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Sizing an Off-Grid Photovoltaic System and Economic Comparison with Petrol Generator Using Life Cycle Cost (LCC) Approach for a Typical Rural Primary Healthcare Center in Nigeria

Okakwu, I.K[1], Olabode, O.E[2*], Ade-Ikuesan, O.O[3], A.E Airoboman[4]

[1]Department of Electrical and Electronic Engineering, University of Benin, Benin City, Nigeria
[2]Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria
[3]Department of Computer and Electrical Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria
[4]Department of Electrical and Electronics Engineering, Nigeria Defence Academy, Nigeria

**Corresponding author: oeolabode59@pgschool.lautech.edu.ng*

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Abstract

It is needless to re-emphasize that modern day healthcare systems require uninterruptible power supply, relying on the national grid for power supply most especially in remote areas in Nigeria is a deliberate attempt to paralysis and underutilize both the human and non-human resources. This paper presents the sizing of a stand-alone photovoltaic system and economic comparison with petrol generator in powering a rural Primary Health Care Center (PHC) in Agbado, Ado-Odo, Ota Local Government, Ogun State, Nigeria. Load survey of the PHC was done in order to know the daily energy demand. The average annual solar radiation and the estimated load for the PHC used as case study are 4.89kWh/m^2/day and 14.40kWh/day respectively. The result obtained from sizing the photovoltaic system reveals that the estimated load will require 5.25kW photovoltaic array capacity, 21 modules (24V, 250W each), 10 batteries (12V, 200Ah each), 3 solar charge controllers (24V, 80A each), 1 unit of 4kW inverter (24V$_{dc}$/220V$_{ac}$, 50Hz), 3x70mm^2 insulated flexible copper cable and 3x2.5mm^2 insulated flexible copper cable. Life Cycle Cost (LCC) technique was used to assess the most economically viable option in powering the PHC. The study also reveals a savings of 64.4% in LCC using PV system as against petrol generators in powering the PHC. The replacement cost constitutes the higher factor affecting the LCC of the PV system constituting about 47.7%, while the operation and maintenance cost forms the least factor with about 28.9%. Also, for that of petrol generator, the fuel cost constitutes the highest factor affecting the LCC, constituting about 87.6%, while the initial capital cost forms the least factor which is about 0.24%. The insights from this study can be reciprocated to other rural PHCs in Nigeria.

Keywords: inverter, Off-grid, photovoltaic system, primary health care center, solar radiation

1.0 INTRODUCTION

Reliable and sustainable energy supply is inevitable and critical for proper healthcare delivery [1]. Therefore, energy supply is a prerequisite to proper healthcare which is very essential for humanity. In Nigeria, reliable and stable energy supply is a major challenge for both urban and rural dwellers [2]. This challenge is more pronounced in rural areas where utility grid extension is impractical owing to rugged terrain and dispersed population [3]. As such, several utility and government interventions on grid extension have been centered in urban cities where grid extension is cheaper and more economical for investors [4]. Improved healthcare services and accessibility to uninterruptible power supply can be perceived as being directly proportional, because common day to day experiences had shown that instability or interruption in power supply hinders treatment plans and even laboratory services to a large extent. [5]. Access to energy supply will improve the productivity of health workers by replacing manual work with automated processes, which ultimately would lead to positive virtuous growth cycle [6]. In line with the submission of United Nations (UN), significant viable development is pivoted by sustainable supply of energy, by inference, universal accessibility to cheaper, dependable and modern energy is a key challenge to be address to achieve the anticipated sustainable growth and development [7].

Aside other professional ethical needs, efficient, reliable and constant power supply is a key consequential need of any named PHCs across the globe [8]. The lack of this energy infrastructure has made most PHCs to result into generating their own power, using conventional fossil-fuel generators which has further impacted negatively on the health of the people due to continuous exposure to fossil-fuel system that has also led to the increased greenhouse gas emissions [9]. Also, the insurgence of several deadly communicable illnesses such as Ebola virus, HIV/AIDS and Zika in developing countries, most predominantly in the rural communities has also led to the distribution of antiretroviral drugs and vaccines that are temperature sensitive, have also compelled the need for scalable and dependable energy supply to rural PHCs in bid to eradicate/ cure these chronic diseases [10]. Furthermore, reliable energy supply is also needed for patients in intensive care unit, child delivery, illumination for proper diagnosis, accident and emergency unit, etc. [11]. Lack of reliable energy supply would increase the risk of losing lives [12]. Hence, the place of steady and reliable power source in safeguarding smooth running of scheduled activities in PHCs cannot be over-emphasized. Therefore, implementation of off-grid photovoltaic system in PHCs would reduce the dependency on conventional energy sources and ensure quality healthcare service delivery to patients. PHC located in rural area of Agbado, Ado-Odo, Ota Local Government, Ogun State, Nigeria was used as a case study in this paper.

2.0 METHODOLOGY

2.1 The Description of Case Study Site

A rural PHC located in Agbado, Ogun State, Nigeria (lat. 6˚69'N and long. 3˚30'E) has been selected for design of an off-grid photovoltaic system. The population of this area is 527,242 based on 2006 census in Nigeria. The monthly average daily solar radiation of the study locations as gotten from Nigerian Meteorological Agency is as shown in Table 1. The location solar radiation data confirms the availability of solar radiation throughout the year.

Table 1: Average monthly Solar Radiation

Month of the year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Solar radiation on the average (Kwh/m^2/day)	5.57	5.74	5.66	5.34	5.01	4.51	3.89	3.73	4.05	4.62	5.18	5.37

2.2 Load profile of the Primary Healthcare Centre

The electrical load profile was obtained from the ratings of various medical equipment in the PHC and their various hourly usage. Table 2 presented a typical load profile of the understudy PHC in Agbado, Ogun state Nigeria.

Table 2: Load Profile of the Case Study

S/N	Electrical Equipment	Quantity	Rated Capacity (W)	Hourly usage per day	Total Energy kWh/day
1	Refrigerator Vaccine	1	40	10	0.400
2	Refrigerator non-medical	1	125	5	0.625
3	Centrifuge	1	70	4	0.280
4	Microscope	1	20	6	0.120
5	Blood Chemical analyzer	1	45	4	0.180
6	Hematology analyzer	1	230	4	0.920
7	CD4 Machine	1	200	4	0.800
8	Radio	1	15	10	0.150
9	CFL bulbs	9	18	12	1.944
10	Ceiling fan	5	75	14	5.250
11	Halogen lamp (security)	1	50	11	0.550
12	Desktop Computer	1	65	8	0.520
13	Printer	1	250	1	0.250
Total Average Energy Consumption					11.989

The annual average load demand is 12kWh/day to avoid underestimation of load demand, the annual average load demand was increased by 20%; Hence, the average load demand was now 14.40kWh/day.

2.3 Sizing PV Array

The energy that can be generated by PV array is given by Eq. 1 [13]:

$$E_{PV} = \frac{E_{LD}}{\eta_{inv} \times \eta_{ch} \times \eta_{PV}} \quad (1)$$

where;

E_{LD}, η_{inv}, η_{ch} and η_{PV} represents the average daily energy demand, inverter efficiency, charge controller efficiency and PV array efficiency respectively.

PV-array area can be modelled as given by Eq. 2 [13]:

$$A_{PV} = \frac{E_{PV}}{E_{Sr}} \tag{2}$$

where;

E_{Sr} is the solar radiation of the study location.

PV-array power output is governed by Eq. 3 [14]:

$$PV_{out} = PS_{STC} \times A_{PV} \times \eta_{PV} \times SF \tag{3}$$

where;

PS_{STC} and SF are the peak solar intensity in standard test condition (1000W/m^2) and losses safety factor (dust-based, module temperature, manufacturer specification tolerance, etc).

The PV modules number required to be linked in series can be modelled by Eq. 4 [14]:

$$NM_S = \frac{V_{system}}{V_{module}} \tag{4}$$

where;

V_{system} and V_{module} are the system voltage and module voltage.

The PV modules number required to be linked in parallel is express by Eq. 5 [14]:

$$NM_P = \frac{PV_{output}}{NM_S \times P_{module}} \tag{5}$$

where;

P_{module} = power output per unit module.

The entire number of modules required is modelled by Eq. 6 [15]:

$$NM_{total} = NM_P \times NM_S \tag{6}$$

The selected PV-arrays are PS-P 60 mono-crystalline silicon with the specifications at standard test condition (i.e. 1000W/m^2 at 25˚C) as shown below [16]:

-Short-circuit Current = 8.17A
-Short-circuit Power = 250W
-System Voltage = 24V
-Module Voltage = 24V
-Inverter Efficiency = 0.90
-PV-array Efficiency = 0.14
-Controller Efficiency = 0.98

The lowest monthly average daily solar radiation of the study site was used and SF assumed to be 1.2 in order to avoid wrong sizing [17].

2.4 Sizing of Battery Storage System

Battery rating is given in Ampere-hour (Ah) while depth of discharge (DOD) is employed to assess the level of usage, in short it can be regarded as the battery life [18]. The days of autonomy otherwise called days of "no sun" connotes number of days wherein the system load is singly supplied by the storage system [19]. The capacity of battery required for one day autonomy is given by Eq. 7 [20]:

$$CB_S = \frac{E_{LD}}{DOD \times \eta_B \times V_{system}} \tag{7}$$

where;

η_B is the efficiency of battery = 0.85 and DOD is assumed to be 0.8. If the selected battery is 12V, 200Ah, then the number of batteries connected in parallel is obtained using Eq. 8 [21]:

$$NB_p = \frac{CB_S}{unit\ battery\ rated\ capacity} \tag{8}$$

The required number of batteries to be linked in series is obtained via Eq. 9 [21]:

$$NB_s = \frac{V_{system}}{unit\ battery\ voltage} \tag{9}$$

Therefore, the entire number of batteries needed is obtained via Eq. 10 [21]:

$$NB_{total} = NB_s \times NB_p \tag{10}$$

2.5 Sizing of Inverter

An inverter is needed in order to convert DC input to AC output. Essential perquisite to bear in mind when sizing inverter is that the input rating of the inverter is expected to be absolutely and at all times higher than the load [22]. Also, both the battery and the inverter must possessed the same nominal voltage rating [23]. The inverter sizing capacity is given by Eq. 11 [24]:

$$P_{total} = 1.25 \times (P_r + (3 \times P_{in})) \tag{11}$$

where;

P_r is the total resistive load and P_{in} is the total inductive load. The inductive load is multiplied by 3 in order for the inverter to be able to accommodate starting current of inductive load. A safe factor of 25% was also needed for system expansion.

2.6 Solar Charge Controller Sizing

Solar Charge Controller is saddled with the responsibility of maintaining the voltage between the photovoltaic array and batteries, with this, prevention of overcharging and proper charging of battery bank is guaranteed. Proper handling of maximum current generated by the PV array is expected of a good charge controller. They are rated against Amperage and Voltage capacity. The rated capacity of the charge controller is modelled using Eq. 12 [24]:

$$I_{rated} = 1.25 \times I_{sc} \times NM_p \tag{12}$$

where;

I_{sc}= short-circuit current of PV-module and 1.25 is the safe factor. The selected controller is 24V, 80A.

The aggregate number of controllers needed to be linked in parallel is obtained via by Eq. 13 [24]:

$$NCC_p = \frac{I_{rated}}{unit\ ampere\ per\ controller} \tag{13}$$

2.7 Sizing of System Cables

The installation of PV system is not complete until the correct cable sizes are selected for wiring the component together. The two cables (DC cable from PV module to inverter through battery bank and solar charge controller and AC cable from inverter to load) linking the PV system is expected to be carefully and properly sized.DC cable rating is governed by given by Eq. 12 above, while the rating of the AC cable is given by Eq. 14 [24]:

$$I_{oi} = \frac{P_{total}}{V_{oi} \times Pf} \tag{14}$$

where;

V_{oi} is the inverter output voltage and Pf is the power factor (0.8).

2.8 Economic Analysis using Life Cycle Cost (LCC)

Life Cycle Cost (LCC) is the sum total cost of initial investment, industry, operation and maintenance, replacement and even decommissioning. LCC is a dynamic economic process used to decide the most cost effective energy source option. The LCC can be calculated using equ. 15 [25]:

$$LCC = C + OM + R + F \tag{15}$$

Where C is the initial capital cost, OM is the operation and maintenance cost, R is the replacement cost and F is the fuel cost. The fuel cost is only applicable to diesel generator and not photovoltaic system.

The OM cost is given by equ. 16 [26]:

$$OM = F_i\ x\ \left[\left(\frac{1+F_{ec}}{d-F_{ce}}\right)\ x\ \left(1-\left(\frac{1-F_{ec}}{1+d}\right)^N\right)\right] \tag{16}$$

Where F_i is 5% of initial capital cost [27], F_{ec} is the escalation rate, assumed to be 20% [26], d is the discount rate, assumed to be 17.71% [27] and N is the number of years.

The replacement cost is modelled as equ. 17 [27]:

$$R_c = P_{in}\ x\ (1+i)^N \tag{17}$$

where P_{in} is the initial capital cost of component replacement and i is the interest rate, assumed to be 15.37% [27]. It is worthwhile to note that batteries are usually the components replaced in PV-systems, while the generator is usually replaced after every 15,000 run hours.

The cost of fuel is obtained in equ. 18 [26]:

$$F = C_{CPL}\ x\ A_{CPD}\ x\ \left[\left(\frac{1+F_{ec}}{d-F_{ce}}\right)\ x\ \left(1-\left(\frac{1-F_{ec}}{1+d}\right)^N\right)\right] \tag{18}$$

Where C_{CPL} is the cost of diesel per liter and A_{CPD} is the yearly diesel consumption

But;

$$\boldsymbol{A_{CPD} = average\ consumption\ per\ day\ x\ 365} \tag{19}$$

3.0 RESULTS AND DISCUSSION

The total energy demand of the case study forms the basis for sizing the various components of the designed PV-system. The estimated total energy demand of the PHC understudy was found to be 14.40kWh/day. Table 3 presents the sizes obtained for each components within the designed PV system, while Table 4 shows the initial capital cost of the petrol generator set proposed in this study.

Table 3: Components sizes, quantity, unit and total cost

Investment Cost of Solar PV System			
Description of Required Components	**Quantity**	**Unit Cost (₦)**	**Total Cost (₦)**
Module of Polycrystalline (250W, 24V)	21	55,000	1,155,000
Trodjan Deep Cycle Battery (200Ah, 12V)	10	180,000	1,800,000
Charge Controller (80A, 24V)	3	180,000	540,000
4kW, 24V/220Vac, 50HZ Inverter	1	220,000	220,000
Insulation flexible copper cable from PV array to battery bank through charge controller and then to input inverter $(3 \times 70mm^2)$	Nil	20,000	20,000
Insulation flexible copper cable from inverter to DB of load $(3 \times 2.5mm^2)$	Nil	3,000	3,000
Installation cost + Civil Works	Nil	400,000	400,000
Item Delivery Cost	Nil	120,000	120,000
Total			**4, 258, 000**

Table 4: Initial capital cost of petrol generator [28]

Investment Cost of PETROL GENERATOR SET					
S/No.	**Model**	**Power Rating**	**Ave. Fuel Consumption Rate (Litres/hour)**	**Current Petrol Price/Litre (₦)**	**Unit Cost of Generator Set (₦)**
1	SUMEC Firman SPG560E2	3.6kVA	1.43	145	124,500
Total					**124, 500**

Shown in Table 3 is various components required for an off-grid photovoltaic system and cost estimation of components. The results showed that to power a typical PHC in Agbado, Ogun state, Nigeria, the system will require 21 modules of 250W each of 24V connected in parallel. Also, for an autonomy of one day, the battery capacity required is around 882Ah, with 2 batteries connected in series to form 5 strings (Parallel Connection), making it a total of 10 batteries required. Furthermore, to ensure that the batteries are well charged and not overcharged, 3 solar charge controllers of 80A each, connected in parallel are required. A 4kW inverter is chosen to meet the load demand of the PHC. A copper cable of $3x70mm^2$ is required to connect the PV-array to the battery bank and then to the input of the inverter, while a $3x2.5mm^2$ copper cable is also needed to connect the output of the inverter to the distribution board of the load. The overall initial capital cost required for a photovoltaic system is ₦4,258,000.00. Table 4 shows the initial capital cost for the petrol generator set which is about 3% of that of PV-system.

Figure 1 shows the LCC comparison between the PV system and petrol generator for a lifetime of 20yrs. The figure depicts a breakeven point of two years for both technologies, which is in concordance with other research output [28-29]. This implies that the petrol generator is more economically viable within the first two years of its usage compared to the Photovoltaic system. However, surpassing this breakeven point, the LCC of the petrol generator increased astronomically as compared to that of PV system. The LCC of the petrol generator was estimated to be ₦51,055,061 and that of Photovoltaic system was ₦18,178,498.

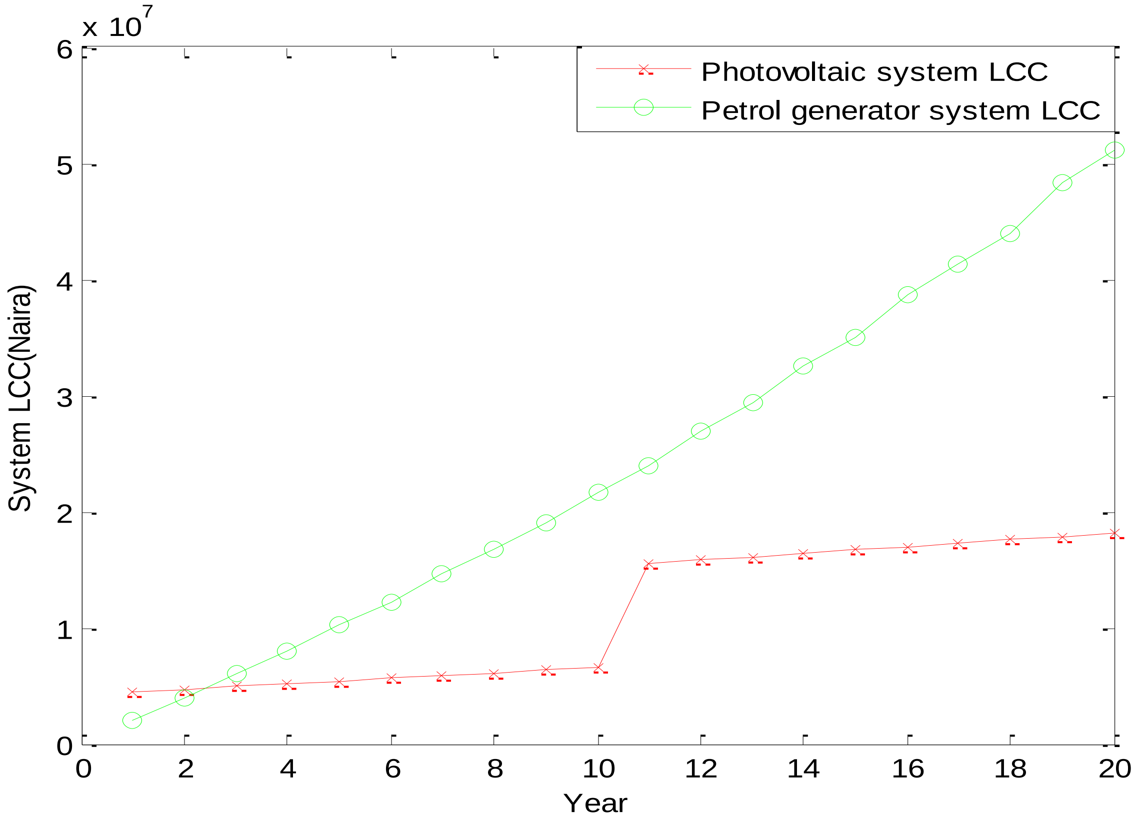

Figure 1: LCC analysis of Photovoltaic system and Petrol generator set

4.0 CONCLUSION

The sizing of an off-grid photovoltaic system and economic comparison with a petrol generator for powering a Rural PHC in Agbado, Ogun state, Nigeria is presented in this paper. Based on the results obtained from this study, an estimated load demand of 14.40kWh/day, it will require a 5.25W photovoltaic array with 21 modules of 250W, 24V each; 10 batteries of 12V, 200Ah each; 4.0KW, 24Vdc/220Vac, 50Hz inverter. The sized off-grid PV-system requires copper cable of 70mm^2 and 1.5mm^2 for connecting between PV-array/batteries/inverter input and inverter output to DB of load. Also, the system cost estimation was ₦4,258,000, while the initial capital cost of the petrol generator is ₦124,500. The study also reveals a savings of 64.4% in LCC using PV system as against petrol generators in powering the PHC. The replacement cost constitutes the higher factor affecting the LCC of the PV system constituting about 47.7%, while the operation and maintenance cost forms the least factor with about 28.9%. Also, for that of petrol generator, the fuel cost constitutes the highest factor affecting the LCC, constituting about 87.6%, while the initial capital cost forms the least factor which is about 0.24%. Therefore, the usual petrol generation system is not economically viable due to high fuel cost and also due to environmental effect. Hence, using a PV-System for powering PHC in Nigeria is cheaper in the long run as compared to using diesel/petrol generator. The Photovoltaic system is environmentally friendly as against the conventional sources of energy such as diesel/petrol generators which causes global warming and impact negatively to the environment.

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