Practical Steps in the Design and Analysis of an efficient Off-Grid Solar Power System for Homes: Panacea for the Lingering National Energy Crises

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Abstract: *The possibility of employing photovoltaic system in the generation of large and 'clean' Electrical Energy to power, at least, homes has generated a whole lot of global interest in the recent past. In the Nigerian situation, it can be a veritable panacea for her continued raging National Energy crises. It is common knowledge that the Power Holding Company of Nigeria has not been able to power industries and cities effectively, not to talk of rural areas. This prevailing abysmal energy situation has thus imposed great constrain in the rapid socio-economic development and transformation of the Nation, and the rural areas in particular, as envisaged in the Millennium Development Declaration. This paper discusses practical steps that may be taken in the design and installation of efficient off-grid solar power system for homes, as a way of reducing, if not ending, the lingering National Energy Crises.*

Keywords: *'Clean', Crises, Energy, Off-grid, Photovoltaic, Solar, Transformation.*

Introduction:

The energy crises and the inevitable blackouts confronting the Nigerian Nation is no longer news. It seems to have defied every, and all, solutions, albeit orchestrated. Orchestrated, in the sense that the Nigerian populace do not know the degree of sincerity, and, or the political-will of government in actually addressing this problem, except paying lip service to the serious issue.

It is clear before every Nigerian that the sale of ***PHCN*** has become more of a ***curse*** than a ***blessing.*** A situation where the buyers only go about collecting monies and imposing all manners of levies without adding a single ***transformer*** or a ***meter*** or a ***pole*** or a ***kilometer of line*** or a ***Mega-Watt of energy,*** has become a matter of serious pains. This paper is here presented and meant to highlight the design and the analysis of an off-grid Solar Power solution for homes, which is 'clean' and reliable, to mitigate the power supply crises we hitherto face.

Sun Energy and the Solar Cell: The sun is the primary source of energy for all surface phenomena and life on earth. Major part of its energy reaches the earth in the form of photons (packers of light energy) and phonons (packet of heat energy - Infrared). When light falls on a surface it is either reflected or absorbed, depending on the colour and nature of the surface [8].
These energies thus require appropriate medium to intercept them for

- Photo-thermal conversion (for heating application)
- Photo-Electric effect, which gives rise to an electric potential (photovoltaic -PV).

The smallest unit in the photovoltaic solar energy converter is the PV cell. This cell is basically silicon diode; and when light strikes its P-N junction, electrons are moved to higher energy level, and the resulting increased lattice vibration causes the release of electron-hole charge carriers. The contact potential (about 0.6 Volts) that appears across the P-N junction, which ordinarily is depleted of charge carriers, causes an interior electric field to build up [5]. This gives the charge carriers direction, resulting in the flow of direct current (d.c) in the external circuit, when it is complete.

Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency known as the *I-V Curve, (Fig.01)*. By definition, V_{oc} and I_{sc} are the x and y intercept of the plot. They simply represent the upper limits for voltage and current. The two important performance parameters of the PV cell, are: I_{mp} and V_{mp}.

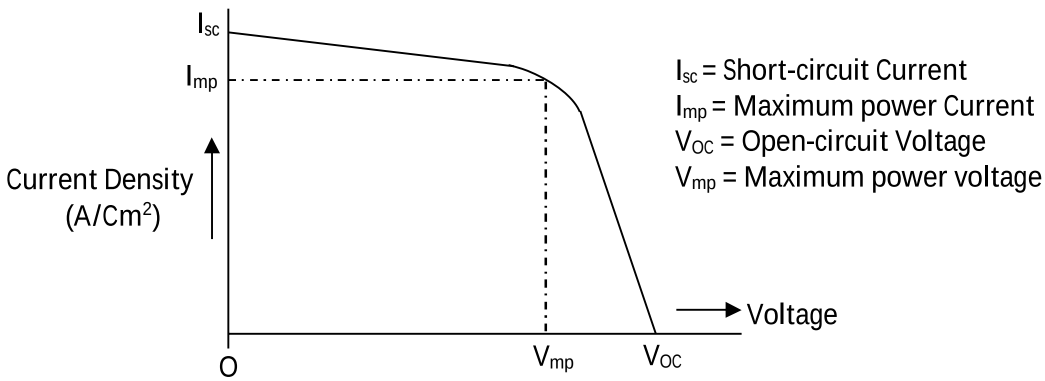

Fig.0:1 PV Cell Current/Voltage curve. [11]

PV cells are made with terminals which are connected in series-parallel (for increased voltage and current) to form solar module. For example, a 12 volt panel will contain 36 cells wired in **series** to produce about 21.6 volts peak output. When under load (charging batteries, for example), this voltage drops to about 12 volts. Thus, solar panels may be wired in series to multiply terminal voltage and in **parallel** to multiply current capacity (more power). These modules become the building blocks for solar electric power generator, which can produce enough power for a house or an entire village.

Types of solar module:-

Mono-crystalline solar panels:
These are very expensive but are the most efficient (about 20%) solar panels. The cells are pure silicon and involve a complicated crystal growth process.

Polycrystalline solar panels:
These cells are a little less expensive and slightly less efficient (about 12%) than mono-crystalline cells because the cells are not grown in single crystals but in a large block of many crystals. This is what gives them a striking shattered glass appearance.

Amorphous solar panels: These are not really crystals, but a thin layer of silicon deposited on a base material such as metal or glass to create the solar panel. These panels are much cheaper and much less efficient.

Advantages of Solar Power System:
The main advantages of Solar system over power generator/utility include:
a) This is free, 'Clean' and renewable energy; and no running cost.
b) It does not use fossil fuels and so does not contribute to the ***greenhouse gasses*** and pollutants emitted into the atmosphere, thus protecting the global environment [3].

c) Photovoltaic d.c power is produced at the location where it is to be used, thereby minimizing transmission losses, and improving reliability.
d) Electric Poles and High tension lines and substations are not required.
e) Failure will not occur.
f) High energy losses are low, and corona effect/radiation not present.
g) Power equipment vandalism and theft, due to Nigerian factor, will not occur.

Design configurations:
The four basic design configurations of PV system are:

i.) ***Borehole*** application for water pumping: This employs line current booster (LCB) to drive d.c pumps. It is designed for daylight operation and so does not require batteries.

ii). ***Hybrid system:*** A PV system is said to be hybrid if it is not the only source of energy to the load(s). In this case, there is an energy source (e.g utility or gen. set) in addition to the module/array. The two energy sources complement each other. The problem with hybrid system is economy. It costs more to install and requires operation/maintenance personnel especially for the auxiliary generator. However, this may be seen as the price for higher reliability.

iii). ***Grid connected:*** The grid-connected may be viewed as a special type of stand- alone system. The connection of its output to the grid makes the grid a load to the system. In its simplest form, it consists of array, an inverter and them the gird (load).

iv). ***Stand-alone (off-grid):*** This configuration refers to when the system operates as the sole source of supply to its load. The inclusion of storage (Fig. 02) in PV systems is aimed at increasing its **availability** and consequently its **reliability.**

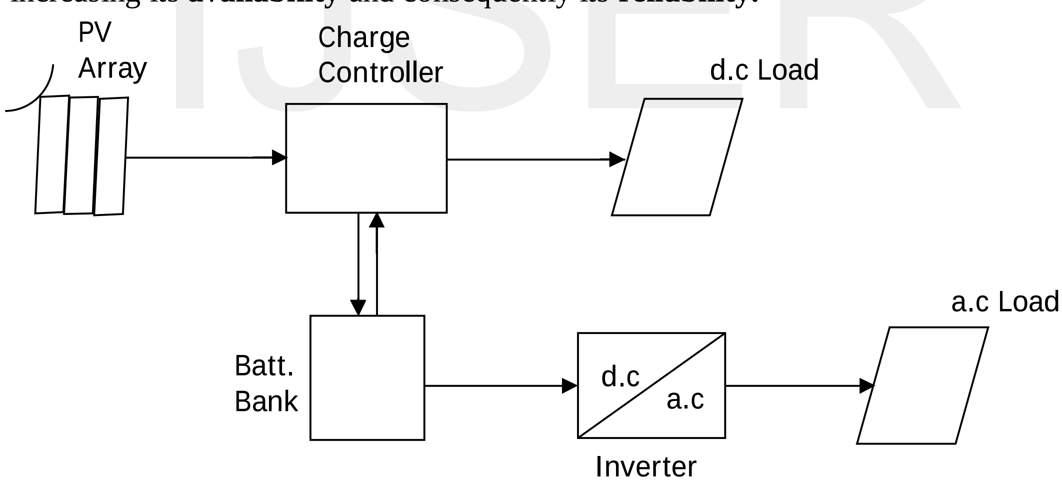

Fig. 02: Stand-Alone (Off-Grid) Solar Power System

Energy Storage, System Control and A.C Loads:
Because of the need to drive loads at periods of no shine and for long periods without charging, ***solar batteries*** (commonly called deep cycle batteries) are of special design and are optimized to operate at low discharge rate; and can be repeatedly discharged to about 70% before another recharge cycle.

Charge controllers protect them from overcharging (which causes plate corrosion, gassing and loss of power) and from discharging below their cut-off voltage, which can cause permanent damage to the battery and loss of capacity. A battery, when fully charged, has the potential of producing a certain number of Ampere-hour (Ah) for a given discharge rate and cell temperature. The discharge rate (usually either C_{20} or C_{100}) refers to the number of hours that a certain charge current can be supplied by that battery. For example, if the battery capacity is stated as C_{20} = 200Ah, then it can provide a current of 10 Amps for 20 hours.

Solar Inverters: Since, in an average home today, most of the loads are a.c, there is the need to incorporate inverters to convert the direct current (d.c) output of the photovoltaic (PV) array into a utility frequency alternating current (a.c – 220V, 50Hz) in order to power a.c loads.

Solar inverters have special features adapted for use with photovoltaic arrays, including maximum power point tracking and anti-islanding protection. Sine waves are a natural product of rotating a.c machinery. Therefore, pure sine wave inverters are the best needed to drive a.c loads. Pure sine wave supply guarantees that the equipment will work to its full specifications.

Power devices (SCR) are used in inverters, and they switch at high speeds. All switching devices are rated for a certain Voltage and Current, so the real rating would always be in kVA. As a power source, the Inverter is rated in KVA; but as a load, it is rated in KW, at unity power factor. That is, a 1000 Watts inverter is also rated at 1000VA. Therefore, when sizing the inverter, it is important to determine the total apparent power of all the loads that the inverter must supply and this will be the minimum rating of the inverter that will be required. The inverter should be over-sized by at least 10%, in order to be able to supply the surge Apparent Power required by the appliances. Inverters are generally only about 80% efficient.

The KVA rating is the apparent power that Electrical equipment is capable of taking, while the watt rating is the real power (or true power) it is capable of consuming or using, as opposed to reactive power (KVAr), as shown by the triangle in Fig03. ***VA*** rating is useful to get the amount of current that a device will draw. Knowing the current helps to properly size the Inverter, wires and circuit-breakers or fuses, that supply electricity to a device, and protect it.

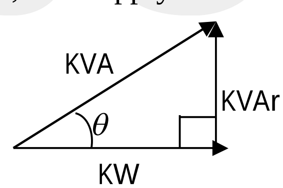

Fig03: Power Triangle

The amount of power the inverter uses just by being turned-on is between (10 to 15)% of its rating; this accounts for its losses, even when it is not supplying load [8]. Solar inverters use *maximum power point tracking* (MPPT) to get the maximum possible power from the PV array.

Design and analysis of a 1KW off-grid (stand alone) Solar Power System for a three bed-room Bungalow:

Major points to note when designing Solar System:

i). The load put on the system is not constant over the period of one day.

ii). The daily load varies over the year.

iii). The energy available from the source (the sun) will vary from day to day, and from time to time, during the year.

Table-1 Daily Energy Demand/Load Analysis (for a 3-bedrom Bungalow)

	Type of load	Capacity of Equip (***watts***)	No. of Equip	Installed Power/capacity (***watts***)	Duration of service (***hrs***)	Total Energy Demand per day. (***watt-hour***)
i)	Lighting (Energy Saver)	18	15	18 x 15 = 270	6	270 x 6 = 1,620
ii)	Security light (Energy Saver)	18	6	18 x 6 = 108	12	108 x 12 = 1,296
iii)	TV	78	1	78 X 1 = 78	8	78 x 8 = 624
iv)	Fan	45	6	45 x 6 = 270	10	270 x 10 = 2,700
v)	Frig	260	1	260 x 1 = 260	12	260 x 12 = 3,120
vi)	Musical Set	60	1	60 x 1 = 60	8	60 x 8 = 480
vii)	Computer Set	14	1	14 x 1 = 14	10	14 x 10 = 140
	Total Load			**= 1,060**		**= 9,980**

For the photovoltaic system, a comparison must be made between the total energy demand per day and the available energy from the sun per day. The designed load is the total power requirement of the connected equipment per day in watt-hour; while the demand, the total Amp-hours needed from the battery(s) per day and possibly, days of autonomy.

Stand-Alone Solar Generator Components:

i). Solar Array
ii). Array Combiner
iii). Solar regulator/Charge Controller
iv). Storage Deep Cycle Batteries
v) d,c Load Equipment
vi). d.c/a.c Inverter
vii). A.c Load Equipment

Solar Power Components Sizing:

The high cost of installing solar systems and the requirement of reliability makes it necessary to carry out what is referred to as ***Sizing;*** this is with the aim of determining the rating of the components of the solar generator needed to supply the designed load for the designed period. A major factor is the degree of solar energy reaching the generators (PV modules) with output at 12 or 24 Volts. The first step in system sizing is to estimate the load to be placed on the system.

i.) ***Sizing Battery:***

From the demand/Load analysis in table-1,

$$\text{Total Charge Demand per Day (Ah)} = \frac{\text{Energy Demand per Day (Wh)}}{\text{System Voltage (V)}} = \frac{9{,}980}{24}$$

$$= 415.83\text{Ah.} \qquad \text{---} \quad (1)$$

$$\text{Battery Bank Capacity, } C_x = \frac{\text{Daily Charge Demand (Ah) x Days of Autonomy } (T_{au})}{\text{Max. Dept of Discharge } (DOD_{max})}$$

Thus, if an autonomy of 3 days and depth of discharge (DOD_{max}) of 70% is considered, then

$$C_x = \frac{E_{tot}}{V_{dc}} \times \frac{T_{aut}}{DOD_{\max}} = \frac{415.83 \times 3}{0.70} = 1,782.13Ah \quad \text{--------------------------------} \quad (2)$$

System autonomy (T_{aut}) is the maximum number of days that the batteries can supply the daily demand, without recharging.

If a battery rating of 200Ah/12V is selected, then number of 200Ah/12V batteries to be connected in series/parallel $= \frac{1,782.13}{200} = 8.911 Batteries$ --- (3)

Thus, the appropriate number of batteries for this load is **10** (200Ah/12V), in series/parallel connection, as shown in Fig.04

Battery Bank Charge and Discharge Rate:

Maximum charging d.c current is given as:

$$\text{Max. Current } (I_{max}) = \frac{\text{Total Watt (W)}}{\text{System Voltage (V)}} = \frac{1,060}{24} = 44.167\text{Amps} \quad \text{-------------------------} \quad (4)$$

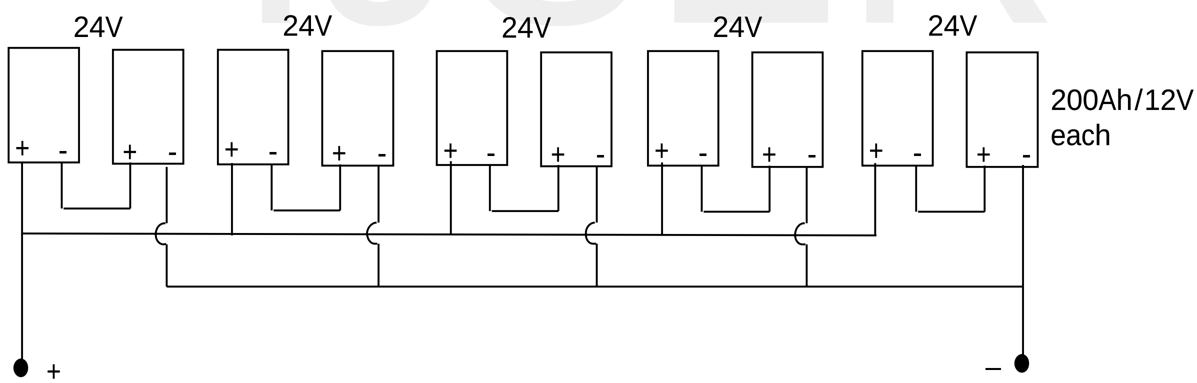

Fig. 04: Deep-Cycle Batteries in Series/Parallel Connection

For Battery Bank Capacity of 1,782.13Ah, the rate of discharge will be given, from expressions (2) and (4), as

$$\frac{Demand(Ah)}{Max.Current(I_{\max})} = \frac{1,782.13}{44.167} = 40.35hrs \quad \text{--} \quad (5)$$

This result gives the time, in terms of number of hours, that the battery bank can support the load for autonomous days.

By the result in expression (5), the battery bank must first be charged for a minimum of 40hours before any load is connected. This initial charge is important for best performance of the battery bank throughout its life, which is an average of 15 years [4].

ii) ***PV Array Sizing:***

- Total energy required per day (from table) is 9,980 Watt-hour
- Select P.V module of desired rating (e.g. a *130W/12V* panel – (Note: 130 Watts is the output of the panel working at 100% efficiency).
- Assuming a panel efficiency of 80%, then Panel output will be 0.8 x 130 = 104Watts. And for an average of 8hrs of shine/irradiation per day, the total energy output per Panel becomes: 104 x 8 = **832 Watt-hours**

Let 10% of daily demand account for losses due to inverter, cabling and at terminals.
This gives 0.1 x 9,980 = 998 watt-hour.
Thus, total demand per day will now become

9,980 + 998 = 10,978 Watt-hours

And the total number of panels becomes:

$$= \frac{10,978}{832} = 13.19\,Panels \qquad \text{-- (6)}$$

Thus, to supply ***10,978 Watt-hour*** of energy to support period of autonomy, ***14 panels,*** each of 130W/12V rating, are required; and will be connected in series/parallel, as shown in Fig. 04 below.

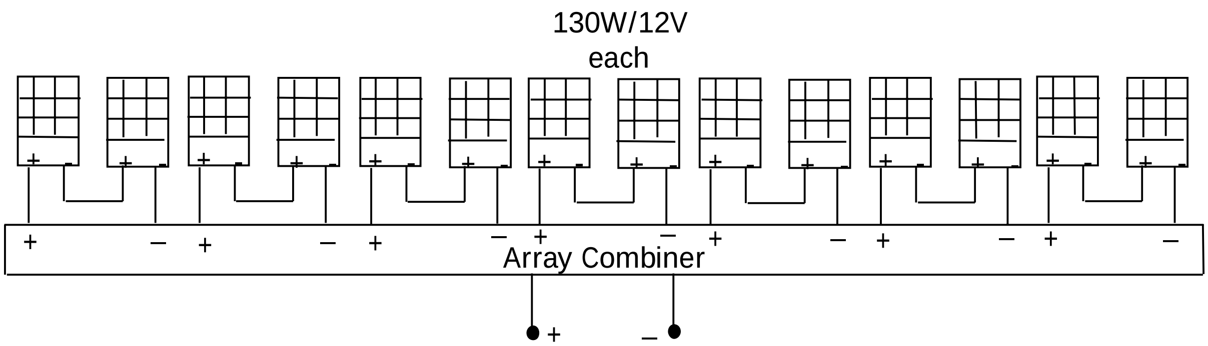

Fig. 05: Solar Array in Series/Parallel Connection

The following are the key technical data of the Solar Panel, with a +/- 5% variance:
Type: BLD130 – 36p, Cell Technology – Poly-Si
Peak Power P_{max} -------------- 130Watts
Peak Voltage V_{mp} --------------- 17.5V
Peak Current I_{max} --------------- 7.45A
Open-Circuit Voltage ----------- 21.6V_{oc}
Short-Circuit Current ----------- 8.08A
Normal Operating Temperature -----45^{0}c +/- 2^{0}c

iii) ***Sizing Charge controller:***

Battery bank charging current (I_{batt}) is given as,

$$\text{Max. Charging Current } (I_{batt}) = \frac{\text{Total Load (W)}}{\text{System Voltage (V)}} = \frac{1{,}060}{24} = 44.167 \text{ Amps} \quad \text{----------(7)}$$

A controller rated **60Amps/24V** is appropriate.

iv) ***Sizing Inverter:***

From the demand table, the total load is 1,060 Watts. If power factor (pf) of 0.65 is assumed, then Apparent Power (VA) is

$$\frac{Watt.Power}{pf} = \frac{1{,}060}{0.65} = 1{,}630.77VA \quad \text{----------} (8)$$

From the figure in expression (8), an Inverter rating of **2KVA** is appropriate.

Location of System, and Angle of Tilt:

Solar power system design must take into cognizance the peculiarity and the realities of the local environment where the power system is to be installed. And the size of the system will depend on the amount of power required (in watts), the length of time it is to be put to use per day and the amount of energy available from the sun per day in the particular area or location where the system is required.

Therefore, for best result, the geographical data of the area must be known .e.g the latitude or the location in degree in relation to the equator and at least one year data of sun irradiation and weather condition of the area. The best angle to tilt solar panels towards the equator is the angle of the Latitude of the location. That is, if the latitude of the location is a positive value, i.e Northern hemisphere, orientate the panels south. In the tropics, the angle can in fact be 10 degrees to either side of this optimum setting without losing much power or efficiency from your panels [10], as illustrated in Fig. 06. By this, the sun energy will be hitting the PV panels at the best angle of maximum solar energy reception, which is 90^0. The sun is known to move along the equator trajectory.

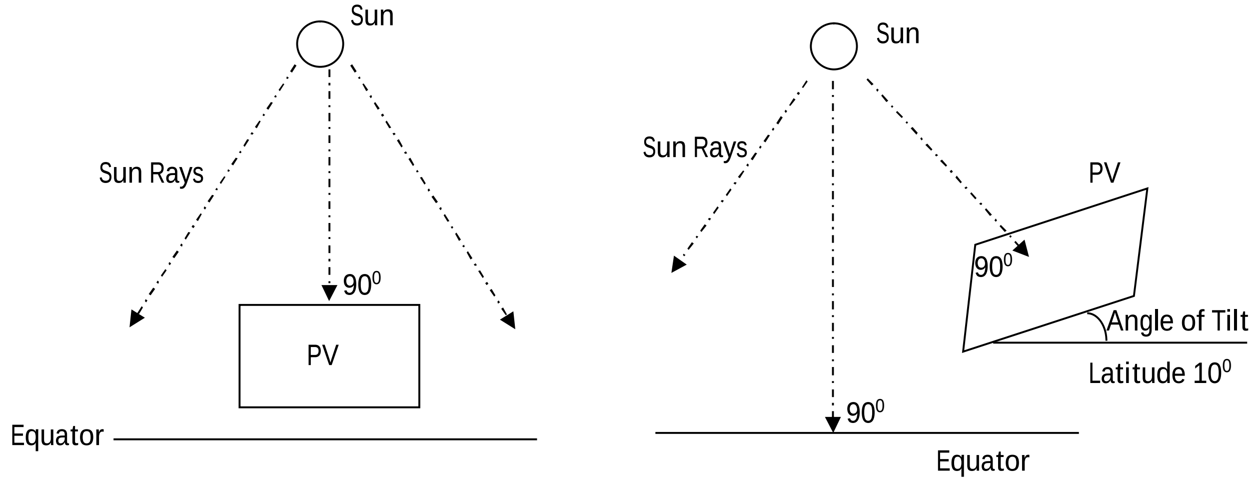

Fig. 06: PV Installation/Angle of Tilt

System Wiring and Installation:
Wiring becomes very complex if there are d.c and a.c circuits/loads. Generally, the simplest procedure is to provide a.c power from an inverter (Fig. 02) and run the whole house using a.c. This however results in a much larger load on the system due to inefficiencies in the inverter and the battery. Inverters are only about 80% efficient.

D.c and a.c circuits must be isolated physically from each other, and polarized 2 pin plugs must be used for d.c wiring, not 3 pin 240 volt plugs and sockets. Cables have their current carrying capacity (CCC). And since current in d.c lines is quite always higher, cables must be correctly sized so that:
- There are not excessive line losses (voltage drops)
- The maximum current rating of any cable is not exceeded.

For example, 220V a.c, 100 Watts load takes 0.455 Amps; and a 100 Watt load running on 12Vd.c takes 8.33 Amps. Generally, cable losses (ac or dc) are not allowed to be more than 5%. Line losses or voltage drops depend on:
- cable cross-sectional area (mm^2)
- cable length, and
- current flow in the wire.

Thus, Voltage drop $$V_{drop} = \frac{\rho L I}{A} \qquad (9)$$

where: ρ, is resistivity of copper wire (in ohm/m/mm^2 = 0.0183)
L, is cable run Length (in m)
I, is current (in A)
A, is cross-sectional area of cable (in mm^2)

Excessively long wire runs will result in loss of voltage and power to the equipment/load and lower efficiency. Inductive loads, such as motors, are particularly sensitive to voltage drops. When they run on voltage levels less than their rated values, they tend to overheat.

Main battery cables are often supplied by the inverter manufacturer. They must not be extended. Their diameters have been carefully selected to minimize voltage drop between the batteries and the inverter. If longer cables are necessary, fit new, larger size cables. Cables from the solar array to the batteries should be selected so that the voltage drop between the array and the batteries is less than 5% of the system voltage.

Cables are specified in terms of the cross-section (mm^2), the type of insulation and the environment in which it to be installed. Cables with an insufficient current carrying capacity rating (CCC) for the currents they carry will overheat, and this will lead to the degradation of their insulation and their eventual failure. The size of the circuit protection selected is dependent on the CCC of the cable; and though it can be smaller than that of the cable, but is never larger.

Whenever possible, PV panels should be installed lower than the highest point of a building. If a mounting frame is used and become the highest point, then in this case, lightning protection may be desirable. Earthing or grounding should be by very thick cable and earth rod should be 1.5m long.

In PV installation, the batteries must first be connected to the controller, the PV panels and then the load. Protection against reverse voltages, due to wrong connection or thunder strike, is achieved by connecting a bypass diode across the PV array as shown in Fig. 07. This protection also minimizes damage from hot spots as a result of defective cells [6].

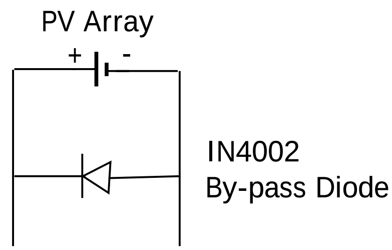

Fig. 07: PV Array Protection against Reverse Voltages

Table-2 PV Generator Cost Analysis:

	Component	*Rating*	*QTY*	*Unit Cost (#)*	*Total Cost (#)*
i)	Solar Panel (Mono-Si.)	130W/12V	14	26,000.00	364,000.00
ii)	Deep Cycle Battery	200Ah/12V	12	48,000.00	576,000.00
iii)	Charge Controller	60Amps/24V	1	70,000.00	70,000.00
iv)	d.c/a.c Inverter	2KVA	1	78,000.00	78,000.00
v)	Array Combiner		1	2,000.00	2,000.00
				Total =	***#1,090,000.00***

This very high initial cost outlay of the modular parts of the solar power generator (table-2) represents its only ***disadvantage***. However, research is continuing to optimize methods of production of these parts, which is aimed at bringing down cost.

Conclusion:

The role of Independent power generation (IPG) is to complement public power in order to meet the overall target of energy supply. Solar PV generators (as renewable energy source) can play a major role in IPG due to its special features: For example, they are modular in nature; they require almost zero maintenance and can be sited at remote locations.

Above all, if properly designed and installed, the batteries or any other modular part can continue to drive the load for an average of 15 years before needing replacement. Although the initial cost of installing solar system is high, it is on the whole a cheaper source of energy because it requires no maintenance and it offers several years of un-interrupted service devoid of noise or pollution or hazardous by-products characteristic of the conventional source of energy, like the diesel or petrol engines.

In order to achieve the MDG's objective, on urban and rural development, the need has arisen to end the energy crises in the Nigerian Nation. Luckily, Nigeria is a tropical country and so Solar energy is readily available, is 'clean' and is free. What remain is the sincerity and the political-will on the part of government to develop the solar energy option, and to provide soft loans for its citizenry, particularly in the rural areas, to install and own Solar power systems, for a sustainable national development and to end this lingering National energy crises.

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