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Typical Off Grid/Stand-Alone Photovoltaic System Design for Household Power Generation in Wukari Metropolis

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Abstract:
Solar photovoltaic system design is mainly predetermined by the system requirement, environmental governing policies, standard and awareness. These and others, are measured ingredients considered in this sustainable design of the stand-alone solar household project in Wukari. In this project, the PV design is mainly influence by the number and types of appliances used. A system capable of supplying energy for a typical house in Wukari was design and components sizing were approved. The key structure's gears such as the photovoltaic panels, battery, charge controller and inverter are stated, taking the insulation level of ten (10) average hours of sunlight per day with an estimate for a total cost of the system. The total electrical supply to the load appliances of 5190W in the building will be from the PV source. To power these appliances, 4 modules with the power rating of 220W under a standard test condition (STC)of 1000W/m^2 and 25°C temperature, 4 batteries of (24V-200Ah) in the battery bank with system battery capacity of 848Ah, one charge controller of 50A-24V is selected and a 2KVA inverter is required. The aim of this work is to size each component of a PV system based on the numbers, types, and wattage of the appliances and design a suitable Off-grid/Stand-alone PV system that can generate reliable 24 hours power supply within the residential household eliminate grid dependency.

Keywords: Inverter, Photovoltaic Module, Renewable Energy, Solar Energy, Solar Irradiant

INTRODUCTION

Renewable energy (RE) has constantly ascended it's global relevant as a good substitute in energy transition and demands, an answer to the current and future global energy wants. Creating room for technological effectiveness [1][2] and increasing global energy efficiency [3] as well reducing capacity lacking in energy transition [4]. Numerous countries have begun to move to renewable energy resource by reason of their geographical locational advantage and local resource [5]. For example, Nigeria is a country that is very close to the latitude, her climate and temperature have features of the equatorial and hot region having two major seasons, the rainy and drought seasons. The regions in Nigeria are bare to sunlight all year round, so, this singularity becomes an advantage for renewable energy production. The Renewable energy systems and integrated systems resources are used in this regard to take advantage of the available renewable energy source [6]. This play an effective role in the production and generation of electrical energy [7], since they purposed to overcome the nation dependency on fossil energy resources [8] also, is the finest option accessible in meeting the demand of sustainable electricity. RE founded system include solar photovoltaic (PV) system, Tidal, Wind and Hydropower system etc. RE sources has in recent time gain more approval for domestic and industrial applications owing to their beneficial features in energy sustainability, low maintenance cost and the environment safety [9][10]. Solar energy resource is one of the most profuse energies that can bear the domestic energy needs for a justifiable economic growth [11]. The rapid trend and increasing use of PV energy is associated with increased efficiencies of solar cell as well as the improvement in panels engineering efficacy and technological advance [12]. In several circumstances, the detoxification plants motorized by renewable source rely on fossil fuel to power generators, ensuing ecological effluence and emission of greenhouse gases [13]. However, this RE energy (solar photovoltaic) is expected to be shaped not only at manufacturing levels but also on a domestic or distinct level [14].

Solar Energy potentials within any given region has crucial key to the commercial and societal growth of any nation, and its rank is snowballing with technical and manufacturing expansions in the world. The greatest and broadly used energy resource for electrical production is the fossil fuels but research has it that these resources have several undesirable effects such as climate change and environmental pollution [15]. The growth of solar energy sources has recently taken the global Centre stage in energy generation and consumption [16]. This can be accredited to the statistic that solar energy is a hygienical energy source with rebuff damaging environmental influence. Solar energy can be renewed to any form of energy by means of processes involving various stages [17]. The accessibility of solar energy is a vital prerequisite in the design and development of its conversion or alteration structures. In the applications of concentrated solar power (CSP) structures, PV system sizing and solar drying schemes designing involve the knowledge of the readiness of comprehensive solar irradiance. The absorption of solar energy each day is typically one of the variable quantities obtain by climatological posts across Nigeria. The greatness and changeability of solar radiation data can take a noteworthy effect on the feasibility examination of a solar energy venture, its thorough design as well as its commercial practicability [18]. A shared approach to enumerating and assessing solar resource in each region is the investigation of daily, monthly, and annual values of Global Horizontal Irradiation. Wukari, the location of the study is vast with high readiness of solar irradiance that support's the course of solar energy conversion system. The application of solar energy to frugally meet the world's increasing energy demand depends upon two factors: available solar energy resource and suitable technological application in harnessing it. Electricity production from PV panel is unswervingly affected by solar radiation; this brands global solar radiation data in a specific region indispensable for solar energy applications [19].

The Principle of Solar Energy Generation

Photovoltaic system is usually intended to deliver a direct current (DC) /alternating current (AC) electric application. The system entails of solar panels connected to the charge controller, battery, and the inverter. The system generates DC power by harvesting sun light into electric current by the PV module connected to the charge controller for regulation of chargers into the battery/battery bank, the battery stored charges and the converted alternating current and powered by the inverter, supplying the alternating current to house loads. The alternating current power is therefore utilized by the operating loads in the home. The Photovoltaic (PV) cells are microelectronic devices that effectively change the solar energy from the sun into electrical energy by means of photovoltaic effect. These working principles of solar cell can be sub-divided into three basic processes (Fig.1):

a. The principle of light absorption to generates charge carrier, holes (p-type) and electron (n-type)
b. The principle of parting of charge movers.

c. The gathering of charge carrier at the electrode creating the potential difference diagonally the p-n junction.

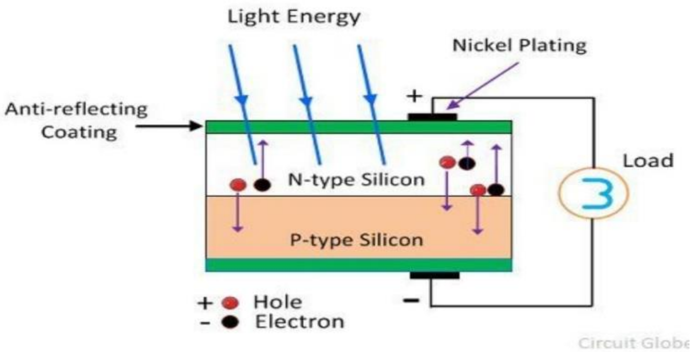

Fig.1: Working Principle of PV cell (@ circuit globe assessed August 15,2023)

The voltage difference grouping that takes place at the p-n junction within the cell in respond to the perceptible radiation that is applied from the sun in doing the work. Several types of semiconductor devices and technologies are developed and used in designing a solar cell with little amount and elevated conversion efficacy. Outmoded solar panels made after silicon crystalline wafers modules are weightier that makes the conveyance process hard. These are usually big sized solar panels shelter with class sheets. A weightier and large solar panel needs a lot of space and occasionally a large roof to fit the huge solar panels in case of high-power utilization [20] [21]. Consequently, this research study keeps an attention on the effectual use of sun energy by solar cell investigation and expansion.

Photovoltaic Cell

The photovoltaic (PV) efficiency was first pragmatic by Alexandra-Edmond Becquerel the year 1939. Then, in 1946 the initial contemporary solar cell was completed using silicon, which was conceived by Russel Ohl [22][23]. Previous photovoltaic solar cells were tinny silicon wafers that convert daylight radiation into electricity. The recent photovoltaic knowledge is founded on the principle of electrons cavity formation and each cell self-possessed two dissimilar layers (p-type and n-type) of a semiconducting material. In the prearrangement of the edifice, once a photon of adequate energy imposes on the p-type and n-type junction, an electron is ejected by acquisition of energy from the outstanding photons and interchanges from one layer to another. This generates electron and hole in the course and by this development, electrical power is produced [24].

Types of Photovoltaic Cell

The numerous types of resources applied for photovoltaic solar cells include many in the like of silicon, they are:

- Single/Mono-crystalline silicon solar cell (Mono-Si).
- Polycrystalline silicon solar cell (poly-Si or Mc.-Si).
- Amorphous silicon solar cell.
- Thin-film solar cell.

Monocrystalline Silicon Solar Cell (Mono-Si):

The substance of this cell is a crystalline silicon semiconductor device. It is manufactured from a single crystal of silicon through a method called Czochralski process [24] [25]. Throughout the industrial or production course, Si quartzes are cut from the big sized slabs. The big sole crystal manufacturing need accurate treating as the procedure of "recrystallizing" the cell is capital intensive and many processes involved. This electric cell has a proficiency in the range of 17%-18% [26]. Also, very stable, and durable in chemical structure. The efficiency of this cell is its advantage over other product but has a high market price because it's a product of pure silicon material. Expected lifespan of these cells is typically 25-30 years [27].

Polycrystalline Silicon Solar Cell (poly-Si or Mc.-SI):

Polycrystalline photovoltaic components are generally constituted of various crystals, combined to one another in one cell. The process of polycrystalline Silicon solar cell is more efficient, which is yielded by chilling graphite mold lined holding melted silicon. They are melted and decanted into a mold, and its formulae a square block which is finally finished into a four-sided wafer with a reduced amount of waste space. Polycrystalline Silicon solar cells are presently the utmost accepted solar cells. It is supposed to dominate up to 48% of the world solar cell production presently [28]. Through the curing of the melted silicon, several configurations are formed. Though they are somewhat economical to construct when compared to mono-crystalline silicon solar sheets but are less effectual ~ 12%-14% [29].

Amorphous Silicon Solar Cell:

Amorphous Silicon (a-Si) Photovoltaic modules can be said to be the most unsophisticated or unrefined solar cell that are first to be mass-produced industrially. amorphous silicon (a-Si) solar cell can be produced at a low treating temperature, so allowing the use of several small, rated polymer, and other supple substrates. These substrates need a smaller expanse of energy for treating [30]. The amorphous silicon cell is reasonably inexpensive and generally accessible. The word "amorphous" with respect to solar cell refers that the encompassing silicon materials of cell has a deficiency of definite prearrangement of atom in the matrix, non-crystalline assembly, or not highly organized. These are construct by cutting nobbled silicon material to the behind substrate. The amorphous silicon solar cells generally are dark in color on the shiny side while silvery on conducting adjacent [31]. The major subject of challenge with amorphous silicon solar cell is it's deprived and unsteady efficacy. The cell effectiveness mechanically cascades at Photovoltaic level. Presently, the efficacies of viability of PV modules differ within the series of 4% - 8%. This easily allow operation at an elevated temperatures and are appropriate for the climatic circumstances wherever sun shines for scarce hours [32].

***Thin Film Solar Cell**:*

Thin-film solar cell is finished with semiconductor deposited on glass, plastic, or metal. This type of solar cells has very tinny light captivating coatings, usually of the order of 1um width [33]. It is the quality that gives thin-film solar modules its flexibility and light in weight. When a glass is used, the film panels are more rigid and heavier. Thin-film solar sheets are less effective with a lesser power capacity compared to Mono and Polycrystalline solar cell types. The efficacy of a thin-film differs is liable on the category of PV material used in the cells but in all, they tend to have efficiencies of about 7%- 18%. Such materials are copper indium dieseling, cadmium telluride, and gallium arsenide.

PV System and Arrangement

Photovoltaic system is premeditated to stream usable power through the means of photovoltaic. It comprises of the prearrangement of respective components, comprising solar panels that grips rays into direct current (DC) electricity, the solar inverter, this change output from direct current

(DC) to alternating current (AC) as well as mounting cabling, charge controller, which control the number of charges going into the battery and prevent them from reverse current. The battery stores charges, including other electric components to set up within the working system [34]. With rising market quest for PV systems and productions notwithstanding, the PV system have presented the consumers with an option to the grid connection. This option has also set-in a new innovative like "Net Metering." Which permits the end users to feed back to the grid power from their PV schemes. This becomes conceivable because of the network-tied link within the system. Likewise, it is also possible to run a system that can operate independently with no desire to be linked to the power grid such arrangements are referred to off-grid systems or standalone systems.

***Off-Grid System/ Stand-Alone System*:**

The term, off-grid system explained that the system is not relating to the gird scheme. Principally, that the arrangement is not connected to the focal national power grid as such is refer to as off-grid PV arrangement [35]. This kind of arrangement is also termed stand-alone arrangement or small grid (Fig.2), that can produce electricity and run its utilities through herself. This system arrangements remain appropriate for powering of a household or a little community. It is practical for an isolated communities in the nations where access to community electrification is limited. Electrical energy generated via the off-gird arrangement or system desires to be deposited or stored in battery bank for effective usage.

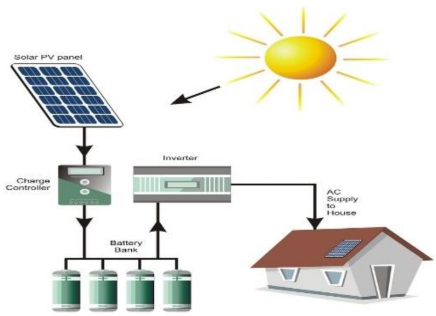

Fig.2: An Off-Grid System (@ circuit globe assessed August 20,2023)

On-Grid System/ Utility Arrangement:

An On-grid coupled photovoltaic power arrangement is an electricity generating system that can be linked to the utility or the national gird [36]. This arrangement comprises of solar panel or panels, inverter, as well as other basic gears to deliver link to the grid (Fig 3).

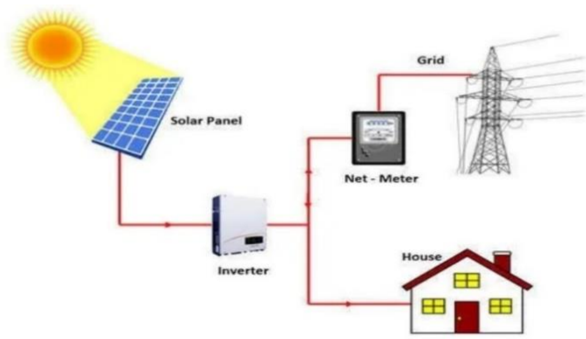

Fig. 3: An On-Grid System. (@ circuit globe assessed August 20,2023)

On-grid linked systems are feasible for various set-up such as household setting, commercial and bigger scale grid tied arrangement different from the off-grid PV schemes. Typically, grid linked arrangement do not require battery backup, since the arrangement produces the energy extra compared to the load, it will automatically transfer this energy to the linked utility gird.

MATERIAL AND METHOD

Materıal

Evaluation of Site and Factors of Efficiency on the PV Module:

The climate and average weather condition in Wukari is that, her raining period is frequently cloudy while the dry period is scorching and partially cloudy over the period of the year. Wukari is situated on coordinates 7.9303°N, 9.8125°E and 189m above sea level, within the Sahel region thereby attracting a lot of solar radiation. Wukari has an average sunlight of 10 hours with average sunrise time of 7.00 hours and sunset time of 18.00 hours, with a sun peak of 6.4 in Wukari between August and November and higher between December to June. Also involved is the identification of position and adherence to factors that will enhance the performance of the panels, the positioning of the sheets (panels) is one of such vital steps in scheming the PV system. Other thoughts and guidelines that was possess while evaluating the site for PV potentials [37] are summarized on the Table 1:

Table 1: Factors Effecting PV Cell Efficiency

S/N	Factors	Effects on Panels	Remedy
1	Shade	decreases the maximum power output of the panels	The use of solar pathfinder can provide the sun direction
2	Tilt Angle	Help in capturing the sunlight	Locate the latitude of the home for maximum sun range
3	Solar isolation	As the solar radiation increase, the proton current also increases, in the opposite, the out voltage of the solar cell is less affected	Mind the angle of incidence during the installation.
4	Dust and dirt	Block the sunlight access to the panels	To avoid dust, build up on the panels, horizontal installations is discouraged, and cleaning is done regularly.
5	Installation location	Location defines the panel's inclination or orientation	Roof mounted type was chosen
6	Temperature	Change in temperature affect output voltage negatively than the output current	The panels were installed few inches above the roof for airflow to cool the panels
7	Shockley and Queisser effect	Climate, inclination, latitude, and orientation may affect the panels.	Using Nano designed pane cell, this can improve the panel's efficiency
8	Sun hours	The sun determines the efficiency of the solar panel	The hours of sun radiation over Wukari ten (10) hours and the sun peak hours is 6.4

Also needed for the work include PV modules, Solar batteries, Inverter and Charge controller. Also are the typical residential building appliances within the three rooms and a parlour apartment, with the following electrical materials: Bulbs, Celling Fans, Television, Decoder and Deep freezer.

Method

The initial action in our method was to decide on the load of the system. The determination of this load will serve as a key influence in the project and estimate of the stand-alone PV arrangement. The electric loads obtainable within occupant were summarised with their individual power ratings with normal operational hours through the day, noted to find the power request or demand in watt-hour per day. The outcome was gotten, and these enable the further sizing of our proposed stand-alone photovoltaic system components sizes.
According to [38]. Components are size with the following formulae below.

PV Array Sizing

According to the above parameters, the total power of the required PV array (Ppv) can be calculated as follows [39][40].

The output power of PV array (P_{pv}) is given by:

$$P_{pv} = \frac{E_l}{\eta_s \, \eta_{inv} \, PHS} Sf \quad (1)$$

$$\text{No. of PV modules (panels) } (N_{pv}) \; N_{pv} = \frac{P_{pv}}{P_{peak,1\,pv\,module}} \quad (2)$$

$$\text{No. of Panels in series } (N_{ms}) \; N_{ms} = \frac{V_{dc}}{V_{module}} \quad (3)$$

$$\text{No. of Panels in parallel } (N_{mp}), \; N_{mp} = \frac{P_{pv}}{N_{ms} * P_{module}} \quad (4)$$

Where, Safety factor is noted as (Sf), residensial load or Electrical load (El), the total number of module (panels) (N_{mt}), .

The entire number of panels is assumed by the product of the series and parallel panels, this is.

$$N_{mt} = N_{ms} * N_{mp} \quad (5)$$

The Battery Bank Capacity (C_B)

In the strategy of the battery bank capacity, it is essential to reflect on some vital factors that always govern the obtainability of electricity and the appropriate action of the batteries. These include the days of autonomy (Na), that is, when there is slight, rebuff of solar radiation or overcast days. Also, permissible depth of discharge (DOD), conceivable battery loss, nominal voltage of our chosen battery and projected load energy in Wh. [41]

This stowage capacity of the battery can be calculated by means of equation 6.

$$C_b = \frac{E_l \, N_a}{DOD * V_{dc} * \eta_b} \quad (6)$$

On this project, rolls battery of Series 4000 Deep Cycle batteries was selected with T12 250 of the following features, a capacity of 200AH, voltage of 24V. In this design, the day of autonomy was taken to be 2 days with allowable maximum depth of discharge (DOD) reserved as 60% and efficiency (η_b) of 85%. Calculating the battery size by means of the above variable star, we implore equation 7,8, and 9.,

Total number of battery require (N_{breq}).

$$N_{breq} = \frac{C_b}{V_b} \tag{7}$$

Number of batteries in series (N_{bs})

$$N_{bs} = \frac{C_{dc}}{V_b} \tag{8}$$

Number battery in parallel ((N_{bp}), [40].

$$N_{bp} = \frac{N_{breq}}{N_{bs}} \tag{9}$$

Inverter Sizing.
Once scheming the system inverter size, a definite power drawn from the appliances that will serve at the same time must be decide upon at first step. Too, we must study the option of having big motors with identical elevated starting current by increasing their power factor by 4. Similarly, to permit the system to enlarge, we increase or multiply the sum of the two preceding values by 1.25 as a safety factor (Equation 10).

$$P_{inv} = P_{rs} + P_{lsc} * 1.25 \tag{10}$$

Taking:

- P_{inv} as the power rating of the inverter
- P_{rs} is the power of the gadget running at the same time
- Pısc is the surge cuurent of the gadget.

The Sizing of Charge Controller (ccr)
The size and capacity of the charge controller is rated depending on the power anticipated from the panels (P_{pv}) and the voltage of the system (V_{dc}). Equation 11 was used in determining the charge controller.

$$CC_r = \frac{P_{pv}}{V_{dc}} \tag{11}$$

RESULTS AND DISCUSSIONS

Results
The household applications obtainable at the home are listed with their power rating and the hours of operation throughout the day to get the normal (average) energy demand in Watt-hour per day as presented on Table 2.

For energy calculation of the System, this formula was used.

$$El = p * t$$

El = Electrical load, P = wattage *qty., t = time (hours/day)

Table 2: Appliances, and their power rating

s/n	Appliance	Quantity	Time of service	Wattage (each)	Hours of service/day	Watt hours/day
1.	LED bulbs	6	Night	10	12	720
2.	Celling Fan	3	Night	33	12	1188
3.	Cell Phone charging point	2	3 hours	5	3	30
4.	LED Television	1	6 hours	57	6	342
5.	Solar Charge controller	1	24 hours	1	24	24
6	Deep Freezer	1	12 hours	228	12	2736
7	Decoder	1	6 hours	25	6	150
Sum of Watt hours/day (E_l)						5190Wh

The Solar Panels Calculation and Sizing

The average hours of sunlight in Wukari (PHS) is 10 hours per day [42].

Solar module has the internal losses of 5% and inverter efficiency of 80% i.e., by addition gives 0.85, E_l = 5190Wh/day, Safety factor (S_f) = 1.25, η_s= 0.7%, and η_{inv} = 80% and PHS = 10hours.

$$P_{pv} = \frac{E_l}{\eta_s\,\eta_{inv}\,PHS} Sf = \frac{5190*1.25}{0.7*0.8*10} = 1158.5$$

Therefore, the power of the PV module is 1158.5W and the Panel Specification displayed on Table 3.

Table 3: Specifications of the panel

Category	400W (Monocrystalline)
Maximum Power	400
Maximum power Voltage (Vmp)	40.4
Maximum current power (Imp)	9.90
Open circuit voltage (Voc)	49.3
Short circuit current (Isc)	10.4
Module Efficiency (%)	19.68
Maximum system voltage	DC 1500V/DC1000
Maximum Series Fuse Rating	15A

The number of PV module.

$$N_{pv} = \frac{P_{pv}}{P_{peak,1\,pv\,module}} = \frac{1159W}{400W} = 2.9$$

From the above module calculation, 3 PV modules are required to serve the load.

Battery Calculation and Sizing

The battery bank capacity is given by.

V_b = 24v, DOD = 60%, η_B = 85%, Na = 2, V_{dc}=24V, E_1= 5190

$$C_b = \frac{E_l\, N_a}{DOD * V_{dc} * \eta_b} = \frac{5190*2}{0.6*24*0.85} = 848\text{Ah}.$$

Total number of battery (N_{tb})

$$N_{breq} = \frac{C_b}{C_{sel}} = \frac{848Ah}{200Ah} = 4.24$$

Number of batteries require for the system is 5.

Inverter Calculation and Sizing

Table 4 shows the energy consumption with surge factor.

Table 4: Energy consumption with surge factor.

s/n	Appliance	Quantity	Surge factor	Wattage	Watt hours/day
1.	LED bulbs	6	1	10	60
2.	Celling Fan	3	4	33	396
3.	Cell Phone charging point	2	1	5	10
4.	LED Television	1	1	57	57
5.	Solar Charge controller	1	1	1	1
6	Deep Freezer	1	4	228	912
7	Decoder	1	1	25	25
Sum of Watt hours/day (E_l)					1461Wh

$$P_{inv} = P_{rs} + P_{Isc} * 1.25$$

$$P_{rs} = 359\text{W},\ P_{Isc} = 1102\text{W}$$

$$P_{inv} = (359 + 1102) * 1.25 = 1737\text{W}$$

An inverter of standard rating 2KVA of 24V is essential to serve the load.

Charge Controller Calculation and Sizing

The charge controller is rated depending on the power of the PV module (P_{pv}) and the voltage of the system (V_{dc}).

Where P_{pv} = 1159W, V_{dc} = 24V

$$CC_r = \frac{P_{pv}}{V_{dc}} = \frac{1159}{24} = 48.3\text{A}$$

Therefore, charge controller of 50A of 24V is required. Below is the summary of the components sized on the system.

Table 5: Component sizing for the Proposed Off-Grid PV System

Components	Descriptions	Results
Load Estimate	Total load Estimated	5190Wh/day
PV Module	PV Module Capacity needed	1159W (400W *3)
Battery Bank	System power bank capacity	200Ah * 5.
Charge Controller	Capacity of the charge controller	50A*1

Inverter	Capacity of the Inverter	2KVA

Cost Estimate

Table 6: The components Estimate.

Appliances	Models	Rating	Quantity	Unit Price (Naira)	Cost of component
PV Module	PSM 400W	400W-24V	3	50,000.	150,000.
Battery	ST500	24V-200Ah	5	110,000.	550,000.
Charge controller	MPPT	50A-24V	1	22,999.	22,999.
Inverter	HT	2KVA-24V		199,200.	199,200.
Sub-total cost					812,199.
Other costs of balancing the system like wires, fuses, circuit breakers etc.) (10% of Sub-total)					81220.
Overall total of the Project (Cost in local Currency, Naira)					1,003,419.

DİSCUSSİONS

In this study, the projected stand-alone PV arrangement was designed based on projected load demand in watt-hour/day evaluation of home applications. The outcome of the projected daily energy need of 5,190KWh/day, presented on Table 2. In a case study of Ogwashi-Ukuwu, a research conducted by Nwabuokei [43], under the application of similar pricinple, an estimated daily energy consumption of 7,875KWh/day was considered. The comprehensive upshot of components sizes presented on Table 3, comprising of 3 PMS400W-24V PV modules which can produce an array power of 1159W. The battery bank storage facility was designed to meet the energy demand (E_l) in this study. A total number of 5 batteries with the rating of 24V-200Ah ST500 with a bank capacity of 1000Ah on a targeted required amp-hours of 848. Having two (2) and three (3) batteries each connected in series and then parallel them for a better output. MPPT Charge Controller of 50A-24V was selected and a 2kVA inverter was recommended to meet the power need of our design. To complete the system design, a cost estimate of N893,419.00 (1,168.52 US Dollar) was obtained (Table 6).

CONCLUSION

The design of photovoltaic off-grid stand-alone PV energy source was sucessfully carried out. This arrangement is usually envisioned for use in an area where power supply is unstable, as well as in a settlement where access to the grid system is disconnected or inaccessible. The system is highly recommended for used in Wukari Nigeria, where the solar radiation is high enough even in rainy season. If this sun resource is professionally tapped, it will be sufficient to serve as a substitute to the electrical energy demand in the area all year round. This work also provided a complete cost plan for a stand-alone household arrangement with its details cost assessment for an individual application.

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