Design and Economic Viability Analysis of a Solar Photovoltaic Based Microgrid for an Off-Grid Community in South-Western Nigeria

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ABSTRACT

Access to electricity in rural Nigeria is only about 36% and extension of the conventional grid is faced with challenges that make these communities difficult to connect. There is need for alternative ways of powering rural areas; and this paper provides the design of a solar powered microgrid for a village in south-western Nigeria. A typical Solar PV microgrid is composed of: Solar Panels, Charge Controllers, Inverters, Battery Bank, Distribution Grid, Meters, and Cables. The design is a process of determining capacity (in terms of power, voltage and current) of each of these components to meet the load requirement. The economic viability of this design was conducted with Hybrid Optimization of Multiple Energy Resources (HOMER) software. This provided the Net Present Cost (NPC), Initial Capital and Levelized Cost of Electricity (LCOE). The site was inspected and found to be suitable for a solar PV microgrid. The annual average Global Horizontal Irradiance is 4.85 kWh/m2/day, average daily energy demand was estimated as 167kWh. A total of 157 solar modules (Foresolar 300W), 7 solar controllers, battery bank of 114 (200AH) batteries and 20kW of Inverter capacity are basically required. The NPC from the best result is $600,340; the initial capital is $326,224 and the LCOE is $0.24/kWh. This design can provide adequate electricity for this case-study location. However, the LCOE of $0.24/kWh is far more expensive than the currently subsidized residential cost of grid electricity which is $0.07/kWh. Deploying this full-scale microgrid as designed is not economically viable for this location at this time. However, smaller versions of solar PV solutions for basic lightning and charging of small devices could be economically deployed.

Keywords: Design, Economic Viability, Analysis, Solar Photovoltaic Based Microgrid, Off-Grid Community, South-Western Nigeria

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1. INTRODUCTION

According to the U.S. Power Africa fact sheet on Nigeria, access to electricity in rural Nigeria is only about 36% (Power Africa fact sheet on Nigeria (2018) Access to energy, especially in rural communities, represent a central pillar of development and the correlation between access and a wide range of social goods is overwhelming. Most of the rural settlements in the oil-rich Niger Delta, along Nigeria's international boundaries, in the mountainous areas of northern Nigeria and in remote locations from their state capitals are not connected to the National Grid and do not have access to electricity (Kelech et al., 2014). Electricity in the rural areas in Nigeria can be provided via grid and non-grid energy sources. However, several challenges often make the extension of the national grid very difficult, and this necessitates the consideration of alternatives. This paper presents the design and economic viability analysis of a solar photovoltaic based microgrid for a rural community in south-western Nigeria. This is a typical rural community which is not connected to the grid and it is a representation of other rural communities.

Solar photovoltaics entail the process of converting sunlight directly into electricity. Nigeria is located between 4∘N and 14∘N latitude and hence receives a vast supply of solar energy all year round (Osinowo et al., 2015). Due to increased efficiency, decreasing cost and increased environmental concern, photovoltaic installations have increased dramatically in recent years. The U.S. Department of Energy Microgrid Exchange Group defines a microgrid as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [4]. A microgrid can connect and disconnect from the grid to enable it operate in both grid-connected or island mode. A solar microgrid is a small-scale solar powered grid that can operate independently to supply energy for limited number of consumers as in a village or a hamlet. It generally consists of a solar PV array, a battery bank, charge controller or control system, inverter, cables for power distribution and safety devices. The requirement and size of a microgrid is calculated by adding the power needs of individual homes in the community that is to be powered.

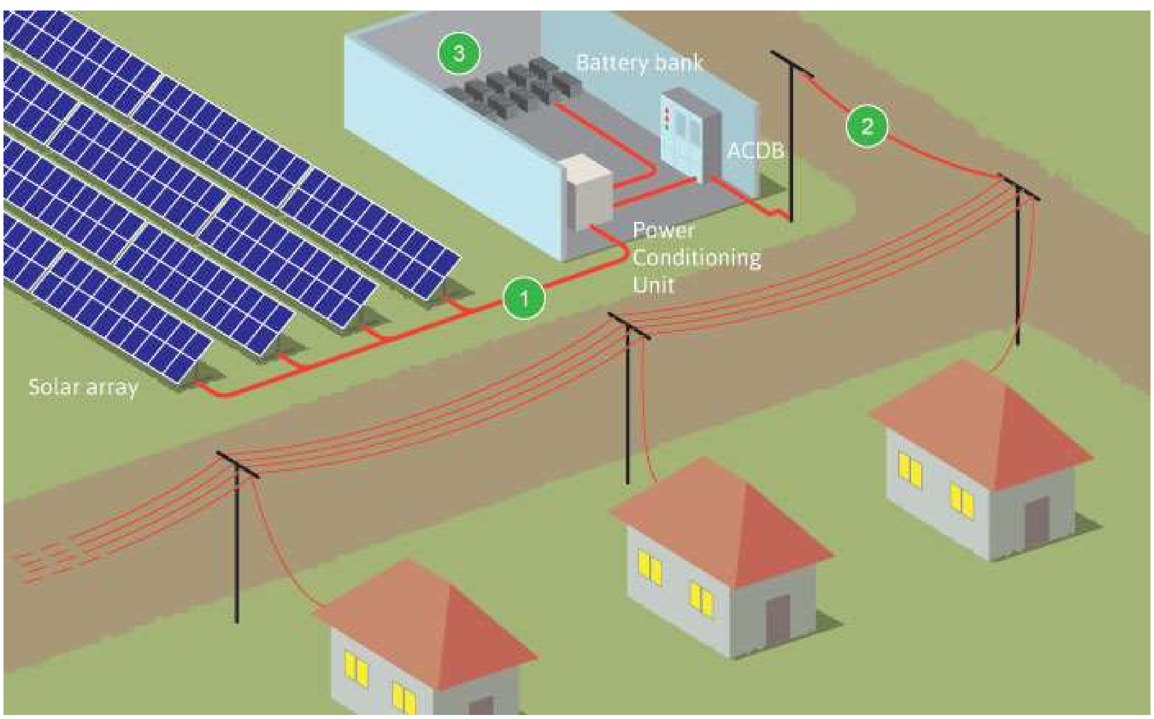

Figure 1: Schematic a Solar PV microgrid (www.krishitechnologies.com)

There are several costs associated with solar PV deployment. U.S. National Renewable Energy Laboratory lists the following categories as benefits for solar PV; electricity generation and capacity, transmission and distribution (T&D) cost deferrals, reduced line losses, fuel cost hedging, emissions reductions and associated health benefits. Costs of solar and other DER technologies include the initial capital and debt financing costs, operations and maintenance (O&M), interconnection and grid integration, which vary depending on the degree of DER penetration into the existing electric grid. There are different computer applications that can aid in designing and economic evaluation of solar PV microgrid. (Yousif et al., 2012) designed and simulated a grid connected PV power plant using HOMER software. (Oladeji et al., 2015) also used HOMER to size and simulate a Solar PV stand-alone system for the National Centre for Hydropower Research and Development (NACHRED) in Ilorin, Nigeria

(Ghasem et al., 2016) used the Non-Dominated Sorting-based Hybrid Cuckoo Search Optimization (NSHCSO) software to optimally design a Renewable Energy based microgrid involving Solar PV, Wind Turbine and Storage batteries. Distributed Energy Resources – Customer Adoption Model (DER-CAM) is also used in microgrids. It is a powerful and comprehensive decision support tool that primarily serves the purpose of finding optimal distributed energy resource (DER) investments in the context of either buildings or multi-energy microgrids.

NOMENCLATURE

AC	Alternating Current
DC	Direct Current
E_d	The daily average energy demand
V_{dc}	AC voltage of the system
T_{shd}	Average sun hours of the site per day
E_d	The daily average energy demand (watt-hours)
I_{dc}	Total DC current
I_{rcc}	Required charge controller current
I_{oi}	Inverter output current
P_{KVA}	Inverter output power
B_{Ah}	Energy storage capacity of the battery bank
DoD	Depth of Discharge of the battery
HOMER	Hybrid Optimization of Multiple Energy Resources
NPC	Net Present Cost
LCOE	Levelized Cost of Electricity
PV	Photovoltaic

2. DESIGNING THE SOLAR PV MICROGRID

A solar PV powered microgrid is a viable energy solution anywhere with reasonable solar irradiance. As Nigeria is located close to the equator, solar energy remains a major energy source. The figure below shows the Photovoltaic power potentials in kWh/kW$_{peak}$ in different parts of Nigeria.

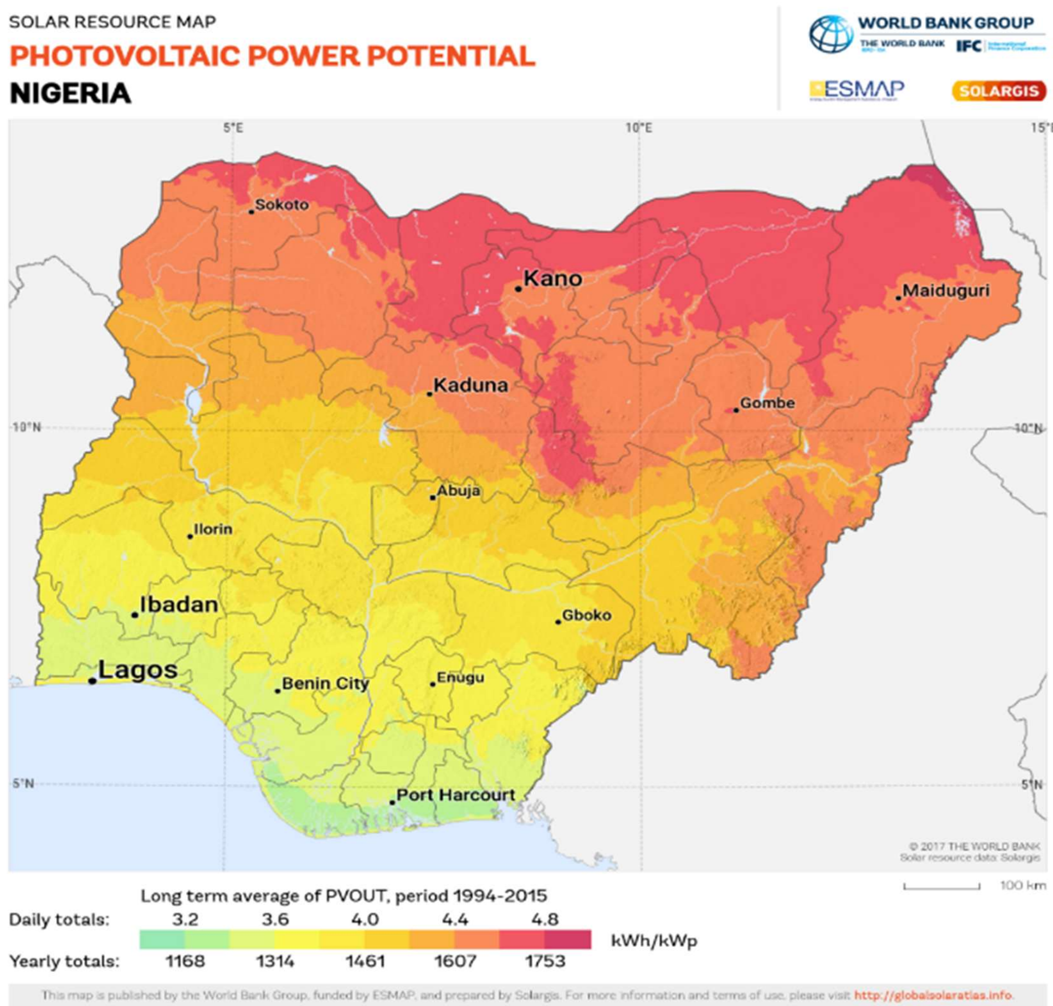

Figure 2: Map of Photovoltaic Power Potential in Nigeria

Solar PV microgrid systems are custom designed for their particular situation. However, in a typical Solar PV powered microgrid, the following components and equipment are needed:

- Solar Panels
- Charge Controllers
- DC/AC Inverters
- Battery Bank
- Distribution Grid
- Meters
- Cables (DC & AC)

2.1 Design Methodology

PV system design is a process of determining capacity (in terms of power, voltage and current) of each component of a stand-alone photovoltaic power system with the view to meeting the load requirement of the residence for which the design is made (Abhik et al., 2015). The case study in this paper is Jato village, Oyo State, Nigeria. The method adopted for this design entails 9 steps.

Step 1: Site inspection and radiation analysis

Site inspection entails a number of activities aimed at ascertaining the physical suitability of a location for solar PV microgrid. Shadow analysis is important as it will help to find out the time duration for which solar radiation falls on solar arrays. Solar irradiance is basically the power per unit area received from the sun in form of electromagnetic radiation. This varies with time of the day, location, season and weather condition. Therefore, the design of stand-alone solar system cannot have only one standard. Location is a major influence in photovoltaic power system design, and specifications of PV systems therefore vary from place to place. An important step in the planning and design of a solar PV system is to acquire the solar resource data for the site because the amount of electrical energy that can be generated depends on the radiation intensity throughout the year for the location.

Step 2: Estimation of Load Requirement

Here, the load requirement and energy consumption is determined/estimated. For a typical *existing* facility, the load profile is determined by listing all the residential applications with their power ratings and hours of operation at different seasons to obtain the total average energy demand in Watt-Hours. However, in estimating the energy consumption of this community, it is necessary to have an idea of the population and number of households in order to project how much energy would be consumed per time. According to the IEA, annual per capita electricity consumption in Nigeria was 140 kWh in 2015, or roughly 12 kWh per capita per month. The National Bureau of Statistics' per capita household electricity consumption estimate for Southwest Nigeria is 23kWh/month. (Olaniyan et al., 2018) estimated per capita household electricity consumption based on two approaches: the appliances approach; and the expenditure approach. The two approaches gave a median of 30kWh and 26kWh respectively as per capita residential electricity consumption for Southwest Nigeria [8].

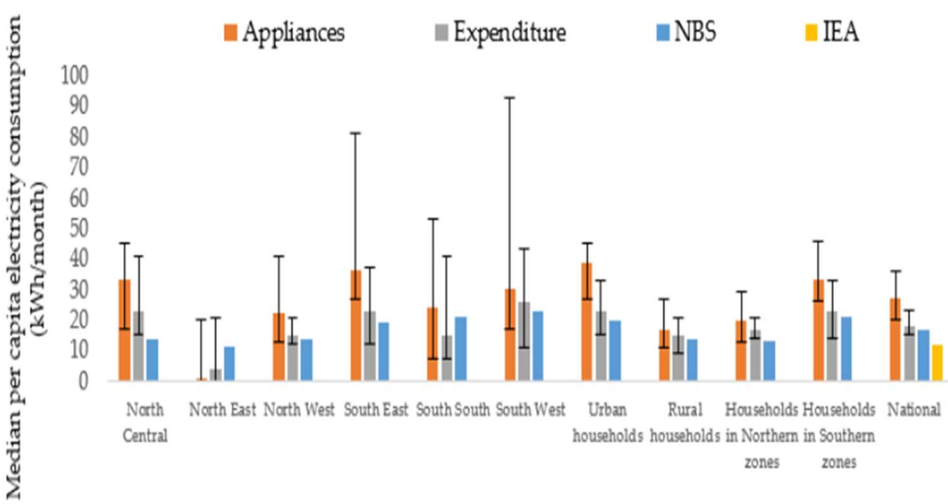

Figure 3: Chart showing per capita energy consumption in Nigeria.

For the purpose of this work, a monthly per capita electricity consumption is used. It is Divided by 30 to get the daily per capita electricity consumption (E_{pc}). The population is also estimated by multiplying the number of households by the average number of inhabitants per house. The *daily average energy demand* (E_{daily}) to be used will therefore be a product of the daily per capita energy consumption and the estimated population of the community.

$$E_d = E_{pc} \times Population \text{ -------------------- (1)}$$

Step 3: Choice of System voltage

For buildings, once the load is determined, DC Voltage of the PV system has to be fixed. Generally, it is taken as high as possible so that less current will be required to meet the high energy requirement. Lower current through cables will reduce electrical energy loss, because cable has resistivity and high current will cause joule heating of cable. Otherwise, much thicker wires are required which will increase cost of the system.

Step 4: Determine Capacity of Solar PV array

The Solar PV array is the main component of a stand-alone PV system. It is the combination of solar modules. The PV modules are connected in series (string) to obtain the required system voltage. The strings are then connected in parallel for the array to produce the desired current.

To determine the size of the PV, the following vital information should be known:

- The DC voltage of the system (**V_{dc}**)
- The average sun hours of the installation site per day (**T_{shd}**)
- The daily average energy demand in watt-hours (**E_d**)

The required daily average Energy demand should be determined for accurate PV sizing. This is given by:

$$E_{rdd} = \frac{E_d}{\varepsilon_b \varepsilon_i \varepsilon_c} \text{ --------------------------------- (2)}$$

Where: ε_b = battery efficiency; typically, about 85% for lead acid battery
ε_i = inverter efficiency
ε_c = controller efficiency

The average peak power which is obtained by dividing the required daily average Energy demand by the sun shine hours per day is given as:

$$P_{ave,peak} = \frac{E_{rdd}}{T_{shd}} \text{ ------------------------------- (3)}$$

The total dc current is then given as:

$$I_{dc} = \frac{P_{ave,peak}}{V_{dc}} \text{ ------------------------------------ (4)}$$

The number of modules in in a string/series (N_{sm}) is obtained by dividing the system dc voltage (V_{dc}) by the rated voltage of each module (V_{rm}):

$$N_{sm} = \frac{V_{dc}}{V_{rm}} \text{ --- (5)}$$

The number of module strings in parallel (N_{pm}) can be obtained by dividing the total dc current (I_{dc}) of the system by the rated current (I_{rm}) of one module as given below:

$$N_{pm} = \frac{I_{dc}}{I_{rm}} \text{ --- (6)}$$

The total number of modules (N_{tm}) that form the array is determined by multiplying the number of modules in series by the number of parallel modules as shown below.

$$N_{tm} = N_{sm} * N_{pm} \text{ ------------------------------ (7)}$$

Step 5: Charge controller specification
The solar charge controller is generally sized in a way that will enable it perform its function of current control. A good charge controller must be able to withstand the array current and must be designed to match the voltage of the PV array and that of the battery bank. MPPT charge controller is specified based on PV array voltage handling capacity.

The charge controller sizing is done in a way to ensure that it is able to withstand the product of the total short circuit current of the array and a certain safe factor (F_{safe}). The safe factor is necessary in order to allow for a reasonable system expansion. Thus, the required charge controller current is given as:

$$I_{rcc} = I_{sc}^{m} \times N_{pm} \times F_{safe} \text{ ---------------------(8)}$$

Where: I_{sc}^{m} is the short circuit current of selected module
F_{safe} is Factor of safety; usually taken as 1.25

Required number of charge controller is obtained as in the equation below:

$$N_{cc} = \frac{I_{rcc}}{I_{cc}} \text{ ------------------------------------(9)}$$

Where I_{cc} is the current specification of selected charge controller

Step 6: Inverter capacity determination
An inverter is rated by its output power (P_{KVA}) and DC input voltage (V_{dc}). Power rating of the inverter should not be less than the total power consumed in different loads. On the other hand, it should have the same nominal voltage of battery bank that is charged by solar PV module. In a household, consumption of power in appliances can be classified into two categories: resistive power (P_{res}), such as in light, heater, iron, etc., and inductive power (P_{ind}), such as in fan, motor, etc. Typically, capacity of the inverter is taken to be the sum of all the loads running simultaneously and 3.5 times the total power of the inductive loads to take care of surge protection.

Further, the obtained value is to be multiplied by 1.25 to get the requirement, if an option of 25% extra is kept for a reasonable future load expansion. We get the power (P_{inv}) that should be deliverable by inverter as follows:

$$\boldsymbol{P_{inv} = 1.25(TP + 3.5P_{ind})} \text{ --------------- } \quad (10)$$

Where P_{ind} is Power of all inductive load with high surge current

TP is Power of all loads running together ($TP = P_{res} + P_{ind}$)

Power rating of inverter is related to the real power that is delivered by inverter as output by the power factor as given by the following expression:

$$\boldsymbol{P_{KVA} = \frac{P_{inv}}{PF}} \text{ ----------------------------------- } \quad (11)$$

Power factor is usually taken as 0.8

Step 7: Battery capacity determination

The battery type generally considered for use in solar PV power system application is deep cycle battery, specifically designed such that in an event it is discharged to low energy level, it can still be rapidly recharged over and over again for years. The battery should be large enough to store sufficient energy to operate all loads in all the seasons of the year and in night, cloudy, rainy and dusty days of the month. Battery storage is conventionally measured in Ah (ampere-hour). The energy storage capacity of the battery bank (B_{Ah}) is determined by the daily energy requirement and required number of backup days (N_{backup}) using the following equation

$$\boldsymbol{B_{Ah} = \frac{E_d \times N_{backup}}{\varepsilon_i \varepsilon_b V_{dc} \times DoD}} \text{ ---------------------------- } \quad (12)$$

DoD is Depth of Discharge of the battery which is the percentage of the battery that is allowed to deplete before recharging.

In order to meet the energy demand as outlined above, a number of batteries have to be connected in series (to meet system voltage specification) and in parallel (to meet current specification).
The number of batteries connected in series (N_{BS}) is obtained by system DC voltage and voltage of individual battery using the equation,

$$\boldsymbol{N_{BS} = \frac{V_{dc}}{Voltage\ of\ single\ battery}} \text{ --------------- } \quad (13)$$

The number of batteries which will be connected in parallel (N_{BP}) can be obtained by the equation below,

$$\boldsymbol{N_{BP} = \frac{B_{Ah}}{Ah\ capacity\ of\ a\ single\ battery}} \text{ ---------- } \quad (14)$$

The total number of batteries (N_{TB}) can then be obtained by the equation,

$$\boldsymbol{N_{TB} = N_{BS} \times N_{BP}} \text{ ---------------------------- } \quad (15)$$

Step 8: DC Cable Sizing

In the design of a PV power system, it is important to select the correct size and types of cables for onnecting the components. There are two types of cables to consider: PV array to battery bank and charge controller cable, as well as inverter to distribution point cable.

PV array to battery bank and charge controller

The cable is selected based on the current between the array and the battery bank which is given above as I_{rcc}.

Inverter to Distribution point cable

The cable here is selected based on the maximum continuous output current from the inverter which is obtained from the equation below.

$$I_{oi} = \frac{P_i}{V_{oi} \times P_f} \text{ ---------------------------------- (16)}$$

Step 9: PV Module orientation and land requirement

In the installation of PV modules for microgrid, it is important to specify the orientation and land space requirement. The direction that a solar panel faces is referred to as its orientation. The orientation of the solar array is very important as it affects the amount of sunlight hitting the array and hence the amount of power the array will produce. Solar modules should be installed so that as much radiation is collected as possible. Ideally, the solar modules should be tilted at an angle to the horizontal (β°), facing true south (if installed in the northern hemisphere) such that there is 90 degrees between the sun (at solar noon) and the PV module. To have a module face directly towards the sun at all times would require a solar tracking frame to be installed. This can be expensive, so it is not common practice for most PV applications.

The correct tilt angle varies with the times of year and the latitude of the site. It is recommended that the tilt should be within 10 degrees of the listed angle (Odesola et al., 2019 and Olaniyan et a.,2018). For example, a system used throughout the year at a latitude of 25° can have a tilt angle of 15° to 35° without a noticeable decrease in annual performance. In specifying the amount of land space required, the amount of space between rows of modules (where there are more than one row) is calculated and the land requirement for the array is derived. The row spacing between two modules which are facing towards sun, and located just behind one another is measured by the following equation.

$$Row\ Spacing\ (\gamma) = (x).\frac{\cos\cos(Azimuth\ angle)}{\tan\tan(Altitude\ angle)} \text{----- (17)}$$

Where *x* is the height of the module from ground.

Economic Viability Analysis

The economic viability of this design is carried out using the HOMER software. This analysed the entire cost of this design and optimized for the best combination of approaches. The Net Present Cost (NPC), Initial Capital and Levelized Cost of Electricity (LCOE) will be analysed among other variables.

2.2 Design Results

Site Inspection and Radiation Analysis
Nigeria is located between latitude 4°N and 14°N and longitude 2°E and 15°E respectively with total area of 923,768 and falls within the tropical zone. The case study location, Jato village in Oyo state, Nigeria is located around 7°31'27" N; 3°51'40" E. It is a small settlement with just about 24 houses. The major occupation of the people is crop farming. There is a primary school in this village where the children from within and nearby communities' school. There are suitable locations for solar PV array in this community that are devoid of overcasts from nearby trees and/or buildings. This implies that the solar panels will not be shaded at any time during the day. The terrain is also relatively sandy, so building the structure for the panel installation will not be an issue.

The figure below shows the Arial view of this community and possible locations for the PV array.

Figure 4: Arial view of Jato village

Temperature

The temperature data for this case study location was obtained from the NASA surface meteorology and Solar Energy database. It provides Air temperature, monthly averaged values for 22 years (July 1983 – June 2005). This is provided below.

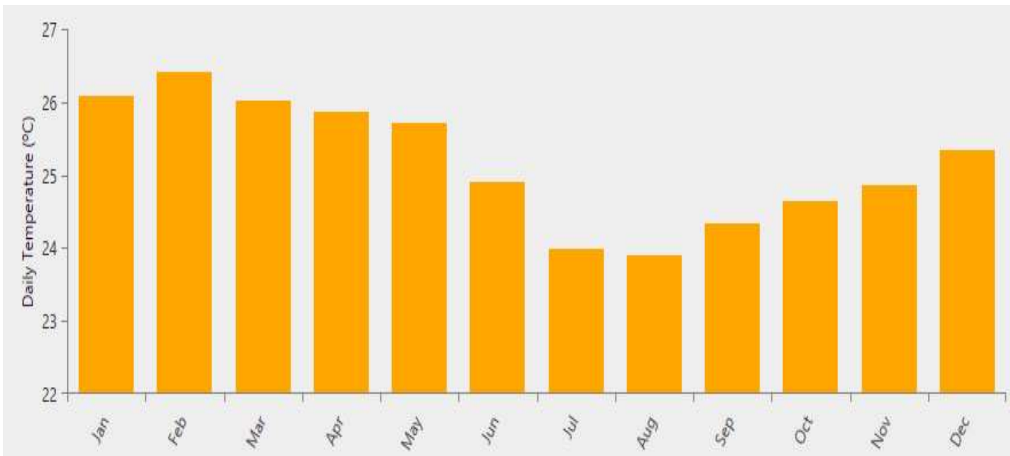

Figure 5: Graph of Average daily temperatures for different months.

The annual average ambient temperature is provided as 25.17°C.

Solar Irradiance

The solar irradiance data used is the Global Horizontal Irradiance (GHI). The monthly average Solar GHI for this location is obtained from the National Renewable Energy Lab database. This is provided in the chart below.

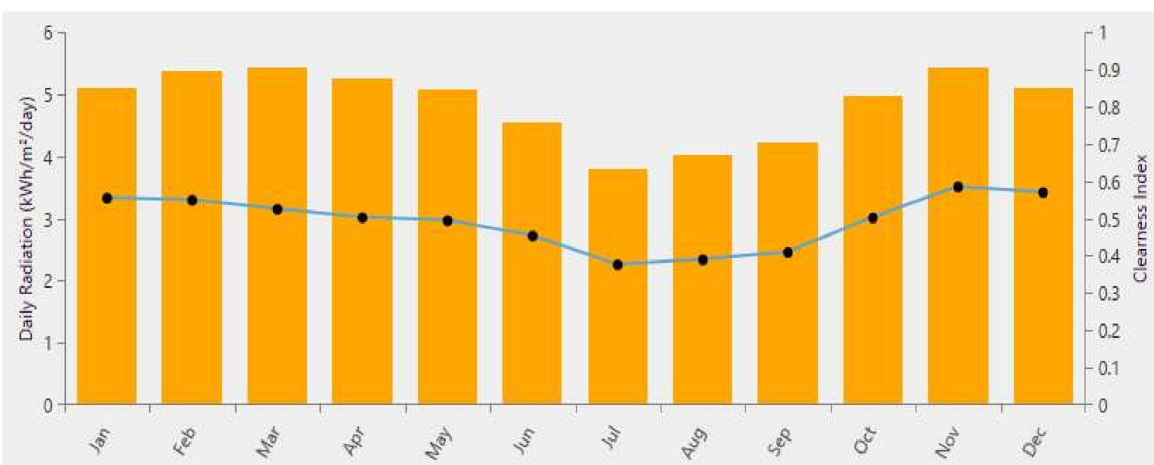

Figure 6: Monthly Average Solar GHI

Annual average GHI for this case study as obtained from HOMER is therefore **4.85kWh/m²/day**

Estimation of Load Requirement
For the purpose of this work, 26kWh/month per capita electricity consumption is used. Dividing by 30 gives daily per capita electricity consumption (E_{pc}) value of 0.87kWh/day.
The average daily energy demand, E_d is estimated as **167kWh** based on equation (1)

Choice of System voltage
Voltage level at solar system depends on the system size, battery and solar array capacity and skill level of operating staff at the site. The voltage for this system has been taken to be 96V DC. Since the community to be powered will be using AC appliances, like in other similar communities that are connected to the grid, the service (distribution) voltage is chosen to be 230V AC single phase.

Solar PV array capacity
Based on the equations outlined earlier, the required PV array is analysed in the table below. The selected PV module is *Foresolar 300W Polycrystalline.*

Table 1: Analysis of Solar PV requirement.

Parameter	**Calculated Value**	**Remarks**
Required daily average Energy demand, E_{rdd}	224.3 kWh	Equation (2)
Average Peak Power, $\boldsymbol{P_{ave,peak}}$	46.54 kW	T_{shd} taken as 4.82, Equation (3)
Total DC current, $\boldsymbol{I_{dc}}$	484.8 A	Equation (4)
Number of modules in in a string/series (N_{sm})	2.666	Equation (5)
Number of module strings in parallel (N_{pm})	59.04	Equation (6)
The total number of modules (N_{tm})	157.04 (Approx. 157)	Equation (7)

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04V/°C to 0.1V/°C, for every one-degree centigrade rise in temperature. This is why the modules should be installed in such way that there is enough air circulation in the back of each module, so that its temperature does not rise and reducing its output. An air space of 4 – 6 inches is usually required to provide proper ventilation.

Charge Controller
The charge controller requirement is analysed below.

Table 2: Analysis of Charge controller requirement

Parameter	**Calculated Value**	**Remarks**
Required charge controller current	653.87 A	Equation (8)
Charge Controller rated current	100 A	Product Data sheet
Rated Voltage of Controller	96 V	Product Data sheet
Required number of charge controllers	6.54 (approx. 7)	Equation (9)

4.6 Inverter

In determining the Inverter capacity, the peak load requirement of the case study community is obtained from the load profile as modelled by HOMER. For locations outside U.S., HOMER uses the Koeppen-Geiger climate classification system to match the location with one of a similar climate in the U.S.

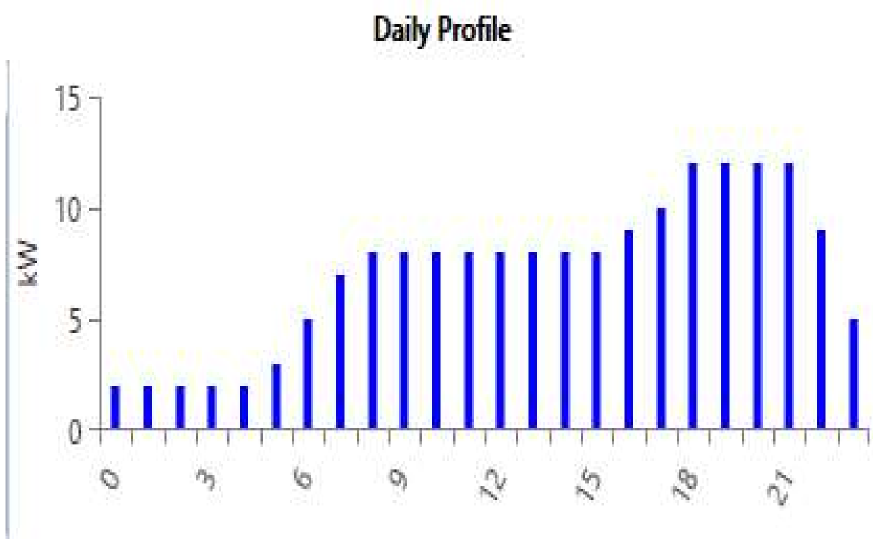

Figure 7: Average Daily Load Profile as plotted by HOMER.

The required inverter capacity should be very close to the peak load value. However, with the assistance of HOMER, peak load of 20.46kW was determined. Therefore, an Inverter size about 20kW is required.

Battery Capacity

The required battery bank is analysed below

Table 3: Analysis of Battery bank requirement.

Parameter	Calculated Value	Remarks
Battery bank storage capacity, B_{Ah}	2,861AH	Equation (12)
Number of batteries connected in series (N_{BS})	8	Equation (13)
number of strings to be connected in parallel (N_{BP})	14.3	Equation (14)
The total number of batteries (N_{TB})	114.4 (approx. **114**)	Equation (15)

3. Economic Viability Analysis

Using the Hybrid Optimization of Multiple Energy Resources (HOMER) software as stated earlier, the designed microgrid was analysed for its economic viability. This entails the best approach for deploying it.

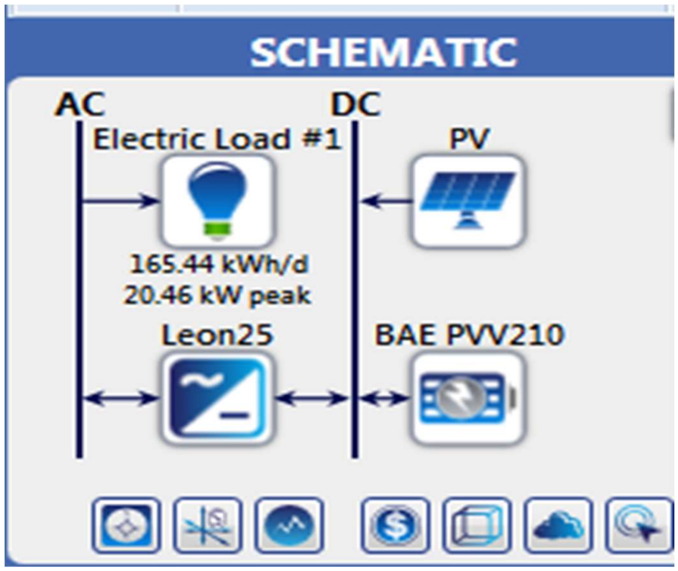

Figure 4.5: Schematic of Designed PV Microgrid in HOMER

For this analysis,

- The Inflation rate was taken as 12% p.a.
- Discount rate – 8%
- Project lifetime – 25 years
- Minimum renewable energy fraction – 90%
- System design precision was set to 0.01
- NPC precision – 0.01
- Focus Factor – 50

The NPC from the best result is given as $600,340. However, the initial capital is given as $326,224, with the rest of the NPC spread over the reference lifetime set at 25years.

The initial capital for this project is high as well as the NPC. The LCOE obtained is $0.24 per kWh. This far more expensive than the residential cost of grid electricity in Nigeria which is $0.07 per kWh.

Grid electricity supply is highly subsidized in Nigeria and this may not be a viable project to embark on depending on what it would cost to provide the same electricity from other remote sources or the by grid extension, operation and maintenance as well as cost of electricity over the same protracted period of time.

4. CONCLUSION

Several PV based microgrids have been deployed in Africa. Of particular interest is the largest Solar PV powered microgrid in West Africa (250 kilowatt-peak, with a 10km distribution grid) in Assoukoko village, Togo. The site (Jato Village) was inspected and radiation data was obtained from different international laboratories through the Hybrid Optimization of Multiple Energy Resources (HOMER) software. Suitable locations for solar PV array in this community, that are devoid of overcasts from nearby trees and/or buildings were identified. The temperature data obtained from the NASA surface meteorology and Solar Energy database gives the annual average ambient temperature as 25.17°C. The annual average GHI is 4.85kWh/m^2/day. After determining the average daily energy demand, E_d as 167kWh and deciding on system voltage of 96V, other parameters, as outlined in the design methodology were calculated and outlined in design results.

Total number of PV module required is 157, Charge controllers – 7, Inverter – 20kW, and the total number of batteries (12V, 200AH) required in battery bank is 114.

The Economic viability analysis was carried out using HOMER software which optimized for best combination of resources. The Net Present Cost (NPC) and Initial Capital of this design were found to be $600,340 and $326,224 respectively. Also, the obtained LCOE is $0.24 per kWh which is far above The cost of Residential (R2) electricity – $0.07/kWh – under the Ibadan Electricity Distribution Company.

Deploying a full-scale microgrid as designed is not economically viable for the location at this time. However, smaller versions of solar PV solutions that would allow residents get basic lightning and charging of devices could be economically deployed. It is recommended that priority be given to grid-based power supply than solar PV except in cases where it is extremely difficult to do so.

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