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Techno-Economic Design of a Standalone Solar PV System for TY Danjuma Conference Building, Rivers State University, Port-Harcourt

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Abstract:
Photovoltaic systems (PVs) are a clean and pollution-free energy source that can be used on various scales, including grid-tied and off-grid systems. Standalone systems are easier to operate than grid-tied systems, and the PVs are commonly installed on rooftops. This study aims to address the issue of frequent grid-power cuts and high operational costs of diesel fuel, which can affect productivity from PV systems during working hours. To achieve this objective, a load survey was conducted and design calculations were made to normalise the peak watt power to 42kWp as demanded. Computational and analytical methods were applied to analyse the power delivery components required for the loads. The analysis revealed that the cost of running a diesel-powered generator over five years is estimated at ₦81,852,003, excluding procurement costs. On the other hand, the cost of acquiring the solar components for the study case building is estimated at ₦41,474,470.32 with zero fuel cost. The resulting computation provides 140 numbers of PV panels, 48 numbers of 12V/200Ah deep cycle batteries, a 25kVA inverter (or with two sets of inverters, 15kVA and 10kVA, 48Vdc/220Vac), 6 numbers 48Vdc/150Amp solar charge controllers or a single 48Vdc/900Amp solar charge controller. The results obtained are in line with the load requirements and the prevailing market for available components. The typical lifespan of most components used in PV systems usually falls within the range of 5 to 10 years. Solar-powered systems offer more advantages in terms of daily, monthly, or yearly running and maintenance costs, and eliminate power cuts as compared to diesel-operated generators used in the case study. The long-term operational benefits of solar PV systems can hardly be ignored.

Keywords: Accessories, Battery and Battery bank, Inverters, Load survey, Solar PV modules, Solar charge controllers.

I. INTRODUCTION

A photovoltaic effect is the direct conversion of energy from the sun (sunlight) to electricity using photovoltaic cells. Series-parallel connection of these cells becomes a module. Several connections of these solar modules become an array of solar modules which generate a larger quantity of electricity. Standalone PV systems are off-grid generation and distribution systems. It is a unidirectional power processing system tied to the consumer to load. Energy consumption is a daily activity.

Abdulkarim (n.d.) asserts that solar energy is the best option given the high cost of fossil fuels, the dangers of nuclear power, and the unreliability of hydropower. The sun emits a tremendous quantity of energy. In a single year, it emits more energy than humanity has ever utilised. Variable zones have variable radiation levels due to variations in sunshine hours. However, the average amount of solar radiation that reaches Earth is 939 W/m^2, after atmospheric reflection, absorption and scattering. Since the invention of solar energy conversion devices, a plentiful supply of solar energy has been continuously used to produce power and energy in a variety of human endeavours. The application photovoltaic system could be on a large scale or in a small-scale generation of power. That is, it could be off-grid (standalone) or grid-connected in terms of large-scale generation. The most fundamental need of everyone in the world is energy and it is needed more than ever as expected. The energy from burning coal, oil and gas called fossil fuels are widely used but these energy sources are non-renewable and harmful to the environment, especially their wastes. All the energy on Earth comes primarily from solar energy. Solar energy is energy from the sun. It is renewable, inexhaustible and environmentally pollution-free [1].

Elbreki et al., (2016) identified that even though renewable energy sources are widely available worldwide, developing nations have been struggling to maintain a steady and consistent electricity supply. There is not a nation on the planet that does not have access to one or more renewable energy sources, such as biomass, hydro/water, sun, wind, and water. These sources are all natural and simply require technology to harness and drive their energy and turn it into power using the right mechanism. Since energy is the foundation of a country's industrialization, a state's development will be hampered or slowed when supply cannot keep up with demand. When it comes to renewable energy, the sun provides us with two primary forms of energy: light and heat. Solar thermal systems heat water, and a molten state while solar PV systems convert sunlight into electricity; Plate 1 demonstrates the difference between these two types of solar power systems adapted from Elbreki et al., (2016). Photovoltaic systems convert light into electricity by absorbing direct or diffuse sunlight. This results in the generation of DC electric power, which can be stored in a battery system or fed into an inverter for AC distribution. PV cells and modules do not use heat, making them suitable for photodetectors like infrared detectors [2]

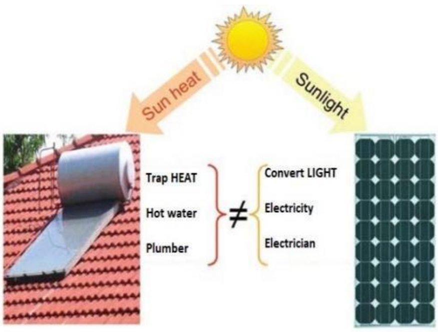

Plate 1: Two main types of solar power systems. Adapted from [2]

Askari *et al.* (2015) suggested that optimal solar panel types and conditions can make the sun a cost-effective, efficient, and reliable energy source, paving the way for future advancements in solar energy production and storage. In their research, they presented four (4) types of solar panels commonly available as Monocrystalline Solar Panels (Mono-SI), Polycrystalline Solar Panels (p-Si), Thin-Film: Amorphous Silicon Solar Panels (A-SI) and Concentrated PV Cell (CVP). Among the four types, concentrated PV cell has 41% followed by monocrystalline 20% [3]

According to Benjamin and Dickson (2017), Nigeria has a great deal of potential for using solar energy because of its abundance of sunshine. With a land size of 765 square kilometres and an elevation of 307.4 metres, Ilorin, Kwara State is a case study. That Ilorin is ideally situated for solar radiation. To give residential units in remote locations without access to the country's electrical grid a cleaner and more efficient alternative energy source is required. The paper suggests a solar system configuration with an 82-degree tilt angle. The effect of global climate change has been an impeding problem all over the world; it is required that Nigeria put more effort into the energy sector if it wants to advance the economy and have sustainable energy for the future. Renewable energy technology could drive the energy sector faster [4].

In a related publication, Awad *et al*. (2021) presented a case study design of a stand-alone photovoltaic power system in Gaza-strip and generalised a program simulation to provide the necessary components requirements. They noted that, for regular power supply, a battery storage system and charge controller for charging and discharging of the battery bank is necessary considering days of low insolation or cloudy days. Fig. 1 shows a typical solar PV standalone power generating system [5].

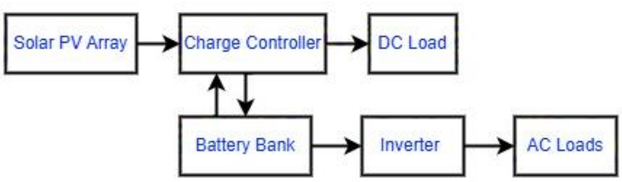

Fig. 1: Solar PV standalone power generating system. Adapted from [5]

Furthermore, Hamza et al. (2018) pointed out that the population's rapid growth and the industrial sectors' increasing activity need a comparable rise in electricity generation. Incorporating solar photovoltaic (PV) systems into the country's energy mix can significantly lessen the energy issue and aid in the development of distant areas. For the Gombe household load, a standalone photovoltaic power system was thus chosen [6]. Photovoltaic panels can be set up to operate as a standalone system or as a grid-connected system, according to Dheeban et al.'s (2019) design of a standalone PV system. Those isolated systems are simpler to set up and more dependable. The growth of rural areas is observed via the solo system. Standalone PV systems are very much easier to set up and function excellently when battery back-ups are included; however, the various system components for standalone were modelled using MATLAB Simulink as seen in [7].

In a comparable small-scale project, Ezugwu (2012) designed and installed a 200-watt solar power system to supply the department's appliance with reliable, effective power if the mains fail. The following parts—solar panels, inverter, batteries, charge controller, etc.—were chosen after estimating the predicted load because steady power was not guaranteed. Systems for generating power from solar energy are less expensive than those that use fossil fuels [8].

In a comparable design by Karafil and Özbay (2018), the components were designed with the load and energy requirements of the photovoltaic (PV) system-powered stand-alone farmhouse in Bilecik City in mind. The residence was found to use 5.58 kWh of energy on average each day. The PV panels were installed on the roof at a 40° tilt angle, which corresponds to the city's latitude. The necessary balance of system (BOS) components was identified [9].

Kumar et al. (2014) presented a very simple solar-powered umbrella with the necessary design parameters calculated. The solar octagon umbrella panels consist of 8 separate flaps that were connected from one side to an octagon centre shape. The design comprises load calculation, sizing of solar panel, battery and battery bank, etc [10].

In a similar spirit, Dioha and Kumar (2018) present a technical paper intending to estimate the technical perspective of rooftop solar PV in Nigeria using the PVSyst software and computational logical method to simulate and evaluate the annual energy yield of the rooftop solar PV, etc., with selected cities throughout the nation [11]. Solar power systems are among the greatest renewable energy technologies available, according to Khamisani (n.d.). They are not only reasonably priced but also environmentally benign. He employed design techniques in his research to apply to various off-grid applications, and naturally, he proposed an off-grid bus shelter. One definition of off-grid or freestanding systems is autonomous systems that are not linked to any electrical grid. They are typically utilised in areas with limited access to grid infrastructure and are available in various sizes as seen in [12].

Also, as seen in Olayiwola *et al*. (2021) one of the most promising answers to the pressing issue of electrification for many remote consumers is stand-alone photovoltaic systems. In their paper [13], they employed a step-by-step design of a freestanding solar system for a residential building with the necessary components computed. A 50kW daily usage for the isolated system was taken into consideration in the Echendu & Amadi (2018) study. The hardware and software of a solar tracker with an embedded control system program were demonstrated. To accomplish this, they make use of programmable microcontrollers (PIC16F877A), power relays (NTE-R22-5), DC gear motors with linear actuators (HARL-3618), etc. A comparative test was conducted between the created solar tracking device and a fixed PV panel with an equivalent rating, as they have described in their work. The fixed PV panel produced 5W at 8:00 am and reached a maximum of 25.62W at 1:00 pm, before decreasing to 10.6W at 6:00 pm, according to their test results; in contrast, the panel equipped with a sun tracking device generated 14.3W at 8:00 am reached a maximum of 25.83W at 1:00 pm and decreased to 16.28W at 6:00 pm. When compared to a fixed panel, the efficiency is increased by 33% when a solar tracking system is used [14]. In contrast to a fixed rooftop or ground-mounted system, the solar tracking device used here required an additional expenditure—increased output power when combined with a solar tracking device. The researchers Obojor-Ogar et al. (2023) focused on calculating system losses and sizing solar power system components using PVSysts software. Unfortunately, the system performance reported in their work was 58.83%, whereas 41.17% of the energy produced was considered wasted as a result of the cumulative losses [15].

The stepwise technique was used in the work of Sharma and Sharma (2010) to determine the ideal size of a stand-alone photovoltaic system with a design load of 1kWP, 2kWP, 5kWP, and 10kWP [16]. Ikechukwu and Chibueze (2022) presented in their paper that the annual average solar irradiation considered was 4.71kWh/m2/day in the study. Hybrid Optimization of Multiple Energy Resources (HOMER) software was used to perform the techno-economic analysis of the standalone system for Umudike, Abia State, Nigeria. A photovoltaic system of 78.2kW was estimated. The minimum and annual operating cost of energy (COE) presented was $0.829 and $13,355 whereas the system's initial capital cost was equal to $330,211 and a net cost of $442,683 to provide uninterrupted power supply [17].

Alves et al. (2014) discussed the financial implications of using solar and diesel energy for drip irrigation. They found that while solar systems have lower operating costs than fossil fuel systems, the cost of energy used to pump water to an irrigation site is still higher for diesel. To pump water into the irrigation system, two scenarios were presented: (a) solar, battery, and electric motor; and (b) diesel fuel, diesel-powered generator, and electric motor. Although a solar system requires a larger initial investment than a diesel-fuelled system, in terms of operational costs, solar power is more cost-effective than diesel power. Keep in mind that solar energy is emission-free and green [18].

Similarly, Nwobi et al. (2014) used Life-Cycle costing and analysis to perform a cost-comparison study between the solar-powered system and the fossil-fuel-powered system. Their research indicates that the solar system can power the pump's 0.75kW load. On the other hand, if the costs of the two systems are compared throughout their 20-year life cycle, the fossil-fuel-powered system will come out on top by more than 200%. Also, fossil-fuel-powered systems discharge carbon emissions annually whereas solar energy systems do not [19].

Currently, the Nigerian public power supply (PPS) is still erratic, not constant, however, rendering man-hour loss, etc. during working hours. Nigeria faces a major problem with constant power supply from the grid, affecting commercial, and private businesses, institutions and students' research performance. Efforts to improve the power supply in Nigeria are a year-by-year discussion in the budget, but there is still no substantial improvement. As seen in research, the total electrification in urban and rural areas is below 40%. We have seen that the constant power supply to the T.Y Danjuma building in this case study is hindered by finance and maintenance constraints - the high cost of petrol and diesel is not left out. Thus, this research aims to access, evaluate and provide the techno-economic design and benefit of a standalone solar PV system for the TY Danjuma Conference Building. Located at Electrical Engineering Department, Rivers State University, Port-Harcourt, Rivers State. In other words, provision of solar power-based (balance of system) electrical services for the Conference Building with an efficient and readily available alternative power supply to all appliances during working hours. To this effect, we will carry out the following objectives as stated:

i) To use the necessary data (load survey) and information acquired to estimate the net total load demanded;
ii) To determine and size the balance of the system (components) to be used such as solar PV panels, charge controllers - either PWM or MPPT model, DC /AC converter (inverter), battery bank (using deep cycle batteries), connecting accessories, protective device, etc.
iii) To proffer techno-economic analysis between solar PV and diesel-generator (long-run) in a standalone system for effective power supply, etc.

There are several advantages one may enjoy when it comes to the use of Standalone solar PV systems for alternative power supply.

i) The source of fuel is free (from sunlight) during the day.
ii) Solar-powered are eco-environment friendly. It does not produce harmful waste and can be used anytime and anywhere during the daylight but requires a storage system during nightfall.
iii) It saved the grid from a large amount of electrical energy intake and frequent grid collapses.
iv) Save time and no worries about the public power supply from the grid when properly installed.
v) Overall maintainability is low
vi) Almost zero operational cost

II. MATERIALS AND METHOD

A. *Materials*

Solar power offers a promising solution for harnessing clean renewable energy and for the energy needs of the TY Danjuma Conference Building, Electrical Engineering Department. Location: Rivers State University, Nkpolu-Oroworukwo, Port-Harcourt, Nigeria. The following key components will be selected accordingly:

(i) 24Volts rating of solar PV modules
(ii) Charge controller(s) with PWM or MPPT
(iii) Deep cycle DC batteries (for Battery Bank)
(iv) Inverter(s)

Accessories Required

(i) Digital voltmeter
(ii) Battery clips
(iii) Switches
(iv) Connectors,
(v) Cables (2.5mm^2, 4mm^2 and 16mm^2 wires)
(vi) Trunk boxes , etc.

B. Methods Utilised

In line with [4, 16 - 20], both computational and analytical methods will be adopted here chronologically to provide a detailed balance of systems required for the alternative clean energy to the load demanded. Without a thorough load audit, the solar-powered system and its delivery gadgetry would not be adequately sized. Hence, detail load survey, useful assumptions, design calculations, etc., to efficiently provide the requirements.

B (i) Load Survey

The building under consideration is office-used and used at least 8 hours per day during working hours. The net load accessed are as follows:

i. 4 No. of Air conditioners, each rated 1.5 hp (Horsepower). (1.5hp = 1119W)
ii. 15 No. 13A Socket outlets. Each at (Assumed 300W consumable/socket)
iii. 13 No. lighting points (using 45Watts LED lamp/point)
iv. 4 No. lighting points (security light) (using 100Watts LED lamp/point)
v. 5No. ceiling fans at (60 -70 watts)

B (ii) Calculation of Loads in Watts

First, we calculate the total load required that the solar power system needs to provide. Applying equation (1).

$$Total\ No. of\ load = No. of\ load(s) x\ wattage\ of\ load(s) \quad (1)$$

a) Air-conditioners: Each 1.5 hp Air-conditioner (1.5hp = 1119W).

The total load is 4 x 1119W **= 4476W = 4.476kW**

(No Diversity factor applied because, during 8 hours of working in the office, the Air-conditioners will be used)

b) 13Amps socket outlets: Assuming each socket outlet is to be loaded to 300W.

15No. x 300W = 4500W. Since all the sockets will not be loaded/used at the same time. Applying a diversity factor of 0.8, we have 0.8 x 4500W = **3600W**

c) Lighting Points: The power consumption of lighting points depends on the type of bulbs used. For this calculation, we used 45W per lighting point within the office and 100W LED lamps outside the office (security light).

Hence, for **13 lighting points**, the total load is 13 x 45W = 585W. Applying a diversity factor of 0.9. we have 0.9 x 585W **= 526.5Watts**

For **4 lighting points** (security lights) we have 4 x 100W = 400W. Applying a diversity factor of 0.7. we have 0.7 x 400W = **280W**

For Ceiling fans: A typical ceiling fan consumes around 60-70 watts. Therefore, for 4 ceiling fans, the total load is 4 x 65W = 260W. Applying a diversity factor of 0.9 (since all the fans may not be used at the same time). We have 0.9 x 260W **= 234Watts**

Net total load: Air-conditioners + 13Amp wall sockets + Lighting Points + Ceiling fans.

Net total load = 4476W + 3600W + 526.5W +280W + 234W = 9116.5W **= 9.1165kW**

But for proper sizing of the power delivery components (solar power system); we will add 25% load capacity to the calculated netload.

Hence, we have 25% of 9116.5W **= 2279W**

Corrected net total: 9116.5W + 2279W **= 11395.625W.** Approximately we have **11400W = 11.4kW**

Using a power factor of 0.8, we have 11400W/0.8 = 14250VA = 14.25kVA

The corrected net total load required is 11.4kW or 14.25kVA

Net total energy consumption per day

$$= \text{Net total load in Watt x useful hours/day} \quad (2)$$

From equation (2), the net total energy consumption per day = 11400 x 8h/day = 91200Wh/day = 91.2kWh/day

Corrected Watt-hours per day for the building = 91.2kWh/day

The assumption applied as per (Jignesh, 2016) [20].

All e**lectrical load** will be used for 8 hours/day

Solar system details:

i. Solar system voltage (as per battery bank) = 48V DC
ii. Loose wiring connection factor = 20%
iii. A daily sunshine hour in summer = 6 hours/day
iv. A daily sunshine hour in winter = 4.5 hours/day

v. A daily sunshine hour in monsoon = 4 hours/day

Inverter / Battery Details:

i. Additional further load expansion (Af) = 20%
ii. Efficiency of inverter (Ie) = 80%
iii. Inverter power factor = 0.8
iv. Required battery backup (Bb) = 2 hours.
v. Battery bank voltage = 48V DC
vi. Loose connection/wire loss factor (LF) = 20%
vii. Battery efficiency (n) = 90%
viii. Battery ageing factor (Ag) =20%
ix. Depth of discharge (DOD) =50%
x. Battery operating temp =46ºC

Table 1: Temperature Correction factor [20]

Temp. ℃	80	70	60	50	40	30	20
Factor	1.00	1.04	1.11	1.19	1.30	1.40	1.59

B (iii) Solar Panel and Array Sizing

To generate the required power, we need to size the solar panel array properly. Solar panels' capacity is often given in watts (W) or kilowatts (kW). To generate 11.4kW, the solar panel array's capacity should ideally be greater to account for inefficiencies and variations in sunlight. Solar panel direction for South-South West (22.5deg), Rivers State. Table 2 shows the Port-Harcourt solar insolation average of 4.1kW/m^2/day. We will use this data. Further computational steps of the system components, concerning power consumption demand, sizing PV module, solar module/ panel in the array, etc., are shown below:

Table 2: **Port Harcourt Average Solar Insolation [21]**

Measured in kWh /m^2/day onto a solar panel set at 100 deg (Optimal summer setting)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
5.15	5.13	4.63	4.43	4.10	3.42	3.13	3.30	3.30	3.57	4.13	4.91
Total = 49.2 kWh/ m^2/day											
Average = **4.1**kWh/ m^2/day											

Step 1: Calculating the Power Consumption Demand in Watt-hour/day

Determination of total watt-hour per day consumed by the appliances. We have to ascertain the corrected total watt-hours per day needed from the PV modules. As seen in [4] the factors affecting solar PV systems under consideration are: (1) wiring connection losses (10%) and (2) battery losses (20%).
The total factor is equal to 30%.

Now, taking 100% plus the 30% factors of the calculated total watt-hours per day; that is 130% (1.3pu) of the energy required from the solar modules. Hence, we multiply the total watt-hour per day by 1.3. We have the net corrected total watt-hour per day which must be supplied by the solar modules (panels).
Load energy required = **11400**W x **8**hours = **91200Wh/day**

Hence, **net corrected total energy** required from the solar PV panels = 91200Wh/day x 1.3 **= 118560Wh/day or 118.56kWh/day**

Step 2: Correction factor for PV Modules (Panels)

The total watt-peak rating needed for the PV modules to operate the appliances; the net corrected total watt-hours per day required from the PV module as calculated earlier is divided by the ***panel generating factor***. Note, that the solar irradiation varies in different locations, and so does the panel generating factor. The panel generating factor is obtained by taking into account the correction factor for a solar PV module. The correction factor for a single solar PV module is in reality as seen in [4]. Equation (3) calculates the panel generating factor (PGF).

Correction factor for single solar PV module:

(1) Take 85% due to temperature above 25 ℃
(2) Take 95% due to sunlight not striking the panel straight on (caused by glass having increasing reflectance at lower angles of incidence)
(3) Take 90% due to not receiving energy at the maximum power point (factor not used if there is an MPPT controller)
(4) Take 95% allowance for dirt
(5) Take 90% allowance for the panel being below specification and for ageing

PGF = Solar Irradiation x Total correction factor on the solar panel (3)

Since an MPPT solar charge controller uses the 90% correction factor due to loss, not receiving energy at the maximum power point is removed.
Therefore, the total correction factor applied = 0.85 x 0.95 x 0.95 x 0.90 = **0.69**

Step 3: **Calculating the Total No. of Solar Panels in Array**
From Table 2, the average solar irradiation in Port-Harcourt, Rivers State, was calculated as 4.10kWh/m^2/day.
Therefore, the ***panel generating factor (PGF)*** = 0.69 x 4.10 = 2.829

Total Watt-peak (Wp) of the PV module capacity required

$$= \frac{Total\ PV\ \ watt{-}hour\ required\ per\ day}{Panel\ generating\ factor} \quad (4)$$

Total Wp of the PV modules capacity = $\frac{118560Wh/day}{2.829}$

= 41,909Wp ≈ **42000Wp or 42kWp**

Selecting the type of solar module based on efficiency, durability and availability. See in [3]

Using 300watts, 24V **(Mono-crystalline**) solar panel due to better efficiency. Determination of the **total number of PV**

panels/modules needed, the total Wp of PV panel capacity calculated is divided by the capacity of a single solar panel. That is by 300 watts.

Total number of PV panels needed $= \frac{42000}{300} =$ **140** solar PV modules.

300 Watt, 24 volts Monocrystalline Solar Panel Specification [22]

Maximum Power/Pmax(W) 300
Maximum Power Tolerance +3%
Open Circuit Voltage 43.2
Short Circuit Current 8.85
Max Power Voltage 36
Max Power Current 8.35
Weight (Kg) 20.5
Dimensions(mm) 1000
Max System Voltage 27.00VDC +-0.5
Max Over Current Protecting Rating(A) 15
Module Application Class A

300Watt, 24 Volts Monocrystalline Specification [23]
Maximum Power at STC: 300W
Maximum System Voltage: 1000VDC
Optimum Operating Voltage (Vmp): 32.25V
Open Circuit Voltage (Voc): 39.82V
Optimum Operating Current (Imp): 9.33A
Short-Circuit Current (Isc): 9.78A
One Piece Dimensions: 64.96 x 39.25 x 1.57 inch
One Piece Weight: 42.8 lbs

Step 4: Modules (Panels) Connections
Multiple solar panels are connected in a series-parallel connection to achieve the desired wattage and effective voltage. However, in a series-parallel connection both capacity (Watt) and Volt are increased.

$$\text{No. of solar panels in each string} = \frac{\text{Solar System Volt}}{\text{Each Solar Panel Volt}} \qquad (5)$$

No. of solar panels in each string= 48V/24V = 2 Nos. (i.e., Series connections)
Total No. of Solar Panel = 140 Nos.

(2Nos. in series and 70 Nos. in parallel connections)
The computational reference [4].

B (iv) Battery Bank Sizing

A set of batteries connected in a manner (series-parallel) to give a common output power and voltage is known as a Battery bank. The battery bank stores the energy produced by the solar panels through a charge controller connected to the circuit. The battery must have sufficient capacity to provide the necessary power in sunlight, during periods of low sunlight, and on cloudy days. The most common type of battery for a solar PV system is a deep-cycle battery. Deep cycle batteries are specially designed to charge low and fast every day for years. The battery sets must be large enough to store enough energy to run devices at night and on cloudy days [4]. It is recommended to have a battery bank with a capacity of at least 2 - 3 days' worth of energy consumption. So, we will consider 2 days of autonomy.

Step 5: Size of Battery and Bank:
The following inverter/battery details mentioned above are needed in the sizing of the batteries and bank, we have:

i). Add further load expansion factor (Af) = 20%
ii). Efficiency of inverter (Ie) = 80%
iii). Inverter power factor = 0.8
iv). Required battery backup (Bb) = 2 hours.
v). Battery bank voltage = 48V DC
vi). Loose connection/wire loss factor (LF) = 20%
vii). Battery efficiency (n) = 85%
viii). Battery ageing factor (Ag) =20%
ix). Depth of discharge (DOD) =50%
x). Battery operating temp =46ºC

The battery capacity in Amp hour is given by equation (6)

$$Battery\ capacity\ (Ah) = \frac{\textbf{Total Watt-hour/day used by the appliances}}{(\mathbf{0.85\ x\ 0.5\ x\ nominal\ battery\ voltage})} \text{ x Days of autonomy} \qquad (6)$$

Where:
0.85 is the battery efficiency factor at a 15% loss value and 0.5 is the battery 50% discharge depth (DOD) value We measured a nominal battery voltage of 48V with two (2) independent days. Independence days are required days for the system, to operate when electricity is generated by solar PV panels [4],[16 - 20]. Applying the equation (6) and recalling the corrected energy required per day by the appliances, we have:

$$Battery\ capacity\ (Ah) = \frac{\frac{\mathbf{91200Wh}}{\mathbf{day}}}{(\mathbf{0.85\ x\ 0.5\ x\ 48})} \boldsymbol{x\ 2} = \mathbf{8941.18\ Ah}$$

Battery Bank capacity = 8941.18Ah
Now, using a 12V/200Ah deep cycle battery; easily accessible in the market, we will have

$$\frac{8941.18\ Ah}{200Ah} = 44.71$$

No. of deep cycle batteries calculated is 44.71 approximately **45 No.**

Step 6: Arrangements of the Batteries
Series-parallel connections of the batteries are arranged to achieve the system voltage and power. We have a calculated battery bank capacity of 8941.18Ah ≈ 9000Ah

Using 12V/200Ah per single battery capacity
Solar system voltage = **48 V**
No. of batteries in series = 48V/12V = **4 Nos**. (**in series connection**)

No. of batteries in parallel connection = 45/4 = 11.25 string (**in parallel connection).** We will use 12 strings in the parallel connection to achieve a **9600Ah battery bank and the Total number of batteries now required is 48No.**

B (v) Inverter Sizing

The maximum load demand should be at least equal to the inverter capacity. To handle surges or starting currents from specific appliances, it's a good idea to select an inverter with a little excess capacity. To realise the capacity requirement, we will carry out the calculations shown below.

Inverter Capacity (Watts) =

Total Load Demand x Safety Margin (7)

Usually, there is a 25% to 30% safety margin. Although a 30% margin is frequently a wise decision, we can change it depending on the unique characteristics of the loads.

Step 7: Calculate the Size of the Inverter:

Total electrical load in Watt = 11400 Watt = 11.4kW

Total electrical load in VA =

$$\frac{\text{Net total load in W}}{\text{Power factor}} \text{ VA} \quad (8)$$

Total electrical load in VA = 11400/0.8 = **14,250VA as earlier calculated**

Size of Inverter =

$$\frac{\text{Net total load in W x Correction factor}}{\text{Efficiency of inverter}} \text{ VA} \quad (9)$$

Size of Inverter = (11400 x (1+0.3)) / 0.80 = **18525 Watt**

= 18.525kW

Size of Inverter in Apparent power =18525 / 0.80

= 23156.25VA = 23.2kVA

Size of Inverter = **18.6 kWatts or (23.5kVA - 25kVA)**

Inverter rating: 23.5kVA, 48Vdc/220Vac

B (vi) Charge Controller

A charge controller is essential to manage the charging of the batteries from the solar panels. We must ensure the size can handle the maximum current generated by the solar panel array. The solar charge controller is typically rated against the amperage and voltage capacities of the solar panels and the battery bank. The solar charge controller is selected to match the voltage of PV arrays and batteries which then enables the selection of the right solar controller for the solar system design. According to standard practice, the sizing of the solar charge controller is to take the short circuit current (Isc) of the PV array and multiply it by a safety factor of 1.25 (see in [4]). There are two main charge controllers such as MPPT (more efficient and expensive) and PWM (less efficient, cheap and simpler). We will compare Equation (10) and Equation (11) concerning the charge controller rating. In this paper, we used a **maximum power point tracking (MPPT) charge controller**. Thus,

Solar charge controller rating =
Short circuit current of PV module x modules in parallel x 1.25 (10)

For the solar panel products from [22], the short circuit current (Isc) of a 300-watt module is 9.78A. Since we have 70 modules in parallel from our computation and arrangement of the modules. Using a safety factor of 1.3 and using equation (10) we have:

$$Solar\ charge\ controller\ rating = 9.78Amp\ x\ 70\ x1.3$$
$$= 889.98\ Amp$$

We can use equation (11) as well to compute the solar charge controller rating. Thus,

$$Solar\ charge\ controller\ rating\ (in\ Amps) =$$

$$\frac{Solar\ Panel\ Array\ Capacity\ (Watts)}{Solar\ Panel\ Array\ Voltage\ (Volts)}\ Amp. \quad (11)$$

$$Charge\ Controller\ rating\ (\ in\ Amps) = \frac{42000\ (Watts)}{48(Volts)}$$
$$= 875Amp.$$

Both calculations yield approximately the same result, thus, we will use ***48V, 900Amp to 48V, 1000Amp*** rating solar charge controllers for effective solar power system delivery. However, in the absence of 48V, 900Amp, six solar charge controllers (each 48V, 150Amp.) can be used to achieve the desired charging. Each 48V, 150Amp MPPT charge controller will be configured to control the sub-arrays of solar modules.

C. Techno-economic Perspectives of Solar Energy Utilization (Diesel vs. Solar)

We will illustrate briefly the cost implication between fossil fuel (diesel and generator) and solar-powered system and their power delivery components. As seen in Chris, (2023), the cost of running a generator depends on the amount of fuel it will consume, the generator size, and the load connected. A typical 25kVA diesel-generator consumption rate is 6.06 litre/hour working at full load [24]. As of September 2023, the cost of Nigeria's diesel price is N1004.98/litre (Global petrol prices.com, 2023) [25]. See Table 3.

Table 3: Generator and diesel fuel

Diesel Generator	**Price (N)**
Brand New 25kVA soundproof, Perkins	N3,650,500 – N4,350, 500
Diesel fuel	N1004.98/litre

From Table 3, If the diesel- generator is to run for 8 hours/day. Then, the running cost for 8 hours/ day will be 6.06 litre/hour x 8 hours/day x N1004.98/litre = N48,721.43/day.

For 28 working days, we have N48,721.43/day x 28days = N1,364,200.05 (Running cost per 28days)

If we add the purchasing cost of the generator from Table 3 plus the 28days running cost, neglecting maintenance cost at the moment, we will have **N5,714,700.051**

Excluding Generator Procurement Cost

Assuming 28 days/month in operation for 1 year. It will be

N1,364,200.05 X 12 = **N16,370,400.6/year**

For 5 years: N16,370,400.6/year X 5years = **N81,852,003**

This is just fuel cost for 5 years and that is if the fuel price is stable otherwise fuel cost for operating the Diesel-generator will also be increasing.

The cost implications of solar components are somewhat expensive but that is the initial procurement and installation cost, however, no purchasing of fuel. The solar energy is free. Table 4 shows the cost of standalone solar-powered components in the prevailing market accessed online.

Table 4: Cost of standalone solar-powered components

Components	Quantity	Price (N)/unit	Total (N)
Solar energy (sunlight)	4.1kWh/ m^2/day	-	0
300-Watt Mono. Solar Module	140	99,000	13,860,000
12V/200Ah Deep Cycle Battery	48	286,999	13,775,952
Inverter 15kVA, 48Vdc/220Vac	1	1,250,000	1,250,000
Inverter 10kVA, 48Vdc/220Vac	1	1,060,000	1,060,000
Solar charger controller ***48V, 150Amp rating***	6	1,921,419.72	11,528,518.32
			41,474,470.32

It is a clear indicator that, the overall cost of fossil fuel and solar sources for 5 years of operation cannot be neglected, rather appreciative of the utilization of solar sources. The running and maintenance cost associated with the diesel-generator will be higher as compared to the solar power system in the long run.

III. Results and Discussion

A. Results

A (i) Results of Load and Energy Components

The expected load demands presented is 11.4kW or 14.25kVA. The net total energy consumables per day is 91.2kWh/day

A (ii) Results of Solar Loading

Solar panel direction for South-South west was 22degree. Average solar irradiation 4.1kWh/m^2/day. The total energy required from the solar PV panels 118.56kWh/day (output from the solar array). Total Peak- watts of PV module capacity = 42000Wp = 42kWp.

Type and rating of solar panel: 300Watts, 24Volts Monocrystalline panels. Plate 2 shows a typical 300-watt, 24V Monocrystalline Solar Panel adapted from [22].

A (iii) Results of Modules Connections

2 Numbers in series (Row connections)
70Numbers in column (Parallel connections)
Total number of (300Watts, 24Volts solar modules): 140

Plate 2: 300 Watt, 24V Monocrystalline Solar Panel [22]

A (iv) Results of Modules Connections

Battery and Battery Bank Capacity
Battery type and rating: 12V/200Ah deep cycle batteries.
Number of batteries: **48**
Batteries connections (Series-parallel), (4 x 12 batteries)
Numbers in series connections: **4**
Numbers in parallel connection: **12**

Fig. 2 shows the battery arrangement constituting 12 strings of parallel connections of each 12V/200Ah batteries

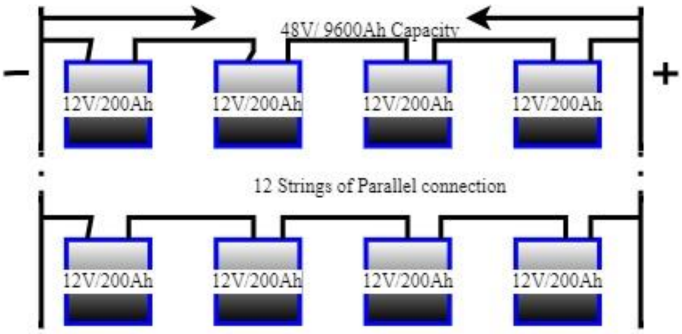

Fig. 2: 48V/9600Ah series-parallel connection of batteries (Battery bank)

A (v) Inverter Rating

(23.5kVA – 25kVA), 48Vdc/220Vac

We can use two inverters connected in parallel to achieve the desired total output. Fig. 3 shows a parallel connection of two Inverters. Therefore, we can have 10kVA, 48Vdc/220Vac and 15kVA, 48Vdc/220Vac

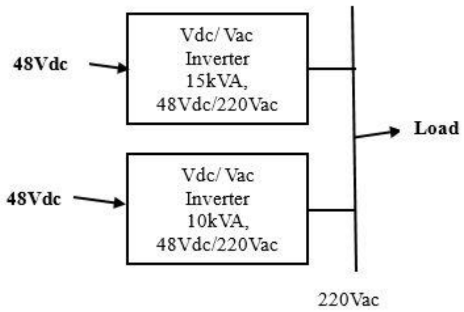

Fig. 3: Parallel connection of two or more Inverters

A (vi) Solar Charge Controller

Using Maximum power point tracking device (MPPT) of current range:48V/900Amp - 48V/1000Amp.

B. Discussion

One of the major parameters in the utilization of renewable energy harvesting components is the evaluation of the electrical load demand. Of course, power is generated to supply these loads. In the evaluation of the load, consideration of future additions to the loads is considered. To this effect, the actual electrical load under demand is 9.1165kW and 25% of this computed load is added to actualise the net total load demand of 11.4kW.

Evaluation of various required ratings and types of connections were realised. The total watt-peak of PV module capacity is 42kWp. The solar panels considered should be at least a minimum of 300 watts per module. Plate 2 shows a typical 300-watt, 24V Monocrystalline Solar Panel adapted from [22] for the installation. Monocrystalline solar panels are efficient in power conversion though expensive. The benefit outweighs the initial installation cost in due time.

The module/panel installation is 2 x 70 solar modules. Two in series connections while 70 in parallel connections. Fig. 2 shows the 48V/9600Ah series-parallel connection of the battery bank. It is also a 4 x 12 battery bank. Four batteries in series connections and 12 strings (each 4-number series connection). The inverter size computed will have a minimum of 23.5kVA and a maximum of 25kVA,48Vdc/220 Vac or (we can use one 15kVA and one 10kVA,48Vdc/220Vac) and the MPPT charger controller size should be a minimum of 900Amp to 1000Amp rating. We can parallel two or more charge controllers to achieve the desired requirements when high-powered solar arrays and batteries are involved especially in the off-grid system. In this case, separate sub-solar modules for each charge controller while charging a common battery bank.

IV. CONCLUSION

In the design of a standalone solar powered based electrical services for buildings (off-grid) the following assessment and selection must be made: the electrical load demand must be known, selection of solar module(s)/ panel(s) resulting in arrays of the solar modules, battery and battery bank, inverter selection, solar charge controller whether MPPT or PWM depending on the load characteristics. Other accessories such as connecting cables, circuit breakers, main switch, clips, trunking pipes, etc., are part of the installation requirements. A cohesive study of the pieces of literature paved the way for the modalities taken to justify our findings.

The system effective load under consideration was 11.4kW and of course, the solar power modules will generate more than the load demand to account for losses, also considering cloudy days, non-sunlight days, etc. The solar module's configuration was to produce a watt-peak power of 42kWp. The solar modules evaluated were 140 numbers, 48 numbers of deep cycle batteries each (12V/200Ah rating), inverter rating of $25kVA_{max}$ (15kVA and 10kVA 48Vdc/220Vac inverters), 6 numbers of 48V/150Amp rating MPPT charge controller. Or a single 48V/900Amp MPPT charge controller could be used if available in the prevailing market.

Based on an economic evaluation, the operational cost of a diesel-powered generating system over five years amounts to N81,852,003, exclusive of the generator procurement cost. In contrast, the cost of acquiring solar components, excluding installation fees, is N41,474,470.32. In practical terms, a standalone solar-powered system is more economically viable in the long run than a diesel-operated generator. Many developed and developing countries are transitioning to almost entirely renewable energy systems due to the multitude of benefits offered by renewable energy sources. While there is a high initial acquisition and installation cost for solar power system components, their operating costs are nearly zero. Additionally, some components have a lifespan of 5-10 years, compared to the significant fuel running cost of a diesel generator over five years, making the solar-powered system more cost-effective. Investing in the solar-powered system may offer significant long-term benefits, although it is important to note that the payback period is estimated to be over 5-10 years.

V. RECOMMENDATIONS

i). Due to the long-run benefits of solar-powered systems, we are recommending that off-grid power generation incentives (by reduction of import taxes) be given to investors and developers of such renewable systems.

ii). The solar PV modules should be mounted ‘rooftop’ since the building roofing is adequate to accommodate the number of solar modules.

iii). Since the prevailing market to access the components, there will be a few variations in the configuration especially the solar modules and the solar charge controller to have sub-arrays of the modules to each charge controller whereas the battery bank remains intact.

iv). The selected ratings should not be compromised rather they can have a slightly higher value due to load characteristics.

v). Procurement and installation procedures must be of good standard.

vi). Ensure to embrace zero carbon dioxide emissions, etc.

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