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Design of a Photovoltaic Mini-Grid System for Rural Electrification in Sub-Saharan Africa

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Abstract

This paper presents a detailed design of a photovoltaic (PV) system for use in the rural electrification of remote settlements that are far off from the electricity grid. Since investment in building transmission lines from the grid to these localities is not viable, a good solution is an installation in these areas of standalone photovoltaic systems. The design process comprises the choice and dimensioning of the solar panels, the battery storage, DC-AC inverter, and mini transmission grid to the different homes. The design is for a 15 kW PV system including an economic evaluation and analysis using Hybrid Optimization of Multiple Energy Resources (HOMER) software. Data on the average monthly solar radiation and temperature were obtained from various sources, including, Photovoltaic Geographical Information System (PVGIS) for Africa. From this data the study area receives a monthly average solar insolation of 6.16 kWh/m^2/day with the worst month being August with 5.22 kWh/m^2/day. The total daily electrical energy consumption is estimated to be about 72.525 kWh. Simulation results using HOMER software shows that the overall capital cost of the PV system components is $122,337, a replacement cost of $12,889 and an operation and maintenance cost of $29,946 over 10years. A financial analysis of the system showed that the design was both viable and sustainable with low maintenance cost.

Keywords

Photovoltaic, Solar Radiation, Rural Electrification, Mini-Grid, System Dimensioning

1. Introduction

In Sub-Saharan Africa, the cost of electricity is still very high and not easily accessible. Rural electrification requires considerable resources. Decentralized production projects based on renewable energies could enable the exploitation of this market for it to become a key driver of economic growth and prosperity. However, access to electricity supply remains a distant dream for the majority of the population living in the rural areas [1]. Limited access to electricity continues to be a major impediment to development in many parts of the world. Renewable energy offers a great opportunity to accelerate access to electricity through small-scale, mini-grid and stand-alone projects, as well as income-generating opportunities for rural populations. The electrification of areas that are not accessible to the main electricity grid can easily be achieved through decentralized generation using photovoltaic (PV) and wind turbine stand-alone systems, supplying their loads through mini-grids. These mini-grids can eventually be connected to the national grid.

The relative simplicity of PV solutions is a great advantage within a national rural electrification strategy especially as load densities remain relatively low [2]. Several studies have shown that solar radiations are high in most countries of Sub-Saharan Africa year-round, enough to power solar energy projects [3]. Furthermore, PV implementation increases the quality of energy services, reduces dependence on fossil fuels, and consequently reducing the environmental impacts associated with the use of these fuels.

A mini-grid is composed of an electricity production system that may be combined with a storage system for the energy produced and an electricity distribution system that supplies energy to some isolated loads that are usually not connected to the national electricity grid. The process of designing mini-grid consists of selecting the components and configurations for each sub-system that will deliver safe, reliable, cost-effective energy services that meet the needs of the consumers [4].

The sharp drop in the cost of PV panels highlights their comparative advantage, as compared with fossil fuels whose prices are on a continuous rise. With the growing demand for safe and reliable electrical energy, PV systems have remained the least utilized in Sub-Saharan African countries and yet one of the safest and most reliable forms of energy. PV systems have shown their potential in rural electrification projects in many countries around the world [5].

To protect our environment and increase electricity access in remote areas, clean energy alternatives like PV systems can be of great importance. A solar based mini-grid is a PV system with a dedicated distribution network within a small geographical area, or a cluster of villages, supplying alternating current (AC) [6]. Essentially, it consists of PV panels of a certain capacity, solar inverters for converting the DC power to AC power, housing for the battery storage and plant control systems. In areas where there is no grid connection or where diesel generation is the main power source, PV plants are very highly recommended.

The present design is for Chewel and Fuga; two neighbouring villages situated in the Central River Region (CRR) of The Gambia that are not connected to the main electrical grid, but the results obtained can be replicated elsewhere in Sub-Saharan Africa. These areas rely mainly on fossil fuel generators which are expensive to run and difficult to maintain. In this age of information technology, most people rely on the use of electrical and electronic equipment to carry out their economic and social activities. PV systems can produce electricity for radios, mobile phones, lighting and can generate high levels of electrical power that can be used by both the households and other businesses.

The total installed capacity of electric power in The Gambia stands at about 65 MW [7]. This capacity is divided into two generation and transmission categories. The Greater Banjul area is supplied by two large HFO power plants located in Kotu (25 MW at peak load), Brikama (26 MW) and the Batakunku and Tanji wind power plants (120 kW/150 (kVA) and 900 kVA respectively). The Batakunku and Tanji power plants are Independent Power Producer (IPP) [1].

Electricity is transmitted from these stations for distribution via five radial 11 kV feeders and three 33 kV feeders [4]. The second category of power supply consists of seven National Water and Energy Company (NAWEC) owned small-scale power plants that operate on diesel generator sets, served by standalone electricity subsystems in the provincial centers as shown in **Figure 1**. Together, these small-scale plants have an installed capacity of about 13.75 MW [3]. Approximately 250 km of 30 kV transmission lines are installed in the provincial grids plus 135 km of MV/LV lines and 94 km of LV overhead lines. Approximately 44% of the electricity produced is consumed by households. Small scale industries, hotels and larger industries use approximately 39% and commercial entities about 8%. The remaining 9% is consumed by government services and NAWEC [7].

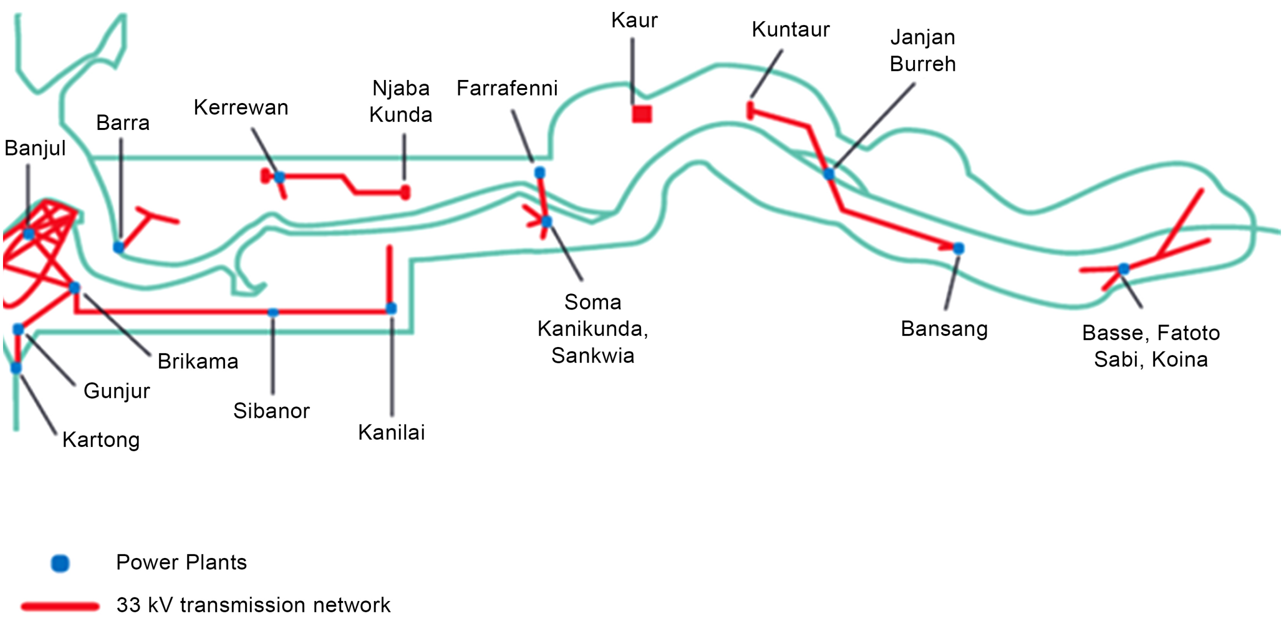

Figure 1. The Gambia electricity infrastructure.

2. Assessing the Demand

Chewel and Fuga are two neighbouring villages isolated from the main electricity networks. It is incumbent to examine the actual energy requirement for each household and systematically seek to reduce power consumption (watts) and the maximum coincident load. The benchmark is in fact the rate of consumption or power per hour (Wh). In comparison with the capacity of the batteries in ampere-hours (Ah), the rate of consumption is converted into the same unit. This reduces the risk of oversizing the installation. The energy demand of the locality has a direct correlation with some parameters such as the size of the photovoltaic modules required to charge the batteries, the capacity of the storage batteries required to meet the needs of the consumers without having to use a generator at night or on dark days and the conductor used in the distribution system. Improper dimensioning of the system makes it more difficult to cover the capital investment and recurring costs of the system and therefore to ensure system sustainability.

The Gambia has a good renewable energy (RE) resource, including considerable solar energy and some wind power along the coast. It also has a considerable land area classified as forest. A summary of the solar energy potential available in The Gambia is shown in **Figure 2**. It is based on the Renewable Energy Master Plan (REMP) drawn up in 2006.

The solar radiation data was collected through REMP at eight measurement stations spread across the country. The study concluded that The Gambia enjoys high solar radiation in all regions with average solar radiation at 4.4 - 6.7 $kWh/m^2/day$ as shown in **Figure 2**. The periods of high insolation are between March and May when the diurnal variation between the minimum and maximum radiation values is small. Even during the rainy season, much of the country receives sufficient amounts of solar radiation at about 5 $kWh/m^2/day$. However, the solar radiation range is considered to be higher because of cloud cover [1].

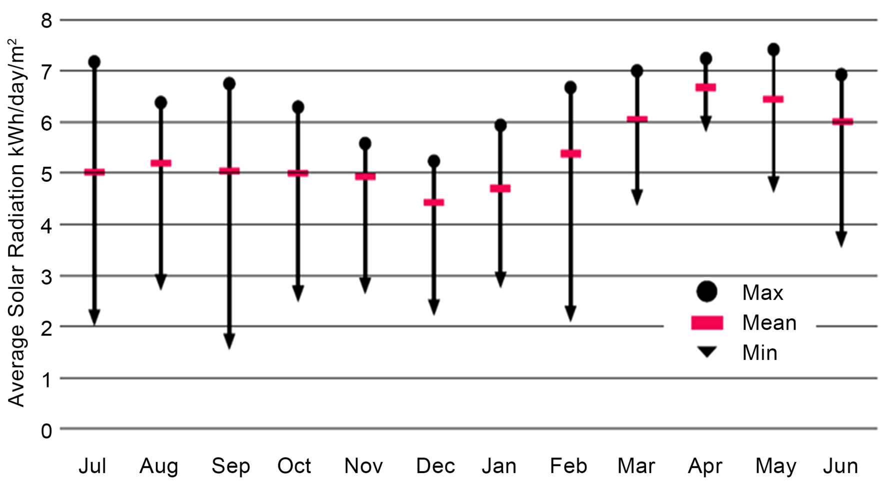

Figure 2. Solar radiation in the Gambia.

The typical load curve for a village is generally composed of a prominent peak in the evening corresponding to lighting loads, a morning/midday peak, and a base load. The base load is generally present in the morning, and in some cases extends to night hours. In many cases the peak load is two to five times higher than the highest power level of the base load. The energy demand in rural areas during night hours is quite limited (or non-existent in small villages) and hence the load level during the night is generally very low compared to the evening and morning peaks [8].

The daily electrical energy demand is the amount of electrical energy that is required by the consumers to be supplied by the solar PV electricity generation system. Daily energy demand is estimated by taking the ratings of electrical appliances that are used in a day and the time that they are used during the day or night time. The information then forms a load list which when multiplied by the duty cycle of each appliance provides the kWh consumed in a day. A tally of the individual appliance energy demands gave the estimated energy demand of the site under consideration. Domestic electrical load data was recorded from residents through oral interviews and physical inspection. The data collected for Chewel and Fuga is shown in **Table 1** and **Table 2** respectively.

Table 1. Domestic electrical load data for Chewel.

Appliance	Power (Watt)	Quantity	Hours per day	kW	kWh/day
Lamps (Energy Saving)	18	100	5	1.80	9.00
Radio	15	10	6	0.15	0.90
Television	100	5	6	0.50	3.00
Satellite receiver	20	5	6	0.10	0.60
Refrigerator	200	5	8	1.00	8.00
Laptop	100	3	5	0.30	1.50
Fan	75	10	5	0.75	3.75
Misc. (charging)	25	5	5	0.13	0.63
Total Daily Load				4.73	27.38

Table 2. Domestic electrical load data for Fuga.

Appliance	Power (Watt)	Quantity	Hours per day	kW	kWh/day
Lamps (Energy Saving)	18	150	5	2.70	13.50
Radio	15	30	6	0.45	2.70
Television	100	10	6	1.00	6.00
Satellite receiver	20	10	6	0.20	1.20
Refrigerator	200	10	8	2.00	16.00
Laptop	100	5	5	0.50	2.50
Fan	75	15	5	1.13	6.63
Misc. (charging)	25	5	5	0.13	0.63
	Total Daily Load			**8.11**	**49.16**

Chewel and Fuga are two adjacent settlements separated by a distance of less than a kilometer, located in the CRR of The Gambia with a combined population of about 130 inhabitants, and 32 households. The total combined power consumed by all appliances in the two settlements is estimated at about 12.84 kW, and the total combined energy consumed per day is almost 76.53 kWh.

3. System Dimensioning

After determining the amount of load required by the community, it is necessary to adequately size the other components of the PV system, notably the number of PV modules to be operating in parallel, the size of the storage battery bank and the transmission lines (mini-grid) for the expected loads. This step is critical to the success of the project because it has a significant impact on the project cost. Unnecessarily oversizing a PV system increases the cost that the community must cover, and can lead to wastage of resources. Under-sizing it will lead to consumer frustration and dissatisfaction with service quality, a dissatisfaction that can easily lead to the loss of consumers and consequent inability of the remaining consumers to cover costs.

Table 3 shows the average monthly solar irradiation for the locality of study [9]. The irradiance was calculated to be approximately 6.25 kWh/m^2/day for this location and the worst month is August with average irradiance of about 5.22 kWh/m^2/day. The angle of tilt for the PV modules is determined by multiplying the latitude (13.46˚) by 0.87, which gives 11.71˚. Here,

H_h: Irradiation on horizontal plane (Wh/m^2/day)

H_{opt}: Irradiation on optimally inclined plane (Wh/m^2/day)

H(11): Irradiation on plane at angle 11.7˚

I_{opt}: Optimal inclination (deg.)

Table 3. Monthly solar irradiation.

Month	H_h	H_{opt}	H (11)	I_{opt}
Jan	5430	6220	6070	41
Feb	6180	6790	6690	32
Mar	7440	7700	7680	18
Apr	7030	6870	6930	1
May	7070	6560	6700	−14
Jun	6420	5860	6010	−21
Jul	5890	5460	5580	−17
Aug	5350	5160	5220	−5
Sep	5660	5710	5730	10
Oct	6000	6410	6340	26
Nov	5550	6280	6150	38
Dec	5200	6060	5890	44
Year	6100	6250	6250	15

The main components of the PV system, presented in **Figure 3**, include the PV array, the battery storage bank (and the charge controller), the DC-AC inverter and the transmission lines (mini-grid) [10]. The switchgear consists of circuit breakers, fuses and switches (circuit protection devices) that function to protect, control and isolate the other components from possible damage. These components need to be properly sized for the system to work reliably and efficiently.

3.1. DC-AC Inverter Sizing

The DC-AC inverter is responsible for converting the DC voltage from the PV array or storage batteries to AC at the appropriate voltage level for consumption by the loads. To size the inverter, the possibility that all the loads may be turned on at the same time and run continuously is considered. This however, means that most of the time that the inverter is running, it is operating at a smaller load than its rated load [11]. Running the system at a lower load reduces the efficiency and consequently some energy is wasted.

$$\text{Inverter size} = \text{total load power} \times \text{oversize factor} \tag{1}$$

where;

oversize factor = 1.15

total load power = 12.83 kW

Inverter size =12.83 × 1.15 = 14.75 kW

Therefore an inverter size of 15.00 kW is chosen. The chosen inverter supplies loads connected to the mini-grid. The battery storage is charged with power from the PV array after passing through the switchgear that contains the charge controllers and system protection devices. The switchgear provides the logic for the power supplied to come directly from the PV array, when the batteries are fully charged during the day.

3.2. Sizing of the Storage Batteries

The capacity of the storage batteries needed depends on the requirements for the system to deliver uninterrupted supply, and the amount of money available to provide for this privilege. In most cases, it makes sense to provide sufficient storage capacity to ensure that electricity should be available for three to five consecutive days without sunlight [12]. However, batteries should not be completely

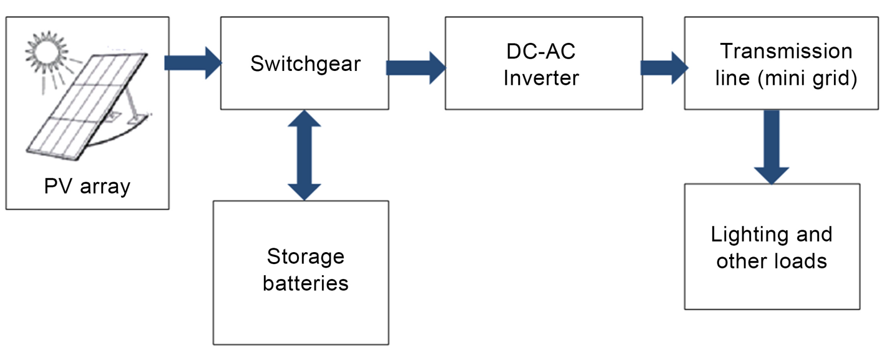

Figure 3. Typical PV system components.

discharged, as this reduces their useful life. Consequently, the installed capacity will be less than the nameplate rating. When the battery is supplying the inverter during poor weather or at night, the losses at the battery and inverter must also be taken into consideration in sizing battery storage.

On the other hand, the system voltage should be able to compensate for the voltage drop that occurs when discharging to the load as the current drawn by the load varies. The battery system design parameters are; daily energy demand, days of autonomy, battery safe depth of discharge, battery efficiency, inverter efficiency and the system voltage. The total design load is determined as that seen at the DC bus or the battery bank is given by the formula;

$$E_{tot} = \frac{E_{ac}}{\eta_{inv}} \quad (2)$$

where;

E_{tot} = total daily energy demand from the DC bus in kWh

E_{ac} = design daily energy AC load in kWh = 76.53 kWh

η_{inv} = average energy efficiency of the inverter [12] = 95%

To convert the average total daily energy into Ah, which is the usual unit used to measure battery capacity; the operating voltage of the batteries commonly referred to as the system voltage is considered. System voltages are generally 12, 24 or 48 volts and the actual voltage is determined by the requirements of the system. It is worthy of note that two or more batteries connected in series keep the same capacity as one of them and accumulate their voltage. Two or more batteries connected in parallel accumulate their respective capacity and keep the same voltage. Since the batteries and the inverter are usually a long way from the PV array, then a higher voltage of 48 V (four 12 V batteries connected in series) is chosen to minimise copper losses in the cables.

To convert watt-hours, E_{tot} to Ah, we divide by the battery system voltage, V_{dc} [13]. This means that the daily Ah demand will be:

$$\text{Daily Demand}\left(\text{Ah}\right) = \frac{E_{tot}}{V_{dc}} = \frac{80.55\ \text{kVAh}}{48\ \text{V}} = 1.68\ \text{kAh} \quad (3)$$

Battery capacity is determined by the ability of the battery to supply peak power demand. The critical design parameters include:

- Maximum Depth of Discharge, DOD_{max} = 70% (Specified by the battery manufacturer [13]).
- Number of Days of autonomy, T_{aut} = 3 (is the maximum number of days that the batteries can supply the daily demand assuming that there is no input from the PV array).

Therefore;

$$C_x = \frac{\text{Daily Demand} \times T_{aut}}{DOD_{\max}} \quad (4)$$

where C_x is battery storage capacity,

$$C_x = \frac{1.68\ \text{kAh} \times 3}{0.7} = 7.19\ \text{kAh}$$

$$\text{Discgarge Current} = \frac{\text{AC power}/\eta_{inv}}{\text{system voltage}} \tag{5}$$

$$\text{Discharge current} = \frac{12.83\ \text{kW}/0.95}{48\ \text{V}} = 281.25\ \text{A}$$

$$\text{Discharge rate} = \frac{\text{Daily Demand}}{\text{Discharge Current}} \tag{6}$$

$$\text{Discharge rate of battery} = \frac{7.19\ \text{kAh}}{281.25\ \text{A}} = 25.57\ \text{h}$$

The ambient temperature affects the performance of lead-acid batteries which are the most commonly used in PV systems. The storage capacity depends on the temperature of the batteries and even though care is taken to keep the batteries at the optimum temperature, it is always safer to make allowance for variations. In stand-alone PV systems special attention must be paid to the battery bank, which is often said to be the weakest component of the system and the highest contributor to its life cycle cost. If the temperature is lowered, the duration of use will increase but there is a risk of freezing [13]. The nominal capacity of a battery (which the manufacturer provides for 25˚C) increases with temperature at a rate of approximately 1%/˚C. A correction factor is therefore usually applied to the capacity as a function of temperature [13].

The lowest 24-hour average temperature for the year is 18˚C at Chewel and Fuga, and the correction factor at 25-hour rate obtained from [14] is 0.97. Therefore, the revised battery capacity would be:

$$\text{Battery capacity} = \frac{C_x}{\text{temperature correction factor}} \tag{7}$$

$$C_{36} = 7191/0.97 = 7413.40\ \text{Ah}$$

The number of parallel strings (N_p) is obtained as:

$$N_p = \frac{\text{overall battery bank capacity}}{\text{selected battery capacity}} \tag{8}$$

$$N_P = 7413.40\ \text{Ah} \div 200\ \text{Ah} = 36\ \text{batteries}$$

This number is rounded down from 37.10 for compatibility and symmetry.

The number of batteries in series (N_S) is determined by the system voltage divided by the voltage of the selected battery.

$$N_s = \frac{\text{load nominal voltage}}{\text{battery nominal voltage}} \tag{9}$$

$$N_S = 48/12 = 4\ \text{batteries}$$

$$\text{Total number of batteries}(N) = N_p \times N_s \tag{10}$$

$$N = 36 \times 4 = 144\ \text{batteries}$$

The batteries considered for this design process have a nominal voltage of 12 volts. The rated capacity is the maximum amount of energy that can be withdrawn from the battery. It is indicated in ampere-hours (Ah) or watt-hours (Wh).

Since the amount of energy that can be removed also depends on the time required for the process of extraction (the longer the process, the more energy can be obtained), the capacity is often indicated according to the discharge time. The nominal capacity for the battery used is 200 Ah, the efficiency is 90%, minimum state of charge is 40%, float life is 10 years and maximum charging current is 50 amperes. The storage capacity is proportional to power consumption; as power consumption increases, so does storage capacity. The depth of discharge as well as the recommended voltage of the system, are constant coefficients.

3.3. Sizing the PV Array

It is essential to consider the nominal voltage of the system against the nominal voltage of the panels [13]. The panels have to be connected in series/parallel combinations to give the nominal system voltage. For example, if the system works at 48 V as previously decided, and the panels are 24 V each, groups of two panels in series must be connected in parallel. Any renewable energy source of electricity must be oversized to ensure that the battery can be recharged from maximum depth of discharge in an acceptable period while still meeting the daily load requirements [13].

The worst month is determined by considering the month during which the ratio of PV array output to load energy consumption is the smallest. From **Table 3**, the average monthly solar irradiance is 6.25 $kWh/m^2/day$ for the site under consideration and the worst month is August with an average irradiance of 5.22 $kWh/m^2/day$. When designing a PV system that will meet a specified amount of energy, the PV array must produce at least that amount of energy required to supply the peak load, while allowing for charging of the battery as well as derating of the PV modules [12]. The maximum irradiation depends on the tilt angle and orientation of the PV array. The tilt angle for maximum irradiation coincides with the latitude of the geographical location. In this case the latitude is 13^0 and the modules should be orientated to face the equator.

The PV array is derated due to certain factors such as manufacturer's tolerance, dirt or dust cover and temperature effects. The manufacturer's tolerance for most modules is usually within the range of ± 3%. Over a period of time dirt such as dust cover or salt (if the installation is near the coast), can build up on the array and decrease the output. During the design process, the output of the module should therefore be derated to take into account this soiling. In this paper, the value of the derating factor is assumed to be approximately 0.93.

The operating temperature of a PV module has a strong impact on its voltage and therefore on its performance. The operating temperature depends on many factors related to the module manufacturing process, the semiconductor used, the location of the module and the assembly of the module at that location [15]. Module output power decreases with temperature above the ambient temperature of 25˚C and increases with temperatures below 25˚C. The average cell temperature is always higher than the ambient because of the glass on the front of the module. The output power and/or current of the module must therefore be based on the effective temperature of the cell.

The peak power (P_{peak}) of the photovoltaic installation is defined as the expected daily energy consumption divided between the peak solar hours and the expected performance of the PV array (η_{pv}). If we wish to design a system that can operate for three days even if there is no sunshine, we need to multiply the maximum daily energy consumption by three. The necessary parameters for the PV module include the maximum voltage, the maximum current and the maximum power. These parameters are usually given by the manufacturer for a temperature of 25˚C.

$$P_{peak} = \frac{E}{H_p \times \eta_{pv}} \tag{11}$$

H_p corresponds to the average daily solar irradiation of the geographical area under study in peak sun hours. This is multiplied by a factor depending on the inclination of the panels. However, to be conservative, the irradiation rate of the most restrictive month (typically August in Chewel and Fuga) is often used. The total daily energy demand for the two villages from **Table 1** and **Table 2** is about 76.54 kWh. The performance of the panels is generally about 95%. The number of modules required will be the result of dividing the peak power (P_{peak}) of the installation by the rated power (P_{mod}) of the solar module:

$$N_{\text{mod}} = \frac{P_{peak}}{P_{\text{mod}}} \tag{12}$$

To be more precise, besides the performance of the solar panels, a little margin for temperature effects can be considered (l, typically 5%). Combining these formulas and considering the efficiencies of the different sub-systems with the derating factors we obtain an overall efficiency of 0.83 for the PV array system.

$$N_{\text{mod}} = \frac{E*(1+l)}{P_{\text{mod}} * H_p * \eta_{pv}} \tag{13}$$

where,

l = temperature effects coefficient

E = total daily design energy demand from the DC busbar

η_{pv} = efficiency of the PV sub-system

P_{mod} = rated module output power

The derated output obtained from the Neety Euro Asia Solar Energy (NEASE) PV module was 108.6 watts [6]. Putting all these values into Equation (13), the number of PV modules is obtained as 256. It is essential to consider the nominal voltage of the system against the nominal voltage of the panels. The panels have to be connected in series/parallel arrangement to give the nominal system voltage. For this case with a system voltage of 48 V and PV module rated voltage of 24 V, two panels are connected in series for each string, giving a total of 128 strings connected in parallel to give 256 PV modules calculated for this system.

3.4. Sizing the Switchgear System

The switchgear system which contains the charge controller and other switching and protection devices, is normally sized so that it is capable of carrying at least 125% of the array short circuit current and to withstand the open-circuit voltage of the PV array. If there is a possibility that the array could be increased in the future, then the regulator is oversized to cater for future growth. The PV output power is obtained from Equation (11) as 35.8 kW. Considering a rated current per module of 3.05 A, the short circuit current for the PV array becomes 390 A, while the open-circuit voltage is 48 V. So the fuses and circuit breakers in the switchgear system must be rated at least 400 A/60 V.

The DC-AC inverter converts the DC power from the batteries or PV array at 48 V to AC power at 220 V. The system uses power electronic devices (such as thyristors) and a center-tapped step-up transformer rated at 20 kVA to produce a nearly pure sine wave power output, required by the loads. The transformer output is fed directly to the transmission lines. The charge controller controls the charge from the PV array and in discharge cuts off the DC receivers using blocking diodes if the battery goes down to low voltage. The DC-AC converter is wired to the battery through the switchgear.

3.5. System Layout

The dimensioning of a PV installation is the search for a balance between the satisfaction of the expressed energy demand and the power to be installed both from the PV modules and the batteries. From the controls presented by the suppliers of the PV components, the components are selected and adapted to the dimensioning. Other configurations of installations would be possible with other modules, batteries, regulators and inverters.

When all the design aspects discussed above have been completed, the distribution system can be laid out. This involves the location of the powerhouse, the placement of the transmission lines, and the choice and location of poles. Village power systems relying on mini-grids need to be sustainable and with replicable designs for conditions found in villages [16]. There is a need to review the specific needs and to use the most cost-effectively methods to address these needs. The location of the installation has to be decided. There are some important points that must be taken into account.

From a social point of view, it is better not to install the system too far away from households and families to protect it from acts of vandalism, and to integrate it into the community. Throughout the day the surface of the panels should not be in shadow. In case of obstacles, a deviation from its orientation towards the equator is tolerated, up to 20˚ east or west [15]. It is also essential that some panels do not cast shadows on others. The shaded part of a panel does not create energy but dissipates it, with a significant increase in temperature. The batteries should be placed in an enclosure or in a covered, well-ventilated room, as they are sensitive to humidity and temperature variations. Finally, the layout of the various elements of the installation must be such that the wiring is as simple and as short as possible. This reduces the cost of the installation and minimizes energy losses as well.

For the Chewal/Fuga case presented in **Figure 4**, two conductors from the powerhouse serve the entire community at a voltage set at 220 V. To ensure a system that can easily be maintained and for which construction materials and consumer appliances can readily be found locally, this voltage is chosen to coincide with the standard in use in the country.

The powerhouse is located in the middle of the load center, so that single-phase lines take off from there in several directions. The mini-grid is comprised of a pair of conductors that pass by each consumer and the service drop simply taps both of these lines [16]. The two settlements, shown in **Figure 5** are located at about 13˚26'4'' North and 14˚39'26'' West, in the CRR of The Gambia.

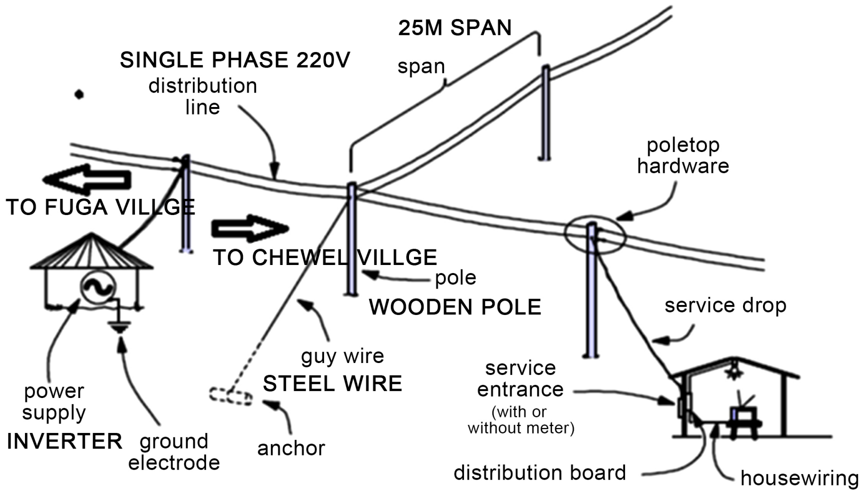

Figure 4. Chewel/Fuga mini-grid layout.

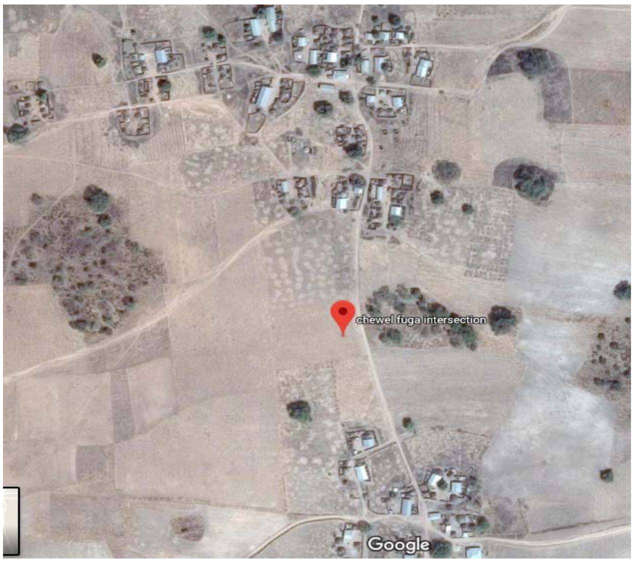

Figure 5. Satellite photo of Chewel and Fuga villages.

In protecting the system against lightning discharges in the vicinity of a transformer or distribution line, commercially available lightning arresters are installed. These normally come with a weatherproof enclosure, connection leads, and a mounting stud or bracket. They are connected to the distribution line (or transmission line), and should be close to the equipment or accessory requiring protection, such as just outside the powerhouse or the service entrance.

4. Economic Analysis of the System

The economic analysis of an energy production system provides two types of information: the updated costs of the system and the annual costs it generates. In our calculations, the choice of the economic lifetime is linked to the fact that the estimated lifetime of the PV modules is about 20 years. These cost estimates shown in **Table 4** do not include the mini-grid components such as poles, transmission line cables, etc. PV module prices have declined dramatically and, under some circumstances, PV is now cost-competitive with incumbent technologies [17]. Battery prices usually constitute 40% of the total system cost. The main concern of the population of these two villages is to have an electricity system that provides them with a minimum level of comfort at the lowest possible cost. A heavy investment is neither justified, nor major costs.

The design process begins by enumerating the important input data that demonstrate the technical specifications, resources and the costs which are relevant for designing the entire system in Hybrid Optimization of Multiple Energy Resources (HOMER) software. The following data were used as inputs for modelling the mini-grid PV system using HOMER tools.

- PV array size of 15 kW, with a capital cost of $38,400, replacement cost of $15,000 and the maintenance together with operating cost per year assumed to be $50.
- A peak load demand of 9 kW, and an average daily energy demand of 44 kWh/day, with a load factor of 0.202.

Table 4. System components cost estimation.

Component	Quantity	Unit price ($)	Total price ($)
PV module	256	150	38,400
Battery	144	365	52,560
Inverter	3	3519	10,557
Charge controller	4	520	2080
String combiner	4	392	1568
Circuit breaker	12	34	408
Total	-	-	105,573
Cables and wiring	10%		10,557
GRAND TOTAL			$116,130

- Solar irradiance of 5.610 kWh/m^2/day, a clearness index of 0.534 and the average temperature of 30.2˚C.
- The selected battery is 6FM200D of 12V with a nominal capacity of 200 Ah and an efficiency of 90% and capital cost of $365. The approximated replacement cost and O&M costs for one unit of this battery have been assumed as $365 and $50/year, respectively.

The main factors that were considered in this design include the solar resource that indicates the clearness index as well as the average daily radiation for each month based on latitude and longitude, the PV array, the average primary load, the battery type, the converter type, the AC and DC buses.

The analysis was done for different PV sizes using HOMER software as shown in **Figure 6** and a specific system of 15 kW capacity was chosen to be optimum since it is more economical and reliable in terms of cost and availability of the supply. **Figure 7** shows the cash flow analysis.

It uses a PV system of 15 kW capacity with an inverter of 15 kW and a total of 96 batteries at 4 batteries per string. The total NPC calculated by HOMER is equivalent to $164,192 and the Levelized Cost of Energy (COE) as well as the cost of operation, are $1.060 per kWh and $4303 per year respectively. The simulation results also detail the cash flow summary, as depicted in **Figure 8**, indicating the Capital, Replacement, Salvage, Operation and Maintenance costs. **Figure 8** illustrates the initial capital cost within the first year of $164,192, a fixed operating cost of $4303 per year, the first replacement cost of the inverter in the fifth year, and the first replacement cost of the battery in the tenth year. It also indicates zero fuel cost since the system is purely operated on PV. The electricity production results shown in **Figure 9** closely mimic the input global horizontal radiation of the location, with the highest production in the months of January and February, and the lowest in the months of July and August in the rainy season.

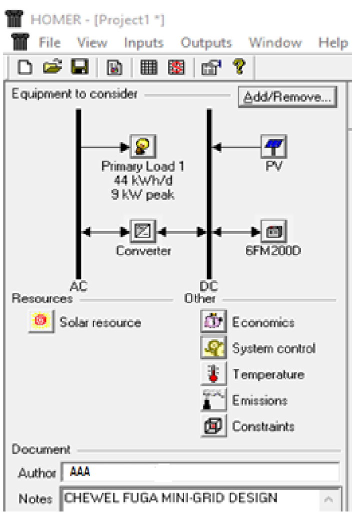

Figure 6. HOMER Inputs window, for modelling a 15 kW PV system for Chewel and Fuga villages.

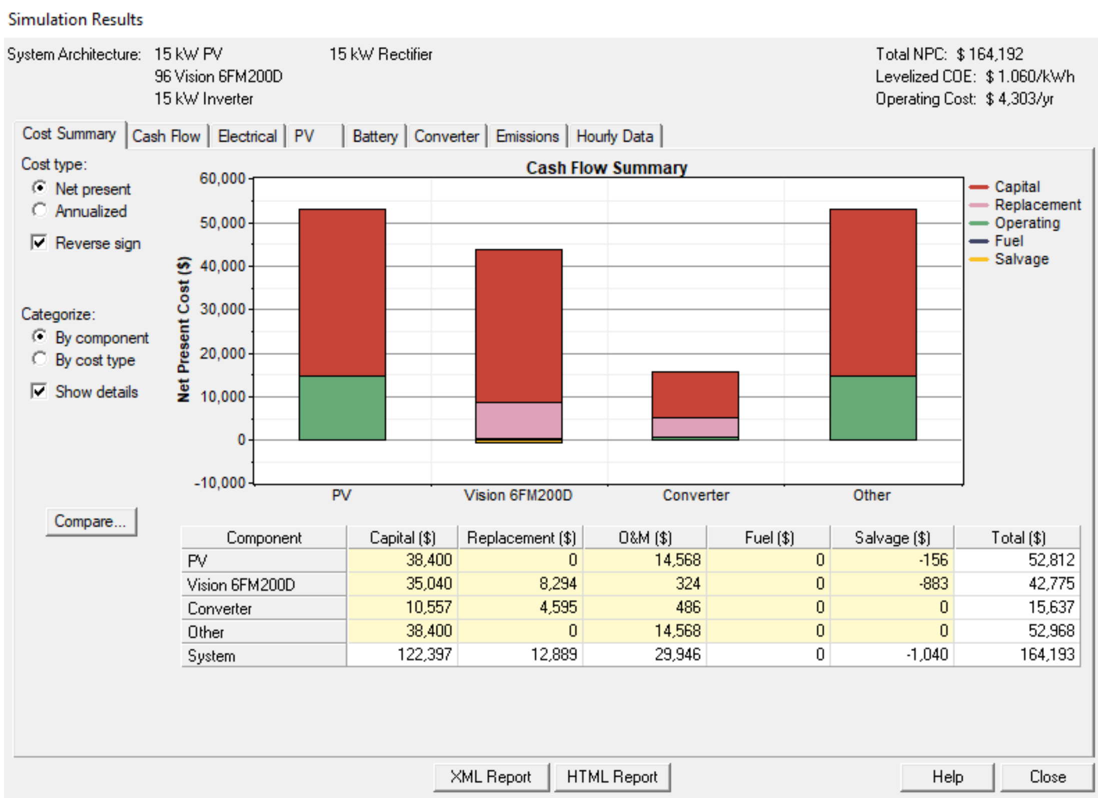

Figure 7. Simulation results showing cash flow summary and Net Present Cost (NPC).

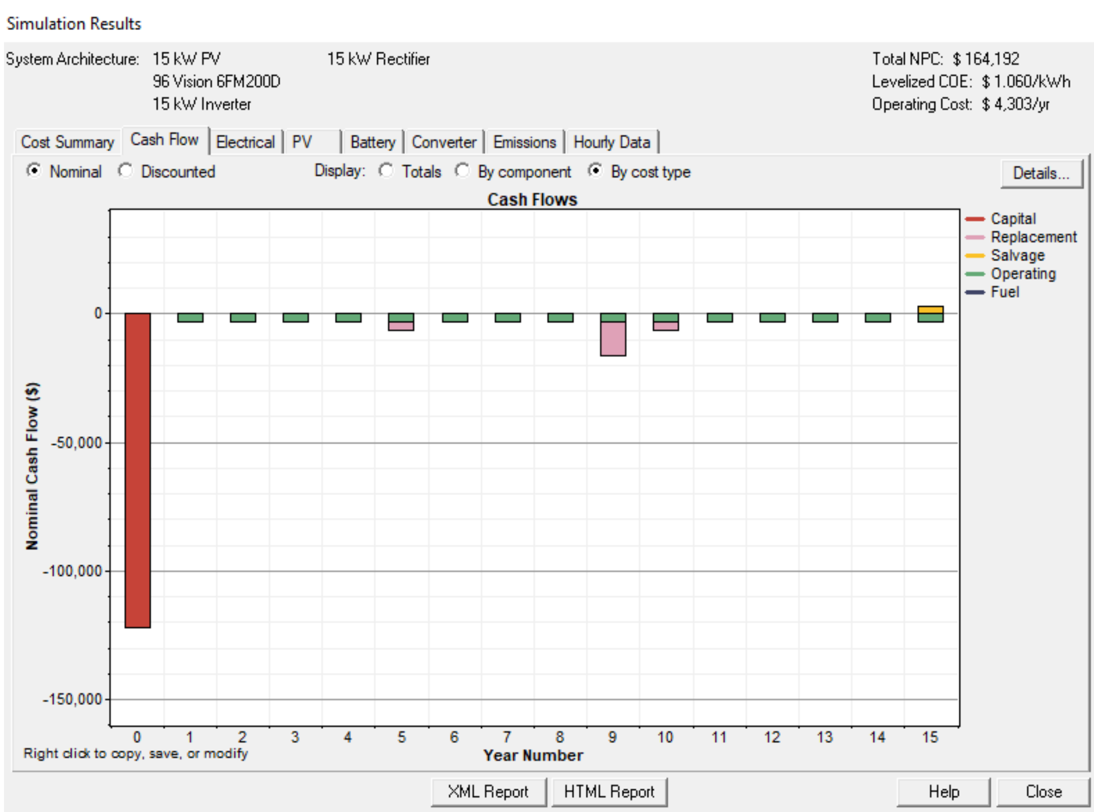

Figure 8. Cash flows results.

Figure 9. Average monthly electricity production results.

The battery bank state of charge results in **Figure 10** shows that between midnight and 9 am, the state of charge is between 76% and 88%, from 10 am to 11 pm the state of charge is above 90%. The frequency histogram shows that a 90% state of charge occurs above 35% of the time within the month. This result is significant because it shows that the battery's minimum depth of discharge is respected, which increases the life span of the batteries.

Figure 11 shows the inverter output results, which indicate that the peak output of the inverter is about 7.2 kW and the average daily output is 5 kW during the day from 9 am to 6 pm.

5. Discussion

The aim of this work was to design and analyse the use of a PV system to produce electrical power to ameliorate the electricity need in Rural Gambia. The design was based on a typical load profile of two neighbouring villages in the CRR of The Gambia. These villages are not connected to the national electricity grid and most of the population does not have access to electricity. This region of the country receives a large amount of sunlight with an annual average solar radiation of 6.16 kWh/m^2/day, and an average temperature above 31˚C. The average daily load demand for Chewel and Fuga is estimated to be about 27.375 kWh/day for a peak load of 4.725 kW and 49.150 kWh/day for a peak load of 8.100 kW respectively.

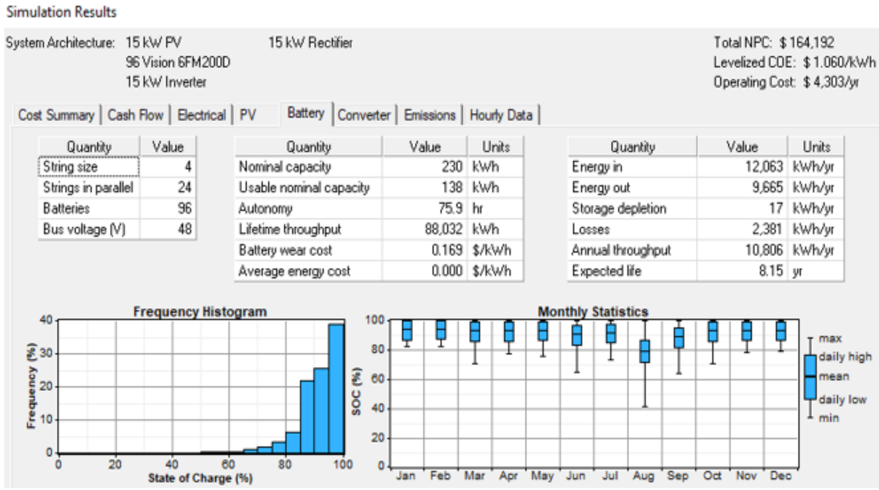

Figure 10. Battery bank state of charge results.

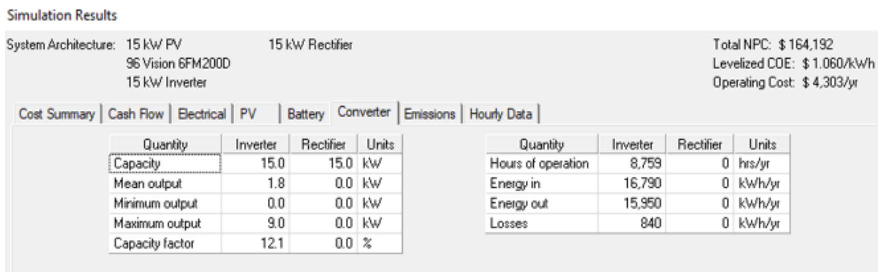

Figure 11. Inverter output results.

The overall system was designed with the above data which was used as inputs to the HOMER Software. The simulation results show a PV system of 15 kW capacity with an inverter of 15 kW and a total of 96 × 12 V batteries at 4 batteries per string. The total Net Present Cost (NPC) calculated by HOMER is equivalent to $164,192. The Levelized Cost of Energy (COE) as well as the cost of operation is $1.060 per kWh and $4303 per year respectively. The simulation results also show the cash flow summary which indicates the Capital, Replacement, Salvage, Operation and Maintenance (O&M) costs.

6. Conclusions

This work has shown that a PV system can be used in a sustainable way to produce electrical power to supply electricity to the two communities of Chewel and Fuga in Rural Gambia. This was done by considering the global horizontal radiation at the selected site and by considering the domestic load obtained during a site visit in September, 2019. An evaluation of the climate data as well as the potential of renewable energy resources available in that area, was used to design the most cost-effective and feasible solution to the electricity needs of the entire community. The method of gathering climate data and solar resources has been a useful approach to understand where this system can be most suitable, in other areas of Sub-Saharan Africa [18].

The system was modelled in HOMER software, and simulations were conducted to determine the best system configuration that would be more economical and reliable for supplying power to these rural areas by predicting the increase in load demand and consumption over time [19] [20]. As shown by the HOMER simulation results, the use of photovoltaic technologies for electricity production and supply is both feasible and sustainable. If this design is implemented, it will be a solution for the population in these villages which are not connected to the national electric grid. It has also been proven that in addition to being one of the most abundant renewable energy resources available in The Gambia, Solar PV energy is indeed a good alternative for electricity generation due to its low maintenance cost and independence from the main electricity grid, [21] [22]. The results obtained for these two settlements in the Gambia are good enough and can be replicated in most isolated settlements in Sub-Saharan Africa.

Statement on Funding and Data Availability

The authors did not receive any funding for this work; carried out as routine research expected of the authors at their various institutions. The data used to support the findings of this study and presented in the tables and figures which are available for public consumption was obtained from publicly available sources and referenced accordingly.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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