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Research paper

Sizing a 3 kW_p Retrofitted Grid-Connected Photovoltaic System: a Case Study in Tropical Malaysia

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Abstract

The work presents a tropical case study of sizing 3 kW_p retrofitted grid-connected photovoltaic system (GCPV) installed in Klang, Malaysia. The sizing was based on customer's budget requirement of RM 22, 500 and conducted through a designated mathematical approach. The mathematical approach involved technical aspects which aligns the voltage and current specifications of both PV array and inverter. Besides, this approach includes possible severe climatic condition of solar irradiance and ambient temperature variations. By implementing the sizing mathematical approach in this study, the final PV array configuration is 1 x 9 (1 parallel x 9 series). This study was also conducted to compare between the actual and the predicted energy yield to reflect customer satisfaction. Based on the result, the percentage differences are acceptable for February and March 2018. Interestingly, the percentage difference for January 2018 was over-predicted and the abnormality was suggested to be resulted from the inaccuracy of the Peak Sun Hour (PSH) estimation. In conclusion, this study is significant as an overview on the sizing and performance reliability of GCPV system in tropical Malaysia to meet up the customer satisfaction.

Keyword: *sizing, photovoltaic, inverter, grid-connected, energy yield.*

1. Introduction

As the conventional fuel resources throughout the world continue to decrease, the renewable energy resources and technologies have been widely used to recompense the reduction of the conventional fuel resources [1]. Photovoltaic (PV) technology is one of the most promising technologies and if it properly utilized, it able to fulfill a big fraction of the total energy demand [2]. PV energy is a safe, clean, renewable and environmentally friendly energy source [3]. This technology converts solar energy to electricity by using solar cell embedded in a PV module [1].
There are two main applications for PV systems, which are grid-connected PV system (GCPV) and stand-alone PV system (SAPV) [2]. GCPV system integrates the PV technology with the main grid, while SAPV is an off grid system where the PV technology is not connected to the utility network[2]. In GCPV system, an inverter is used to convert direct current (DC) generated by the PV modules into alternating current (AC) that can be consumed by local loads or injected into the electricity grid [4]. GCPV system varies from small residential (2 kW to 10 kW), commercials (100 kW to 500kW) and large utility scales (>10 MW) [4].
There are a few techniques in sizing of the PV array with inverter for GCPV system namely simulations, intelligent method, genetic algorithm and PV-to-inverter ratio. In Malaysia, the technique used to design and sizing the GCPV must be verified by Sustainable Energy Development Authority (SEDA) Malaysia. In addition, the sizing techniques and the safety specifications as regulated by SEDA are compulsory upon designing and sizing any GCPV system in Malaysia.
The Feed-in-Tariff (FiT) system in Malaysia sets the rate and helps the Distribution Licensees to buy the electricity produced by renewable energy from Feed-in Approval Holders. The Distribution Licensees will pay for the energy supplied to electricity grid for a specific duration [5]. FiT rates for individual (residential) are divided into two categories: small system (with capacity for only up to 4 kW) and big system (capacity up to 12 kW) [5]. The sizing of the GCPV must be calculated thoroughly to ensure the maximum efficiency of performance of the system. The achievement of the GCPV system sizing model applied, is measured by the actual system performance.
However, although there are many reports on the actual GCPV system performance including energy yield (Y_f) in Malaysia [6] [7] [8] [9], the comparison between the actual energy yield and the predicted energy yield based on the sizing model is still very limited. The comparison between predicted and actual performance reflects the customer satisfaction of the installed GCPV. Therefore, this study will focused on GCPV system sizing and also the comparison between expected energy yield and actual energy yield.
The performance of GCPV system can be affected by climate conditions. The GCPV system is directly affected by solar irradiance, rain, and clouds; and indirectly by PV module operating temperature that depends on ambient temperature and wind speed [10]. By referring to the Köppen-Geiger climate classification, Malaysian climate is under equatorial rainforest fully humid climate [6] with uniform temperature, heavy rainfall frequently throughout the year and high in humidity. Typically, range of daily irradiation in Malaysian is about 4.21 kWh/m^2 to 5.56 kWh/m^2 and annual solar irradiation is 1,643 kWh/m^2 [6]. Average daily temperature for Malaysia is 32 °C (day) and 24 °C (night) [8].
The purpose of this study is to size a 3 kW_p retrofitted GCPV system and to compare actual energy yield and predicted energy yield of the system. This case study is significant to provide real

evidence in addressing customer satisfaction of the GCPV system installed. This work would also be beneficial for Malaysia future solar projects development, particularly for residential in optimizing the sizing model of GCPV system [5].

2. Description of the GCPV System Chosen as the Case Study

The PV modules were mounted in a retrofitted way for a GCPV system of a residence in Klang, Malaysia as shown in Fig. 1. The inverter, solar log data logger, AC junction box and DC junction box are depicted in Fig. 2. The utility, which is Tenaga Nasional Berhad (TNB) in this case study monitors the PV energy generation via internet from the PV export meter as shown in Fig. 3.

Fig. 1: Photovoltaic modules mounted on rooftops (Retrofitted GCPV System).

3. Methodology

3.1. Scope and Limitation of Study

The sizing of PV array with inverter for a GCPV system for this study is limited to certain issues such as financial budget, capacity of GCPV system, location of the GCPV system, and sizing model used. The allocated budget is RM 22,500 based on the market price and customer agreement with installer in 2015 [12]. The GCPV system chosen is located in Bandar Bukit Raja, Klang, Selangor with the capacity limited to 3 kW_p. The designated GCPV system in this study has been approved by SEDA Malaysia [13]. The model used to size and analyze the GCPV system is based on the mathematical model approach as regulated by SEDA.

3.2. Concept in Sizing of the PV Array with Inverter in GCPV System

In general, the sizing of the GCPV system is a mathematical approach to match the PV array electrical output to inverter electrical input. The PV array which consists of PV modules has its own electrical specifications depending on the type and model chosen. The same condition implies to the inverter of the system. The sizing method taken into account electrical safety margins due to variations of climatic parameters that will affect the PV electrical output. Fig. 4 shows the position of safety margins (designated as f_{s1}, f_{s2} and f_{s3}) in the system which allow the GCPV system to be continuously operated in severe climatic condition of the chosen site. The severe climatic condition refers to the possible maximum irradiance (G), maximum module temperature (T_c) and minimum module temperature (T_c). The concept of matching the PV array electrical output with inverter electrical input can be divided into two steps. First is matching of the PV array voltage to inverter voltage (refer to Fig. 4) and second is matching of the PV array current to inverter current (refer to Fig. 5). The mathematical approach will be further discussed in the mathematical model section.

3.3. Steps of Sizing PV Array with Inverter

The sizing of the GCPV system has to be conducted according to six sequential sizing steps. Step 1 determines the design constraints in sizing such as area, energy requirement and budget requirement. Step 2 determines the number of total possible PV modules that will fit the rated power of the inverter. Step 3 determines two extreme voltage limits produced by PV array that affected by module temperature on site known as the maximum voltage and minimum voltage. Step 4 estimates the maximum and minimum number of PV modules in series per string. Step 5 determines number of modules in parallel based on the matching between maximum current of the inverter and the maximum short circuit current of the PV array. Finally, step 6 determines the optimum array configuration (combination of PV modules or number of parallel and series of the PV modules) of the GCPV system [7].

3.4. Mathematical Model of Sizing GCPV System

The mathematical models applied for the GCPV systems sizing in this case study are listed as below [7]:
Step 1: Determination of the total PV array power, P_{arr_stc} and the total possible number of PV module affordable, N_t, based on budget.

$$P_{arr\_stc} = \frac{Budget}{k_{cos}} \quad (1)$$

$$N_t = \text{round down}\left[\frac{P_{arrSTC}}{P_{modSTC}}\right] \quad (2)$$

Where, $k_{\_cos}$ is cost index of PV and $P_{\_modSTC}$ is power module at STC.

Step 2: Determination of the range of total possible number of PV modules that matches a specific inverter.

$$N_t = \text{RU}\left[\frac{P_{nominv}}{P_{stcmod} \times f_{d1}}\right] \text{ to RD}\left[\frac{P_{nominv}}{P_{stcmod} \times f_{d2}}\right] \quad (3)$$

Where, $P_{\_nominv}$ is nominal power of inverter, f_{d1} is design factor 1, f_{d2} is design factor 2, RU is round up and RD is round down.

Step 3: Determination of the extreme limits (V_{oc_max} and V_{oc_stc}) of voltage produced by the PV modules.

$$V_{oc\_max} = V_{oc\_stc} \times \{1 + [(\gamma_v/(100\%)) \times (T_{c\_min} - T_{stc})]\} \quad (4)$$

$$V_{mp\_min} = V_{mp\_stc} \times \{1 + [(\gamma_v/(100\%)) \times (T_{c\_max} - T_{stc})]\} \quad (5)$$

Where, γ_v is temperature coefficient of voltage, T_{c_min} is minimum module temperature, T_{stc} is module temperature at STC, V_{mp_min} is minimum maximum power voltage, V_{mp_stc} is maximum power voltage at STC and Tc_max is maximum module temperature.

Step 4: Determination of the number of maximum, Ns_max and minimum, Ns_min modules in series per string.

$$N_{s\_max} = \text{RD}\left[\frac{V_{maxinvMPPT} \times f_{s1}}{V_{ocmax}}\right] \quad (6)$$

$$N_{s\_min} = \text{RU}\left[\frac{V_{mininvMPPT} \times f_{s2}}{V_{mpmin} \times f_{cab}}\right] \quad (7)$$

Where, $V_{\_maxinvMPPT}$ and $V_{mininvMPPT}$ are maximum and minimum MPPT input voltage window of inverter, f_{s1} and f_{s2} indicate safety margins 1 and 2. f_{cab} indicate cable loss factor.

Step 5: Determination of the number of string, N_p in parallel.

$$N_p = RD\left[\frac{I_{dcinv}}{I_{scstc} \times f_{s3}}\right] \quad (8)$$

Where, I_{dcinv} represents direct current in inverter, I_{scstc} represents short circuit current at STC and f_{s3} represents safety margin.

Step 6: Determination the optimum array configuration, N_t.

$$Nt = Np \times Ns \quad (9)$$

Where, N_p is number of parallel string and N_s is number of modules in series.

3.5. Mathematical Model of Expected Energy Yield

When the sizing of a GCPV system has been successfully executed (as according to Section 3.4), the optimize number of parallel and series connections of the PV modules are obtained. This eventually means that the peak array capacity of the GCPV system has been determined too. Based on the optimum configuration, the predicted Y_f produced by a working GCPV system can be calculated. The predicted Y_f can be calculated by [7]:

$$Y_f = P_{arr\_STC} \times PSH \times k_{deration\_y} \times \eta_{sub\_system} \quad (10)$$

Where, $k_{deration\_y}$ includes mismatch factor (k_{mm}), temperature power average factor ($k_{tem\_p\_ave}$), dirt factor (k_{dirt}) and age factor (k_{age}). While η_{sub_system} includes inverter efficiency (η_{inv}) and cable efficiency (η_{cable}).
$k_{tem\_p\_ave}$ and average module temperature, $T_{cell\_p\_ave}$ can be calculated by using:

$$k_{tem\_p\_ave} = 1 + \left[\left(\frac{\gamma_p}{100\%}\right) \times (T_C - T_{STC})\right] \quad (11)$$

$$T_{cell\_p\_ave} = T_{amb\_ave\_max} + T_{elevated} \quad (12)$$

Where, $\gamma_{\_p}$ is temperature coefficient of power, $T_{amb\_ave\_max}$ is average maximum ambient temperature and $T_{elevated}$ is elevated module temperature (25 °C).
PSH obtained from actual energy yield data can be calculated by reversing Eq. 10 as shown below:

$$PSH = \frac{Y_f}{P_{arr\_STC} \times k_{deration\_y} \times \eta_{sub\_system}} \quad (13)$$

The percentage differences between the predicted energy yield and the actual energy yield can be calculated as:

$$\text{Percentage difference: } \left|\frac{\text{Actual} - \text{Theoretical}}{\text{Actual}}\right| \times 100 \quad (14)$$

In this case study, the customers approved FiT rate by SEDA is RM 0.93 per kWh generated. The approved FiT rate by SEDA Malaysia is given in an official document. The monthly predicted FiT income can be determined based on the predicted monthly energy generation is as shown below [5]:

$$Y_{monthly} = SY \times \text{nominal power} \times \text{days in month} \quad (15)$$

Where, $Y_{monthly}$ is monthly Y_f and SY is specific yield
Thus, the FiT income is expressed by:

$$\text{FiT income} = Y_{monthly} \times RM\ 0.93 \quad (16)$$

The data of the actual Y_f has been collected for 3 months which are January 2018, February 2018 and March 2018. The data was based on daily energy output from the GCPV system and obtained from a dedicated website (Solar-Log website) provided by the X-company.

4. Result and Discussion

4.1. Sizing Based on Budget Requirement

The steps applied for sizing GCPV system in this case study were using approach dedicated for Malaysia [12]. In applying the sizing mathematical model as explained in Eq.1 until Eq. 9, 18 parameters were involved as shown in Table 1.

Table 1: Parameters taken into sizing calculation.

No.	Parameter	Values	Comment
1.	Max power rating of PV module at STC (P_{modstc})	315 W	[14]
2.	Nominal output power of inverter (P_{nominv})	3000 W	[15]
3.	Design factors (fd1)	1	Assumed
4.	Design factors (fd2)	0.9	Assumed
5.	Open circuit voltage at STC (V_{oc_stc})	46.2 V	[14]
6.	Minimum voltage at STC (V_{mp_stc})	37.2 V	[14]
7.	Temperature Coefficient of V_{OC} (γ_v)	-0.31 %	[14]
8.	Minimum temperature (T_{c_min})	20 °C	Assumed [16]
9.	Temperature at STC (T_{stc})	25 °C	
10.	Maximum temperature (T_{c_max})	75 °C	Assumed [16]
11.	Max MPPT input voltage of inverter ($V_{maxinvMPPT}$)	500 W	[15]
12.	Safety margins ($fs1$)	0.95	Assumed
13.	Min MPPT input voltage ($V_{mininvMPPT}$)	125 W	[15]
14.	Safety margins ($fs2$)	1	Assumed
15.	Cable loss (f_{cab})	0.97 %	MS1837:2018
16.	Max input current (I_{dcinv})	11.5 A	[15]
17.	Current at STC (I_{scstc})	9.01 A	[14]
18.	Safety margin ($fs3$)	1.25	Assumed

Applying the mathematical model of sizing for this study, the calculations are shown as below:

Step 1

$$P_{arr\_stc} = \text{Budget}/k_{cos} = RM22{,}500/RM7.5 = 3kWp \quad (1)$$

The total PV array power affordable based on budget is 3 kW_p.

$$N_t = RD\,[P_{arrSTC}/P_{modSTC}] = RD\,[3000/315] = 9.5 \sim 9 \quad (2)$$

(P_{modSTC} refer Table1)
The total number of JINKO 315 W_p PV modules according to the budget is 9.

Step 2
$N_t = RU\,[P_{nominv}/(P_{stcmod} \times f_{d1})]$ to $RD\,[P_{nominv}/(P_{stcmod} \times f_{d2})]$
$= RU\,[3000/(315\times1)]$ to $RD\,[3000/(315\times0.90)] = 9.5$ to 10.58

$$= 10 \text{ to } 10 \quad (3)$$

(P_{nominv}, f_{d1}, $f_{d2}$and P_{modSTC} refer Table1)
The range of total possible number of JINKO 315 W_p PV that matches STECAGRID 3010 inverter is 10 to 10.

Step 3
$V_{oc\_max} = V_{oc\_stc} \times \{1 + [(\gamma_v/(100\%)) \times (T_{c\_min} - T_{stc})]\}$

$$= 46.2V \times \{1 + [(-0.31)/100] \times (20-25)\} = 46.92V \quad (4)$$

(V_{oc_stc}, γ_v, T_{c_min} and T_{stc} refer Table 1)
Maximum open circuit voltage that produced by JINKO 315 W_p PV modules based on estimated minimum PV module temperature of 20 °C is 46.92 V. This step, estimated the maximum input voltage from a single PV module to be injected to the inverter.

$$V_{mp\_min} = V_{mp\_stc} \times \{1 + [(\gamma_v/(100\%)) \times (T_{c\_max} - T_{stc})]\}$$

$$= 37.2V \times \{1 + [(-0.31)/100] \times (75-25)\} = 31.434V \quad (5)$$

(V_{mp_stc} and T_{c_max} refer Table 1)
Minimum maximum voltage produces by JINKO 315 W_p PV modules based on estimated maximum PV module temperature of 75 °C is 31.434 V. This implies that the estimated minimum input voltage from a single PV module to be injected to the inverter is 31.434 V.

Step 4

$$N_{s\_max} = RD\left[\frac{V_{maxinvMPPT} \times f_{s1}}{V_{ocmax}}\right] = RD\left[\frac{500 \times 0.95}{46.92}\right] = 10.12 \sim 10 \quad (6)$$

($V_{maxinvMPPT}$ and f_{s1} refer Table 1)
Maximum number of modules that can be connected in series is 10 modules.

$$N_{s\_min} = RU\left[\frac{V_{mininvMPPT} \times f_{s2}}{V_{mpmin} \times f_{cab}}\right] = RU\left[\frac{125 \times 1}{31.43 \times 0.97}\right] = 4.19 \sim 5 \quad (7)$$

($V_{mininvMPPT}$, f_{s2} and f_{cab} refer Table 1)
Minimum number of modules that can be connected in series is 5 modules.

Step 5

$$N_p = RD\left[\frac{I_{dcinv}}{I_{scstc} \times f_{s3}}\right] = RD\left[\frac{11.5}{9.01 \times 1.25}\right] = 1.021 \sim 1 \quad (8)$$

(I_{dcinv}, I_{scstc} and f_{s3} refer Table 1)
This means that the number of parallel connection allowable is only one.

Step 6

$$N_t = N_p \times N_{smax} = 1 \times 10 \quad (9)$$

Maximum array configuration is 1×10.
$N_t = N_p \times N_{smin} = 1 \times 5$
Minimum array configuration is 1 ×5.

The sizing result for this case study is shown in Table 2. Interestingly, although Eq. 3 and Eq. 6 both indicates that the range of possible PV module in series to be installed is 10. The budget constraint has limited the number of module to only 9 (refer Eq. 2 for detail).

Table 2: Results of sizing GCPV system based on budget requirement of RM22, 500.

Parameters	Value and Units
PV array power (P_{arr_stc})	3000 Wp
Number of PV modules that can be installed (N_t)	9
Number of PV modules that matches a specific inverter (N_t)	10 to 10
Maximum open circuit Voltage (V_{oc_max})	46.92V
Minimum Maximum power Voltage (V_{mp_min})	31.43V
Maximum number of PV modules in series (N_{s_max})	10
Minimum number of PV modules in series (N_{s_min})	5
Number of string in parallel (N_p)	1
Optimum array configuration ($N_t = N_p \times N_s$)	$N_{t\_max} = 1 \times 10 = 10$ $N_{t\_min} = 1 \times 5 = 5$
Final configuration ($N_t = N_p \times N_s$)	$N_t = 1 \times 9 = 9$

4.2. Energy Yield Performance

This section focuses on making comparison between actual Y_f and the predicted Y_f. The actual Y_f can be obtained from the Solar-Log website [13] provided by the system installer whiles the predicted one was based on the Y_f mathematical model as in Eq. 10. In applying the mathematical model, three parameters namely PSH, $k_{deration\_y}$ and η_{sub_system} were estimated. On the other hand, P_{arr_STC} is based on the capacity of total PV modules installed representing the array capacity at peak rating. In this case study, the predicted Y_f were calculated for daily and monthly basis for January 2018 until March 2018. The remaining parameters of the $k_{deration\_y}$ and η_{sub_system} which are k_{mm}, $k_{tem\_p\_ave}$, k_{dirt}, k_{age}, η_{inv} and η_{cable} were based on assumptions or taken from datasheets as listed in the Table 3 below:

Table 3: Parameters taken into calculation of Y_f.

Parameter	Values	Comment
Mismatch factors (k_{mm})	1	[15]
Temperature factors ($k_{tem\_p\_ave}$)	Varies	Calculated (Eq. 11)
Dirt factors (k_{dirt})	0.97	Assumed [2]
Age factors (k_{age})	1	Assumed (the modules are clean and newly)
Effieciency of inverter (η_{inv})	0.98	[16]
Cable loss (η_{cable})	0.97	MS1837:2018
Peak Sun Hour	4.66 h	[13]

Two parameters were assumed namely k_{dirt} and k_{age}. k_{dirt} is assumed 0.97 as applied in a case study in Damansara, Malaysia [2]. Meanwhile k_{age} is assumed to be 1.00 because it was newly installed. The other parameters were taken from datasheet except for $k_{temp\_p\_ave}$ and PSH, which were calculated. The daily predicted Y_f were calculated for January 2018 to March 2018 as listed in Table 4:

Table 4: Daily predicted Y_f from January 2018 to March 2018.

Month	Y_f, (kWh)		
Day	January 2018	February 2018	March 2018
1	**11.36***	11.09	11.20
2	11.31	11.15	11.15
3	11.25	11.09	11.15
4	11.36	11.09	11.09
5	11.31	11.15	11.09
6	11.15	11.31	11.09
7	11.09	11.25	11.20
8	11.15	11.09	11.09
9	11.31	11.09	11.04
10	11.31	11.09	11.09
11	11.57	11.09	11.09
12	11.57	11.09	11.09
13	11.46	11.04	11.09
14	11.36	11.15	11.09
15	11.31	11.15	11.04
16	11.31	11.09	11.15
17	11.09	11.09	11.09
18	11.25	11.09	11.09
19	11.15	11.09	11.09
20	11.25	11.15	11.15
21	11.25	11.09	11.09
22	11.15	11.09	11.09
23	11.15	11.15	11.09
24	11.20	11.15	11.09
25	11.20	11.04	11.09
26	11.25	11.09	11.09
27	11.20	11.09	11.41
28	11.15	11.09	11.09
29	11.15	-	11.09
30	11.15	-	11.04
31	11.09	-	11.09

Total	348.82	311.26	344.49
Average	**11.25**	**11.12**	**11.11**

The actual Y_f from Solar-Log website and calculated PSH based on Equation 13 from January 2018 to March 2018 are listed in Table 5 below:

Table 5: The actual Y_f and PSH obtained.

Month	January 2018		February 2018		March 2018	
Day	Y_f, kWh	PSH, h	Y_f, kWh	PSH, h	Y_f, kWh	PSH, h
1	4.56	**1.87***	8.7	3.65	9.19	3.82
2	5.47	2.25	7.4	3.09	8.58	3.59
3	5.15	2.13	9.58	4.02	4.69	1.96
4	5.36	2.20	9.81	4.12	11.95	5.02
5	5.39	2.22	7.91	3.31	9.01	3.78
6	8.12	3.39	5.55	2.29	8.86	3.72
7	9.58	4.02	8.48	3.51	9.42	3.92
8	8.85	3.70	10.58	4.44	12.09	5.08
9	7.28	3.00	10.77	4.52	13.25	5.59
10	6.65	2.74	10.15	4.26	9.35	3.93
11	2.29	0.92	11.89	4.99	12.01	5.04
12	3.84	1.55	10.44	4.39	13.49	5.67
13	5.19	2.11	11.64	4.91	9.23	3.88
14	6.58	2.70	9.78	4.09	13.65	5.73
15	7.93	3.27	10.38	4.34	10.98	4.63
16	6.86	2.83	11.1	4.66	7.46	3.12
17	9.6	4.03	9.62	4.04	10.91	4.58
18	6.17	2.56	10.02	4.21	10.49	4.41
19	8.79	3.67	10.59	4.45	9.44	3.97
20	7.62	3.16	8.84	3.70	8.71	3.64
21	8.91	3.69	11.47	4.82	12.86	5.40
22	10.76	4.50	9.81	4.12	6.91	2.90
23	7.78	3.25	10.47	4.38	13.18	5.54
24	6.55	2.73	10.42	4.36	12.43	5.22
25	8.64	3.60	13.03	5.50	12.84	5.39
26	3.82	1.58	11.89	4.99	9.02	3.79
27	9.25	3.85	12.67	5.32	6.87	2.81
28	9.02	3.77	12.09	5.08	14.3	6.01
29	10.56	4.41	-	-	12.27	5.15
30	9.85	4.12	-	-	12.96	5.46
31	10.69	4.49	-	-	12.9	5.42
Total	227.11	94.32	285.08	119.57	329.3	138.19
Average	7.33	3.04	10.18	4.27	10.62	4.46

The reason to find the PSH from actual Y_f is to make comparison between predicted PSH used (4.66 h) and daily PSH. The difference in PSH used will significantly affect the predicted Y_f obtained.

An example of monthly comparison for actual Y_f and predicted Y_f for January 2018 were shown in Fig. 6. While, the monthly comparison for actual Y_f and predicted Y_f for January 2018 until March 2018 were tabulated in Table 6.

The predicted Y_f range between 11.0 kWh until 11.6 kWh, while the actual Y_f range between 2.2 kWh until 14.3 kWh. The average percentage difference ranges from 4.6% to 53.48%.

From Fig. 6, 11^{th} January shows the biggest difference between predicted Y_f and actual Y_f. Meanwhile 22^{nd} January shows the smallest difference between predicted Y_f and actual Y_f. This is probably due to the actual PSH on 11th January was 0.9 h while PSH on 22nd January is 4.5 h, compared to the constant daily estimated PSH throughout the month of 4.66 h.

The predicted monthly Y_f ranges from 302 kWh to 358 kWh. Consequently, these translate to predicted gross income between RM 281 to RM 333 per month.

Table 6: Comparison between January 2018, February 2018 and March 2018.

Parameters	January 2018	February 2018	March 2018
Predicted energy yields range	11.0 kWh until 11.6 kWh	11.0 kWh until 11.4 kWh	11.0 kWh until 11.4 kWh
Actual energy yields range	2.2 kWh until 10.7 kWh	5.5 kWh until 13.0 kWh	4.6 kWh until 14.3 kWh
Average percentage difference	53.48%.	9.22 %.	4.6 %.
Predicted monthly energy generation	344.1 kWh to 358.98 kWh	302.2 kWh to 310.8 kWh	334.8 kWh to 353.4 kWh
Predicted gross income generation	RM 320 to RM 333.85	RM 281.0 to RM 289	RM 311.0 to RM 328.0

The GCPV system monthly Y_f performance for January 2018, February 2018 and March 2018 were evaluated based on the percentage differences. The percentage difference between predicted Y_f and actual Y_f for January 2018 is the highest while March 2018 is the lowest. This is because the estimated daily PSH used in the calculation for the 3 months was a constant of 4.66 h. The value of PSH was obtained from the average yearly solar irradiation matrix for the location of this case study, which is 1701.29 kWh/m2 [13]. The total solar irradiation for January is the lowest compared to February and March since January is a rainy month for every year [2]. On contrary, March has the highest PSH throughout the year [2]. From the analysis, the main reason for high percentage difference in January is due to the over-prediction of daily PSH. Furthermore, the ambient temperature for January was found to be also the lowest compared to February and March.

3. Conclusion

This study provides the sample of evidence for the customer satisfaction regarding to the installed GCPV system performance in tropical Malaysia. Based on the budget requirement, the sizing of the 3 kW_p GCPV system has been conducted by mathematical model approach. The result from the mathematical model approach which includes several boundary conditions namely electrical specification, safety, irradiance and temperature shows that that final configuration for 3 kW_p is 1 × 9 that represent 1 parallel string of 9 PV modules connected in series. The performance of the GCPV system between actual Y_f and predicted Y_f on monthly basis does not seem satisfying. However, the performance cannot be concluded yet due to the incomplete one year data. Therefore, we suggest further work to be undertaken to monitor the performance of the installed GCPV system precisely.

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Fig. 1: Photovoltaic modules mounted on rooftops (Retrofitted GCPV System).

Fig. 2: (a) The inverter, (b) solar log data logger, (c) AC junction box and (d) DC junction box.

Fig. 3: (a) PV export meter and (b) TNB meter.

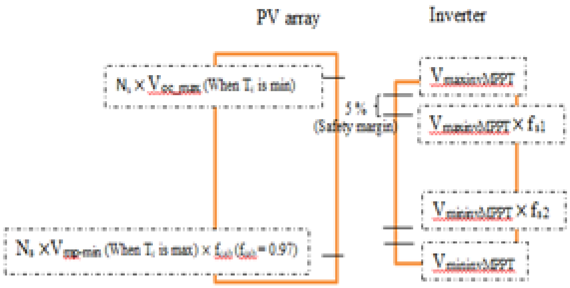

Fig. 4: Matching of PV array voltage to inverter voltage.

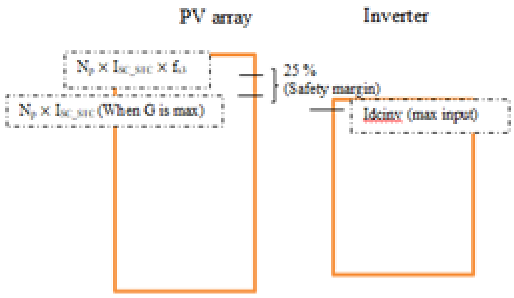

Fig. 5: Matching of PV array current to inverter current.

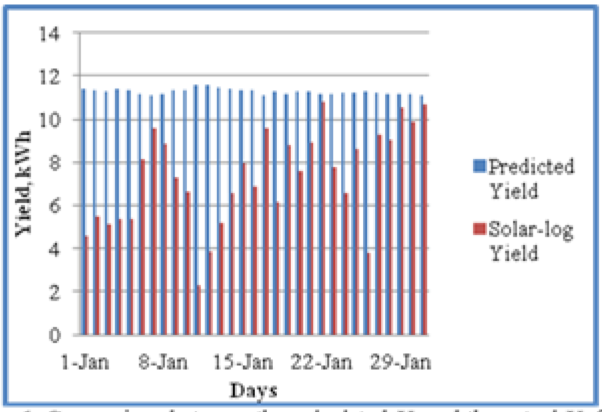

Fig. 6: Comparison between the calculated Y_f and the actual Y_f for January 2018.