IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 13, Issue 5 Ver. I (Sep. – Oct. 2018), PP 53-61
www.iosrjournals.org

Stand-alone solar PV system sizing for critical medical equipment to meet an emergency energy demands in Ghana: Tanoso Community Hospital in Kumasi.

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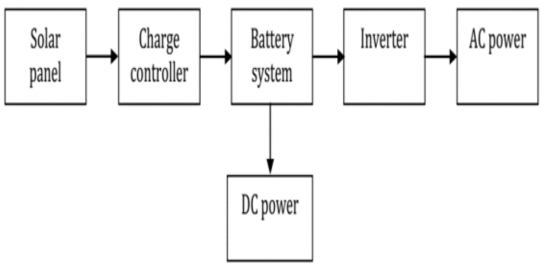
Abstract: *The revolution photovoltaic systems toward energy demands across the world is becoming immeasurable, and the increasing demand for energy in Africa, make the situation no different as most consumers are now turning to photovoltaic systems. However, reliable electrical power supply remains a challenge for many health facilities, especially in Ghana. In view of this, we present a comprehensive case study design and sizing of a stand-alone photovoltaic system for critical loads at a hospital in Ghana, called Tanoso Hospital in Kumasi metropolitan area taking into consideration their energy demands. The efficiency of large photovoltaic systems are enhanced through accurate sizing. The Stand-Alone PV sizing, which is dependent on solar irradiation data at the site of the hospital, electrical load data of the critical loads and the investment of the solar photovoltaic system components, is assisted by the PV System software to deduce the optimal sizing of solar PV components for the Hospital. The results indicate that the stand-alone solar PV power together with power from the national grid is feasible for the Tanoso hospital and reduce electricity tariffs overall. The system is also very reliable and cost-effective as payback returns were achieved within a relatively short period of a little above two years.*

Keywords – *Energy, Photovolatic, Stand-alone, Efficiency, Sizing*

Date of Submission: 23-09-2018 Date of acceptance: 08-10-2018

I. Introduction

The sun is considered a good energy source because of its cleanliness and consistency unlike other forms of energy such as coal and oil and gas [1]. It is also environmentally friendly and does not cause the emission of greenhouse gases particularly, the carbon dioxide gases into the atmosphere.



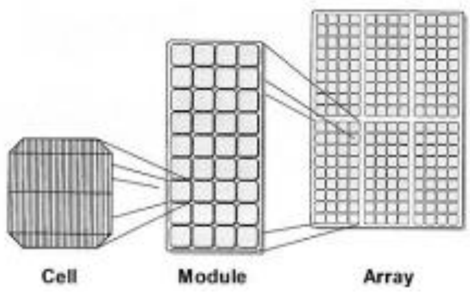


Figure 1 (a) Solar PV Operating System (b) Basics of the Solar Cell

Solar Photovoltaic system is used for different purposes such as water heating system and serving as a source of energy for homes and companies thus reducing electricity tariffs. It is a readily source of power as solar energy is available throughout the surface of the earth. Solar PV systems can either be grid connected or not. A grid-connected solar PV system can transfer extra energy generated by the solar installation into the national grid while Off-grid solar PV systems (stand-alone) cannot do likewise. The Stand-Alone solar PV systems comprise the charge controller, battery, inverter, electrical load and the PV module [2]. The main objective of the study is to precisely size a stand-alone photovoltaic system for the critical loads at the Tanoso Community Hospital.

(a) **(b)**

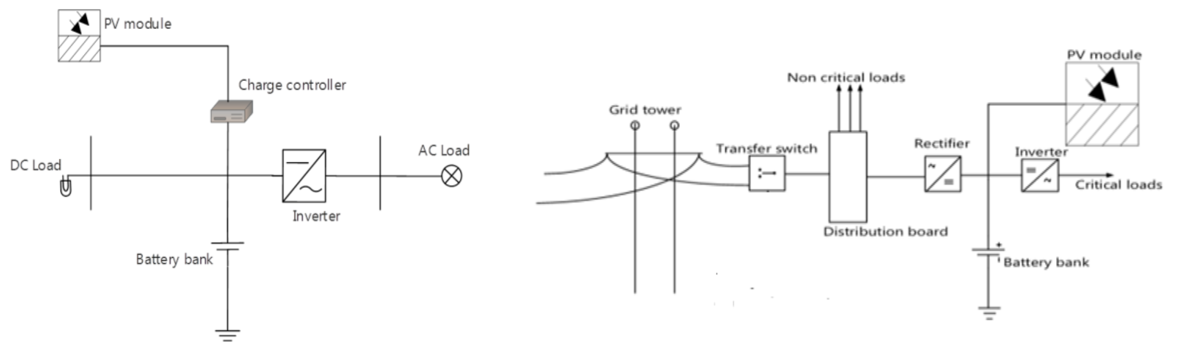


Figure 2. (a) Stand-Alone PV System (b) Critical and non-critical loads energy distribution

In this paper, two types of loads are categorised. The first is the 'critical load' which defines loads in constant need of electrical power, with the lack of stable power to these loads capable of resulting in patient fatalities at the hospital. Such loads include surgical theater units, oxygen generation units, equipment sterilization units, laboratory operations, x-ray rooms, incubator rooms, centrifuge machines, dialysis machines and diagnostic ultrasound systems among others as shown in figure 3.

Figure 3. (a) Autoclave (Critical Load) (b) Computer and Printer (Non-critical load)

The 'non-critical loads' refer to loads in which intermittent power to these loads will not affect the lives of patients. Some of these loads include general lighting, air-conditioning, and refrigerators in the hospital, water pumping units, photocopiers, scanners, computers, TVs and fans. However, there are some loads which can function as both critical and non-critical in the hospital due to the location and functionality of such loads. For instance, lighting fixtures in the Out-patient department are regarded as not so essential especially during the daylight periods as compared to these same lighting fixtures in the surgical theaters. Again, a refrigerator in the morgue or in the hospital pharmacy for storing low-temperature dependent medicines is considered critical as compared to that in the hospital shop for storing drinks and other confectioneries. Power supply to the critical loads is a mixture of power from the national grid and the stand-alone photovoltaic system whilst the non-critical loads are solely placed on power supply from the national grid as shown in figure 4.

Figure 4. Critical Loads (a) Surgical Theater (b) Oxygen Supply Machine

The power generated from the solar PV system is also utilised during peak periods to supplement that of the national grid and also during power outages. Therefore, prior to installation the energy ratings of all the critical loads are accounted for.

II. Load Assessment of the Tanoso Hospital

Tanoso is a modern day town located in Kumasi, the capital of Ashanti Region in Ghana with geographical coordinates 6° 41' 53.921" N, 1° 41' 26.265" W. The local weather is characterised by high levels of sunshine in the dry season and fairly average in the monsoon season. A load profile highlights a depiction of the use of power throughout a certain period. It illustrates energy consumption patterns of the various electrical loads. The profile is heavily reliant on measurements. The solar PV system is multi-crystalline silicon (multi-c-Si) and roof-mounted with a tilt angle of thirty (30) degrees.

Figure 5. (a) Front view of the Tanoso Hospital (b) Roof-mounted solar PV Systems at the hospital (c) Engineers taking solar irradiation measurements

Measuring the irradiation levels at the hospital, December is having the highest level of irradiance of approximately 5.1 kW/m^2 and September having the minimum of less than 1kW/m^2. This record features irradiation level of months in the year 2016-2017.

Table 1 Total energy consumption for critical loads in several departments of the hospital

Load	Total Mean Power	Hours/Day	Days/Week	/7days	W.h.
Surgical Theater	**3527**	**1**	**3**	**7**	**1512**
General Ward	**236**	**0.5**	**3**	**7**	**51**
X-ray and Ultrasound Units	**1195**	**1**	**4**	**7**	**683**
Pharmacy	**107**	**24**	**7**	**7**	**2568**
Family Planning/Counselling Unit/Maternity Unit	**977**	**24**	**4**	**7**	**13399**
Laboratory/Sterilisation Unit	**537**	**3**	**3**	**7**	**690**
Total	**7030**				**18903**

Surgery lights were also included and have wattage of approximately 54W. The second inventory also featured the cooling systems comprising of air-conditioners, fans and fridges, sterilization machines, water heaters and laundry machines. The third inventory included energy profiling of X-ray machines, incubators, diagnostic ultrasound machines, the anesthesia machines with the last audit covering desktops, scanners, photocopiers, printers, and water related equipment such as pumps.

Table 2. Monthly Global Insolation for Tanoso, Kumasi (a) 2017-2018 (b) 2016-2017

(a)

MTH 2017-2018	IRRADIATION (kWh/m^2)	OPTIMUM ANGLE (°C)	OPTIMUM ANGLE IRRADIATION (kWh/m^2)	Daily Mean of bright sunshine hours
JAN	5.38	31.0	5.98	8
FEB	5.57	21.0	5.79	8.1
MAR	5.56	8.00	5.53	8.2
APR	5.46	5.00	5.39	7.5
MAY	5.17	13.0	5.18	7.4
JUN	4.58	15.0	4.62	4.6
JUL	4.22	13.0	4.22	4.8
AUG	3.92	6.00	3.87	4.9
SEPT	4.03	2.00	3.98	5.8
OCT	4.71	15.0	4.77	6.9
NOV	5.08	28.0	5.49	7.5
DEC	5.05	33.0	5.70	7.7

(b)

MTH (2016-2017)	IRRADIATION (kW/m^2)	OPTIMUM ANGLE (°C)	OPTIMUM ANGLE IRRADIATION (kW/m^2)
JAN	5.22	30.4	5.68
FEB	5.40	20.6	5.50
MAR	5.40	7.8	5.25
APR	5.30	4.9	5.12
MAY	5.01	12.7	4.92
JUN	4.44	14.7	4.39
JUL	4.09	12.7	4.01
AUG	3.80	5.9	3.68
SEPT	3.91	1.9	3.78
OCT	4.57	14.7	4.53
NOV	4.93	27.4	5.22
DEC	4.90	32.3	5.42

It showed that the month of December leads with the peak irradiance of 5.6kw/m^2 and September lagging with less than 0.5kW/m^2. All inventory of electrical equipment was taken. The first inventory recorded loads of the lighting system with fluorescent light tubes of 30W each coupled with some LEDs (18W each).

The PV system software was primarily considered and chosen because it could perform different simulations according to different energy configurations, generate a financial report and provide a detailed graph of irradiation levels [7]. Also, in the case of solar irradiation measurements, the solar Irradiation tool was used in the collection of irradiation levels at different tilt angles from the solar panels. All the inputs applied during modelling were from equipment capacity, quantity and technical specifications [8]. Local prices formed the basis of prices for components such as cost of hardware, installation, labour and other electrical and non-electrical accessories.

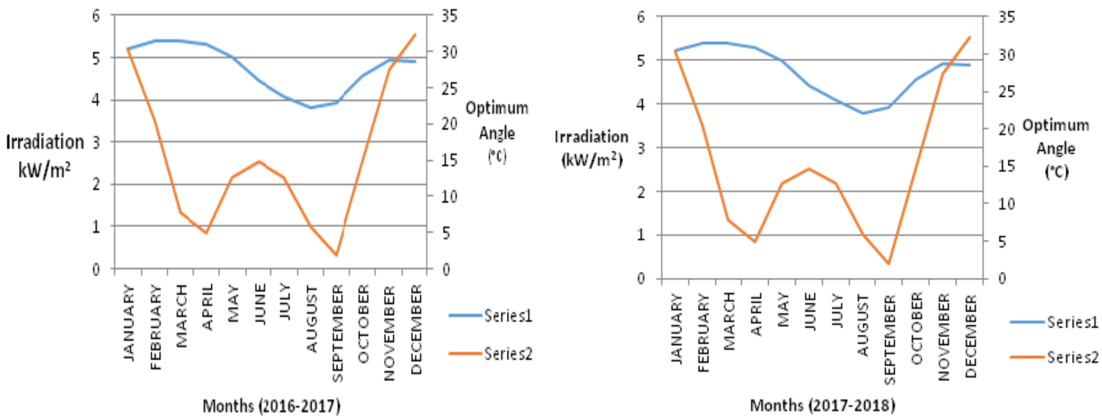


Figure 6. Irradiation-Optimum Angle measured in different months at Tanoso hospital for (a) 2016-2017 year (b) 2017-2018 year.

III. Photovoltaic sizing

PV system sizing refers to the computation of PV components' capacity required to make the complete PV system meet the necessary load demand [9]. It comprises calculating the monthly average of the daily load, determining load and insolation for critical design month (worst month), sizing of battery bank, inverter and charge controller and finally sizing of PV array. The series connection of PV modules is termed as PV module string. For voltage increase, series connection of PV modules is used and for current increase, parallel connection of PV modules is preferred.

Inverter Sizing

The inverter is the heart of the photovoltaic system. It makes 220 volts AC from the 12volts DC stored in the batteries. It can also charge the batteries if connected to a generator or the AC line. Some types are the CC/CC used to supply the continuous charges and the CC/AC used to supply alternatives charges under 220V AC in the case of photovoltaic systems.

(a) (b)

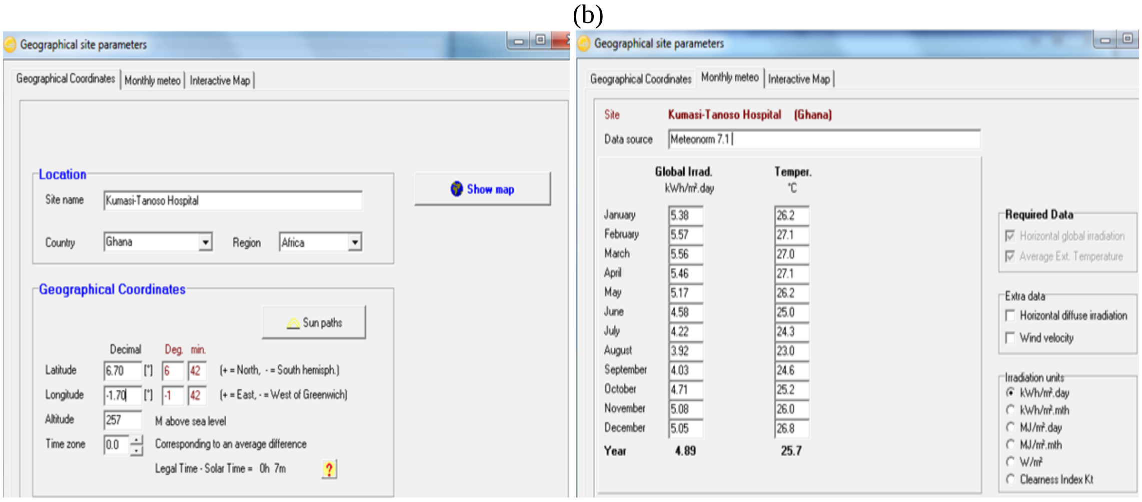


Figure 7. (a) Geographical Coordinates of the Tanoso Hospital in PVSyst (b) Average Solar Irradiation Data

Figure 8. (a) Average Solar irradiation per month (b) Solar insolation and cost analysis in PV System

Most modern inverters without batteries have the Maximum Power Point Tracking (MPPT) that automatically varies the voltage of the solar PV array to be able to operate at a Maximum PowerPoint. For inverters with batteries, the battery charge controllers possess this feature. The inverter also has the ability of shedding non-critical loads and giving continuous supply of power to critical loads in the event of a power outage. Again in the event of a power outage, the inverter must be switched off [10].

Figure 9. Arrangement of inverter, Charge Controller and Batteries

The output power of the inverter is matched to the AC power required by the load. The inverter size should correspond to the AC power needed by the total electrical load. It must also be ensured that the input DC voltage must be in the range of the nominal voltages of solar PV arrays which is 12V, 24V or 48V for a battery reliant system [3]. Without the battery based system, the input DC voltages must range from a little over 240V to 600V. The grid connected inverter can be oversized or undersized by 30% taking into consideration the size of the PV module.

Table 3. Inverter Sizing Computation

Inverter Sizing	
The amount of wattage that can be run at any point in time is given by: Wp = 7030W	The inverter needed must be able to accommodate this value at a constant AC voltage. Thus the selection of the inverter as 10000watts, 48-Vdc, 230Vac. inverter

The stand-alone PV inverter chosen had the following properties: the MPPT voltage range (50-145V), Output power (10kW),with the connection: 50Hz-60Hz grid frequency and 1 phase 2 wire connection and the efficiency of the inverter being: 95% and an AC voltage of 230 Volt.

Sizing battery capacity

Batteries store electrical energy in the form of charges. They comprise multiple cells connected together. The size of the cell depends on the amount of charge stored in a cell. 2V, 6V and 12V are the nominal voltages of batteries commonly available. In solar photovoltaic systems, batteries are used to store electrical energy gathered from PV modules for later use. The electrical energy stored in the cell is proportional to its size. All the stored energy is not delivered to the load as a result of the depth of discharge of the battery. The depth of discharge, DOD, represents the amount of energy that can be expended from the battery [4].

NOMINAL RATINGS		
MAXIMUM POWER (+7%/ +2%)	Pmax	250W
OPEN CIRCUIT VOLTAGE	Voc	37.5V
SHORT CIRCUIT CURRENT	Isc	8.76A
VOLTAGE AT POINT OF MAXIMUM POWER	Vmpp	30.3V
CURRENT AT POINT OF MAXIMUM POWER	Impp	8.24A
MAXIMUM SYSTEM VOLTAGE	Vmax	1000V
MAXIMUM SERIES FUSE	Imax	5A

Figure 10. Parameter of Sharp Solar Module NU-RD 250 at Standard Test Conditions

Approximately 80% of the battery's capacity is useful. The opposite of 'DOD' is the state of charge (SOC) which represents the amount of energy stored in a battery. The most commonly used batteries in a solar photovoltaic system include alkaline batteries and lead acid batteries. Batteries designed for grid connected systems are sized to operate for shorter hours compared to the stand alone systems. The batteries store electrical power in the form of a chemical reaction. Without storage you would only have power when the sun was shining or the generator was running. The batteries guarantee the energy supply continuously, by stocking the energy. They should be resistant to repetitive cycles; it means that to support long charges in the day and discharges in the night. They have a good yield of charge, even for the weak charges of current. Battery capacity in solar PV systems are dependent on the AC energy consumption and are inversely proportional to the battery's DOD, temperature coefficient, nominal voltage and inverter efficiency.

Table 4. Battery Sizing Calculation

Battery Sizing	
Total Average Energy use	**23628.75Wh**
Days of Autonomy	**2 days**
According to the selected battery (200AH, 12V-DC), the amount of energy stored is given by:	E_{st} = (23628.75 x 2) = **47.258kWh** E_{st} = Energy Stored in the battery
In considering energy safety levels	$E_{safe} = (E_{st}/M_{dod})$= (47.258kWh / 0.75) = **63.01kWh**
Capacity of the battery	$C = E_{safe} / V_b$ = 63.01kWh / 12V = **2625 Amps h** E_{safe} = Safe Energy Storage V_b = DC voltage of 1 battery
Total number of batteries	N_{batt} = C / Cb = 2625 / 200 = 13.125 batteries N_{batt} = Number of batteries C = capacity of battery Cb = capacity of battery bank

$$C = (Eac \times Aut) / (Eiff \times Volt \times DOD \times Tcoeff) \quad (1)$$

Where: C is battery capacity;

- *Eac* is AC energy consumption of equipment;
- *Aut* is days of autonomy;
- *Eiff* is inverter efficiency;
- *Volt* is nominal voltage of battery;
- *DOD* is depth of discharge;
- *Tcoeff* is battery temperature coefficient.

The battery temperature coefficient depicts the efficiency of a battery at different temperatures and this value is usually provided from the manufacturer's data sheet.

Sizing charge controller

The charge regulator ensures the optimization of the electricity production of PV panels. Its duty is also to protect the batteries against deep discharge, then to limit the terminal charge (protection against the overcharges).

Table 5. Sizing of PV Array

PV Array Sizing	
Daily Energy requirement from the solar PV array	$E_d = (E_t/E_{ff})$ = (18903Wh/0.8) = **23.629kWh/day** E_d = daily energy requirement E_t = total energy of critical loads E_{ff} = inverter efficiency
Peak power of the PV	$P_p = (E_d / A_t)$ = 23.629kWh/day / 6.78 = **160.2kW** P_p = Peak Power E_d = daily energy requirement A_t = average sun hours
Total module current	$I_{dc} = (P_p / V_{dc})$ = 160200 / 48 = **139A** I_{dc} = Total module current P_p = Peak Power V_{dc} = System DC voltage
Number of parallel modules	$N_p = (I_{dc} / I_r)$ = (139A / 8.24) = 16.9 = **17** N_p = Number of parallel modules I_{dc} = Total module current I_r = Rated current of one module
Number of series modules	$N_s = (V_{dc}/V_r)$ = 48 / 30.3 = 1.58 = **2.0** N_s = Number of series modules V_{dc} = System DC voltage V_r = module rated voltage
Total number of modules used, Nm, is given by:	Nm = Ns * Np = 2 * 17 = **34 modules**

The amount of voltage and current from the solar PV panels to the battery is controlled and regulated by the solar charge controller. This is to prevent the battery from being overcharged which goes a long way to prevent the battery from overcharging. Series and shunt controllers are the two types of charge controllers due to their mode of connection and wiring. A shunt controller bypasses current via a device to dissipate excess power while in series controllers' the current flow is controlled by opening and closing of a circuit between the battery and the solar PV array. Shunt controllers are normally applied to small systems while series controllers are reserved for larger systems. Charge controllers can also be classified according to the controlling algorithm and can either be Pulse Width Modulation (PWM) charge controllers or the Maximum Power Point Tracking (MPPT) charge controllers. The Pulse width modulation (PWM) controllers control the process of charging by adjusting the frequency and the width of the current pulses being delivered to the battery. PWM controllers minimize the charging current. The Maximum Power Point Tracking (MPPT) charge controllers' algorithm can operate a photovoltaic system array at its maximum power point over several operating conditions and at a much higher voltage than the battery voltage. The MPPT technique has enabled controllers to harvest power by up to 30%.

Table 6. Costs and Equipment-payback Returns (as at June, 2018)

PART		QUANTITY	PRICE (GHC)	Lifespan (years)	PRICE (USD)
250watts solar panels		36	950*36=34200.00	25	6,000.00
200Ah gel batteries-deep cycle		12	1800*12=21600.00	10	3,789.47
60Amps MPPT charge controller		3	2000*3=6000.00	25	1,052.63
10000watts inverter		1	7800*1=7800.00	25	1,368.42
Auxiliaries Cost			5,000.00	-	877.19
Installation Cost			3000.00	-	526.32
	Total Initial Capital Investment		77,600	-	13,614.03

The solar charge controller is normally rated in current and voltages. The size of the solar charge controller is derived from the short circuit current (I_{sc}) of the PV array. The voltage of the charge controller must be set up such that it does not interfere with the inverter [9].

IV. Economic Estimation and Payback Analysis

The payback period represents the measure of the number of years taken for the annual cash flow to equal the project cost. The lifecycle of the system is taken as 25 years with the lifetime span of batteries taken as 8 years. The discount rate was taken as 22% per annum(8).

Table 7: The lifecycle of the system is taken as 25 years

	Installed Cost (GHC)-77,600.00			
Year	Replacement Cost	Avoided Electricity Cost of the Hospital (GHC)	Net Cash Flow of the Hospital (GHC)	Cumulative Cash Flow (GHC)
1	0.00	2000.00	2000.00	2000.00
2	0.00	4000.00	4000.00	6000.00
3	0.00	6000.00	6000.00	12000.00
4	0.00	8000.00	8000.00	20000.00
5	0.00	10000.00	10000.00	30000.00
6	0.00	12000.00	12000.00	42000.00
7	0.00	14000.00	14000.00	54000.00
8	**0.00**	**16000.00**	**16000.00**	**80000.00**
9	0.00	18000.00	18000.00	96000.00
10	**56160**	**20000.00**	**36160.00**	**59840.00**
11	0.00	22000.00	22000.00	81840.00
12	0.00	24000.00	24000.00	105840.00
13	0.00	26000.00	26000.00	131840.00
14	0.00	28000.00	28000.00	159840.00
15	0.00	30000.00	30000.00	189840.00
16	0.00	32000.00	32000.00	221840.00
17	0.00	34000.00	34000.00	255840.00
18	0.00	36000.00	36000.00	291840.00
19	0.00	38000.00	38000.00	329840.00
20	**146016.00**	**40000.00**	**106016.00**	**223824.00**
21	0.00	42000.00	42000.00	265824.00
22	0.00	44000.00	44000.00	309824.00
23	0.00	46000.00	46000.00	355824.00
24	0.00	48000.00	48000.00	403824.00
25	0.00	50000.00	50000.00	453824.00

The lifecycle cost methodology is one of the measured ways of calculating the financial viability of the PV system. The lifecycle cost (LCC) is the sum of the capital cost and the net present worth of the solar PV components and includes acquisition costs, maintenance costs, operating costs and replacement costs. It is expressed mathematically as:

$LCC = I + Mpv + Rpv – (Spv + Ypv)$……………………………………………………..………….(2)

Where I = acquisition cost of the solar system

Mpv = maintenance cost present worth

Rpv = replacement cost present worth

Spv = salvage value present worth

Ypv = yearly savings

The maintenance costs are the costs accumulated in the operation period of the system. It includes cleaning, property taxes and technician salaries as well as insurance. The replacement cost represents the cost of changing a new device for an old system. In solar PV installations, this system is applied more often to the batteries which are to be replaced every 8-10 years. In this paper, the deep cycle batteries are to be changed in the 10th and 20th years respectively as the lifespan of the solar installation is pegged at 25 years. The computed costs were GHC56160.00 and GHC146016.00 respectively. The replacement cost is calculated as:

Replacement cost = 2.6 x cost of immediate past battery purchase cost…………..……………….……(3)

The monthly electricity tariff for the hospital (critical and non-critical loads) was GHC 4000.00. GHC2000 was saved monthly with the introduction of the solar PV system for the critical loads.

V. Conclusion

There is a great tendency for the use of stand-alone photovoltaic stations distributed in remote areas due to the known benefits of this source of energy. In this paper, the author introduces the procedures employed in building and selecting the equipment's of a stand-alone photovoltaic system based on the Watt-Hour demand.

In this case study, a hospital in Ghana, with medium energy consumption was selected. Factors related to the design and sizing of the system have also been presented. Over- and under-sizing have also been avoided to ensure adequate, reliable, and economical system design.

The procedures used could be employed and adapted to applications with larger energy consumptions based their geographical locations, however, the appropriate design parameters of these locations should be employed. The research has a payback of approximately eight (8) years. Based on the research findings in this study, it is deemed and recommendable to relegate critical loads in health facilities to solar systems for alternate energy provision. It is cheaper, more reliable and environmentally friendly.

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IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) is UGC approved Journal with Sl. No. 4198, Journal no. 45125.

Akom Kinsley" Stand-alone solar PV system sizing for critical medical equipment to meet an emergency energy demands in Ghana: Tanoso Community Hospital in Kumasi" IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) 13.5 (2018): 53-61.