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Off-Grid Connected Photovoltaic System for Rural Residential Electrification in Malaysia

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Abstract: This project presents the design and system configurations for an off-grid connected photovoltaic (OGPV) system for rural residential electrification. The main difference between photovoltaic systems is in the type of sources available to supply electricity. Therefore, this project aims to design an OGPV system capable of providing reliable electricity supply in rural areas of Malaysia especially in Sabah and Sarawak. In order to achieve the objectives, there are a few comparisons from past projects in order to identify which case or method is the best to be used. The mathematical calculation is one of the methods in order to determine the relevant rate for each component involved in the off-grid PV system. PVsyst software is also used to design and simulate the system. The results from both mathematical calculation and PVsyst software simulation will be compared in order to ensure the results are synchronized. This proves that the result of the proposed design is suitable to be implemented with the exact rate of power load.

Keywords: Off-Grid Connected Photovoltaic System, PVsyst Software, Mathematical Calculation

1. Introduction

There are 32.7 millions of Malaysian citizens and 7.4 million of them are from rural areas [1]. Based on the statistics made at the year 2013, East Malaysia, electricity coverage is about 79 percent, compared to 99.62 percent in West Malaysia [2]. A PV system can be categorized into three types which are off-grid system, hybrid system and grid-connected system [3]. This project used an off-grid solar PV system (OGPV) which is one of the best solutions for the rural electrification. It can provide electricity supply to load directly and also store the energy to the battery for the usage of user. Apart from that, another aim of this study is to analyze for suggestion of photovoltaic (PV) system implementation in Kampung Stass, Bau which located 55 km from Kuching, Sarawak. The targeted community is consisting of a household with an average of 5 electrical loads. Comparison and analysis are done based on the results and data obtained from mathematical calculation and PVsyst software simulation. Hence, a suitable

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system configuration of an OGPV system can be produced in accordance with the total load determination.

The off-grid connected PV system is a system which no relating to the grid facility in supplying the electrical energy [4]. It is called stand-alone as it can generate the power and run the appliances on its own. Hence, it is suitable to be implemented in a targeted community. The process of OGPV system is shown in Figure 1.

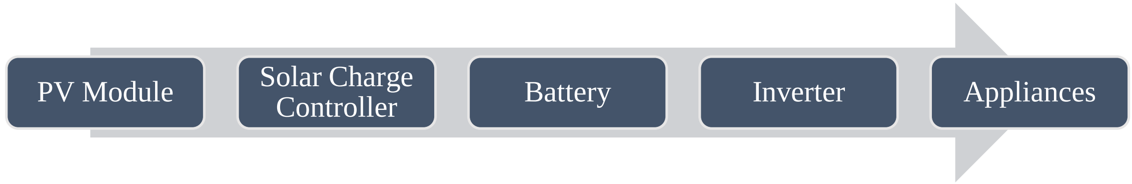

Figure 1: Process of OGPV system

2. Materials and Methods

The main content of the methodology for this project is focusing on the development of the Off-Grid Connected Photovoltaic (OGPV) system by using mathematical calculation and PVsyst software simulation.

2.1 OGPV Design Using Mathematical Calculation

Mathematical calculation is used to determine the value of the system configuration and rate of each component involved. The calculation for the crucial and main component will be elaborated.

2.1.1 Determine the Load Determination

The total load can be determined by using the power rating multiply with its quantity for each of the load. The calculation on the total power of load in the OGPV system is defined by following Eq.1 [5].

$$Watt_{Total} = n \times P \qquad Eq.1$$

2.1.2 Determine the Number of Solar Panel

The number of the solar panels is determined based on the total power consumption of the system divided with the power rating of the solar panel which already manufactured from the factory which defined in Eq.2 [5].

$$N_{PV} = \frac{P_{Total}}{P_{PV\_Rate}} \qquad Eq.2$$

2.1.3 Determine Solar Charge Controller Rating

The solar charge controller can be rate by multiplying the number of solar panels with the short circuit current (I_{sc}) of the selected solar panels which shown in Eq.3 [5]

$$I_{CC} = (N_{PV} \times I_{SC} \times k_3) \qquad Eq.3$$

The I_{SC} is the value of short circuit current of the solar panel while k_3 is the value for safety factor considering loss which is commonly 1.3.

2.1.4 Determine the Rating of Battery

The battery rating is necessary in order to decide the type and number of batteries that will be used in the system. The equation is defined as Eq.4 to Eq.6 [5].

$$Wh = P_{Total} \times RT_{hour} \qquad Eq. 4$$

where Wh is the watt-hour value of the battery, P_{Total} is the total load while the RT_{hour} is the run time of the system.

The total of watt-hour value:

$$Wh_{Total} = \frac{Wh}{\eta} \qquad Eq. 5$$

where Wh_{Total} is the total watt-hour of the batter, Wh is the watt-hour value of the battery and η is the efficiency of the inverter which considered as 85%.

The rate of ampere-hour of battery:

$$Ah = \frac{Wh}{Wh} \qquad Eq. 6$$

where Ah is the value for ampere-hour of the battery, Wh is the load power of the system and Wh is the voltage value of the battery.

2.1.5 Determine the Number of Battery

The number of batteries can be determined by the total ampere-hour rate of the battery. It is crucial in order to decide and prepare a suitable and relevant quantity of storage to store generated power by the system. The equation is defined as Eq.7 and Eq.8 [5].

$$P_{Battery} = V \times Ah \qquad Eq. 7$$

where Wh is the power rate of battery, V is the voltage value of battery and Ah is the rating of battery in ampere-hour.

The number of battery can be defined:

$$N_{Battery} = \frac{t_{backup\_system}}{t_{backup}} \qquad Eq. 8$$

where $N_{Battery}$ is the number of battery, t_{backup_system} is the backup time required for the system and t_{backup} is the backup time of battery.

2.1.6 Determine the Power Inverter Rating

The inverter is functions to convert direct current (DC) output to alternating current (AC). The rate of the power inverter can be defined as Eq. 9 to Eq.10 [5][6].

$$P_{Loss} = P_{Total\_load} + 25\% \qquad Eq. 9$$

where P_{Loss} is the total losses of the power, P_{Total_load} is the total power load and 25% is considered the total load should be less than 25% of the inverter rating.

Power inverter rating can be rated:

$$P_{inverter} = P_{Total\_load} + P_{Loss} \qquad Eq. 10$$

2.1.7 Identify the Sizing of Cable

The suitable cable sizing in accordance with the power load of the system is crucial. The minimum cross-sectional area required for the solar panel which can be defined in Eq. 11 [7] .

$$A_{min\_string\_dc\_cable} = \frac{2 \times L_{dc\_cable} \times I_{mp\_stc} \times \rho}{Loss \times V_{min\_string}} \qquad Eq. 11$$

where the $A_{min\_string\_dc\_cable}$ is the minimum cross-sectional area of the cable, L_{dc_cable} is the length of the longest string cable (m), I_{mp_stc} is the maximum operating current in the cable (A), ρ is the resistivity of cable (Copper = 1/56 and aluminum is 1/34), $Loss$ is the maximum allowable voltage loss in conductor (3% loss according to the MS1837) and the V_{min_string} is the minimum voltage of string at maximum power (V).

2.1.8 Identifying the Rate of DC Surge Protection Device (SPD) and DC Breaker

DC surge protection device (SPD) is used to protect the system from damaged by various faults occur to the system. Hence, Eq. 12 shows the equation used to determined the minimum voltage rating of the DC SPD and DC Breaker while Eq. 13 shows the equation of the minimum current rating of the DC SPD and DC Breaker [8].

Minimum voltage rating:

$$V_{DC\_SPD\&Breaker} > V_{OC\_pv\_stc} \times 1.2 \times N_{pvs\_act} \qquad Eq. 12$$

where $V_{DC\_SPD\&Breaker}$ is the minimum voltage rating for the DC SPD & DC Breaker, $V_{OC\_pv\_stc}$ is the open circuit voltage of the PV panel at the standard test condition and N_{pvs_act} is the actual series number of PV panels connect in series.

Minimum current rating:

$$I_{DC\_SPD\&Breaker} > I_{SC\_pv\_stc} \times 1.3 \times N_{pvp\_act} \qquad Eq. 13$$

where $I_{DC\_SPD\&Breaker}$ is the minimum current rating for the DC SPD & DC Breaker, $I_{SC\_pv\_stc}$ is the short circuit current of the PV panel at the standard test condition and N_{pvp_act} is the actual number of PV panels connect in parallel.

2.1.9 Performance Analysis

The performance of the system also focusing to the reduction of the carbon dioxide emission by the OGPV system.

2.1.9.1 Determine the Carbon Dioxide (CO_2) Avoidance

By referring to the SEDA Official Website, the ratio of carbon dioxide emission are between Peninsular Malaysia and East Malaysia are different and can be predicted with the ratio as follows [9]:

$$Peninsular\ Malaysia = 0.585\ \frac{tCO_2}{MW_h} \qquad Eq. 14$$

$$East\ Malaysia\ \&\ Labuan = 0.525\ \frac{tCO_2}{MW_h} \qquad Eq. 15$$

2.2 OGPV Design Using PVsyst Software

PVsyst software is used in this project to simulate and determine the performance of off-grid connected OGPV system. It can analyse different variables of configuration for the evaluation of the result of the system design. The parameters set in the software are including each component involved in the system with accordance to the site location as follows in Table 1:

Table 1: Site specification

Description	Detail
Geographical Location	Sarawak, Malaysia
Postcode	94000
Longitude	109.9955438
Latitude	1.3928024

3. Results and Discussion

The section is presented into two subtopics which are the results obtained from the mathematical calculation and PVsyst software simulation. Lastly, proposed design is included and summarized. The total load is determined by using a quantitative method which is using phone call due to the pandemic as it is hardly to go for site-visit in Table 2.

Table 2: Load determination of selected house in Kampung Stass, Bau

Load	Quantity (Unit)	Power (W)	Hour/day	Total Power (W)	Energy (Wh/day)
Lighting (fluorescent tube lamp)	4	20	7.0	80	560
Television (42 inches)	1	120	6.0	120	720
Refrigerator (1 door)	1	400	24	400	9600
Wall Fan	1	50	5.0	50	250
USB Charging Port	2	5	5.0	10	50
	Total			660	11,180

3.1 OGPV system design using mathematical calculation

Mathematical calculation is required in this project as it defines the practical with theory simultaneously. The value for each component is summarised as shown in Table 3.

Table 3: Value of components after applied mathematical calculation

Component	Value of Calculation	Proposed Value
Load power	660 Watt	660 W
Number of solar panel	2.38 units	3 units
Battery rating	408.3 Ah	500 Ah
Number of Battery	1.983 units	2 units
Charging current of battery	25 A	25 A
Charging time of battery	10 hours	10 hours
Inverter rating	743.75 W	800 W
Solar Charge Controller	34.671 A	45 A

Size of Cable Cross-sectional area	1.00 mm^2	1.00 mm^2
	Voltage drop of cable	
V_{drop} in string	3.80 V	3.80 V
V_{drop} in array	1.46 V	1.46 V
	Value of DC SPD & SPD Breaker	
Voltage Value	235.30 V	235.30 V
Current Value	9.89 A	9.89 A

3.2 OGPV system design using PVsyst software

PVsyst is used as proposed software to obtain the data for a relevant OGPV System configuration. By inserting the rating of all the system configuration and the power load determination of the house, the suggested OGPV is obtained from the software simulation.

As the parameters of each component is insert in the PVsyst software, the results in Figure 2 shows are the recommendation for each components involved needed to run the system smoothly.

PV Array Characteristics

PV module		**Battery**	
Manufacturer	Mitsubishi	Manufacturer	Generic
Model	MLU-250HC	Model	Open 12V / 250 Ah
(Original PVsyst database)		Technology	Lead-acid, vented, plates
Unit Nom. Power	250 Wp	Nb. of units	2 in series
Number of PV modules	3 units	Discharging min. SOC	20.0 %
Nominal (STC)	750 Wp	Stored energy	4.8 kWh
Modules	3 Strings x 1 In series	**Battery Pack Characteristics**	
At operating cond. (50°C)		Voltage	24 V
Pmpp	681 Wp	Nominal Capacity	250 Ah (C10)
U mpp	28 V	Temperature	Fixed 20 °C
I mpp	25 A		
Controller		**Battery Management control**	
Universal controller		Threshold commands as	SOC calculation
Technology	MPPT converter	Charging	SOC = 0.92 / 0.75
Temp coeff.	-5.0 mV/°C/Elem	approx.	27.5 / 25.1 V
Converter		Discharging	SOC = 0.20 / 0.45
Maxi and EURO efficiencies	97.0 / 95.0 %	approx.	23.5 / 24.4 V
Total PV power			
Nominal (STC)	1 kWp		
Total	3 modules		
Module area	5.0 m²		
Cell area	4.2 m²		

Figure 2: PV characteristics of proposed design

Figure 3 shows the results of array losses which including losses from thermal factor, DC wiring and mismatch.

Array losses

Thermal Loss factor		**DC wiring losses**		**Serie Diode Loss**	
Module temperature according to irradiance		Global array res.	19 mΩ	Voltage drop	0.7 V
Uc (const)	20.0 W/m²K	Loss Fraction	1.5 % at STC	Loss Fraction	2.3 % at STC
Uv (wind)	0.0 W/m²K/m/s				
Module Quality Loss		**Module mismatch losses**		**Strings Mismatch loss**	
Loss Fraction	-0.8 %	Loss Fraction	2.0 % at MPP	Loss Fraction	0.1 %
IAM loss factor					
ASHRAE Param: IAM = 1 - bo(1/cosi - 1)					
bo Param.	0.05				

Figure 3: Array losses of proposed design

Figure 4 shows the detailed user's need obtained from the PVsyst software to produce graph on the annual values and its hour distribution with accordance to the power load determination of the house.

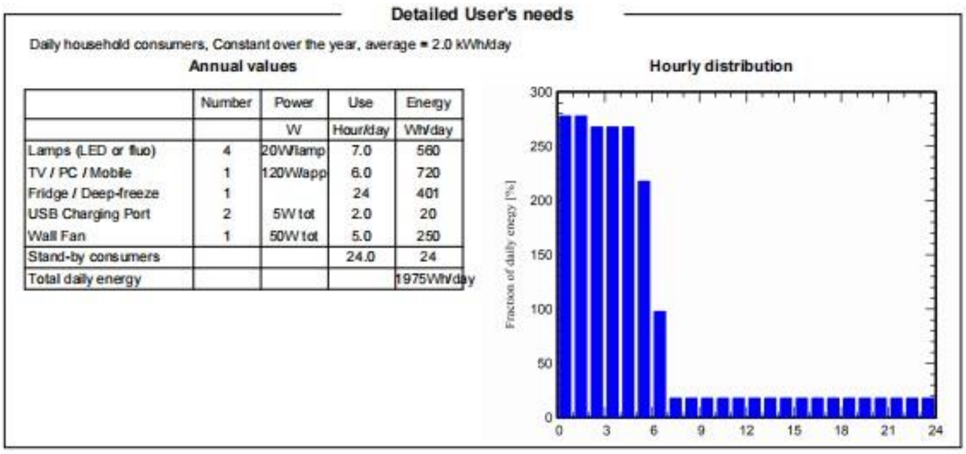

Figure 4: Performance ratio

Figure 5 and 6 shows the results of global horizontal irradiation, effective global and shadings, available solar energy, unused energy (battery full), missing energy, energy supplied to the user, energy supplied to the load and solar fraction.

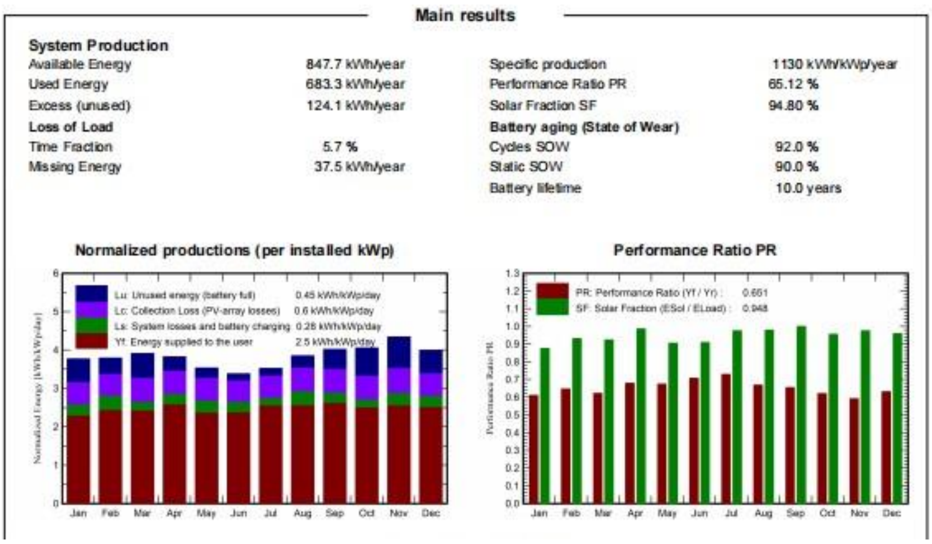

Figure 5: Main results of proposed system

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 ratio
January	109.1	114.0	70.81	13.83	7.622	53.60	61.22	0.876
February	104.6	103.0	64.64	8.29	3.827	51.47	55.29	0.931
March	128.5	117.5	73.47	14.55	4.636	56.58	61.22	0.924
April	130.9	110.3	69.27	7.84	0.800	58.44	59.24	0.986
May	135.6	104.4	65.38	5.71	5.793	55.43	61.22	0.905
June	130.5	96.6	60.46	3.53	5.366	53.88	59.24	0.909
July	137.4	104.1	65.27	4.08	1.513	59.71	61.22	0.975
August	140.3	114.7	71.97	6.94	1.301	59.92	61.22	0.979
September	130.7	116.7	73.49	11.25	0.000	59.24	59.24	1.000
October	128.2	122.2	76.69	16.43	2.703	58.52	61.22	0.956
November	123.8	127.0	80.03	17.96	1.424	57.82	59.24	0.976
December	116.6	120.6	76.20	13.68	2.512	58.71	61.22	0.959
Year	1516.3	1351.1	847.68	124.08	37.496	683.31	720.80	0.948

Legends
GlobHor Global horizontal irradiation
GlobEff Effective Global, corr. for IAM and shadings
E_Avail Available Solar Energy
EUnused Unused energy (battery full)
E_Miss Missing energy
E_User Energy supplied to the user
E_Load Energy need of the user (Load)
SolFrac Solar fraction (EUsed / ELoad)

Figure 6: Main results of proposed system

3.3 Performance Analysis

The data of the system is obtained by using mathematical calculation and PVsyst software simulation. The data is compared in order to obtained the average value so that it is relevant to be implemented to the OGPV system as shown in Table 4.

Table 4: Table of comparison between mathematical calculation with PVsyst software simulation

Mathematical Calculation	Comparison Subject	PVsyst Software
2.38 units	PV Module	3 units
408.3 Ah (2 units)	Battery Rating	12V, 250 Ah (each unit)
1.983 ≈ 2 units	Number of Battery	2 units
743.75 W	Inverter Rating	800 W

3.3.1 Rating of Components

The rating of each component used in this system is shown in Table 5. The rating is chose based on the research and comparison done from previous studies.

Table 5: Rating of Components

Component	Type	Brand	Rating
Solar Panel	Monocrystalline	Mitsubishi PV-MLU250HC	250 Wp
Battery	Lead-Acid	Powerbatt	250 Ah, 12 V
Inverter	-	ATD-5952	800 W
Solar Charge Controller	MPPT	Grape Solar, GS-MPPT-45	45A

4. Conclusion

This paper proposed an off-grid connected photovoltaic (OGPV) system design for residential electrification at Kampung Stass, Bau Sarawak. The proposed system is proven to be relevant as it is able to generate enough electricity for the total of 660 W of electrical loads. Besides, the results obtained from mathematical calculation and PVsyst software are slightly synchronized especially for the main components involved in the OGPV system. Thus, reliable performance in generating electrical energy for rural area residential electrification is achieved based on the system configuration made from the software simulation and mathematical calculation.

The recommendation and the function of the OGPV system can be proposed few modifications or recommendation could be applied in future. The recommendation that can be improved for future work are as follow:

i. Bigger load which involving a whole residential area with bigger system configuration for reliable performance of OGPV System.
ii. Adding generator as standby system which can provide electrical energy when there is absence or insufficient of solar energy for the PV array to produce enough electricity for the system.
iii. Change some of the component involved into more economical and cheaper yet functional element to decrease the amount of early-costing and perhaps could increase the return of investment of the project.

Acknowledgement

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