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Performance Analysis of Stand-Alone Photovoltaic (SAPV) System for Category I Health Clinic in Orlu, Imo State, Nigeria

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Abstract

In this paper, performance analysis of stand-alone photovoltaic (SAPV) system for Primary Health Centre in Orlu, Imo state was conducted. The USAID categorisation of health clinics is used to identify the Primary Health Centre as Category I Health Clinic with corresponding daily and yearly energy demand of approximately 11500 Wh/day and 4197.5 KWh/year respectively. PVsyst software solution was used to model and simulate the entire PV system. 22-year air temperature and monthly and annual averaged insolation incident on a horizontal surface obtained from National Aeronautics and Space Administration (NASA) online meteorological portal was used. The results showed that the SAPV system has yearly energy output of 5269Kwh/year with performance ratio of 58.4%, effective operating or nominal efficiency of 8.83%, loss of load probability of 7.1% and unit cost of energy of 81.5 Naira per KWh. The SAPV is designed to be affordable for the Primary Health Centre in Orlu, Imo State, Nigeria.

Keywords: Photovoltaic, Standalone power system, loss of load probability, load demand, insolation, performance ratio, air temperature, nominal efficiency

1 Introduction

Quality healthcare delivering requires availability of both personnel and requisite facilities and enabling environment [1, 2, 3, 4, 5]. In this wise, regular electric power supply is essential to power the health facilities and provide conducive environment for the health care personnel and the patients as well [6, 7, 8]. Such adequate power supply is usually lacking in the various healthcare centers, especially in the remote areas in the developing countries. In most cases, the national grid is either completely absent in such locations or the grid connections are not functional due to poor maintenance [9, 10, 11]. More so, the high cost of extending or maintaining grid connection to the distant remote areas with meager population density discourages such grid extension to the remote areas. In such case, alternative energy source such as standalone solar power systems are the suitable options for providing electricity to the remote healthcare facilities [12, 13, 14].

Consequently, in this paper, standalone photovoltaic (SAPV) solar power system is proposed for Primary Health Centre located in a remote area in Orlu, Imo state. In order to design such SAPV power system, the daily load demand profile is first determined and the meteorological data are obtained after which the design and analysis can be conducted [15, 16, 17, 18]. In this paper, PVSyst simulation software is used for the design and performance analysis of the SAPV power system for the Primary Health Centre [19, 20, 21, 22, 23]. The system parameters are selected so that the standalone PV power system will be affordable to such small health facility in the remote community in Orlu.

2 Methodology

2.1 The Daily Load Demand Profile for the Category I Health Clinic in Orlu LGA

In most literature, the daily load demand profile is usually the first step in the design of SAPV power system. In this paper, the electric load demand data are compiled from site survey, along with health clinic's load demand profiles provided by USAID. According to USAID [24], rural health clinics generally fall into one of three categories (Categories I, II and III), based on the type and number of medical devices used in the facility and the frequency with which they are used on a daily basis. Primary Health Centres are the smallest, most basic health facility. Accordingly, the energy demands of a primary health centre will be satisfied through Category I Health Clinic electrification option [24]. Category I Health Clinic contains approximately 0 – 60 beds and has low energy demands between 5 - 10 kWh/day [24]. Table 1 shows the list of the types of equipment usually found in a typical Category I Health Clinics and their energy demands. Table 1 is used for the load demand at the Category I health clinic in Orlu LGA.

2.2 The Site Coordinates and Meteorological Data

When designing any SAPV power system it is essential to obtain the geographic coordinates of the PV module installation site. Afterwards, the meteorological data of the site can be obtained based on the geographic coordinates of the site. In this paper, Google map is used to obtain the coordinates of the Primary Health Centre in Orlu LGA as shown in, Figure 1: Latitude = 5.792345, Longitude =7.023718.

In the study, the meteorological data used include NASA SSE 22-year monthly and annual averaged insolation incident on a horizontal surface (kwh/m2/day) and 22-year monthly averaged air temperature as shown in Table 2. According to the data in Table 2, monthly average values of daily global solar radiation incident on horizontal plane at Orlu is very high especially during months of January, February , March and April, as well as the months of

October , November and December. Also, Table 2 shows that Orlu has annual average global solar radiation of 4.72 KWh/m2/day and annual average daily ambient temperature of 24.91 °C.

Table 1 List of the Types of Equipment Usually Found in Category I Health Clinics and Their Energy Demands (Applies to the Category I Health Clinic in Orlu LGA)

	A	**B**	**C=A(B)**	**D**	**E = C(D)**	**F=E/1000**
Device Description	**Quantity**	**Power (Watts)**	**Total Watts**	**On-Time (watt hours/day)**	**Wattage (hours/ day)**	**kWh/day**
Vaccine Refrigerator/Freezer	1	60	60	6.0	360	3.6
Small Refrigerator (non-medical use)	1	300	300	5.0	1,500	1.5
Centrifuge	1	575	575	1.5	862.5	0.8625
Hematology Mixer	1	28	28	1.5	42	0.042
Microscope	2	15	30	3.0	90	0.09
Lighting	5	60	300	8.0	2400	2.4
Incubator	1	400	400	10	4,000	4.0
Water Bath	1	1,000	1,000	1.0	1,000	1.0
Communication via VHF Radio	1					
Stand-by		2	2	15	30	0.003
Transmitting		30	30	3	900	0.9
Total			2500		11500	11.500

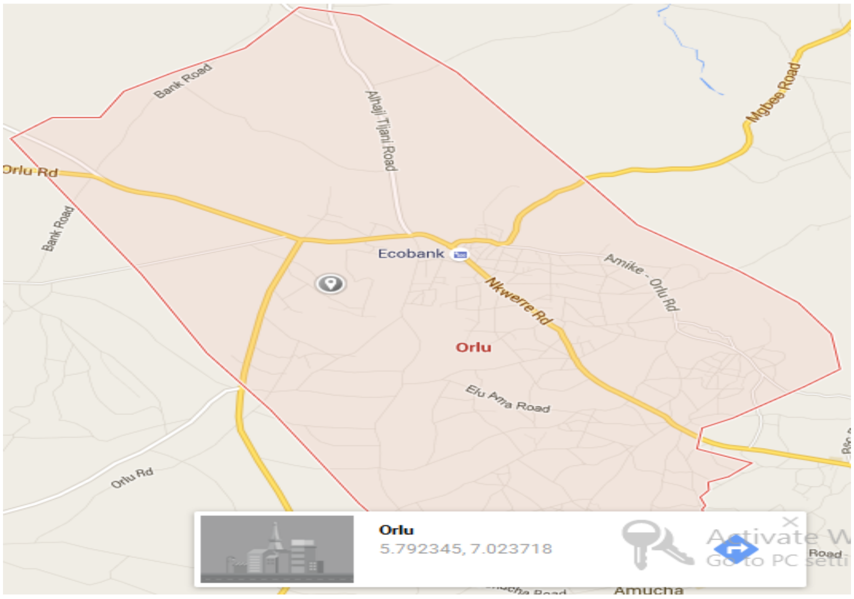

Figure 1 The Google Map Coordinates for the Primary Health Centre in Orlu LGA

Table 2 The monthly and annual average values of daily global solar radiation (Kwh/m/day) on Horizontal plane and ambient temperature (°C) in Orlu Imo State

Month	Monthly Average Values Of Daily Global Solar Radiation On Horizontal Plane (kWh/m².day)	Ambient Temperature (°C)
January	5.53	25.4
February	5.59	25.8
March	5.32	25.7
April	5.09	25.8
May	4.88	25.6
June	4.31	24.8
July	3.85	24
August	3.77	23.9
September	3.94	24.1
October	4.27	24.5
November	4.84	24.7
December	5.29	24.7
Year	**4.72**	**24.91**

2.3 Power Output of PV Array

The power output (P_{pv}) of PV array can be determined as follows [25, 26];

$$P_{pv} = \frac{E_L}{(PSI * \eta_{BO} * K_{loss} * G_d)} \quad (1)$$

$$\eta_{BO} = (\eta_{inverterlosses})\,(\eta_{wiringlosses}) \quad (2)$$

where

E_L is the average daily load energy consumption KWh/day,

G_d is the average solar radiation incident over Orlu in KWh/m2/day,

PSI is the peak solar intensity at the earth's surface (1000 W/m2),

η_{BO} is the efficiency of balance of system and can be determined by Eq (2) [26].

KLoss is a factor determined by the different losses such as: module temperature losses, circuit losses, dust, etc. Typical values for $\eta_{inverterlosses}$, $\eta_{wiringlosses}$ and KLoss are 15%, 10% and 90% respectively [26, 27].

3 The PVSyst Simulation

The standalone PV (SAPV) system for the Category I Health Clinic is simulated using PVSyst 5.21. The eight major steps used in the simulation process are stated as follows:

Step 1: Define the daily load demand profile for the Category I Health Clinic

Step 2: Define the coordinates (latitude and longitude) of the project site where the Category I Health Clinic is located at Orlu LGA.

Step 3: PVSyst Simulation Part I: Use PVSyst Tool Menu to download the solar irradiation and ambient temperature data based on the coordinates (latitude and longitude) of project the site.

Step 4: PVSyst Simulation Part II : Use PVSyst Poject Menu to define the Project which includes the name, the address , and the meteorological file that contains the solar irradiation and ambient temperature data for the project.

Step 5: PVSyst Simulation Part III : Use PVSyst Orientation Menu to define the Tilt Angle and Azimuth Angle for the PV Module.

Step 6: PVSyst Simulation Part IV : Use PVSyst System Menu to define the following

6.1 Daily Load Demand: The Daily Power Demand in watts and the average number of hours the load will be supplied power per day.

6.2 Loss Of Load Probability: The percentage of hours in a year when the power supply will not be able to supply the needed power to the load.

6.3 Days of Autonomy: The number of days the system will supply power from the battery without any solar energy input.

6.4 System DC Voltage : The DC voltage at which the system will operate (the Dc voltage at which the system will charge the battery and supply power to the inverter).

6.5 Select Battery from the PVSyst battery directory : PVSyst has a list of batteries the designer can select from. When a battery is selected , PVSyst provides it terminal dc voltage, Ah rating, manufacturer name , among others. PVSyst also determines the Number of batteries in series and in parallel.

6.6 Select PV module from the PVSyst PV modules directory: PVSyst has a list of PV modules the designer can select from. When a PV module is selected , PVSyst provides it terminal dc voltage, Wp rating, manufacturer name , among others. PVSyst also determines the Number of PV modules in series and in parallel.

6.7 Select Inverter/Regulator/Charger Controller: PVSyst has a list of Inverter/Regulator/Charger Controller the designer can select from. It also provides default regulator.

Step 7: PVSyst Simulation and Result Menu Part V :

7.1 Use PVSyst Simulation Menu to run the simulation after the parameters have been set.

7.2 Use PVSyst Result Menu to view the simulation results and to export the results in Excel file format for further processing.

Step 8: PVSyst Simulation Part VI : Use PVSyst Economic Analysis Menu to capture the prices of the system components, installation cost, maintenance cost, VAT and tax rates and then generate the investment cost and unit cost of energy.

4 Results and Discussion

Figure 2 shows the Category I Health Clinic’s daily load demand, as presented in the simulation results. The Category I Health Clinic has daily power demand of 2500watts which runs for an average of 5 hours per day resulting in daily energy demand of 11500Wh/day.

Figure 3 shows the simulation parameters for the various system components such as battery, PV, regulator etc. According to Figure 3, a total of 43 PV modules, each with 100 Wp are used in the system.

UNIVERSITÉ DE GENÈVE PVSYST	PVSYST V5.06		24/10/15	Page 2/5

Stand Alone System: Detailed User's needs

Project : CATEGORY_I_CLINIC_ORLU

Simulation variant : No shading effects

Main system parameters	System type	**Stand alone**			
PV Field Orientation	tilt	8°	azimuth	0°	
PV Array	Nb. of modules	43	Pnom total	**4.3 kWp**	
Battery	Model	Volta 6SB100	Technology	sealed, tubular	
battery Pack	Nb. of units	32	Voltage / Capacity	**24 V / 1600 Ah**	
User's needs	Daily household consumers	Constant over the year	global	4198 kWh/year	

Daily household consumers, Constant over the year, average = 11.5 kWh/day

Annual values

	Number	Power	Use	Energy
Other uses	1	2500 W tot	5 h/day	11500 Wh/day
Total daily energy				11500 Wh/day

Figure 2 The User's Daily Load Demand of the Category I Health Clinic at Orlu LGA

UNIVERSITÉ DE GENÈVE PVSYST	PVSYST V5.06		24/10/15	Page 1/5

Stand Alone System: Simulation parameters

Project : CATEGORY_I_CLINIC_ORLU

Geographical Site		**CATEGORY_I_CLINIC_ORLU**	**Country**	**NIGERIA**
Situation	Latitude	5.8°N	Longitude	7.0°E
Time defined as	Legal Time	Time zone UT+1	Altitude	117 m
	Albedo	0.20		

Meteo data : MkpatEnin, Synthetic Hourly data

Simulation variant : No shading effects

Simulation date 24/10/15 07h00

Simulation parameters

Collector Plane Orientation		Tilt	8°	Azimuth	0°
PV Array Characteristics					
PV module	Si-mono	Model	**ASE-100-DG-UR/mono**		
		Manufacturer	ASE		
Number of PV modules		In series	1 modules	In parallel	43 strings
Total number of PV modules		Nb. modules	43	Unit Nom. Power	100 Wp
Array global power		Nominal (STC)	**4.3 kWp**	At operating cond.	3.9 kWp (50°C)
Array operating characteristics (50°C)		U mpp	31 V	I mpp	126 A
Total area		Module area	**35.5 m²**	Cell area	30.3 m²
PV Array loss factors					
Thermal Loss factor		Uc (const)	29.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind velocity = 1m/s.)				NOCT	45 °C
Wiring Ohmic Loss		Global array res.	4.0 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss				Loss Fraction	2.0 %
Module Mismatch Losses				Loss Fraction	4.0 % (fixed voltage)
Incidence effect, ASHRAE parametrization		IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05
System Parameter		System type	**Stand Alone System**		
Battery		Model	**Volta 6SB100**		
		Manufacturer	VOLTA		
Battery Pack Characteristics		Voltage	24 V	Nominal Capacity	1600 Ah
		Nb. of units	2 in series x 16 in parallel		
		Temperature	Fixed (20°C)		
Regulator		Model	General Purpose Default		
		Technology	Undefined	Temp coeff.	-5.0 mV/°C/elem.
Battery Management Thresholds		Charging	27.0/26.2 V	Discharging	23.5/25.2 V
		Back-Up Genset Command	23.6/25.8 V		
User's needs :		Daily household consumers	Constant over the year		
		average	11.5 kWh/Day		

Figure 3 The Simulation Parameters of the SAPV for Category I Health Clinic at Orlu LGA

The 43 PV modules occupy a space of 35.5 m^2. Also, according to the main result, Figure 4, the yearly energy output of the system is 5269Kwh/year while the performance ratio is 58.4%. This means that about 41.6% of the total energy produce by the PV modules are either lost or the 41.6% is not supplied to the load and battery bank. The losses are shown in the loss diagram of Figure 5.

UNIVERSITÉ DE GENÈVE PVSYST	PVSYST V5.06	24/10/15	Page 3/5

Stand Alone System: Main results

Project : CATEGORY_I_CLINIC_ORLU

Simulation variant : No shading effects

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	8°	azimuth	0°
PV Array	Nb. of modules	43	Pnom total	**4.3 kWp**
Battery	Model	Volta 6SB100	Technology	sealed, tubular
battery Pack	Nb. of units	32	Voltage / Capacity	**24 V / 1600 Ah**
User's needs	Daily household consumers	Constant over the year	global	4198 kWh/year

Main simulation results				
System Production	**Available Energy**	**5269 kWh/year**	Specific prod.	1225 kWh/kWp/year
	Used Energy	3901 kWh/year	Excess (unused)	1185 kWh/year
	Performance Ratio PR	58.4 %	Solar Fraction SF	92.9 %
Loss of Load	Time Fraction	7.1 %	Missing Energy	297 kWh
Investment	Global incl. taxes	2884350 Naira	Specific	671 Naira/Wp
Yearly cost	Annuities (Loan 10.0%, 25 years)	317763 Naira/yr	Running Costs	0 Naira/yr
Energy cost		**81.5 Naira/kWh**		

Figure 4 Main Result of the SAPV for Category I Health Clinic at Orlu LGA

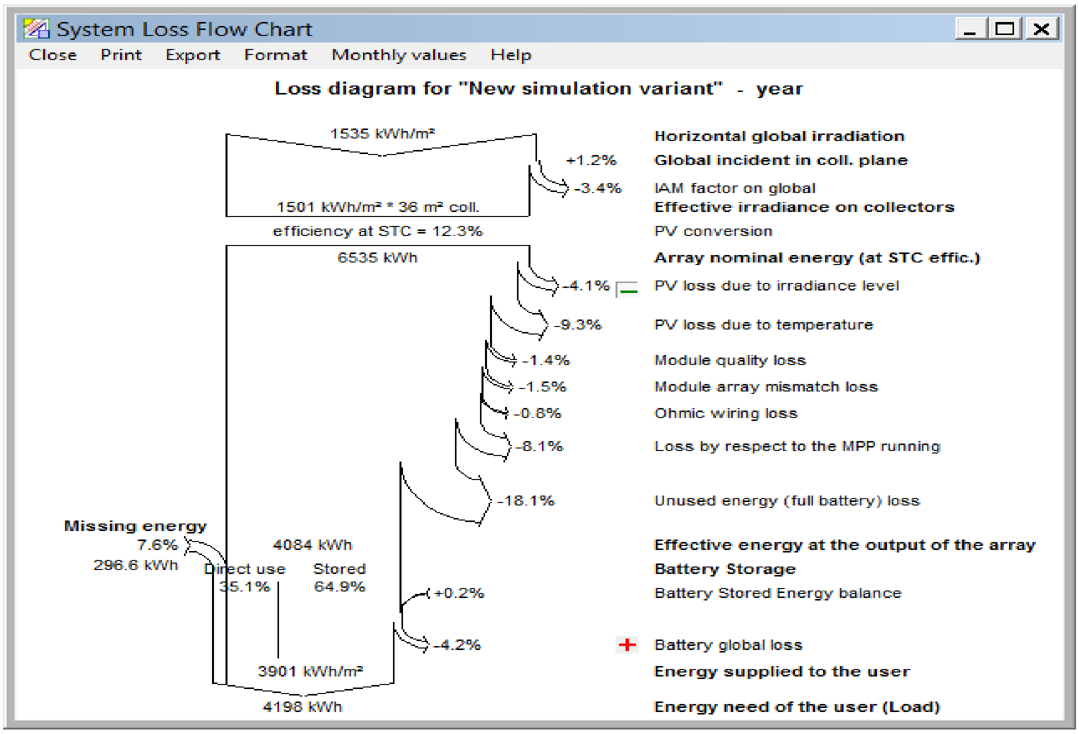

Figure 5 Loss Diagram of The SAPV for Category I Health Clinic at Orlu LGA

The efficiency of the PV module when they operate at STC is different than when they operate at other condition. Figure 6 shows the daily energy output diagram of the system. The effective efficiency ($\eta_{pv(eff)}$) of the PV under its operating conditions is computer from Figure 6 as follows:

$$\eta_{pv(eff)} = \left\{\frac{\left(Effective\ Energy\ At\ The\ Output\ Of\ The\ Array\ in \frac{Kwh}{day}\right)(100)\%}{(Global\ Incidence\ on\ collector\ plane\ in\ Kwh/m^2/day)(Total\ Area\ of\ the\ PV\ module\ in\ m^2)}\right\} \quad (3)$$

The values of the Eq (3) are obtained from Figure 6 and hence, $\eta_{pv(eff)}$ is computed as:

$$\eta_{pv(eff)} = \left\{\frac{(9.4\ Kwh/day)}{(3Kwh/m^2/day)(35.5m^2)}\right\} \text{ x } 100\% = 8.836\% \quad (4)$$

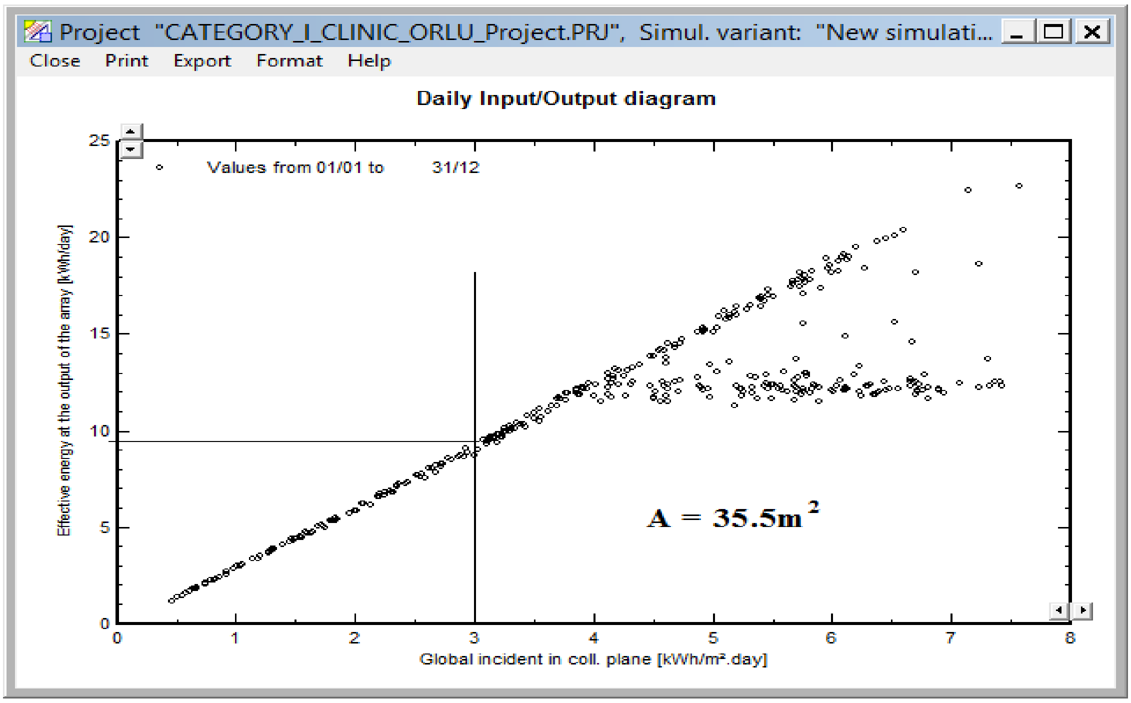

Figure 6 Daily Output Diagram of the SAPV for Category I Health Clinic at Orlu LGA

From Figure 6, the effective efficiency of the PV under its operating conditions at is computed to be 8.83%, which is lower than 12.6% specified by the manufacturer at Standard Test Condition (STC), as shown in Figure 7. According to Figure 8, the PV system supplies about 92.9% of the load demand. The remaining 7.1 % of the load demand cannot be met.

The distribution and duration of the loss of load periods within the year are given in Figure 9. The total Loss of Load (Pr LOL) in a year is 7.1% which is equivalent to yearly T LOL of 623 hours; that is, a total of 623 power outage hours per year, as shown in Figure 9.

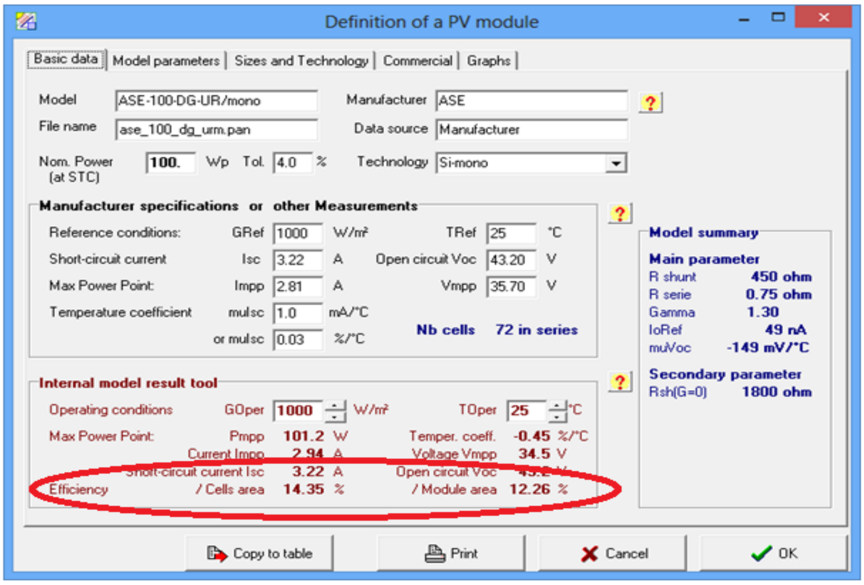

Figure 7 The PV Efficiency at Standard Test Condition (STC)

Simulation variant : New simulation variant

New simulation variant

Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E Avail kWh	EUnused kWh	E Miss kWh	E User kWh	E Load kWh	SolFrac
January	161.2	165.4	618.4	230.2	0.44	356.1	356.5	0.999
February	146.7	147.7	557.3	216.5	0.39	321.6	322.0	0.999
March	148.8	145.6	541.5	195.0	0.36	356.1	356.5	0.999
April	138.0	131.5	458.9	89.7	0.26	344.7	345.0	0.999
May	131.1	122.1	404.1	19.6	0.11	356.4	356.5	1.000
June	106.2	98.2	324.5	22.5	26.31	318.7	345.0	0.924
July	100.4	93.3	295.2	0.9	96.82	259.7	356.5	0.728
August	106.0	99.8	323.1	17.9	48.19	308.3	356.5	0.865
September	102.9	99.4	328.9	41.1	73.93	271.1	345.0	0.786
October	114.1	111.7	385.3	69.3	49.10	307.4	356.5	0.862
November	126.3	127.9	445.4	84.7	0.24	344.8	345.0	0.999
December	153.5	158.5	586.5	198.0	0.40	356.1	356.5	0.999
Year	1535.3	1501.0	5269.2	1185.5	296.55	3900.9	4197.5	0.929

Figure 8 The Solar Fraction Table

Figure 10 gives the economic analysis result. The unit cost of energy produced from the SAPV is 81.5 Naira per KWh. The yearly cost of the project is 317,763 Naira and the Gross investment cost for the project is 2,747,000 Naira. The project lifetime is 25 years.

Simulation variant : New simulation variant

Close Print Export Help

New simulation variant
Energy Use

	EArray kWh	E Load kWh	E User kWh	SolFrac	T LOL Hour	Pr LOL %
January	388.2	356.5	356.1	0.999	1	0.1
February	340.8	322.0	321.6	0.999	5	0.7
March	346.5	356.5	356.1	0.999	2	0.3
April	369.2	345.0	344.7	0.999	1	0.1
May	384.5	356.5	356.4	1.000	0	0.0
June	302.0	345.0	318.7	0.924	54	7.6
July	294.3	356.5	259.7	0.728	201	27.0
August	305.2	356.5	308.3	0.865	100	13.5
September	287.8	345.0	271.1	0.786	153	21.2
October	316.0	356.5	307.4	0.862	102	13.7
November	360.8	345.0	344.8	0.999	2	0.3
December	388.5	356.5	356.1	0.999	2	0.3
Year	4083.7	4197.5	3900.9	0.929	623	7.1

Figure 9 The Loss of Load Probability Table

UNIVERSITÉ DE GENÈVE PVSYST | PVSYST V5.06 | 24/10/15 | Page 5/5

Stand Alone System: Economic evaluation

Project : **CATEGORY_I_CLINIC_ORLU**
Simulation variant : **No shading effects**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	8°	azimuth	0°
PV Array	Nb. of modules	43	Pnom total	**4.3 kWp**
Battery	Model	Volta 6SB100	Technology	sealed, tubular
battery Pack	Nb. of units	32	Voltage / Capacity	**24 V / 1600 Ah**
User's needs	Daily household consumers	Constant over the year	global	4198 kWh/year

Investment

PV modules (Pnom = 100 Wp)	43 units	40000 Naira / unit	1720000 Naira
Supports / Integration		4000 Naira / module	172000 Naira
Batteries (12 V / 100 Ah)	32 units	25000 Naira / unit	800000 Naira
regulator / converter			40000 Naira
Settings, wiring, ...			5000 Naira
Substitution underworth			-0 Naira
Gross investment (without taxes)			**2747000 Naira**

Financing

Gross investment (without taxes)		2747000 Naira
Taxes on investment (VAT)	Rate 5.0 %	137350 Naira
Gross investment (including VAT)		2884350 Naira
Subsidies		-0 Naira
Net investment (all taxes included)		**2884350 Naira**
Annuities	(Loan 10.0 % over 25 years)	317763 Naira/year
Maintenance		0 Naira/year
Insurance, annual taxes		0 Naira/year
Provision for battery replacement	(lifetime 6.8 years)	0 Naira/year
Total yearly cost		**317763 Naira/year**

Energy cost

Used solar energy	3901 kWh / year
Excess energy (battery full)	1185 kWh / year
Used energy cost	81.5 Naira / kWh

Figure 10 The Economic Analysis Result

5 Conclusion

In this paper, PVSyst simulated technical and economic performance analysis of stand-alone photovoltaic (SAPV) system for Category I Health Clinic in Orlu LGA in Imo State, Nigeria, is presented. The USAID categorisation of the health clinics is used in the paper and accordingly, the Category I Health Clinic in Orlu LGA has daily electric energy demand of 11500 Wh/day. The SAPV system at Orlu has yearly energy output of 5269Kwh/year. The SAPV is designed to provide electric power for the essential electric facilities at the health clinic which is located in the remote location of Orlu LGA where the grid power is lacking. The focus in the design is not to provide constant power supply with zero load rejection. Rather, the SAPV is designed with relatively high loss of load probability in order to realize a SAPV system that is affordable to such small health facility in the rural community.

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