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Design of Grid-connected and Stand-alone Photovoltaic Systems for Residential Energy Usage: A Technical Analysis

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Towards realizing the United Nations sustainable development goals, access to clean, cheap and reliable energy, especially electricity, has been considered as one of the vital indices in any community. Hence, this paper presents the design analysis of both a grid-connected and an off-grid photovoltaic (PV) systems for household users in the highly residential city of Ogbomoso in Nigeria using PVGIS software. For the off-grid design, it is estimated that, given a total daily load of 9.57 kWh, a 3.5 kW$_p$ PV array size and a battery capacity of 86 kWh are enough to power the load

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with 5 days of autonomy and 70% depth of battery discharge. For the grid-connected PV system, the annual energy output for a building-integrated PV system is found to be around 4006 kWh; and a total of eight PV modules (each rated 250 W_p, 30.93 V) are stringed to arrive at the desired capacity of 2 kW_p. In terms of performance, the performance ratio (PR) of a building integrated grid-tied PV system at the study location was found to be 71.2% while for a free-standing PV system, the PR was 75%.

Keywords: PV system design; grid-connected PV system; off-grid PV system; PVGIS; performance ratio; sustainable energy transition.

1 INTRODUCTION

There are many issues attributed to conventional power generation; some of these issues are related to high cost, environmental degradation and adverse effects on economy. For this reason, many countries are moving to different forms of alternative energy sources for electric power generation ([1, 2]). More so, the continuous increase in energy demand requires the building of more robust and accessible generation facilities in compliance with the drive to meet the target set in the Kyoto Protocol to minimize greenhouse gas emissions. However, this calls for increasing capacity of existing network and expanding the power networks to remote locations with minimal implications on the sustainability of the environment ([3, 4]). The consequence is the rise in the deployment of renewable distributed generation (RDG), which is a form of small-size generation connected at the distribution network and fueled by renewable energy such as wind or solar energy sources ([5]). In Nigeria, the supply of electricity has never matched the demand despite the vast availability of natural resources - both renewables and non-renewables ([6, 7]). Due to several issues relating to power generation, transmission and distribution, it has been estimated that the grid-connected Nigerian population face electricity problems 60% of the time ([8, 9]). Consequently, a large percentage of the populace depends on fossil-fuel powered generators for their day-to-day energy requirements.

In order to move with the world in ensuring green and clean atmosphere, there has to be a paradigm shift from fossil-fuel powered generators to renewable sources of power generation. Studies ([10, 11, 12, 13]) have shown that Nigeria is rich in renewable energy resources- both wind and solar, which makes the country properly positioned to solve her electricity challenges. With regard to solar source of energy, the daily average of solar irradiation in Nigeria is around 5.5 kWh/m^2/day with about 6 hours of daily sunshine making the country to be categorized among the countries with best solar energy resource ([14, 15]). With respect to wind generation, some locations in northern Nigeria have a yearly wind speed of around 5.4 m/s at 30 m altitude which is great for wind power generation ([10]). Therefore, it is logical to conclude that, with a proper plan to harness the vast renewable energy resources in Nigeria, the problem of power generation in the country can be tackled within short period of time.

Photovoltaic (PV) system, which uses solar energy to generate electricity, can be categorized into grid-connected and stand-alone PV systems. The grid-connected type embraces direct connection to the power network and works in parallel with the supply electrical loads. In this PV system, there is no need for battery storage as it does not give room for autonomy. Its size varies from small distributed rooftop system of few kW to a large central grid-connected system of MW size and employs an inverter for the conversion of DC power generated by the PV array to AC power to be sent into the grid ([16, 17]). Stand-alone or off-grid PV system, on the other hand, does not interact with the utility grid. This type of PV system consists of PV array for generating energy, storage devices such as batteries, power conditioning systems (charge controllers, inverters), and electrical loads which might be AC or DC ([18]). Grid-tied PV system helps in reducing energy and capacity losses in the distribution network as well as preventing or delaying transmission and distribution system upgrade ([19]). Similarly, since energy is sent to the utility grid, the consumer loads are unrestrained. However, the functionality of grid-connected system is dependent on the availability of utility grid. On the other hand, stand-alone PV systems have found applications in remote areas with restricted access to the grid. For example, in rural electrification, telecommunication, water pumping etc. They require more maintenance but provides a strong sense of independence ([18]).

The performance of solar PV systems depends on the weather conditions prevalent in the selected location due to the effects of solar irradiation and operating temperature ([20]). Furthermore, the type of PV module technology plays a crucial role in the overall PV system performance due to variation in module efficiency and temperature coefficients as well as the response of PV module to shading effects, dust, snow and other environmental issues ([21]). Therefore, the evaluation of the performance of solar PV technologies becomes pertinent to the designing of a PV system ([20]). To this end, this technical report is aimed at designing a photovoltaic (PV) system that is capable of producing electricity in the range of 2 kW_p grid-connected type and 3.5 kW_p off-grid PV system for Ogbomosho town (8° 8' N, 4° 15' E), located in the south-western part of Nigeria. PVGIS software ([22]) is employed in this study to perform simulation of the design and the solar radiation data for this location is obtained from PVGIS-SARAH, which is one of the solar radiation databases available within PVGIS. The remaining part of this report is organized as follows: section 2 discusses the methodology used in the study and presents the design details of the PV systems. Section 3 presents the simulation results. The results are then analyzed and discussed in section 4 while section 5 concludes.

2 TOOLS, METHODOLOGY AND DESIGN

For successful implementation of the set design goals in this report, Geospatial tools such as geograpi-cal information systems (GIS) and solar PV data bases are deployed for resource verification and optimal system design for the study site at appropriate stages of analysis. Also, suitable cost and technical feasibility models are used for selecting best PV module technology for both the off-grid and on-grid PV systems.

2.1 An Overview PVGIS Software and PV Resource Assessment

PVGIS is a web-based software that gives users the opportunity to obtain data on solar irradiation and PV system energy generation in nearly all parts of the globe ([23, 22]). Using PVGIS, a number of calculations can be made including the simulation of different types of PV systems, estimation of the optimal tilt angle and finding the optimal azimuth (orientation) of PV modules. Many researchers have utilized the software to model the design of a PV system. For example, ([24]) employed PVGIS software to study the performance of a 10 MW grid-tied PV system in India and a performance ratio of 86.12% was obtained in the study. Other research studies reported in literature have shown the immense benefits of PVGIS for planning and design of PV systems for both standalone and hybrid configurations ([25, 26, 27]). There are about five solar radiation databases (DB) available within the PVGIS with each DB covering different parts of the globe. For this design, the DB employed is PVGIS-SARAH and it is the default DB for Europe, Asia, Africa and South America. It provides hourly solar radiation estimates from the year 2005 to 2016.

2.1.1 Selection of PV module technology

The available PV module technologies can be grouped into three: crystalline silicon, thin film and multi-junction solar PV cells. The dominant ones are the crystalline silicon, which constitutes about 90% of all solar PV technologies available ([28]). Crystalline silicon solar PV cells are sub-grouped into monocrystalline (mc-Si) and polycrystalline (pc-Si) technologies. The Thin film technology consists of one or more thin PV layers placed in a surface such as metal, glass or plastic. Multi-junction cells are made up of many p-n junctions manufactured from various materials, each producing energy. For the purpose of this project, eight different PV modules are considered as presented in Table 1; from which the most suitable One is selected based on the peculiarity of the study site as well as the cost and technical details of the PV modules.

Based on desired capacity (power rating) of the PV system to be designed, a PV module of peak power that is a factor of 2000 W_p is desirable. The available options meeting this criterion are those manufactured by Mitsubishi electric, Europe solar production (ESP) and Sunpower maxeon which are rated 250 W_p, 250 W_p and 400 W_p respectively. However, the monocrystalline maxeon technology, though highly efficient, is not available in high volume in Nigeria at present and highly expensive ([37]). Therefore, based on efficiency and the peak power of the design, the polycrystalline type manufactured by ESP is selected. The specification of the selected ESP PV module at standard condition (STC) is presented in Table 2.

2.2 Solar Resource Appraisal of Ogbomosho, Nigeria

The study site of this study, is the town of Ogbomosho in Nigeria which is situated at an elevation of 347 m above the sea level. The average monthly irradiation on horizontal plane $H(h_m)$, irradiation on optimally inclined plane $H(i_{opt})$ and the 24-hour average of temperature, T_{mean} of the town as obtained from the PVGIS-SARAH database is presented in Table 3.

At this location, the optimal angle at which the highest annual irradiation takes place is estimated by the PVGIS as 14° with a yearly irradiation of 2015.54 kWh/m^2. However, it can be observed that the average yearly irradiation on optimally inclined plane is only 1.9% higher than the average yearly irradiation on horizontal plane. Also, in August, which is the month with the least solar input, the irradiation on horizontal plane is higher than the irradiation on optimally inclined plane. Thus, any of the two irradiation parameters can be used in the design of PV system for this location. In this report, for the off-grid design, irradiation data on horizontal plane is used because of its higher value during the critical month of August while for the grid-tied design, irradiation data on the optimally inclined plane is employed. The month of January has the highest irradiation at 212.27 kWh/m^2/month while the month of August has the lowest at 119.42 kWh/m^2/month. The average daily temperature of the town vacillates between 22.8°C in August and 27°C in March. It is worth noting that the lowest temperature occurs at the month with the lowest irradiation; however, the highest temperature does not occur in the month of January despite having the highest irradiation. Such months with relatively higher irradiation but lower temperature are desirable due to high energy output and good performance of the PV modules.

The ratio of diffuse to global irradiation (K_d), which is defined as the proportion of the total radiation arriving at the ground, varies with global irradiation at optimal angle $H(i_{opt})$, as shown in Fig. 1. When $H(i_{opt})$ is highest in January, K_d is very low, and in August when $H(i_{opt})$ is lowest, K_d has the highest value. This is due to the effect of temperature on irradiation. During high temperature, there is high diffusion in the solar irradiation resulting in lower fraction of the total irradiation reaching the ground and therefore the value of K_d is lower at this period. On the other hand, when the temperature is low, the diffuse radiation is also low and therefore higher proportion of the total irradiation reaches the ground.

2.3 Design of Standalone PV System

The design of the standalone PV systems requires rigorous load estimation for both the basic loads and vital loads, and from this analysis optimal standalone PV system size with sufficient storage capacity and auxiliary power devices will be estimated.

Table 1. Different PV modules considered for the design

Manufacturer	**Cell type**	**Rating**, P_{max} (W_p)	**Efficiency** (%)
Solarwatt ([29])	Monocrystalline	310	18.80
Solar access ([30])	Monocrystalline	240	14.60
Mitsubishi electric ([31])	Monocrystalline	250	15.10
Europe solar (ESP) ([32])	polycrystalline	250	15.30
Sunceco ([33])	Polycrystalline	310	15.98
First solar ([34])	Thin film CdTe	420	17.00
Sunpower maxeon ([35])	Monocrystalline	400	22.60
Trina solar ([36])	Monocrystalline	265	16.20

Table 2. Technical specification of the selected PV module - ESP 250 6P at STC ([32])

Parameter		Specification
Manufacturer		Europe solar production (ESP)
STC Peak Power		250.00 W_p
Optimum operating voltage, V_{mpp}		30.93 V
Optimum operating current I_{mpp}		8.08 A
Open-circuit voltage V_{oc}		37.68 V
Short-circuit current I_{sc}		8.63 A
Efficiency		15.30%
Operating temperature		-40°C to +85°C
3***Temperature coefficients**	$T_{I_{sc}}$	+0.07 %/K
	$T_{V_{oc}}$	-0.34 %/K
	$T_{P_{max}}$	- 0.46 %/K
Dimension		1640 mm X 990 mm X 40 mm
Weight		19.00 kg

Table 3. Solar resource data of Ogbomosho town (8° 8' N, 4° 15' E)

Month	$H(h_m)$ [kWh/m^2/month]	$H(i_{opt})$ [kWh/m^2/month]	T_{mean} [°C]
Jan	191.4	212.27	24.84
Feb	178.48	189.61	26.48
Mar	189.47	191.64	27.02
Apr	178.34	172.93	26.69
May	173.53	162.35	25.64
Jun	152.07	140.95	24.29
Jul	133.03	125.14	23.18
Aug	123.77	119.42	22.83
Sep	136.96	136.16	23.11
Oct	162.52	168.48	23.92
Nov	174.38	190.11	25.25
Dec	183.9	206.49	24.45
Total	**1977.84**	**2015.54**	**24.65**

2.3.1 Load estimation

The first step in designing a stand-alone PV system is to estimate the size of the load to be supplied by the system. A typical home load in Ogbomosho, Nigeria is presented in Table 4, showing that the total daily load is 9.57 kWh at a single phase AC voltage level of 220 V, 50 Hz.

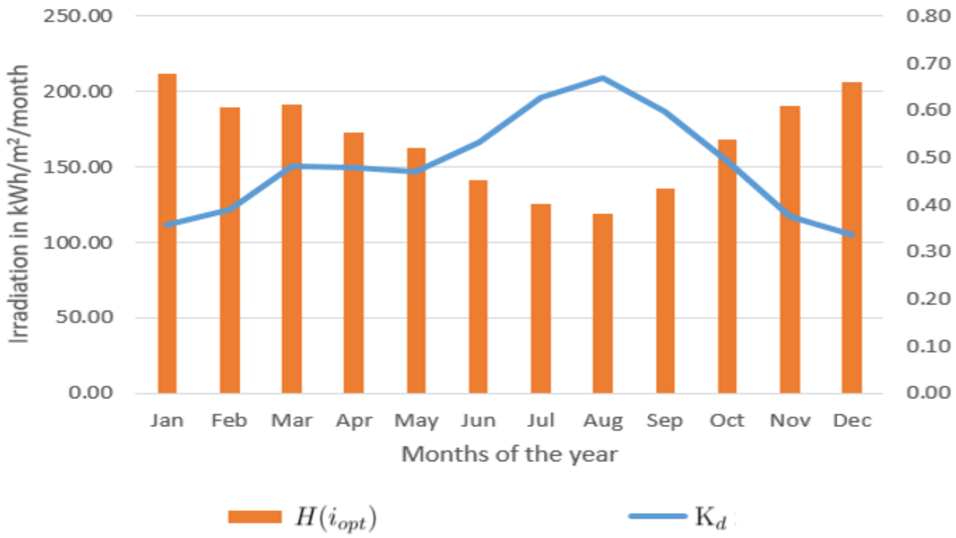

Fig. 1. Average monthly irradiation and ratio of diffuse to global irradiation in Ogbomosho

Table 4. A typical home load in Ogbomosho, Nigeria

Equipment	Quantity	Power (W)	Daily usage (hour/day)	kW	Daily load (kWh)
TV - 32"	1	140	8	0.14	1.12
Ceiling fans	3	70	8	0.21	1.68
Electric kettle	1	1000	0.3	1	0.3
Refrigerator	1	200	10	0.2	2
Laptop	1	50	6	0.05	0.3
Lighting	10	25	8	0.25	2
Iron	1	1000	1	1	1
Microwave	1	1800	0.3	1.8	0.54
Washing machine	1	2200 Wh/cycle	Twice a week	2.2	0.63
Total daily load				**6.85**	**9.57**

2.3.2 Estimation of required PV array size

The critical month when the solar energy is lowest at the location is August Table 3. Therefore, the value obtained during this month is used to determine the daily irradiation which is the daily solar input. The size of the PV array required is then obtained from the formulas:

$$\text{PV array size required (kW}_p) = \frac{\text{Daily energy required (kWh)}}{\text{Daily PV energy output (kWh/kW}_p)} \tag{2.1}$$

where;

$$\text{Daily energy required (kWh)} = \frac{\text{Daily load (kWh)}}{\eta_{inverter} \times \eta_{MPPT} \times \eta_{Battery}} \tag{2.2}$$

$$\text{Daily PV energy output (kWh/kW}_p) = \text{Daily solar input (kWh/m}^2) \times \eta_{PV} \times \text{Module area (m}^2\text{) per kW}_p \tag{2.3}$$

The monthly solar input in August is 123.77 kWh/m^2 (Table 3); therefore, daily solar input in August is $\frac{123.77}{31} = 3.993$ kWh/m^2/day.

The detail parameter of the PV module used in this design is provided in Table 2. At the rated power P_{max} of 250 W$_p$ and PV module efficiency, η_{PV} = 15.3% (0.153):

$$\text{Module area (m}^2) = 1.64 \text{ m} \times 0.99\ m = 1.624\ m^2\text{; hence} \quad (2.4)$$

$$\text{Module area (m}^2\text{) per kW}_p = \frac{1000}{250} \times 1.624 = 6.496 \text{ m}^2\text{/kW}_p \quad (2.5)$$

$$\text{Daily PV energy output (kWh/kW}_p) = 3.993 \times 0.153 \times 6.496 = 3.968 \text{ kWh/kW}_p \quad (2.6)$$

2.3.3 Selecting the DC operating voltage and PV modules arrangement

For an off-grid PV system, the available inverter characteristics and battery size in multiple of 12 V should be considered when choosing the system dc voltage level. In this study, an array voltage of 200 V ($\pm$ 50), considering battery voltage level of multiple of 12 V and inverter input voltage range available, is desired; hence, the array voltage, Vdc of 220 V is selected. Such voltage level is desirable to reduce the current level in the system and consequently reduce the size of the cables and switch gear needed for the installation.

Hence, the number of PV modules in series (length of string) N_s^{PV} is obtained as:

$$N_s^{PV} = \frac{V_{dc}}{V_m} = \frac{220}{30.93} = 7.11 \approx 7 \quad (2.7)$$

Where V_m is the optimum operating voltage of the module, given as 30.93V (Table 2). Therefore, seven modules are connected in series to arrive at dc operating voltage of 216.5 V (i.e. 7×30.93).

The number of modules in parallel (number of strings), N_p^{PV} is given as:

$$N_p^{PV} = \frac{P_{PV}}{N_s^{PV} \times P_{module}} = \frac{3500}{7 \times 250} = 2 \quad (2.8)$$

Where P_{PV} is the PV array size required and P_{module} is the peak nominal power of the PV module. Hence, two number of strings are connected in parallel; in total, 14 modules of solar panel are required with a total ratings of 220 V, 3500 W.

2.3.4 Battery sizing and arrangement

The number of days (n) of autonomy of the battery bank which is the duration of days the battery bank can supply the loads without input energy from the PV array due to poor weather or other factors is selected to be 5. Similarly, the depth of discharge (DOD) is selected to be 70%, for this design; implying that the battery cannot be discharged below 30% of its total capacity. The range of temperature, for the location being considered, is between 23°C in August and 27°C in March (Table 3). At this range of temperature, there is no adverse effect to the operation of the battery.

Thus, the capacity of the battery C_B is given as:

$$C_B = \frac{n \times \text{total daily load}}{\text{depth of discharge}} = \frac{5 \times 9.57\text{kWh}}{0.7} = 68.36 \approx 70\text{kWh} \quad (2.9)$$

The number of battery in series N_s^{bat} is estimated as:

$$N_s^{bat} = \frac{V_{dc}}{V_{bat}} = \frac{220}{12} = 18.3 \approx 18 \quad (2.10)$$

V_{bat} is the battery nominal voltage which is selected to be 12 V. Hence, 18 batteries are connected in series to arrive at a dc operating voltage of 216 V (i.e. $18 \times 12\ V$).
This value is within the voltage range required.

The number of modules in parallel, N_p^{bat} is estimated as:

$$N_p^{bat} = \frac{C_B}{N_s^{bat} \times V_{Ah_B}} = \frac{70}{18 \times 12 \times 200} = 1.62 \approx 2 \quad (2.11)$$

V_{Ah_B} is the battery capacity VAh; using a 12 V, 200 Ah lead acid battery as selected

$V_{Ah_B} = (12 \times 200)$.

Hence, two strings of battery are connected in parallel; and in total, 36 batteries (each with a rating of 12V, 200 Ah) are required. The arrangement is 18 series, 2 parallel connection and the total CB in Wh is:

$$C_B = 36 \times 12\ V \times 200\ Ah = 86400 \text{ Wh} \quad (2.12)$$

The summary of the demand requirement for selecting battery size and the parameters of the battery selected are presented in Tables 5 and 6, respectively.

2.3.5 Inverter design and selection

For off-grid application, the inverters will be sized to be able to bear the maximum power needed for the entire load. Other parameters that are considered are the DC operating voltage level and the AC output voltage. From Table 4, the total load demand is 6.85 kW, and considering a safety factor (SF) of 20 %, the total load required is:

$$\text{Total kW required} = 6850 \times 1.2 = 8.2 \text{ kW} \quad (2.13)$$

Therefore, a 220 Vdc to 220 Vac inverter with capacity of around 8000 W is desirable. Two inverters having 5 kVA capacity each and power factor of 0.8 are selected and connected in parallel to achieve the desired ratings. The specification of the inverter is presented in Table 7.

2.3.6 Charge controller design and selection

The design requirement for the solar charge controller used in off-grid PV system is such that the DC input voltage of the controller needs to match the solar array voltage and the battery bank voltage (220 V). Furthermore, the controller has to be able to withstand the maximum current from the PV array. With the peak capacity of the PV array of 3500 Wp (as determined in previous section), the charge controller current is obtained as:

$$\text{Charge controller current} = \frac{3500}{220} = 17.5\ A \quad (2.14)$$

Hence, based on the above calculation, a 20 A, 220 V charge controller can be selected. This value is safe considering the short circuit current of the PV array which is 8.63 A (Table 2). Since two strings of the PV module are connected in parallel, the total short circuit current of the array is $2 \times 8.63 = 17.3\ A$. The type of the charge controller chosen is MPPT which is used to maximize the array output power. The MPPT continuously monitor and adjust the voltage to produce the maximum power regardless of the time of the day and atmospheric condition.

The summary of the design parameters estimated for the stand-alone PV system for the considered site is presented in Table 8.

2.4 Design of Grid-connected PV System

The design for the grid-connected PV system involves connection to the grid via an inverter. One major design consideration for this mode is that there is no load constraint.

2.4.1 Maximum array power output and PV module arrangement

The standalone systems was designed basically with the peak load demand in mind with the addition of the battery systems for storing excess generation at off-peak load. However, for the grid-connected PV system, 70% of the required capacity for the standalone system was designed with the assumption that excess generation will be fed to the grid and unmet load demand will be cater for by the grid; hence, a 2 kWp PV system is designed.

Considering that the PV efficiency of the selected 250 Wp module is 0.153 (Table 2) with a dimension of (1640 mm $\times$ 990 mm $\times$ 40 mm) and the irradiation for the entire year at optimal angle 14° is 2015.54 kWh/m$_2$/year (Table 3):

$$\text{Module area} = \frac{2000\ \text{W}}{250\ \text{W}} \times 1.64\ \text{m} \times 0.99\ \text{m} = 12.99\ \text{m}^2 \quad (2.15)$$

$$\text{Maximum PV energy output (kWh per year)} = \text{solar input} \times \eta_{PV} \times \text{Module area} \quad (2.16)$$

$$= 2015.54 \times 0.153 \times 12.99 = 4005.83\ \text{kWh/year} \quad (2.17)$$

Table 5. Demand requirement and battery selection parameters

Capacity of load to be supplied (Wh)	9570
Days of autonomy	5
Depth of discharge (DOD)	70%

Table 6. Parameters of the battery selected ([38])

Battery Manufacturer	Xupai 6-CNF-200 (12V 200Ah)
Battery capacity (Ah)	200
Battery nominal voltage (V)	12
Operating DC voltage (V)	220
Number of battery in series	18
Number of battery in parallel	2
Total number of battery	36
Equivalent capacity of battery (Wh)	86400

Table 7. Off-grid inverter specifications ([39])

Model	YKDA-HD5000	
Rated output output capacity	5 kVA X 2	
Rated output power	4 kW X 2	
Rated output voltage and frequency	220 Vac, 50 Hz/60HZ	
Power factor	0.8	
Efficiency	85%	
Rated input voltage	220 Vdc	
Rated input current	23 A	
2*Input dc voltage range	DC shutdown voltage range	180 V 270 V
	DC startup voltage range	280 V 260 V

Hence, with a 2 kWp PV system, which consists of 8 modules of 250 W PV panel, the expected maximum array power output is 4005.83 kWh/year; and in order to arrange the module to target an array voltage of 200 V $\pm$ 50, the maximum operating voltage V_{mpp} of the module is considered. The only possible combination is to arrange all the 8 modules in series to get an output voltage of 247.40 V (i.e. 30.93 V X 8) and the array peak power of 2 kWp.

Table 9 gives the summary of the design specification as calculated for the grid-connected PV system in the study site.

2.4.2 Selecting grid-connected inverters

The PV array in consideration is 2 kWp, therefore a grid-tied inverter with an input of range of 250 Vdc and output of 220 Vac and a capacity of around 2 kW found on ([40]) is selected as

Table 8. Detail summary of the designed parameters for the off-grid PV system

Daily load	9570 Wh
Daily irradiation	3.99 kWh/m^2/d
PV array capacity	3500 Wp
PV module capacity	250 Wp
Number of PV modules in series	7
Number of PV modules in parallel	2
Total number of PV module	14
DC operating voltage	220 V
Battery capacity (each)	12 V, 200 Ah
Number of battery in series	18
Number of battery in parallel	2
Total number of battery required	36
Designed battery capacity	86400 Wh
Inverter capacity	4000 W X 2
Voltage level of the inverter	220 Vdc to 220 Vac
Charge controller	20 A, 220 V

being sufficient. The alternative is to convert the 250 Vdc to a lower voltage level through a buck converter before connecting an inverter with such voltage level.

3 SIMULATION AND RESULTS

The simulation procedure was carried out using PVGIS version 5 and the results obtained are discussed in this section under the standalone and grid-connected technologies.

3.1 Standalone PV System

The input parameters to the software presented in Table 10 are based on the estimated design parameters in the previous section. The discharge cut-off limit is the percentage of full charge that the battery charge is not permitted to fall below. Since the depth of discharge is 70%, the discharge cut-off limit is 30%. The battery performance of the designed off-grid system is shown in Fig. 2. The simulation output shows that there are about 75% of days in the year when the batteries become fully charged while there are 0.05% of days with empty battery and the average energy not captured due to full battery is 4371 Wh.

3.2 Grid-connected System

The input parameters to the software for the on-grid PV system are given in Table 11. As the mounting position of the PV system is building integrated, there is no possibility in the software to choose the optimize azimuth option. Building integrated option is selected because it is cheaper since there is no extra cost of installing stands for the PV modules. Also, the majority of buildings in Ogbomosho have adequate space on their rooftops for such capacity and can easily accommodate the 8 PV modules needed to obtain 2 kWp size for the installation. However, for larger capacities, a free standing PV installation would be the most appropriate. The simulation output as presented in Table 12 shows that the yearly total irradiation is 2010.28 kWh/m^2 while the yearly power generation by the 2 kWp module is 2852.45 kWh. The optimum angle for the PV orientation as estimated by the software is 12°.

3.3 PV tracking System (Grid-Connected)

The assumption made is that the PV tracking system is tied to the grid so that the output of the PV modules is not a function of the local electricity consumption. The provided inputs are presented in Table 13. The average monthly in-plane irradiation and the average monthly energy production from each tracking axis is given in Table 14. The result shows that the two-axis tracking system gives the highest yearly energy output at 3699.58 kWh per year with the in-plane irradiation of 2490.26 kWh/m^2 per year.

4 DISCUSSION AND TECHNICAL ANALYSIS

This section provides an in-depth analysis of the data obtained in section 3 for the three types of PV system and gives a technical comparison of the simulation results with the manual calculation result. The performance ratio of a PV system in the location is also estimated.

4.1 Off-grid PV System: Simulated versus Manual

The results obtained from the manual design of the stand-alone PV system compare well with the simulation outputs. Simulation outputs show that the estimated parameters are able to meet up with the daily energy requirement across the entire year. The average energy not captured, as a result of the batteries becoming fully charged, is slightly less than half of the energy output across the year. With respect to battery performance, the batteries become empty at 0.05% of the year which is equivalent to 4 hours of the entire year and this happens in August. This result shows the criticality of the month of August at the location due to the low value of average irradiation during this period. Increasing the battery size to prevent the batteries from getting fully discharged comes at a significant cost due to the quantity of batteries required to meet up with the system voltage. Similarly, the PV array size can be increased but at a significant cost and should be arranged to meet up with the PV array voltage requirement. This implies that about 7 extra PV modules of the same rating are needed to be stringed to maintain the voltage range. However, it could be noted that, the load consumption is likely going to be reduced in the month of August due to the cool weather which means the usage of equipment such as electric fan is going to be drastically reduced.

4.2 Grid-connected PV System

The maximum PV array power output manually calculated for a 2 kWp system installed at optimal angle using the global irradiation of 2015.54 kWh/m^2/year (Table 1) is 4005.83 kWh/year, as calculated in section 2. However, the software estimates a yearly energy output of 2852.45 kWh/year for the same capacity with slope optimized. Thus, the useful energy estimated by the software (2852.45 kWh per year) is 71.2% of the theoretical value (4005.83 kWh per year). The reason for this difference is attributed to several factors which are not taking into consideration in the course of the manual calculation. The theoretical calculation simply considered the PV module efficiency at STC (temperature of 25°C) while in reality, due to the fluctuations in temperature, the efficiency of the PV module is being affected. Other losses in the system such as the losses in cables, power inverters, losses caused by cell temperature going above 25°C $etc.$ are factored in the simulation model. Furthermore, the mounting position selected is building integrated which has an adverse impact on the PV module temperature due to the restriction of air movement behind the module.

4.3 PV Tracking System

The two-axis system produced the highest energy output of 3699.58 kWh/year followed by the inclined-axis tracking at 3591.5 kWh/year. These values represent around 26% to 30% increase compared to 2852.45 kWh/year obtained for the fix-angle grid-connected PV system. Moreover, the PV tracking system generates higher energy than the maximum energy output from any fix-angle PV system no matter which axis is selected. However, the tracking PV system comes with extra cost of installing movable supports for the PV modules so that the modules can always face the direction of the sun. Hence, in order to compare the useful energy output (estimated through simulation) with the theoretical output, it is necessary to apply the formula:

$$\text{PV energy output from the array (kWh per year)} = \text{solar input} \times \eta_{PV} \times \text{Module area} \quad (4.1)$$

Hence, for the two-axis system with a yearly global irradiation of 2490.26 kWh/m^2;

$$\text{PV energy output from the array (kWh per year)}$$

$$= 2490.26 \times 0.153 \times 12.99 = 4949.30 \text{ kWh/year} \quad (4.2)$$

Table 9. Detail summary of the designed parameters for the grid-connected PV system

Capacity of the PV system	2 kWp
PV module technology	Polycrystalline
PV module efficiency	0.153
Area covered by the PV system	12.99 m^2
Number of PV modules in series	8
Number of PV modules in parallel	1
Total number of PV module	8
Calculated maximum array output	4005.83 kWh/year

Table 10. Inputs for the stand-alone PV system simulation in PVGIS

Solar radiation database	PVGIS-SARAH
Installed peak power (Wp)	3500
Battery capacity (Wh)	86400
Discharge cut-off limit (%)	30
Consumption/day (Wh)	9570
Slope (°)	0
Azimuth (°)	0

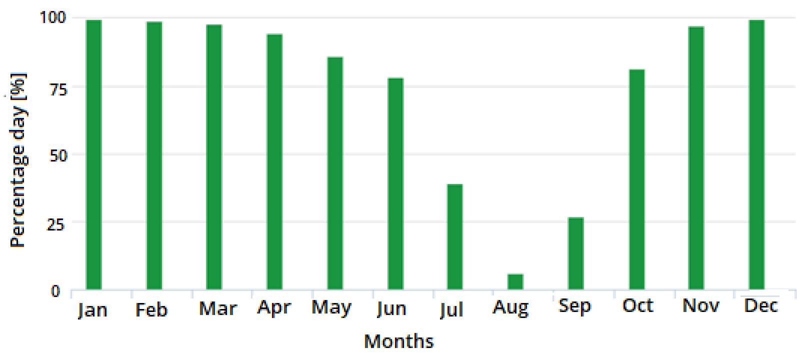

Fig. 2. Battery performance for the stand-alone PV system

Hence, the useful energy is 75% ($i.e.\ \frac{3699.58}{4949.3} \times$ 100%) of the target energy. Thus, the remaining 25% represents the losses in the system. These losses are not as high as the case of the building-integrated grid-connected PV system due to the possibility of air movement behind the PV modules.

Table 11. Inputs for the grid-connected system simulation in PVGIS

Solar radiation database	PVGIS-SARAH
PV technology	Crystalline silicon
Installed peak PV power (kWp)	2
System loss (%)	14
Mounting position	Building integrated
Slope (°)	Optimize
Azimuth (°)	-

Table 12. Outputs from the simulation of the grid-connected PV system

Month	**E_m (kWh/month)**	**H_m(i) (kWh/m^2/month)**
1	290.26	208.44
2	259.64	187.26
3	266.71	190.86
4	247.43	174.87
5	232.6	162.48
6	206.41	142.31
7	184.75	125.64
8	176.18	119.31
9	198.19	136.23
10	239.78	168.07
11	265.31	190.14
12	285.19	204.67
Total	**2852.45**	**2010.28**

Table 13. Inputs/settings for the simulation of the tracking PV system

Solar irradiation database	PVGIS-SARAH
PV technology	Crystalline silicon
Installed peak PV power (kWp)	2
System loss (%)	14
Vertical axis (Slope Optimized)	✓
Inclined axis (Slope optimized)	✓
Inclined axis (slope = 0°)	✓
Two-axis	✓

4.4 Performance Ratio

Performance ratio (PR) shows the ratio of the useful energy to the target energy. The target energy is obtained by multiplying the total irradiation (kWh/m^2) by the module specified efficiency at STC and total installation area (m^2). PR gives an indication of the losses resulting from inverter, cabling, shading, cell mismatch, reflection, outages, module temperatures $etc.$ ([41, 42, 43]). The 71.2% and 75.0% obtained in the previous sections are the measure of the PR of the PV system installed at the location of study. The European PV Guidelines stipulates that a PR of 80% and above represents a good performing PV system while a value below 75% indicates a problem. However, PR below 75% might be regarded as normal in the case of a building-integrated photovoltaic (BIPV) system owing to higher operating temperatures and the shading effect ([44]).

Table 14. Output of the tracking PV system simulation

	Vertical axis		Inclined axis		Two-axis		Horizontal axis	
Month	**H_m(i)** (kWh/m^2)	**E_m** (kWh)	**H_m(i)** (kWh/m^2)	**E_m** (kWh)	**H_m(i)** (kWh/m^2)	**E_m** (kWh)	**H_m(i)** (kWh/m^2)	**E_m** (kWh)
1	260.48	380.88	256.52	377.16	268.37	392.45	242.31	358.76
2	223.56	326.62	226.74	331.57	229.98	335.7	218.85	321.51
3	214.79	316.51	221.96	326.17	222.3	326.64	220.14	323.88
4	203.09	302.54	208.62	310.22	212.77	315.9	212.17	315.06
5	201.93	302.91	199.01	299.18	210.24	314.69	206.3	309.23
6	177.55	269.25	170.97	260.13	183.77	278.35	178.48	270.84
7	151.04	231.59	148.35	227.85	156.59	239.93	153.55	235.51
8	135.46	208.36	137.59	211.63	141.18	216.97	140.46	215.9
9	154.03	234.49	160.44	243.83	161.23	245	160.83	244.48
10	194.58	291.13	200.11	299.17	201.07	300.4	195.73	293.43
11	231.25	337.9	229.3	336.41	237.09	346.26	217.9	321.83
12	257.98	376.11	250.73	368.18	265.67	387.29	234.95	347.74
Total	**2405.74**	**3578.29**	**2410.34**	**3591.50**	**2490.26**	**3699.58**	**2381.67**	**3558.17**

The PR obtained in this design, 71% for building integrated and 75% for free standing, are not far from what other researchers have published in literature for some locations in Nigeria. For example, ([13]) have reported a monthly PR ranging from 71.3% in April and 76.8% in December for Kankia in Katsina state of Nigeria. Similarly, Agbetuyi et al. in ([45]) reported a PR of 0.81 for a grid-connected 1 MW located in Ogun state, a region in the same geo-political zone with the study site (Ogbomosho, Nigeria). Hence, these outcomes confirmed that a PV system installed in Ogbomosho will be more productive and effective at meeting the energy requirement of the inhabitants.

5 CONCLUSION

The design of both grid-tied PV system and off-grid PV system for meeting the load demand in a typical residential location (Ogbomosho town in Nigeria) has been investigated and reported in this assignment. The annual irradiation obtained from PVGIS-SARAH database for this location is found to be around 2000 kWh/m^2 with annual energy output of 2800 kWh for a 2 kWp capacity of building-integrated grid connected PV system. The annual energy output goes as high as 3700 kWh for the same PV array capacity if a dual-axis tracking PV system is employed. However, the tracking PV system comes with extra cost of installing movable supports for the PV modules so that the modules can always face the direction of the sun. The load of a typical home in Ogbomosho is employed for designing an off-grid PV system that is capable of meeting such demand. The estimated daily load is around 9.6 kWh and the design shows that 3.5 kWp PV array with battery capacity of 86 kWh is sufficient to supply the load with 5 days of autonomy and 70% depth of battery discharge.

Moreover, for a building integrated PV system at this location, a PR of 71.2 % is calculated while for a PV tracking system, the PR is estimated 75%. The reason for this difference is discovered to be due to the possibility of air movement behind the PV modules which is not restricted in the tracking system thereby enhancing the cooling and therefore, the efficiency of the modules. Consequently, with this performance, and such amount of solar irradiation and the outcomes of this investigation, it is logical to conclude that the town of Ogbomosho, Nigeria is within the techno-economic investment zone for the installation of higher capacity of PV system as this technology becomes cheaper at higher capacity and more sustainable compared to the conventional sources of electricity.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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