Powering Africa Using An Off-Grid, Stand-Alone, Solar Photovoltaic Model

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Abstract

Over 90 % of Sub-Saharan Africa is without electricity access. The rural areas of the few African countries with access lack electricity. Studies have suggested that solar energy systems hold the key to powering the continent. Although, a vast population currently operate fossil-fuel powered generators to meet their basic electricity needs. The study is designed for a 2-bedroom flat inhabited by an average Africa family. A residential building in Akure, Ondo State, Southern Nigeria has this model installed in a stable and reliable condition. The proposed solar photovoltaic model is composed of solar panels, Direct Current (D.C) cables, charge controller, solar batteries, solar inverter, solar bulbs and instrumentation gadgets. The model is an optimum size solar Photovoltaic installation with a maximum power input of 1,800 W. The maximum allowable load is 1,000 W and a maximum charging D.C voltage of 28.2 V. The solar-powered system is equipped with a set of six (6) 300 Watts monocrystalline solar panels. A commercial maximum power point tracking (MPPT) charge controller was used for this model. Two (2) units of Deep Cycle AGM Solar Batteries connected in series are installed for the solar photovoltaic system. A pure sine wave solar inverter was used in the developed solar PV model to transform D.C electricity available in the batteries to A.C electricity. Themodel is a flexible one which could be scaled up as may be desired or required. The solar photovoltaic model has a very high prospect for powering Africa. The model has ample potentials to fulfil economic, social and environmental objectives which qualifies it as a sustainable energy option to improve the quality of life. The implementation of this form of sustainable energy will open even development of the continent and end the electricity woes of the populace.

Keywords: Africa; Solar Photovoltaic; Global Warming; Electricity, Sustainable Energy.

1.0 Introduction

Sub-Sahara Africa (SSA) comprises of 46 countries of the total 54 countries in the continent excluding the majority of the league of Arab states. There is an increase in SSA population yet 80 % of the 860 million population are without electricity access [1], [2]. Energy is a fundamental right, vital for the survival of mankind and a contributor to the economic development of a country [3]. The continent installed generation capacity is 80 GW less than United Kingdom capacity. The estimated annual per capita energy consumption of SSA is 170 kWh [4]. Sub-Sahara Africa has the least electrification rate of 25% compared to North Africa 93.6% [5], [6]. The few generated electricity further experience technical losses from transmission and distribution with an average loss of 11.3%. Although, countries like Nigeria and Congo have a loss of over 39% [7]. A major way of fast-tracking development and poverty reduction in Africa is to increase access to electricity [8]. An improvement of the existing method of electricity in Africa is here presented.

Electricity access in Africa is mainly through the grid [9]. The electricity grid is powered mainly by hydro and thermal energy sources[10], [11]. Two-thirds of SSA have access to the grid. An estimated 70% of the grid-connected household have electricity access [12]. This high grid connection does not translate into continuous electricity access. In Nigeria, about 95% are connected to the grid with 18% working per time [13]. Similarly, Ghana grid provides 87% grid connection with only 42% having stable electricity. A statistic by Afrobarometer shows that 40% of SSA either do not have a grid or are not connected [12]. Similarly, about 5% SSA are connected to the grid but never works and 5% are connected but work half the time.

However, 25% are connected to the grid with functional electricity access. Although, 16% of SSA are connected to the grid and function most of the time. A total of 9% are connected with occasional electricity supply. However, challenges arise in the grid when electricity demand is more with lower supply compounded by low electricity quality. Similarly, the electricity supply infrastructure (transformers, feeder pillars, pylons, poles, porcelain insulator, conductors, right-of-way) for the electricity grid are usually poorly maintained which results to frequent grid failure. The bulk of electricityis used in the residential [14].

Off-grid electricity access in Africa involved electricity access independent of the national grid. Research suggests that pocket electricity access exists in isolations in several homes in SSA [15], [16]. The development of mini-grid and off-grid has been opined to hold promise for electricity access in SSA [17]. The inhabitant of SSA uses fossil fuel powered generating set an alternative to grid electricity [18]. The depletion rate of fossil fuel resources couple with environmental pollution of fossil fuels has rekindled the interest in renewable energy [19]. In addition, the quality of electricity generated by gasoline and diesel generators is usually poor, unstable, poor efficiency and shortens the life span of the electrical equipment connected to these sources. Renewableenergy can be replenished easily as against non-renewable resources. Forms of renewable energy include solar energy, wind energy, tidal, among others [20].

A Solar Photovoltaic System is a power supply option using solar energy to provide electricity. It is an efficient, safe, cost-effective and reliable means of meeting basic residential electricity requirements[21]. They provide cost savings by eliminating the need to provide power generation, transmission and distribution infrastructure and eliminates the cost of electricity bills after installation [22]. In addition, they provide security, sustainability and an overall green economy.

Although, a retinue of literatureexists that advocates the opportunities and challenges of off-grid solar PV, few reported implementation PV model in residential [23]–[26]. Hence, this study designed a solar PV off-grid stand-alone model to solve electricity woes in SSA. It can also be used as a hybrid alongside grid electricity. This study aims at proffering solution to the epileptic power supply in the continent using solar photovoltaic systems.

1.1   General Description of the Model

The model involves the use of monocrystalline panels for harvesting solar energy (sunshine) during the daytime. The harvested energy is converted to Direct Current (D.C) electricity for solar battery charging. This is subsequently converted to Alternating Current (A.C) electricity by a solar inverter. This energy transformation model is synchronized with the daily natural cycle of sunrise, sunshine and sunset which makes the system to be renewable. An average sunshine hour of $(4 - 7.5)$ hours per day is achievable in Africa with an average solar radiation intensity of (3.0 - 8.0) kWh/m^2/day [27].

Compliance with the specifications provided by this model willenable the electricity storage unit of the system (solar batteries) to achieve up to 3660 charge/discharge cycles which corresponds to an estimated ten (10) year period. After this estimated period, the batteries will have been derated to 80% of their respective initial capacities due to cyclic stresses i.e a battery is considered to have reached its end of life (EOL) when it can no longer deliver 80% of its original rated capacity. Forexample, a 200 Ah battery has reached EOL when its discharge capacity has dropped below 160 Ah. This implies that battery replacement (though optional) may be done at an interval of ten (10) years on grounds of reduced discharge capacity and performance.It is important to note that used, near end-of-life and end-of-life batteries emerging from solar photovoltaic systems have significant economic value based on their respective state of health. Figure 1 shows the relationship between the Depth of Discharge (DOD) and expected number of charge/recharge cycles for a typical AGM solar battery.
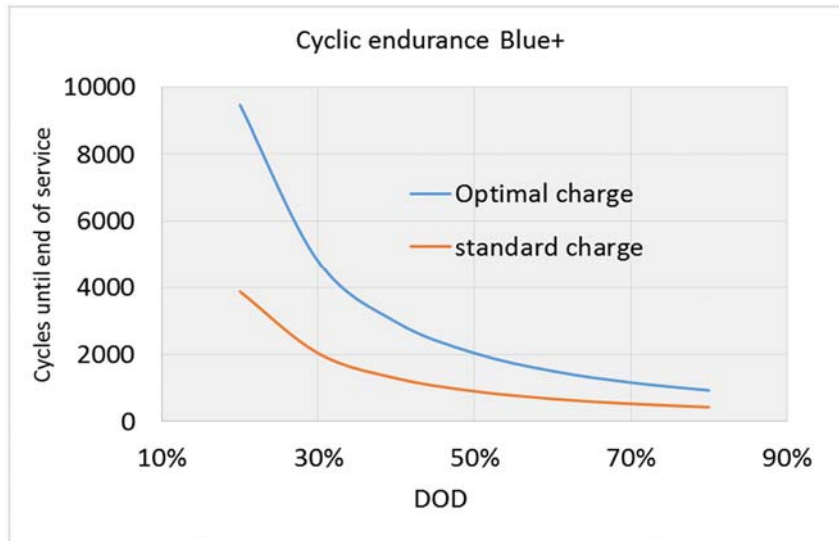
**Figure1.**Cycle life versus depth of discharge of a solar battery

Optimal Charge (OC) is a three-stage charging approach which include Bulk Charging whichconstant current charging to a high battery level (about 80%)[27]. Standard Charge is a bulk charging (constant current charging for a limited period). Optimal charging also includes absorption Charging which is constant voltage, variable current charging to full battery capacity (100%). And finally, OC include float Charging which is involve constant voltage and very low maintenance charging current (for maintaining battery capacity at 100% and mitigate the effect of battery self-discharge).

The MPPT Solar Charge Controller recommended for this Photovoltaic Model is designed with the optimal charging system.

2.0 Methodology

The methodology contained in this section gives basic information about the major requirements for the smooth and successful implementation of the solar photovoltaic model. This section contains the basic operating principle which the proposed solar photovoltaic model is built on. It also includes the technical specifications of the solar photovoltaic model. The electrical ratings of typical household appliances. And the recommended electrical load chart for model reliability and system durability.

2.1   *Operating Principle*: The proposed solar model is built as a stand-alone unit. The solar photovoltaic installation consists of four (4) major electrical components namely a solar panel, a charge controller (solar regulator), a bank of two (2) solar batteries; and a solar inverter. The solar panel converts sunlight into Direct Current (D.C.) electricity for battery charging during the day. The charge controller controls the D.C. electricity and ensures that the battery is properly charged. It also prevents damage to the battery and reduces power lost/discharge. The solar inverter assists in transforming D.C electricity available in the batteries to A.C electricity for electrical appliances and lamps in the residential building. The block diagram of the model is shown in figure 1.
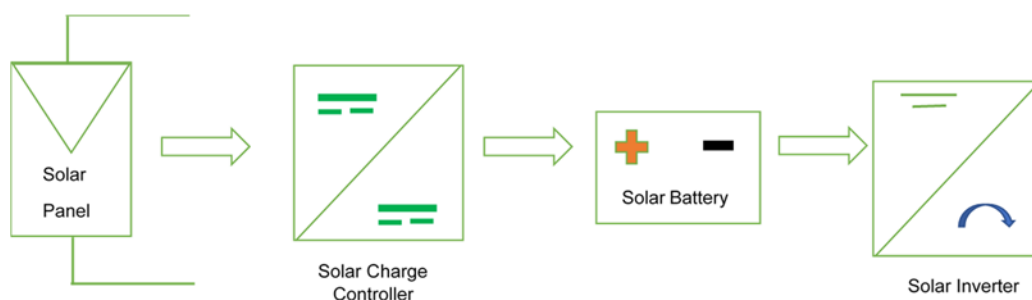
Figure 1. The block diagram of the Solar Photovoltaic model

2.1.1   *The Solar Panel:* The solar-powered system is equipped with a set of six (6) 300 Watts monocrystalline solar panels. The solar panels are classified according to their rated power output in Watts. This rating is the amount of power the solar panel would be expected to produce at Standard Test Conditions (STC) of sunlight intensity 1000 W/m^2 at 25º C. Different geographical locations receive different quantities of average peak sun hours per day. Taking the southern part of Nigeria as a case study, the annual average is approximately 5.6 sun hours per day [28]. This implies that a 300W solar panel based on the average 5.6 sun hours per day, will produce an average of about 1680 Wh per day. The panel orientation, temperature, shading, climate and other factors inhibiting solar panel performance were considered in designing the model.

A set of six (6) solar panels are wired in parallel to increase their current output significantly while maintaining the same voltage. The rated terminal voltage (daylight) of the set of solar panel is within the range of 24 V – 37 V. The exact value which will vary with the available solar radiation intensity. However, through the use of a suitable charge controller, this range of voltages is reduced to 26 V or 28 V as required for safe battery charging of two (2) 12V batteries connected in series.

2.1.2   *The Charge Controller (Solar Regulator):* The charge controller regulates the current from a set of solar panels to prevent the batteries from overcharging. Overcharging causes gassing and loss of electrolyte resulting in damage to the batteries. The charge controller is used to sense when the batteries are fully charged and to stop or decrease the amount of current flowing into the batteries. In addition, the charge controller also prevents the batteries from back feeding or discharging into the set of solar panels at night hence protecting the batteries from flattening. A commercial maximum power point tracking (MPPT) charge controller was used for this model.

2.1.3   *The Solar Battery*: Two (2) units of Deep Cycle AGM Solar Batteries connected in series are installed for the solar photovoltaic system. The batteries are designed to be discharged over a long period of time (about 100 hours). They are recharged numerous times (up to 3660 times) before being derated to 80% of their respective initial capacities. However, they must be maintained above 35% Depth of Discharge (DOD) which corresponds to 65% State of Charge (SOC) through an appropriate energy conservation schedule. This is in contrast with conventional car batteries which are designed to provide a large amount of current for a short amount of time. To maximize battery life, the programmed cut-off voltage of the deep cycle batteries is 25V which correspond to about 35% discharge of their full capacities, i.e. 65% capacity remaining.

The deep cycle batteries are rated in Ampere hours (Ah). This rating specifies the amount of current in Amps that the battery can supply over the specified number of hours. Taking a batteryrated at 200 Ah at the 100 h rate as a case study, the battery can supply a total of 200 Ah over a period of 100 hours. This would equate to 2.0 A per hour for 100 hours.

2.1.4   *The Solar Inverter*: The pure sine wave solar inverter assists in transforming D.C electricity stored in the batteries to A.C electricity for electrical appliances and lamps in the residential building. The inverter is equipped with a Low Voltage Disconnect (LVD) feature. The LVD helps to switch off the A.C electricity supply if the combined voltage of the batteries falls below the cut-off voltage of 21.6 V. However, to achieve system reliability and durability, a low voltage disconnect value of 25 V is recommended for the model. This strategy will prolong the useful life of the battery bank and the individual batteries.

2.2: Case Study of 2-bedroom resident Solar Photovoltaic model in Nigeria.
2.2.1   Background
Africa is home to both the extremely rich, rich, poor and the very poor. The average 2-bedroom is usually occupied by the spouse, two to three kids and sometimes additional guest. The living room is used for entertainment and the bedroom for sleeping. The living room usually houses a TV set, a satellite receiver, a DVD video player, an Audio player, a standing fan and some light bulbs. The bedrooms essential items are the fan, light bulbs. Majority of them have electric Iron, hair dryer/clipper, refrigerator, washing machine, electric kettle. This model was installed in a 2-bedroom apartment in southern Nigeria.

2.2.2 *Technical Specifications of the Solar Photovoltaic Model:* This includes the details of the model capacity, technical specification and the load chart.

2.2.2.1 Model Capacity: The model is an optimum Size Solar Photovoltaic Installation with a maximum power input of 1,800 W. The maximum allowable load is 1,000 W and a maximum charging D.C voltage of 28.2 V. The maximum charging D.C current is 60 A with electricity storage capacity of 200 Ah at 25 V. The system voltage is 25 V (Direct Current). The output voltage for A.C and D.C are 220 V and 25 V respectively.

2.2.3 Technical Specifications of the Major Components of the Proposed Model: The panel consist of six solar panels with an individual rating of 300W, 37V monocrystalline. Two (2) 200Ah Absorbed Glass Matte (AGM) Solar Batteries. The inverter is a 24V, 1.5 kVA Single Phase Pure Sine Wave Solar Inverter. A Maximum Power Point Tracking (MPPT) Charge Controller of 12/24V, 60 A was selected over Pulse Width Modulation (PWM). The extra components are the timer for regulating the Refrigerator (220V A.C) and set of two colour coded 10mm copper wires for proper electrical conductivity and cable protection againstactive heat generation.

3.0 Results and Discussions

The solar photovoltaic model design parameters are here discussed.

3.1 Electrical Ratings of typical Electrical Appliances operated by an average African Family: Table 1 represents the major appliances domicile in a typical Africa 2-bedroom. The living room is used mainly for entertainment and the bedrooms for resting including sleeping.

Table 1. Electrical ratings of a typical Africa household.

S/N	APPLIANCE	POWER RATING (W)	QTY	CUMULATIVE POWER (KW)
1.	Freezer(s)	300	1	0.3
2.	Refrigerator(s)	200	1	0.2
3.	60 Inches Television(s)	120	1	0.12
4.	32 Inches Television(s)	100	1	0.1
5.	Ceiling Fan(s)	75	1	0.075
6.	Standing Fan(s)	60	1	0.06
7.	Compact Fluorescent Lamp(s)	25	4	0.1
8	Submersible Pump(s)	400	1	0.4
9.	Electric Pressing Iron	1000	1	1
10.	Electric Cooker(s)	1000	1	1
11.	Air Conditioner(s)	2300	1	2.3
	Total (KW)			5.66

3.2 Adopted Electrical Load Chart for the Proposed Solar Photovoltaic Model: Electrical Energy efficiency and conservation is a prerequisite for a renewable energy system installation to achieve cost-effectiveness, moderate maintenance requirements, reliability, durability and safety. Hence, the adopted electrical load chart shown in Table 2.

Table 2. Electrical load chart of the model

BASIC MODE	ENERGY CONSERVATION MODE	CONFIGURATION A (9AM - 5PM) [Daytime]	CONFIGURATION B (5PM - 10PM) [Evening]	CONFIGURATION C (10PM - 7AM) [Night]
Refrigerator (Up to 200L) (200W) [10AM - 4PM]	Refrigerator (Up to 200L) (200W) [10AM - 4PM]	1	-	-
32 Inches Television (100W)	32 Inches Television (60W)	1	1	-
Laptop (100W)	Laptop (70W)	1	-	-
Ceiling Fan (75W)	Ceiling Fan (60W)	1	-	1
Standing Fan (60W)	Standing Fan (40W)	1	1	1
Solar Bulb (5W)	Solar Bulb (5W)	2	4	2
Estimate Power Requirement (Average)		200W + (60+70+60+40+10)W = 440W	(60+40+20)W = 120W	(60+40+10)W = 110W
Estimated Energy Requirement (Average)		(200W x 6h) + (240W x 8h) = 3120Wh	600Wh	990Wh
Total AH required for Daytime		(3120Wh / 25V) = 125Ah		
Total Battery Capacity to be Utilized for Evening and Night Modes			(600Wh / 25V) = 24Ah	(990Wh / 25V) = 40Ah
Recommended Battery Capacity for Night Mode @ 25V (Series Connection)			200Ah Energy Storage Unit (Battery) Design Considerations (35% Depth Of Discharge, 65% State Of Charge, Recommended Low Voltage Disconnect: 25V, Charging Cycles: 3660 Cycles, Useful Life: 10 Years)	200Ah Energy Storage Unit (Battery) Design Considerations (35% Depth Of Discharge, 65% State Of Charge, Recommended Low Voltage Disconnect: 25V, Charging Cycles: 3660 Cycles, Useful Life: 10 Years)

ANTICIPATED SOLAR ENERGY GENERATION, STORAGE AND DISTRIBUTION				
Estimated Daylight Hours		12hrs (6:30AM - 6:30PM)		
Estimated Daily Sunshine Hours (Dry Season) (November - March)		8hrs (9 AM - 5 PM)		
Anticipated Daily Sunshine Hours (Rainy Season) (April - October)		6hrs		
Peak Sunshine Hours		6hrs (10 AM - 4 PM)		
Anticipated Power Generation during Peak Sunshine Hour (45% of Name Plate Capacity)		0.45 x 1800W = 810W		
Potential Energy Generation and Storage During Peak Sunshine Hours		810W x 6h = 4860Wh		
Anticipated Electricity Supply and Storage During Peak Sunshine Hours based on System Demand		(3120 + 600 + 990) Wh = 4710Wh		

Excluded electrical appliances for the solar photovoltaic model: electric Cooker with a rating of 1000W, electric pressing Iron rated 1,000W are not included in the load design. Also, the air conditioner of 2,300W, the water heater of 2,200W are also excluded. The microwave Oven (1400W), blender/Mixer (800W), deep Freezer (500W) and 0.5 hp Submersible Pump (400W) were also excluded.

3.3 Key Performance Indicators (KPIs) for the Solar Photovoltaic Model: The following are the necessary criteria which the Solar Photovoltaic model is fulfilling; excellent energy efficiency, the optimum capacity of electricity supply. The benefit also includes affordable capital cost, minimal maintenance cost. There is a negligible operating cost coupled with the reduction of emission. The PV model provides a reliable power supply. It also provides improved security condition of residential premises at night.

3.4 Techno-Economic Assessment: These necessary criteria as defined above have been used as inputs into the techno-economic assessment (feasibility study) carried out for the justifying the preferred energy source for electricity for the residential premises using Decision Matrix Technique. Table 3 gives the techno-economic assessment using a decision matrix technique.

Table 3. Techno-economic assessment for the selection of the preferred energy source for security lamp using decision matrix technique

Power Supply Options	Necessary Criteria	Energy Efficiency of Appliances	Quality of Electricity Supply	Capital Cost	Maintenance Cost	Operating Cost	Emission Reduction	Availability/ Reliability	Security Condition Improvement	Total
	Weighing Factor (WF)	7	6	5	6	9	5	8	6	**52**
Power Supply Options	Weighted Average (WA) = WF/TWF	0.134615	0.115384615	0.096153846	0.11538462	0.1730769	0.096153846	0.1538462	0.11538462	**1**
Solar Photovoltaic	Rating Factor (RF)	9	9	3	6	9	9	9	7	
	Score = RF * WA	1.211538	1.03846158	0.288461538	0.69230769	1.5576923	0.865384615	1.3846154	0.80769231	**7.8461538**
Public Utility	Rating Factor (RF)	7	6	8	7	3	3	3	4	
	Score = RF * WA	0.942308	0.692307692	0.769230769	0.80769231	0.5192308	0.288461538	0.4615385	0.46153846	**4.9423077**
Power Generator	Rating Factor (RF)	7	6	4	3	2	2	7	3	
	Score = RF * WA	0.942308	0.692307692	0.384615385	0.34615385	0.3461538	0.192307692	1.0769231	0.34615385	**4.3269231**
Total										17.115384

From the techno-economic assessment above, it could be observed that the option of power supply from solar photovoltaic having the score of **7.84615388** offers significant potential benefits when employed as an electrical energy source for residential buildings.

4.0 CONCLUSION

The study gave a model for powering a residential building in a typical SSA household. The technical details of the solar PV model for a typical 2-bedroom were provided. The average 2-bedroom is usually occupied by the spouse, two to three kids and sometimes additional guest. The living room is used for entertainment and the bedroom for sleeping. The model is an optimum size solar Photovoltaic installation with a maximum power input of 1,800 W. The maximum allowable load is 1,000 W and a maximum charging D.C voltage of 28.2 V. The solar-powered system is equipped with a set of six (6) 300 Watts monocrystalline solar panels.

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