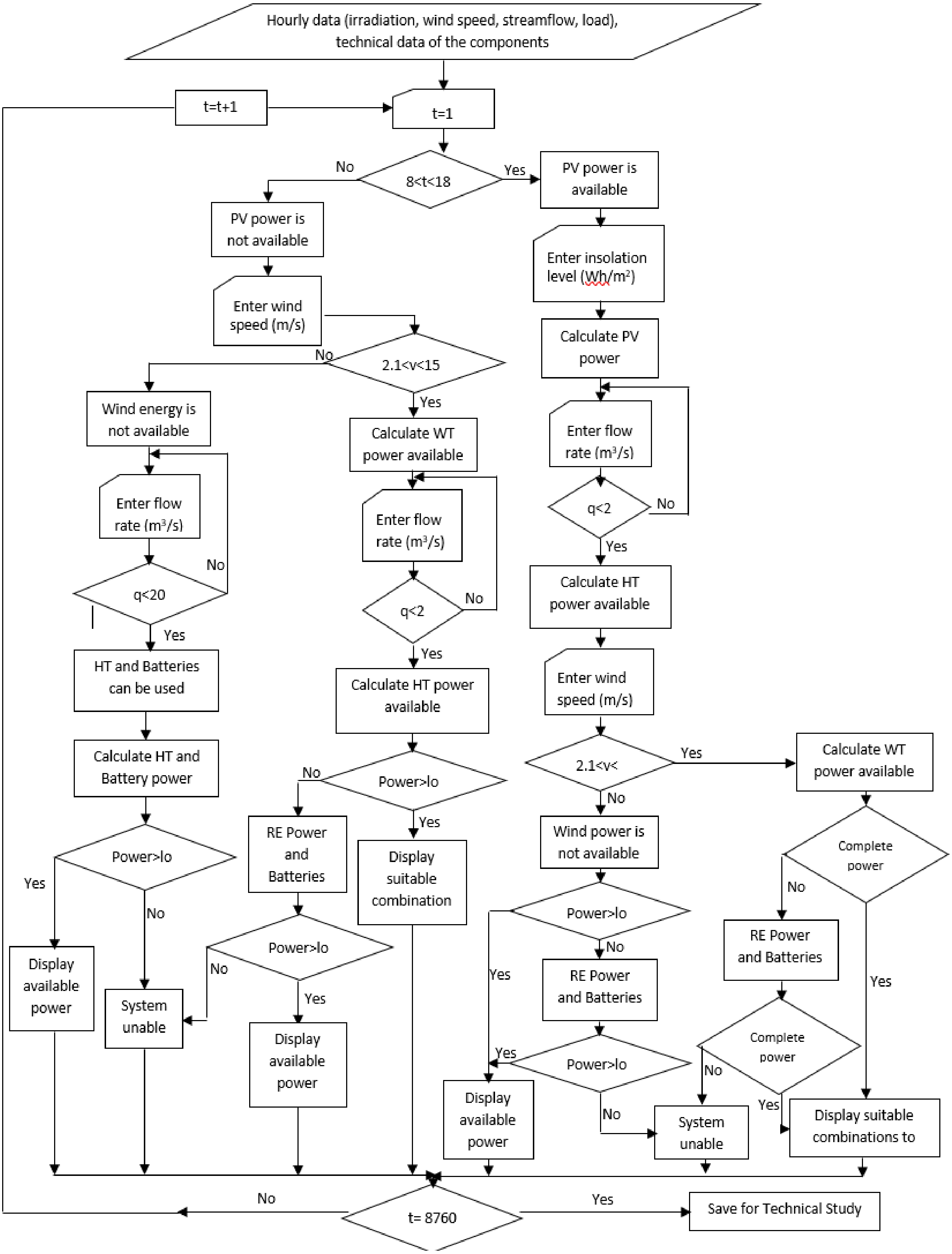

Figure 3. Program flow chart for the modelling of the optimal sizing procedure of integrated system

The program uses probabilistic sizing algorithms and the logic used in this program is designed to follow the Loss-of-Power Supply Probability. This program simulates the operation of a system by making energy balance calculations for each hour in a year, and at the same time decides how the charging and discharging of batteries will be done. The number of PV arrays, number of wind turbines, number of hydro turbines, and battery capacity were the sizing parameters in this program. The input system data are site information, radiation, wind speed, flow rate, the definition of PV modules, wind turbine, hydro turbine, batteries, and a choice of load profiles. This sizing tool determines the component size and configuration; The optimization approach is based on LPSP analysis. It is used in the design of component sizing configuration of integrated PV/Wind/Hydro-Battery system for sustainable power supply at Nkanu-West local government secretariat. Hourly data of solar radiation (kWh/m^2), wind speed (m/s), flow rate (m^3/s), and load power for the Nkanu-west local government secretariat have been used as the program inputs. The determinedg system configuration is composed of PV arrays resulting in total rated power of 10.7 kW, 10 kW wind turbine, 10.3 kW hydro turbine, and 96 units of Surrette 6CS25P Battery (Lifetime throughput 9,645 kWh; Nominal capacity 1,156 Ah; Voltage 6 V). The obtained results are quite detailed, and include, PV Output (kW), Wind Output (kW), Hydro Output (kW), Renewable Energy (RE) Generated (kW), RE Supplied to Load (kW), RE Supplied to Battery (kWh), Battery Supplied to Load (kWh) and shown in the Appendix.

4. Results and discussion

The simulation results in Tables A (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12) in the Appendix A show the contributions of the different renewable sources (PV, Wind, and Hydro) and how the demand is met by the integrated energy system on the 12th day of each of January, February, March, April, May, June, July, August, September, October, November, and December, respectively. It was observed that the variation is not only in the availability of energy sources but also in the demand, but in the case of a shortfall in the energy sources, the battery compensates for the shortage. It is observed that the program sizes the energy sources optimally according to the energy demand and availability satisfying the constraints. The entire operations of the program can be seen in figure 3.

Tables (7, 8, 9, 10, and 11) were gotten from the first month (January – Table 7) and quarterly of a year. A quarter refers to one-fourth of a year. The first quarter (Q1) starts on 1st January and ends on March 31st (March was chosen - Table 8); the second quarter (Q2) goes from 1st April to June 30th (June was chosen – Table 9); the third quarter (Q3) is from 1st July to September 30th (September was chosen – Table 10); Fourth quarter (Q4) is from 1st October to December 31st (December was chosen – Table 11).

The discussion is based on the figures (4a, 4b, 5a, 5b, 6a, 6b, 7a, 7b, 8a and 8b), and these figures (4a, 4b, 5a, 5b, 6a, 6b, 7a, 7b, 8a and 8b) were generated from Tables (7, 8, 9, 10, and 11) as in (figures 4a and 4b were generated from table 7); (figures 5a and 5b were generated from table 8); (figures 6a and 6b were generated from table 9); (figures 7a and 7b were generated from table 10); (figures 8a and 8b were generated from table 11).

From figures 4a, 5a, 6a, 7a, and 8a, the maximum demand of 10.660kW occurs from 18:00hr till 7:00hr and is met by all the renewable energy sources (PV, Wind, and Hydro) along with the battery bank. There are cases where the demand (both minimum and maximum) was met by all the energy sources along with the battery bank but in different limits of hours as in figure 4a (19:00hr till 07:00hr), figure 5a (18:00hr till 08:00hr), figure 6a (16:00hr till 10:00hr), figure 7a (00:00hr till 23:00hr), and figure 8a (18:00hr till 07:00hr). During these times no excess power is available from the renewable energy sources and the battery is in discharging mode. This shows that there is variation (either increase or decrease) in the availability of renewable sources in every hour of a day of each month of the year.

From figures 4b, 5b, 6b, and 8b, the minimum demand of 10.467kW occurs from 7:00hr till 18:00hr and is met by all the renewable energy sources (PV, Wind, and Hydro). It shows that the renewable energy integrated system is effectively sized to supply the load demand as well as charging the battery during day times (8:00hr to 17:000hr) and thus compensates for the shortfall in solar radiation at night when the sunshine is quite low (18:00hr till 7:00hr). But in figure 7b, the case is different; the load demand is met by all the renewable energy sources along with the battery bank. This is because there is no excess power available from the integrated energy system.

From the figures (4a, 4b, 5a, 5b, 6a, 6b, 7a, 7b, 8a, and 8b), it was observed that the program sized the integrated energy system based on:

1) The load is completely supplied by the integrated system (see figures 4a, 5a, 6a, 7a, and 8a)
2) The total RE generated is supplied to the load and battery effectively (see figures 4b, 5b, 6b, 7b, and 8b)

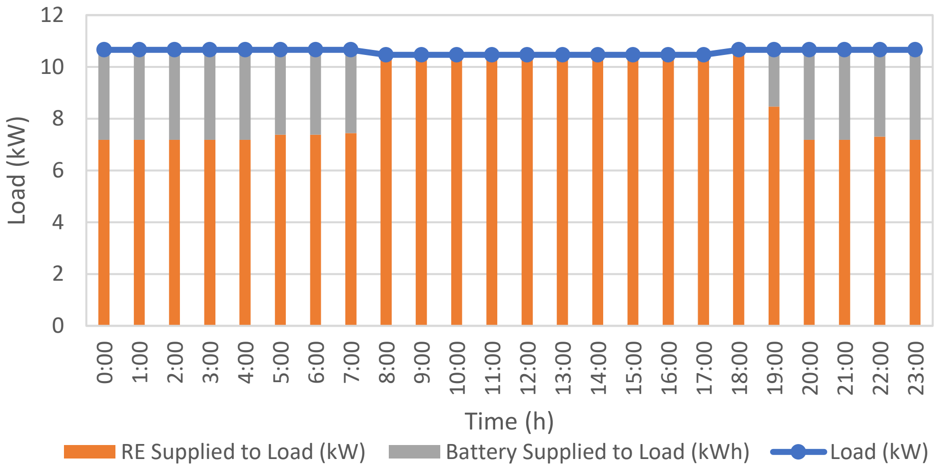

Figure 4a. Load demand, supply made to the load by (i) RE (ii) battery vs time in the first month of the year (January)

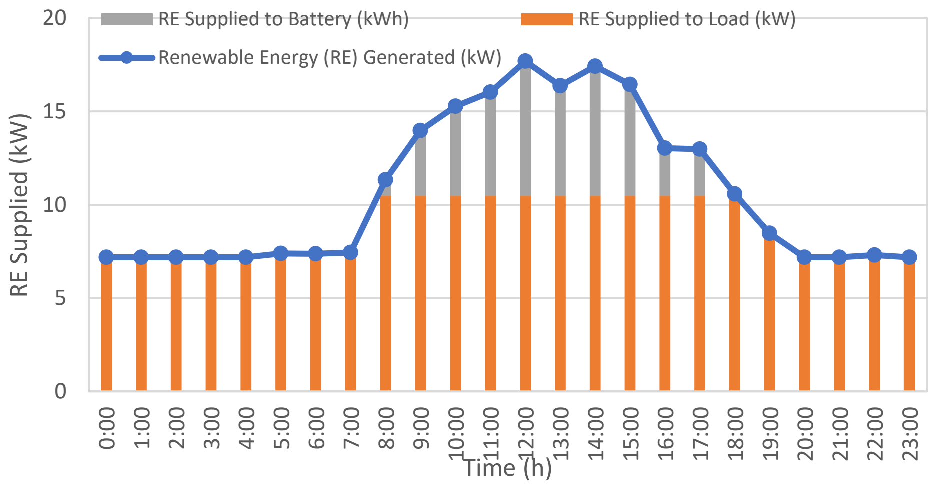

Figure 4b. RE Generated, supplied to the (i) Load (ii) battery vs time in the first month of the year (January)

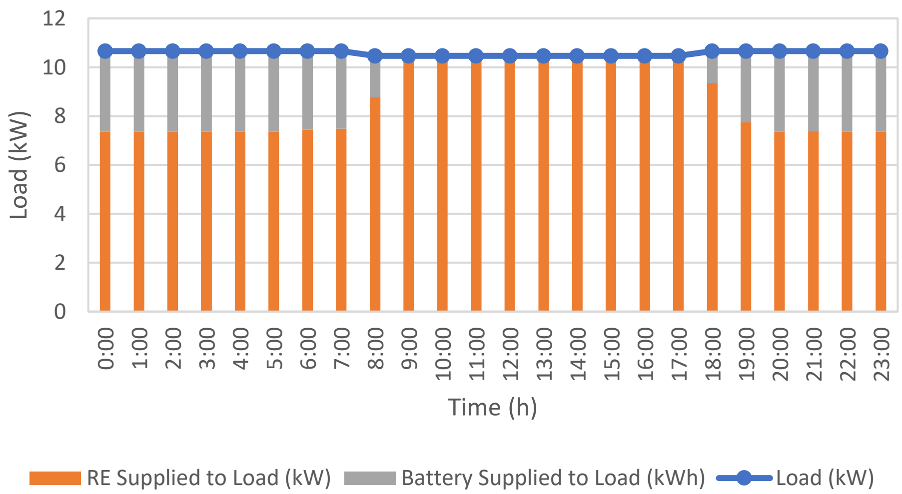

Figure 5a. Load demand, supply made to the load by (i) RE (ii) battery vs time in the first quarter of the year (month of March)

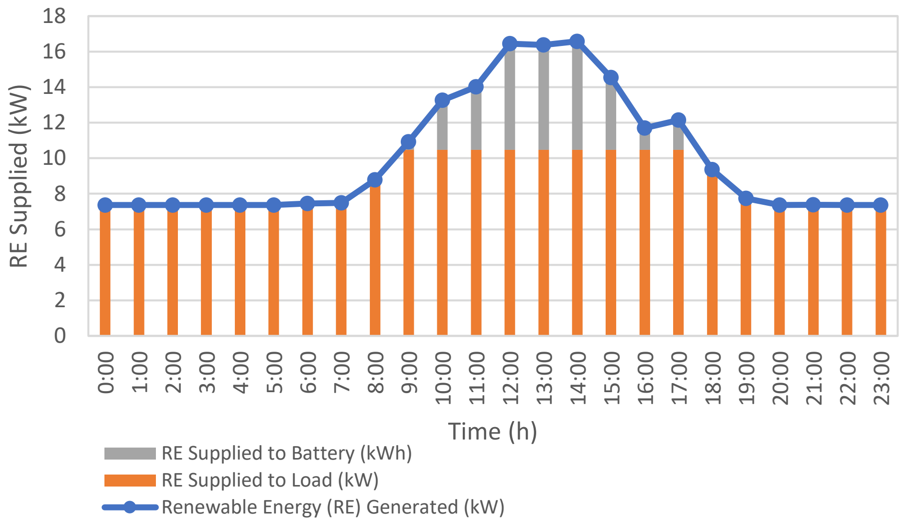

Figure 5b. RE Generated, supplied to the (i) Load (ii) battery vs time in the first quarter of the year (month of March)

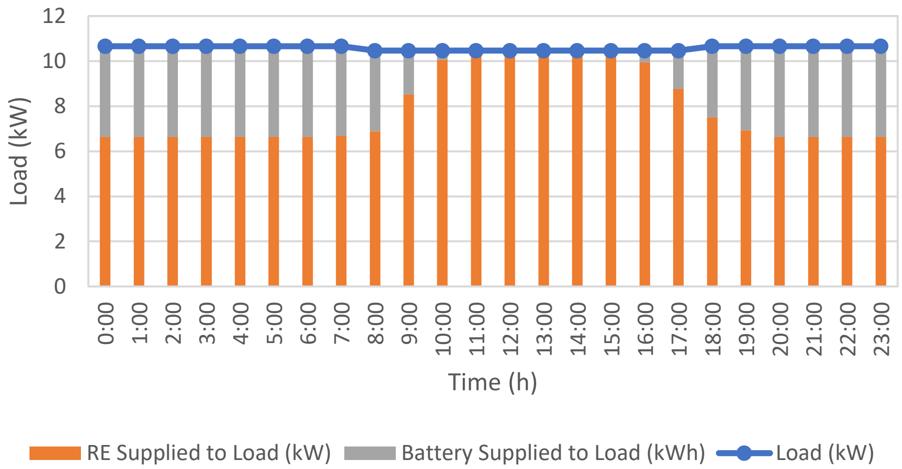

Figure 6a. Load demand, supply made to the load by (i) RE (ii) battery vs time in the second quarter of the year (month of June)

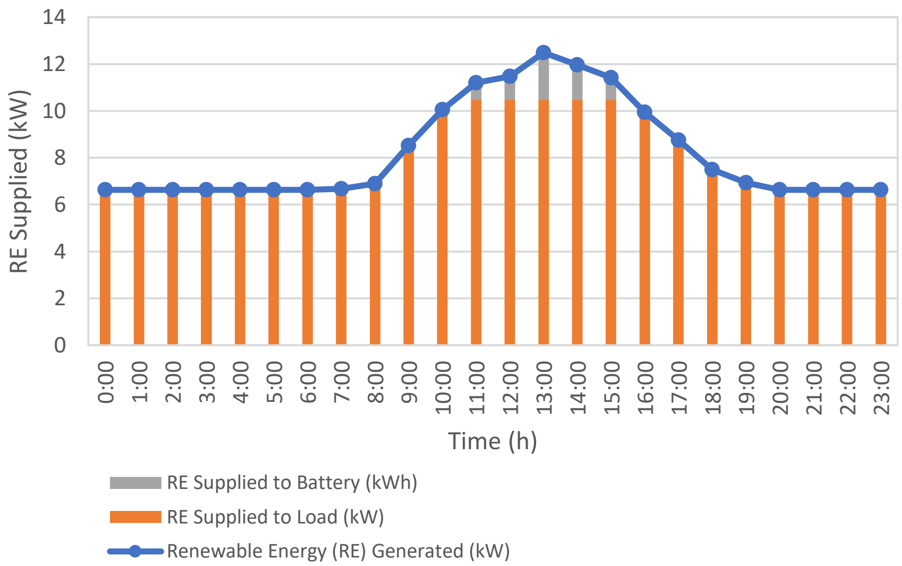

Figure 6b. RE Generated, supplied to the (i) Load (ii) battery vs time in the second quarter of the year (month of June)

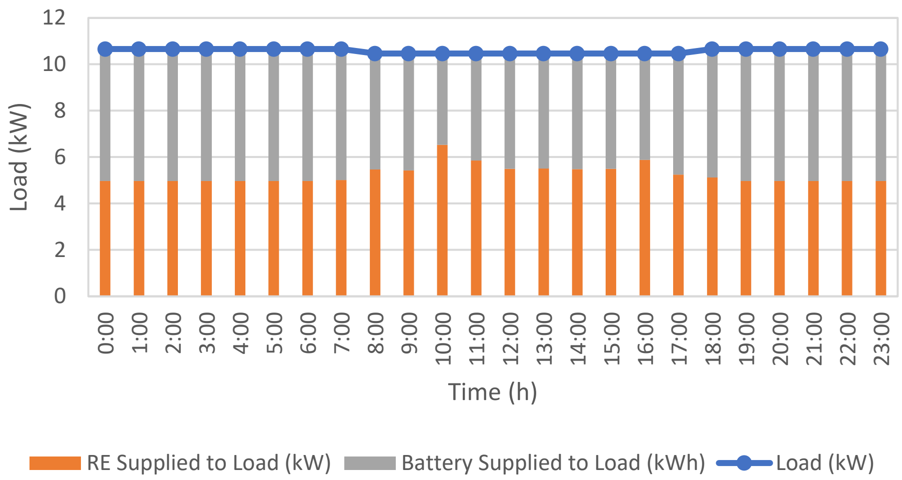

Figure 7a. Load demand, supply made to the load by (i) RE (ii) battery vs time in the third quarter of the year (month of September)

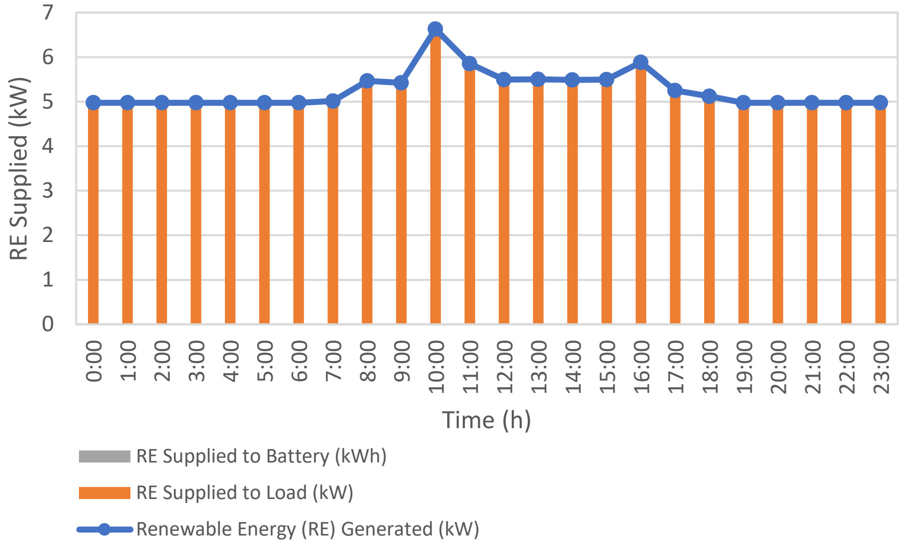

Figure 7b. RE Generated, supplied to the (i) Load (ii) battery vs time in the third quarter of the year (month of September)

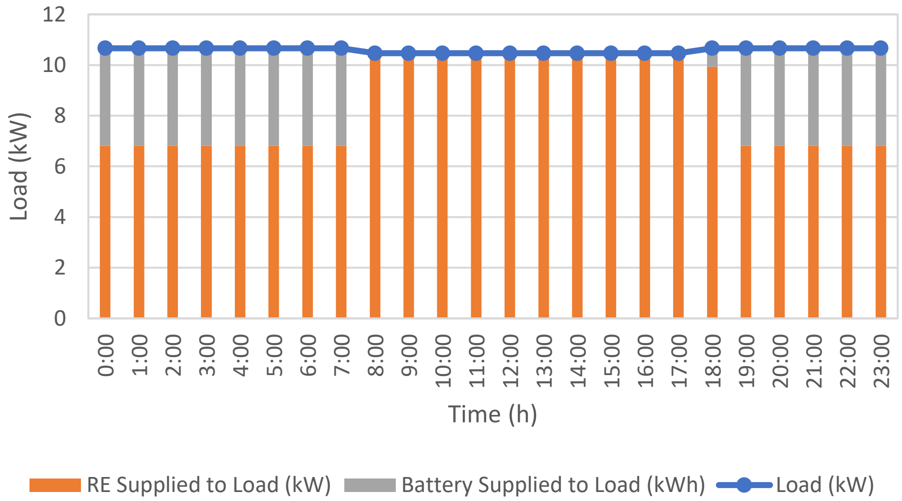

Figure 8a. Load demand, supply made to the load by (i) RE (ii) battery vs time in the fourth quarter of the year (month of December)

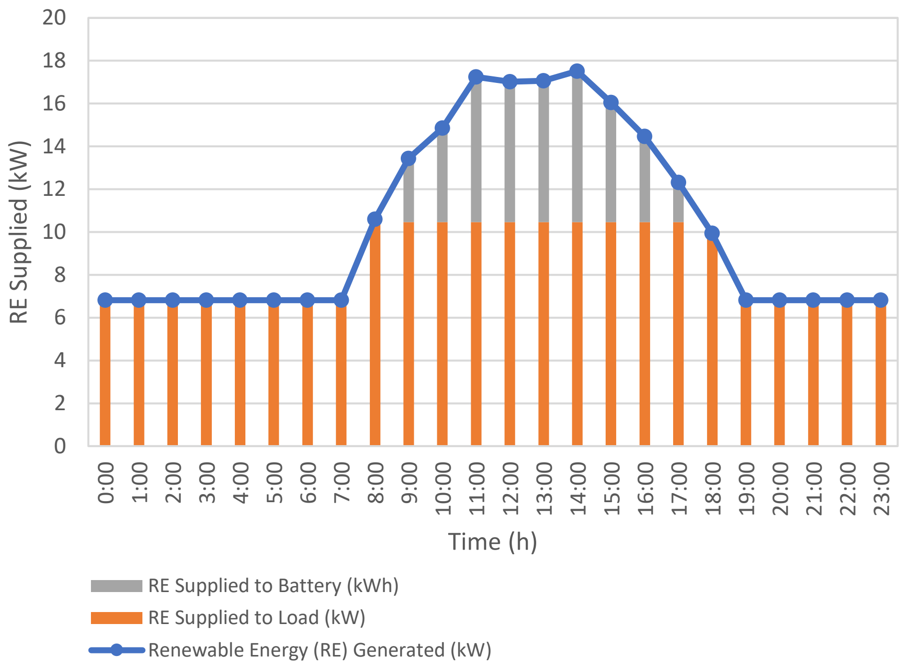

Figure 8b. RE Generated, supplied to the (i) Load (ii) battery vs time in the fourth quarter of the year (month of December)

The following tables presents sample program output for the generated renewable energy.

Table 7. Sample program output for the generated RE, supply made by the generated RE to (i) load (ii) battery, and battery supply to load in the first month of the year (January)

Time (h)	Renewable Energy (RE) Generated (kW)	Load (kW)	RE Supplied to Load (kW)	RE Supplied to Battery (kWh)	Battery Supplied to Load (kWh)
0:00	7.184	10.660	7.184	0.000	3.476
1:00	7.184	10.660	7.184	0.000	3.476
2:00	7.184	10.660	7.184	0.000	3.476
3:00	7.184	10.660	7.184	0.000	3.476
4:00	7.184	10.660	7.184	0.000	3.476
5:00	7.383	10.660	7.383	0.000	3.277
6:00	7.378	10.660	7.378	0.000	3.282
7:00	7.445	10.660	7.445	0.000	3.215
8:00	11.334	10.467	10.467	0.867	0.000
9:00	13.964	10.467	10.467	3.497	0.000
10:00	15.279	10.467	10.467	4.812	0.000
11:00	16.024	10.467	10.467	5.557	0.000
12:00	17.684	10.467	10.467	7.217	0.000
13:00	16.365	10.467	10.467	5.898	0.000
14:00	17.413	10.467	10.467	6.946	0.000
15:00	16.446	10.467	10.467	5.979	0.000
16:00	13.033	10.467	10.467	2.566	0.000
17:00	12.979	10.467	10.467	2.512	0.000
18:00	10.571	10.660	10.571	0.000	0.089
19:00	8.466	10.660	8.466	0.000	2.194
20:00	7.184	10.660	7.184	0.000	3.476
21:00	7.184	10.660	7.184	0.000	3.476
22:00	7.309	10.660	7.309	0.000	3.351
23:00	7.184	10.660	7.184	0.000	3.476

Table 8. Sample program output for the generated RE, supply made by the generated RE to (i) load (ii) battery, and battery supply to load in the first quarter of the year (month of March)

Time (h)	Renewable Energy (RE) Generated (kW)	Load (kW)	RE Supplied to Load (kW)	RE Supplied to Battery (kWh)	Battery Supplied to Load (kWh)
0:00	7.368	10.660	7.368	0.000	3.292
1:00	7.368	10.660	7.368	0.000	3.292
2:00	7.368	10.660	7.368	0.000	3.292
3:00	7.368	10.660	7.368	0.000	3.292
4:00	7.368	10.660	7.368	0.000	3.292
5:00	7.368	10.660	7.368	0.000	3.292
6:00	7.446	10.660	7.446	0.000	3.214
7:00	7.480	10.660	7.480	0.000	3.180
8:00	8.777	10.467	8.777	0.000	1.690
9:00	10.929	10.467	10.467	0.462	0.000
10:00	13.260	10.467	10.467	2.793	0.000
11:00	14.013	10.467	10.467	3.546	0.000
12:00	16.445	10.467	10.467	5.978	0.000
13:00	16.368	10.467	10.467	5.901	0.000
14:00	16.583	10.467	10.467	6.116	0.000
15:00	14.542	10.467	10.467	4.075	0.000
16:00	11.694	10.467	10.467	1.227	0.000
17:00	12.146	10.467	10.467	1.679	0.000
18:00	9.357	10.660	9.357	0.000	1.303
19:00	7.744	10.660	7.744	0.000	2.916
20:00	7.368	10.660	7.368	0.000	3.292
21:00	7.377	10.660	7.377	0.000	3.283
22:00	7.368	10.660	7.368	0.000	3.292
23:00	7.368	10.660	7.368	0.000	3.292

Table 9. Sample program output for the generated RE, supply made by the generated RE to (i) load (ii) battery, and battery supply to load in the second quarter of the year (month of June)

Time (h)	Renewable Energy (RE) Generated (kW)	Load (kW)	RE Supplied to Load (kW)	RE Supplied to Battery (kWh)	Battery Supplied to Load (kWh)
0:00	6.631	10.660	6.631	0.000	4.029
1:00	6.631	10.660	6.631	0.000	4.029
2:00	6.631	10.660	6.631	0.000	4.029
3:00	6.631	10.660	6.631	0.000	4.029
4:00	6.631	10.660	6.631	0.000	4.029
5:00	6.631	10.660	6.631	0.000	4.029
6:00	6.631	10.660	6.631	0.000	4.029
7:00	6.670	10.660	6.670	0.000	3.990
8:00	6.890	10.467	6.890	0.000	3.577
9:00	8.516	10.467	8.516	0.000	1.951
10:00	10.050	10.467	10.050	0.000	0.417
11:00	11.195	10.467	10.467	0.728	0.000
12:00	11.474	10.467	10.467	1.007	0.000
13:00	12.488	10.467	10.467	2.021	0.000
14:00	11.966	10.467	10.467	1.499	0.000
15:00	11.422	10.467	10.467	0.955	0.000
16:00	9.945	10.467	9.945	0.000	0.522
17:00	8.760	10.467	8.760	0.000	1.707
18:00	7.501	10.660	7.501	0.000	3.159
19:00	6.937	10.660	6.937	0.000	3.723
20:00	6.631	10.660	6.631	0.000	4.029
21:00	6.631	10.660	6.631	0.000	4.029
22:00	6.631	10.660	6.631	0.000	4.029
23:00	6.631	10.660	6.631	0.000	4.029

Table 10. Sample program output for the generated RE, supply made by the generated RE to (i) load (ii) battery, and battery supply to load in the third quarter of the year (month of September)

Time (h)	Renewable Energy (RE) Generated (kW)	Load (kW)	RE Supplied to Load (kW)	RE Supplied to Battery (kWh)	Battery Supplied to Load (kWh)
0:00	4.974	10.660	4.974	0.000	5.686
1:00	4.974	10.660	4.974	0.000	5.686
2:00	4.974	10.660	4.974	0.000	5.686
3:00	4.974	10.660	4.974	0.000	5.686
4:00	4.974	10.660	4.974	0.000	5.686
5:00	4.974	10.660	4.974	0.000	5.686
6:00	4.974	10.660	4.974	0.000	5.686
7:00	5.014	10.660	5.014	0.000	5.646
8:00	5.465	10.467	5.465	0.000	5.002
9:00	5.423	10.467	5.423	0.000	5.044
10:00	6.631	10.467	6.531	0.000	3.836
11:00	5.855	10.467	5.855	0.000	4.612
12:00	5.497	10.467	5.497	0.000	4.970
13:00	5.504	10.467	5.504	0.000	4.963
14:00	5.487	10.467	5.487	0.000	4.980
15:00	5.496	10.467	5.496	0.000	4.971
16:00	5.884	10.467	5.884	0.000	4.583
17:00	5.253	10.467	5.253	0.000	5.214
18:00	5.122	10.660	5.122	0.000	5.538
19:00	4.974	10.660	4.974	0.000	5.686
20:00	4.974	10.660	4.974	0.000	5.686
21:00	4.974	10.660	4.974	0.000	5.686
22:00	4.974	10.660	4.974	0.000	5.686
23:00	4.974	10.660	4.974	0.000	5.686

Table 11. Sample program output for the generated RE, supply made by the generated RE to (i) load (ii) battery, and battery supply to load in the fourth quarter of the year (month of December)

Time (h)	Renewable Energy (RE) Generated (kW)	Load (kW)	RE Supplied to Load (kW)	RE Supplied to Battery (kWh)	Battery Supplied to Load (kWh)
0:00	6.816	10.660	6.816	0.000	3.844
1:00	6.816	10.660	6.816	0.000	3.844
2:00	6.816	10.660	6.816	0.000	3.844
3:00	6.816	10.660	6.816	0.000	3.844
4:00	6.816	10.660	6.816	0.000	3.844
5:00	6.816	10.660	6.816	0.000	3.844
6:00	6.816	10.660	6.816	0.000	3.844
7:00	6.816	10.660	6.816	0.000	3.844
8:00	10.599	10.467	10.467	0.132	0.000
9:00	13.432	10.467	10.467	2.965	0.000
10:00	14.848	10.467	10.467	4.381	0.000
11:00	17.248	10.467	10.467	6.781	0.000
12:00	17.015	10.467	10.467	6.548	0.000
13:00	17.069	10.467	10.467	6.602	0.000
14:00	17.518	10.467	10.467	7.051	0.000
15:00	16.047	10.467	10.467	5.580	0.000
16:00	14.461	10.467	10.467	3.994	0.000
17:00	12.308	10.467	10.467	1.841	0.000
18:00	9.936	10.660	9.936	0.000	0.724
19:00	6.816	10.660	6.816	0.000	3.844
20:00	6.816	10.660	6.816	0.000	3.844
21:00	6.816	10.660	6.816	0.000	3.844
22:00	6.816	10.660	6.816	0.000	3.844
23:00	6.816	10.660	6.816	0.000	3.844

5. Conclusion

This paper introduced a new proposed program for sizing the components of standalone integrated renewable energy sources to meet the load demand effectively using any available sources (renewable or battery). The developed program uses two steps in determining the most suitable combination of the renewable source to supply a given load. The first step is the modelling of the optimal sizing procedure of the integrated PV/wind/hydro-battery system, while the second step is optimizing the sizing of the integrated PV/wind/hydro-battery system according to the loss of power supply probability concept. Applying this method to an assumed integrated PV/wind/hydro-battery system to be installed at the Nkanu-West secretariat, the simulation results show that the optimal configuration which meets the desired system reliability requirements (LPSP = 0) is obtained for a system comprising photovoltaic arrays resulting in total rated power of 10.7 kW**,** one wind generator (10 kW), one hydro-generator (10.3 kW), and 96 units of storage batteries (using 1,156 Ah), and on other hand, the device system choice play an important role in energy production. From the simulation results, it is found that the implemented program sizes the sources effectively and the supplied energy is efficiently and rationally utilized. The developed program can also be used as a power monitoring and control system for the integrated system (PV/wind/hydro-battery).

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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