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Sizing And Performance Analysis Of Off-Grid Solar Photovoltaic Power System For Remote Smart City Application-Ready Bus Shelter

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***Abstract*— In this paper, sizing and performance analysis of off-grid Solar Photovoltaic (SPV) power system for remote smart city application-ready bus shelter is presented. A smart city application-ready bus shelter is a shelter built at bus stops with lighting points, mobile phone charging points and above all, wireless sensors and internet connection to enable users of the facility to connect to a wider smart city applications. The PVSyst simulation software was used to implement the components sizing operations and also to determine the various essential performance parameters of the system. The daily load demand is 2298 watt hours per day. The meteorological data of the SPV installation site is downloaded from NASA portal via PVSyst meteorological data import dialogue box. The optimal tilt angle is 9° and transposition factor (FTranspos) of 1.01 for the PV array. The SPV system was modeled with 5% loss of load probability and 4 days of power autonomy and it has a total of eight (8) 105 Ah 12V batteries with 2 connected in series and 4 strings of batteries in parallel. Also, the PV array consists of three (3) 235 Wp Si-mono PV modules with 1 module in series and 3 modules in parallel. The results show that the yearly average performance ratio is 0.652 (0r 65.2%) and in about five months of the year, the system operates at performance ratio below the yearly average. The best performance ratio of 80 % occurred in the month of June. Also, the yearly average produced useful energy is 3.09 kWh/kWp/day while the yearly average array collection losses is 1.315 kWh/kWp/day.**

Keywords*— *Solar Photovoltaic Power, Smart City Application, Off-Grid Solar Power, Bus Shelter power supply, Sizing of solar power system

1. Introduction

Nowadays, the emergence of smart city and related technologies has affected virtually every area of our lives [1,2,3,4]. Smart transport, smart energy system, smart agriculture, cashless polices, zoom meetings, smart learning facilities and the rest of our day-to-day activities are expected to become dependent on smart applications [5,6,7,8,9,10,11,12,13,14,15,16,17,18, 19, 20]. However, for system to be smart, some basic elements must be considered, namely, wireless sensor network and hence Internet connectivity as well as electric power supply [21,22, 23, 24]. In many cases, where the power from national grid is inadequate or unavailable, solar or wind or a hybrid of solar-wind power is used for alternative power supply, especially in Nigeria where there abundance of wind and solar energy resources [25,26,26,27, 28,29,30, 31, 32, 33, 34, 35, 36,37, 38,39, 40,41, 42].

Notably, in this paper, off-grid solar power system for a smart city application-ready bus shelter is presented. The shelter is built at bus stops with lighting points, mobile phone charging points and above all, wireless sensors and internet connection to enable users of the facility to connect to smart city applications. The sensor enables remote monitoring of the immediate environment of the bus shelter and also to remotely control the lighting points and internet signal reception in the immediate surrounding of the bus shelter [43,44,45, 46,47, 48,49, 505,1,52, 53,54, 55,56, 57].
While it may be easier to setup the sensor and Internet connectivity as well as the rest of the electrical facilities for the bus shelter, providing the requisite power supply that can enable those the facility to function effectively can be a running challenge especially in the remote rural area where there is no access to the national power grid. The essence of powering the bus shelter with solar PV power supply is to enable installation of such facility in remote locations is to overcome the problem of no access to the national grid and also to provide clean alternative power supply. However, it is essential that such solar power supply be properly designed and its performance parameters should be

determined. Accordingly, in this paper, the sizing of the solar power system for the bus shelter is presented along with the performance analysis. The study is conducted using PVSyst simulation program. The requisite mathematical expressions for the solar power sizing computation are presented. Also, the daily load profile of the bus shelter and the meteorological data of the bus shelter location are also provided for the study.

2. Methodology

2.1 Sizing of the PV power system for the remote smart city application-ready bus shelter

The main focus of this paper is to determine the effective size of the PV array, battery bank for the solar power and other key components of the PV power system, and also determine some key performance parameters of the PV solar power system realized from those component sizing computations. In order to size the PV array and battery bank for the PV solar power, the optimal tilt angle for the PV array is needed. For any given location latitude (Ø in degrees), the optimal tilt angle (β_{Yopt}) for PV module installation is given in degrees as;

$$\beta_{Yopt} = 3.7 + 0.69\,|\,Ø\,| \quad (1)$$

The transposition factor (Tf) realized with β_{Yopt} is given in terms of the global irradiation on horizontal plane (G(β)) where the angle β = 0° and the global irradiation on optimally tilted plane $G(\beta_{Yopt})$ with angle β_{Yopt} as follows;

$$1/Tf = 1 + \left[4.46(10^{-4})(\beta - \beta_{Yopt})\right] - \left[1.19(10^{-4})(\beta - \beta_{Yopt})^2\right] \quad (2)$$

$$1/Tf = \frac{G(\beta)}{G(\beta_{Yopt})} \quad (3)$$

Hence;

$$G(\beta_{Yopt}) = Tf(G(\beta)) \quad (4)$$

When the daily load demand (E_l) is known along with the average daily peak sunshine hours (PSH), the efficiency of the inverter (η_{inv}), the efficiency of the charger controller (η_{cc}) and the effective cumulative derating factor (f_{dl}), then the output power (P_{pva}) required from the PV array that will supply the daily load demand is computed as;

$$P_{pva} = \frac{E_l}{(\eta_i)(\eta_c)(f_{dl})(PSH)} \quad (5)$$

If N_{pvs} and N_{pvp} are the number of PV panels in series and in parallel respectively, while V_{sys} and V_{pv} are the line voltage of the system and nominal PV panel voltage respectively, then,

$$N_{pvs} = \frac{V_{sys}}{V_{pv}} \quad (6)$$

$$N_{pvp} = \frac{P_{pva}}{N_{pvs}(P_{pv})} \quad (7)$$

If the efficiency of the battery (η_{ba}) , days of power autonomy (n_a) and allowable maximum depth of discharge(DOD_{max}) are given, then the required battery capacity (C_{ba}) is computed as;

$$C_{ba} = \frac{(E_l)\,n_a}{(\eta_{ba})(DOD_{max})(V_{sys})} \quad (8)$$

Again, if N_b N_{bs} and N_{bp} denote the total number of battery in the battery bank, the number of battery connected in series and the number of battery string in parallel respectively, and also C_b denotes the capacity of each battery while V_b denote the nominal voltage of each battery then,

$$N_{bs} = \frac{V_{sys}}{V_b} \quad (9)$$

$$N_b = \frac{C_{ba}}{C_b} \quad (10)$$

$$N_{bp} = \frac{N_b}{N_{bs}} \quad (11)$$

The actual sizing of the PV system component are conducted through simulation using PVSyst software. The key performance parameters considered in the simulation incudes; the array yield (Y_a), the final yield (Y_f) , the reference yield (Y_r) , the performance ratio (PR), the array capture and the system losses. Again, the listed performance parameters are all obtained from the PVSyst simulation.

2.2 The daily load demand and meteorological data of the remote smart city application-ready bus shelter

The daily load demand profile of the remote smart city application-ready bus shelter is presented in Table 1 while the global daily mean irradiation on the horizontal plane (kWh/m².day) for the bus shelter location in Akwa Ibom State is presented in Figure 1. The daily load demand is 2298 watt hours per day. The screenshot of PVSyst dialogue box of the geo-coordinates (Latitude: 5.05 and Longitude: 7.90) for the bus shelter from which the solar irradiation was extracted are given in Figure 2. The PVSyst optimal tilt angle dialogue box showing optimal tilt angle of 9° and transposition factor (FTranspos) of 1.01 for the PV array is shown in Figure 3.

Table 1 The daily load demand profile of the Remote Smart City Application-Ready Bus Shelter (source: [58])

S/N	Electrical Appliance	Quantity	Wattage Rating (Watts)	Hours of operation	Energy Consumed per day (Watts Hours/Day)
1	LED Lights	2	3	14	84
2	High Flux LED	6	18	14	1512
3	Cell Phone Charger	2	5	15	150
4	WI-FI Router	1	20	24	480
5	Solar Charger Controller	1	2	24	48
6	Sensor	1	1	24	24
				Total Watt Hours per day	2298

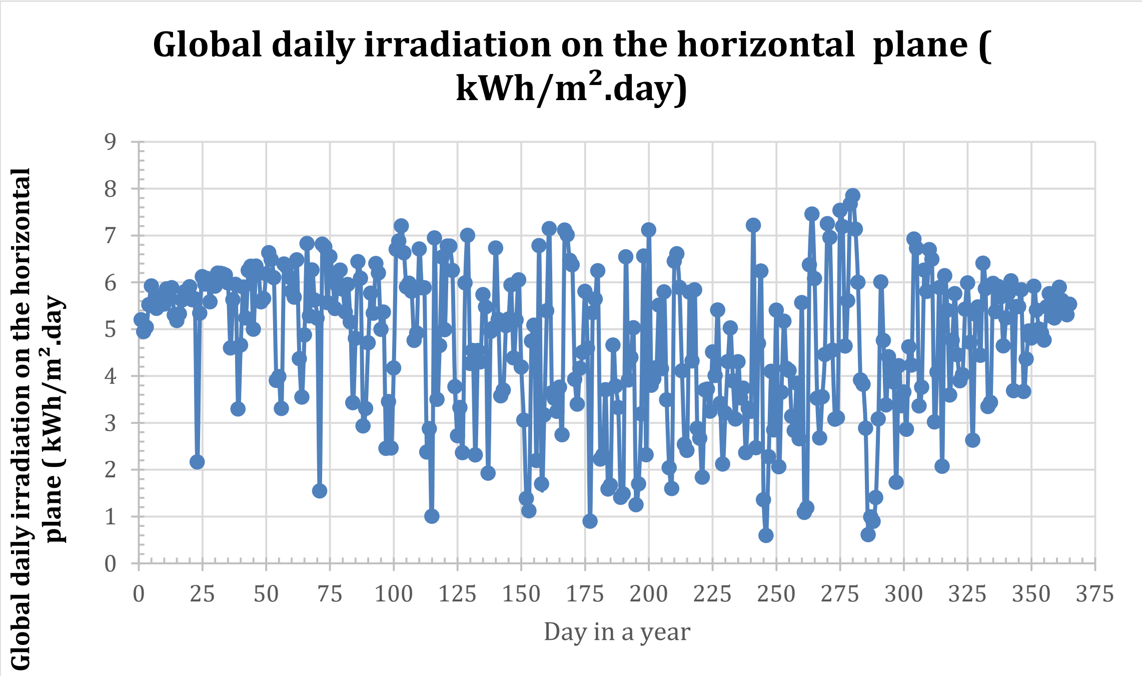

Figure 1 The global daily mean irradiation on the horizontal plane (kWh/m².day)

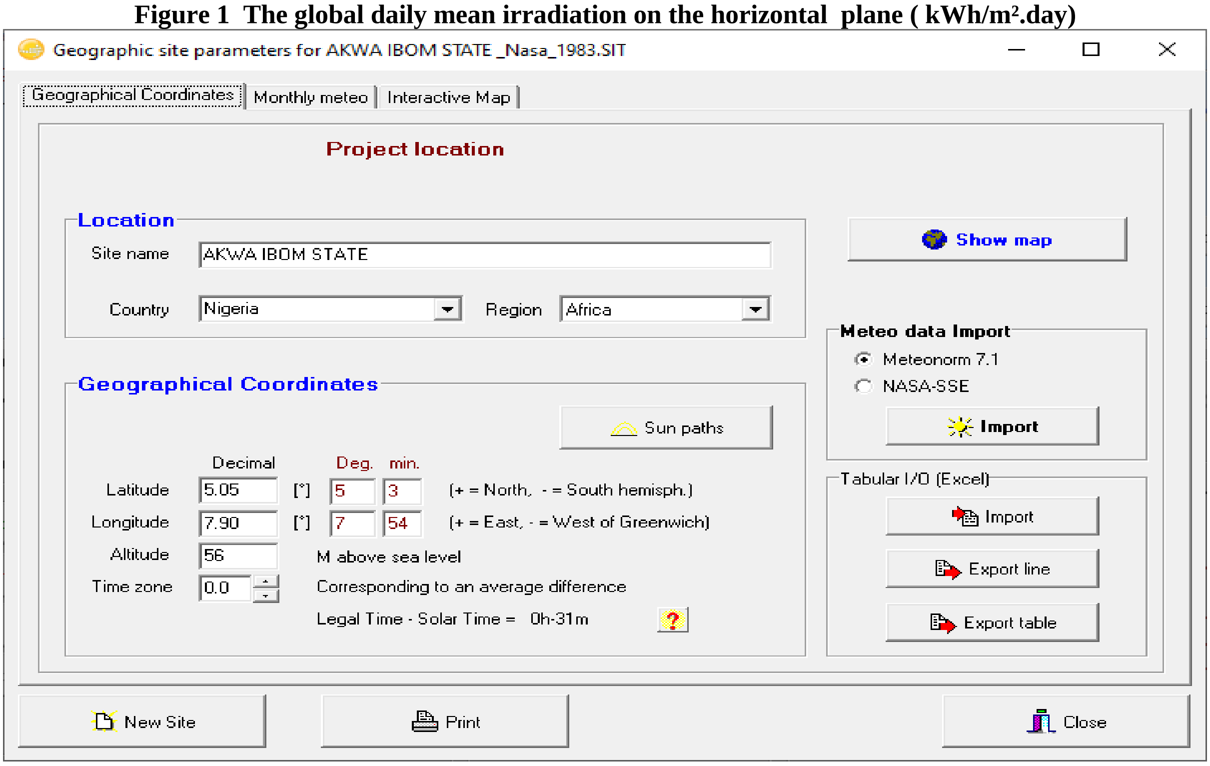

Figure 2 The geo-coordinates of the bus shelter from which the solar irradiation was extracted

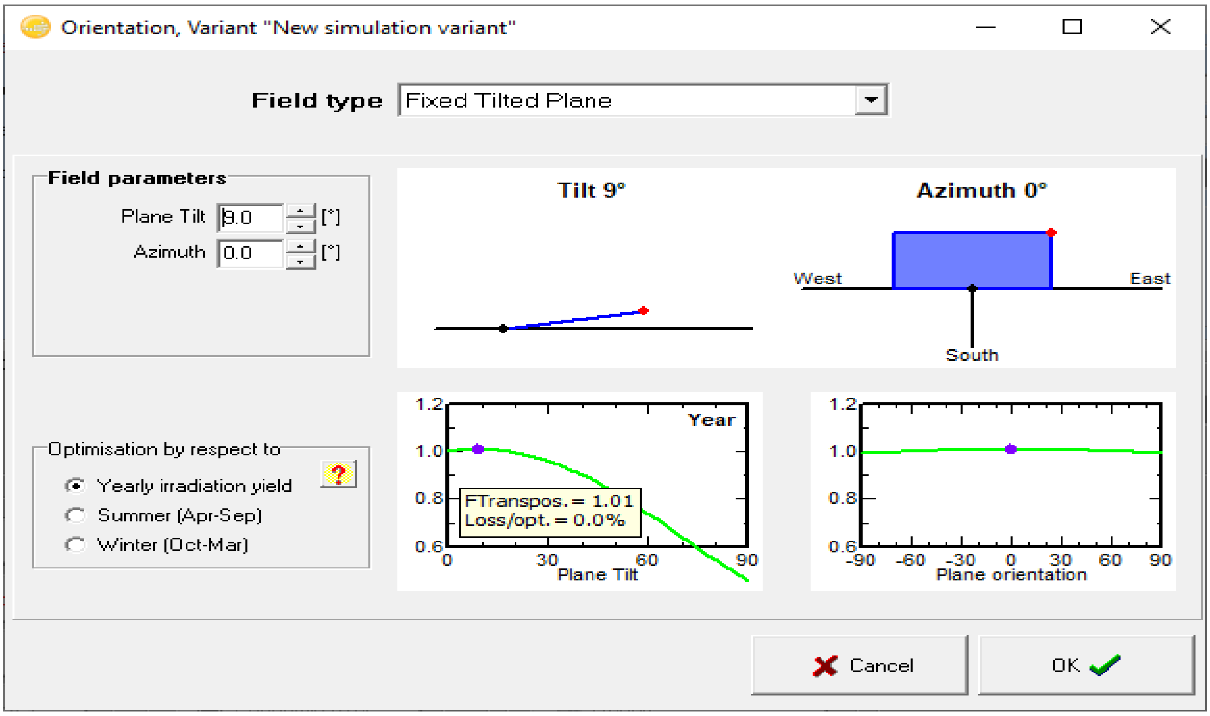

Figure 3 The PVSyst optimal tilt angle dialogue box

3. Results and Discussions

The Standalone PV (SPV) power system model in PVSyst software was used to perform the component sizing and performance analysis. The PVSyst screenshot layout of the standalone solar power system is shown in Figure 4 . The cut section of the PVSyst screenshot for the system components selection and battery bank sizing is shown in Figure 5. According to the information in Figure 5, the SPV system was modeled with 5% loss of load probability and 4 days of power autonomy and it has a total of eight (8) 105 Ah 12V batteries with 2 connected in series and 4 strings of batteries in parallel. The details of the selected battery used for the battery bank are given in Figure 6. The details of the selected PV module used for the PV array of the SPV system are presented in Figure 7 while details of the selected details of the selected battery charger controller used for the SPV system are presented in Figure 8. The SPV system configuration is such that the PV array consists of 3 PV modules with 1 module in series and 3 modules in parallel. The PV module is Si-mono PV produced by Samsung SDI and rated 235 Wp at STC. The PV array has a total of 705 Wp power and a occupies a total area of 4.8 m^2. The battery bank is made up of 8 units of Solar Block SB 12/130A battery produced by Sonnenschein.

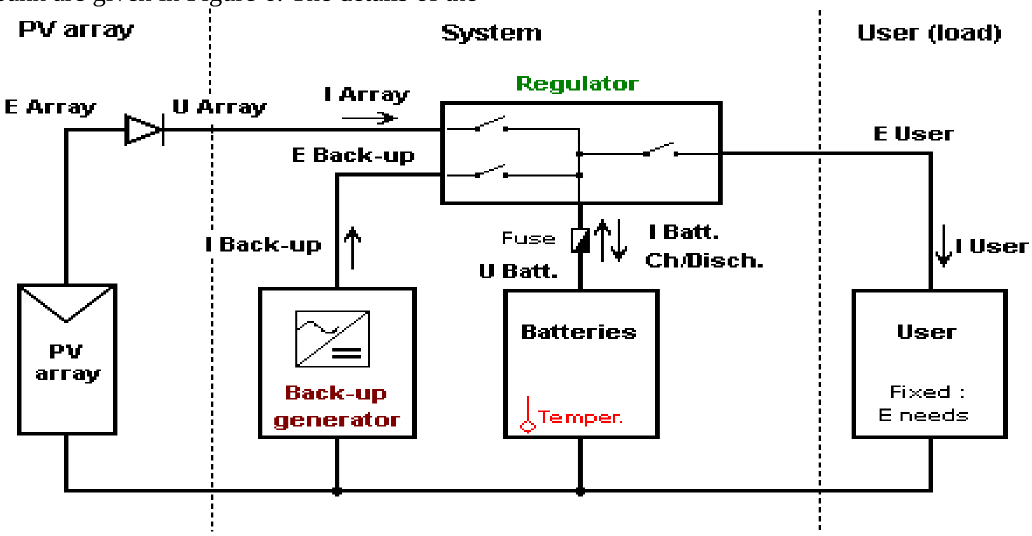

Figure 4 The PVSyst screenshot layout of the standalone solar power system

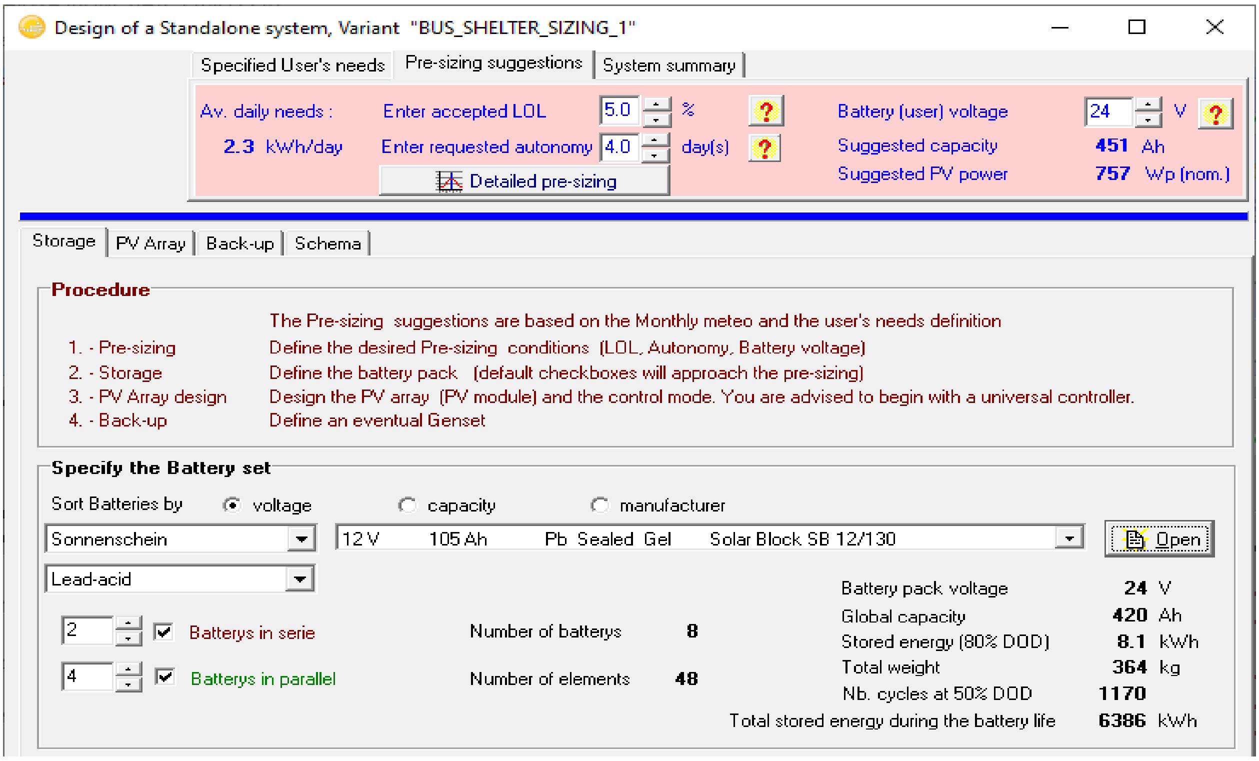

Figure 5 The cut section of the PVSyst screenshot for the system components selection and battery bank sizing

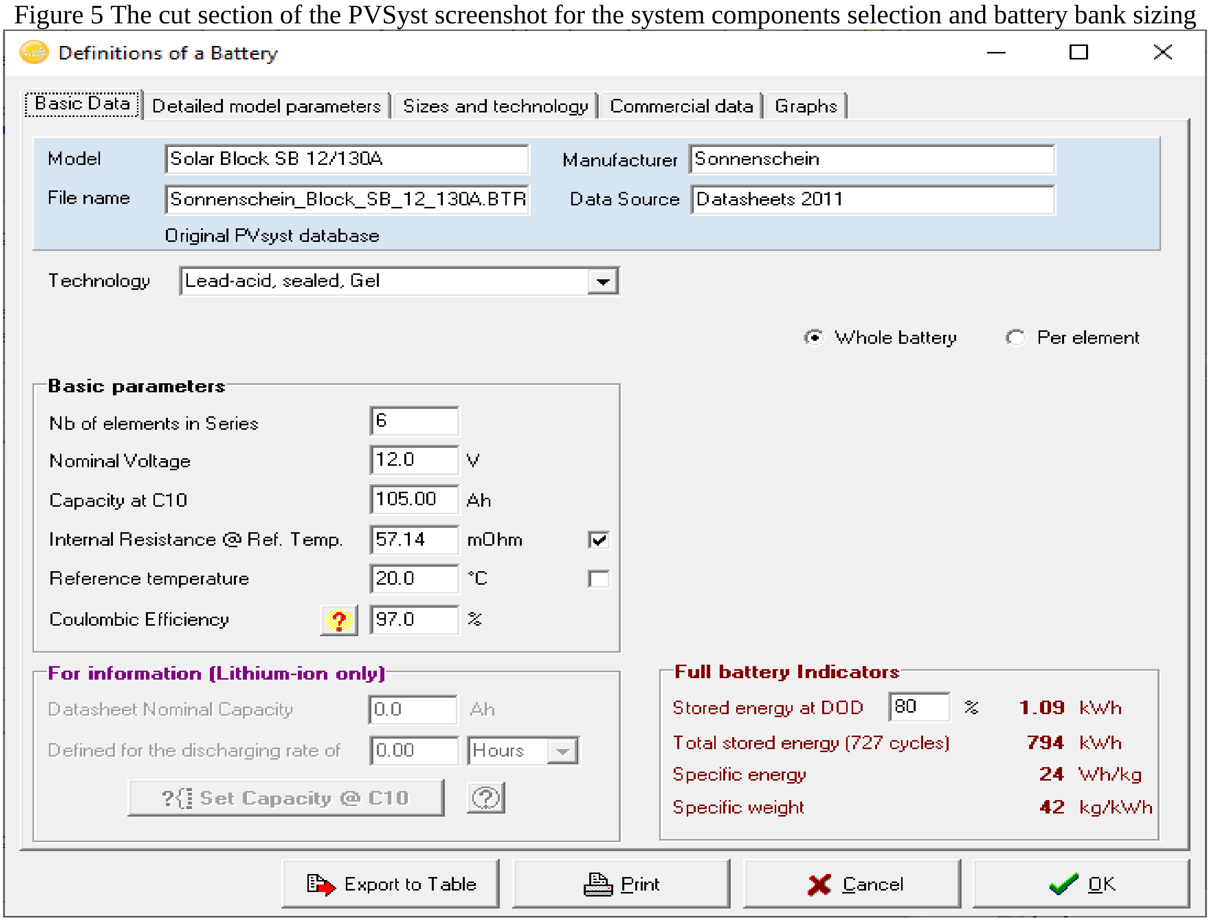

Figure 6 The PVSyst screenshot showing the details of the selected battery used for the battery bank

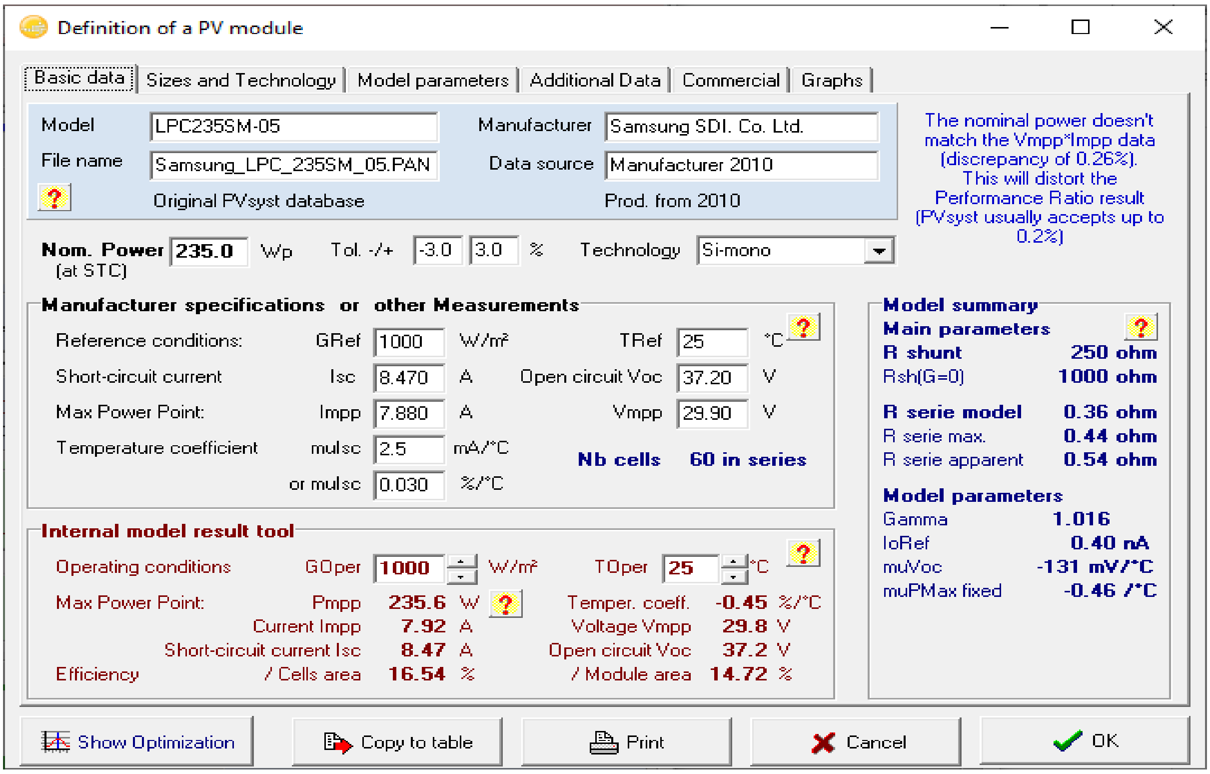

Figure 7 The PVSyst screenshot showing the details of the selected PV module used for the PV array of the SPV system

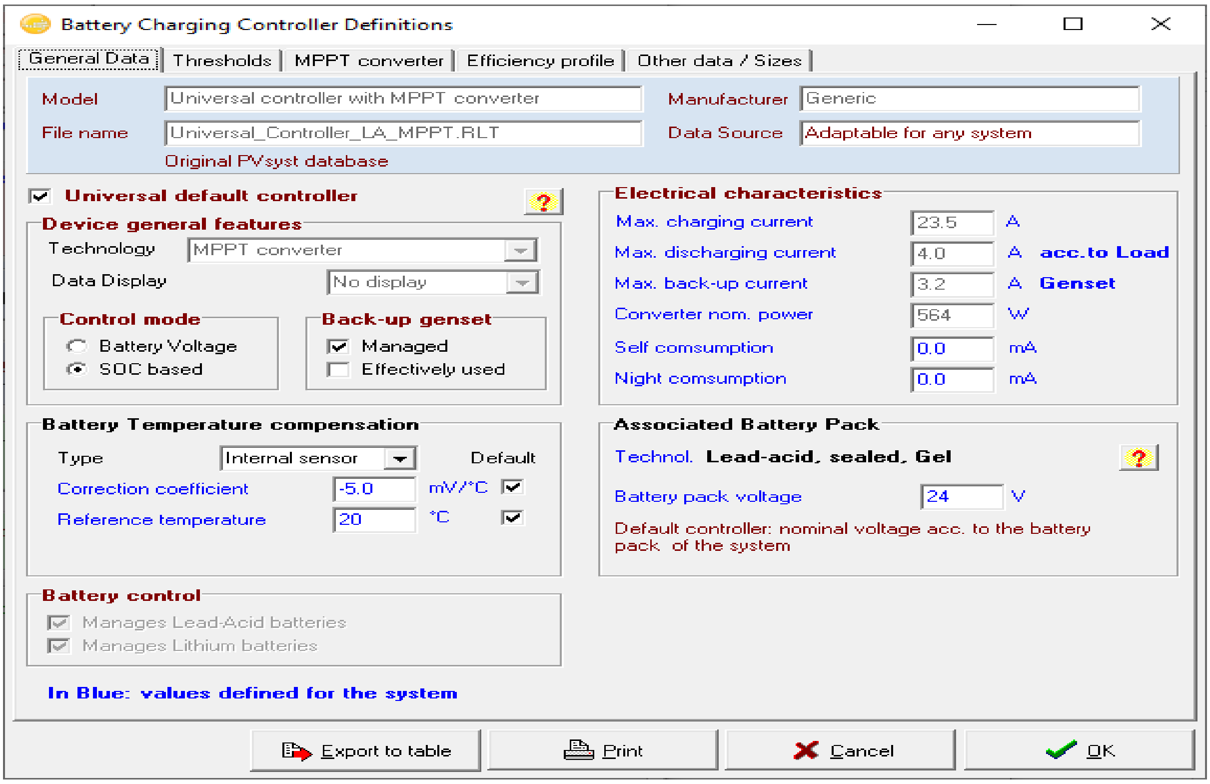

Figure 8 The PVSyst screenshot showing the details of the selected battery charger controller used for the SPV system

The PVSyst screenshot showing the details of the simulation parameters used for the SPV system analysis are shown in Figure 9 while Table 2 shows the results of the different performance parameters of the SPV system. The screenshot in Figure 8 also shows the details of the SPV components as obtained from the PVSysts simulation. Notably, Figure 8 shows the details of the PV module, the PV array, the battery and battery controller details.

The results in Figure 10 shows the normalized performance ratio (PR) expressed in %. The results shows that the average performance ratio is 0.652 (0r 65.2%) and in about five months of the year, the system operates at performance ratio below the yearly average. The best performance ratio of 80 % occurred in the month of June.

The results in Figure 11 produced useful energy or normalized final yield (Yf) expressed in kWh/kWp/day.

The results shows that the average produced useful energy is 3.09 and in about four months of the year, the system produced useful energy are below the yearly average. The maximum produced useful energy occurred in about 8 the months.

The results in Figure 12 normalized array losses or array collection losses (Lc) expressed in kWh/kWp/day. The results shows that the average array collection losses is **1.315** and in about six months of the year, the array collection losses are above the yearly average. The minimum array collection losses occurred in the month of August.

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Stand Alone System: Simulation parameters

Project : **BUS_SHELTER_SIZING**

Geographical Site	**AKWA IBOM STATE**			Country	**Nigeria**
Situation		Latitude	5.05° N	Longitude	7.90° E
Time defined as		Legal Time	Time zone UT	Altitude	56 m
		Albedo	0.20		
Meteo data:	**AKWA IBOM STATE**		NASA-SSE satellite data, 1983-2005 - Synthetic		

Simulation variant : **BUS_SHELTER_SIZING_1**

Simulation date 30/12/22 00h08

Simulation parameters		System type	**Stand-alone system**		
Collector Plane Orientation		Tilt	9°	Azimuth	0°
Models used		Transposition	Hay	Diffuse	Perez, Meteonorm
PV Array Characteristics					
PV module	Si-mono	Model	**LPC235SM-05**		
Original PVsyst database		Manufacturer	Samsung SDI. Co. Ltd.		
Number of PV modules		In series	1 modules	In parallel	3 strings
Total number of PV modules		Nb. modules	3	Unit Nom. Power	235 Wp
Array global power		Nominal (STC)	**705 Wp**	At operating cond.	626 Wp (50°C)
Array operating characteristics (50°C)		U mpp	26 V	I mpp	24 A
Total area		Module area	**4.8 m²**	Cell area	4.3 m²
PV Array loss factors					
Thermal Loss factor		Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss		Global array res.	19 mOhm	Loss Fraction	1.5 % at STC
Serie Diode Loss		Voltage Drop	0.7 V	Loss Fraction	2.4 % at STC
Module Quality Loss				Loss Fraction	1.5 %
Module Mismatch Losses				Loss Fraction	1.0 % at MPP
Strings Mismatch loss				Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization		IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
System Parameter		System type	**Stand Alone System**		
Battery		Model	**Solar Block SB 12/130A**		
		Manufacturer	Sonnenschein		
Battery Pack Characteristics		Voltage	24 V	Nominal Capacity	420 Ah
		Nb. of units	2 in series x 4 in parallel		
		Temperature	Fixed (20°C)		
Controller		Model	Universal controller with MPPT converter		
		Technology	MPPT converter	Temp coeff.	-5.0 mV/°C/elem.
Converter		Maxi and EURO efficiencies	97.0 / 95.0 %		
Battery Management control		Threshold commands as	SOC calculation		
		Charging	SOC = 0.90 / 0.75	i.e. approx.	27.0 / 25.1 V
		Discharging	SOC = 0.20 / 0.45	i.e. approx.	23.5 / 24.4 V
User's needs :		Daily household consumers	Constant over the year		
		average	2.3 kWh/Day		

Figure 9 The PVSyst screenshot showing the details of the simulation parameters used for the SPV system analysis

Table 2 The results of the different performance parameters of the SPV System

	Yr	Lu	Yu	Lc	Ya	Ls	Yf	PR
	kWh/m².day		kWh/kWp/day		kWh/kWp/day		kWh/kWp/day	
January	**5.91**	**0.911**	**5.91**	**2.133**	**3.77**	**0.514**	**3.26**	**0.552**
February	**5.81**	**0.962**	**5.81**	**2.177**	**3.63**	**0.37**	**3.26**	**0.561**
March	**5.35**	**0.708**	**5.35**	**1.802**	**3.55**	**0.29**	**3.26**	**0.609**
April	**4.97**	**0.416**	**4.97**	**1.43**	**3.54**	**0.28**	**3.26**	**0.656**
May	**4.5**	**0.019**	**4.5**	**0.901**	**3.6**	**0.34**	**3.26**	**0.724**
June	**4.07**	**0.001**	**4.07**	**0.784**	**3.29**	**0.031**	**3.26**	**0.8**
July	**3.68**	**0.001**	**3.68**	**0.681**	**3**	**0.334**	**2.67**	**0.724**
August	**3.67**	**0**	**3.67**	**0.63**	**3.04**	**0.269**	**2.77**	**0.755**
September	**3.92**	**0.001**	**3.92**	**0.741**	**3.18**	**0.468**	**2.71**	**0.692**
October	**4.35**	**0.285**	**4.35**	**1.157**	**3.19**	**0.263**	**2.93**	**0.673**
November	**5.1**	**0.358**	**5.1**	**1.364**	**3.74**	**0.479**	**3.26**	**0.639**
December	**5.7**	**0.899**	**5.7**	**2.039**	**3.66**	**0.398**	**3.26**	**0.572**
Year	**4.75**	**0.377**	**4.75**	**1.315**	**3.43**	**0.336**	**3.09**	**0.652**

The Table 2 legend is as follows: the reference yield (Y_r), the normalized array yield (Y_a), the normalized final yield (Y_f) , the normalized performance ratio (PR), Normalized unused/loss energy (Lu), Normalized potential production (Yu), Normalized array losses or array collection Losses (Lc) and Normalized system losses (Ls).

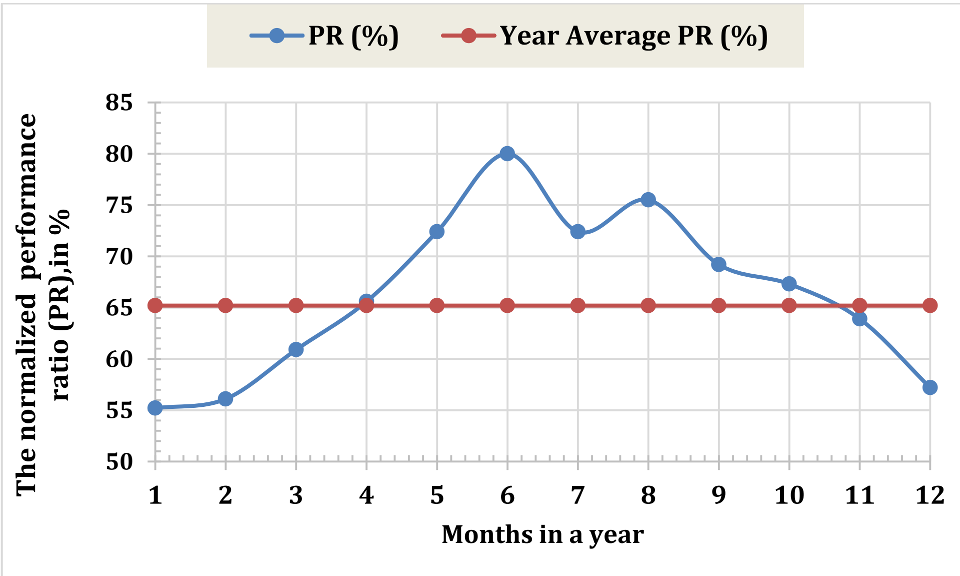

Figure 10 **The normalized performance ratio (PR) expressed in %**

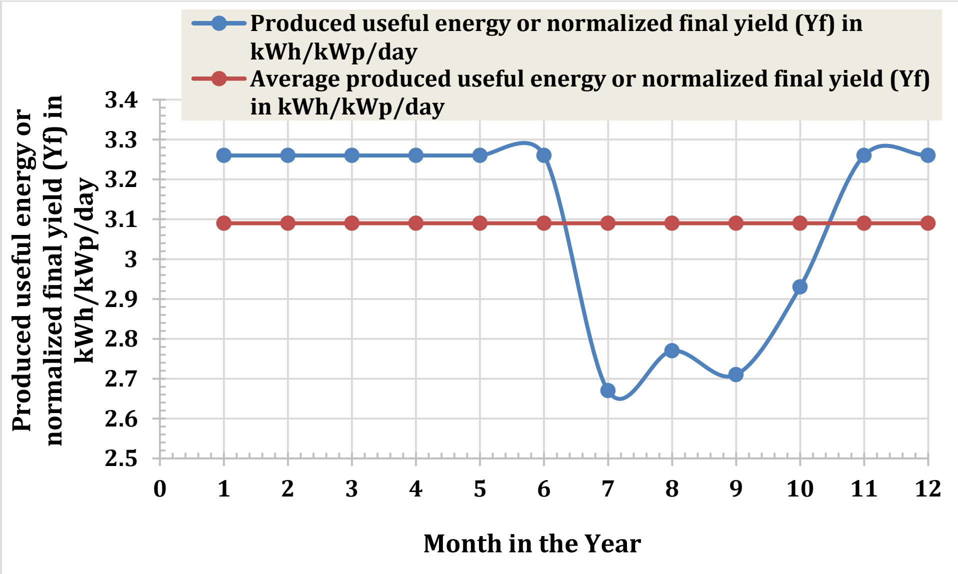

Figure 11 **Produced useful energy or normalized final yield (Yf) expressed in kWh/kWp/day**

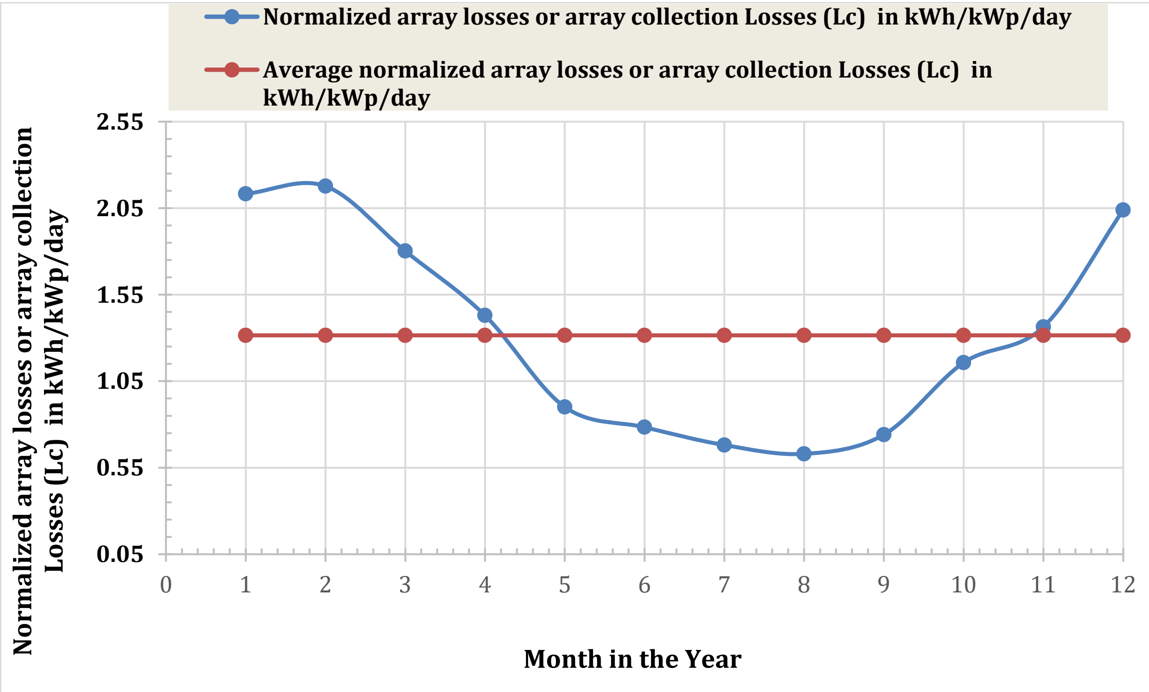

Figure 12 Normalized array losses or array collection Losses (Lc) expressed in kWh/kWp/day

4. Conclusion

The paper presents the mathematical model for sizing an off-grid solar PV power system designed using the daily load demand of a bus shelter built with requisite sensors and internet connectivity for smart city applications. Also, the paper used PVSyst simulation software to implement the actual sizing of the off-grid solar PV power system and also to determine the various essential performance parameters of the system. The meteorological data of the SPV installation site is downloaded from NASA portal via PVSyst meteorological data import dialogue box. The various PVSyst screenshots showing the system simulation parameter selection and settings, as well as the results obtained from the simulation are presented along with some graphical plots and discussions of the system performance parameters. In all, the key system components (PV module, battery, battery charger, etc.) sizes are presented. In addition, the results identified the yearly average and the values of the different system performance parameters for the different months in the year.

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