

## Development of Grid-Connected Photovoltaic System Design Tool for Residential Building

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**Abstract:** This work presents the development and simulation of the design tool for a grid-connected photovoltaic system for residential buildings. The main difference between the grid-connected photovoltaic (GCPV) system and a standalone photovoltaic (SPV) system is GCPV system is with the grid while the SPV system is without connecting the system to the grid. The grid-connected photovoltaic system sizing calculation is very complex. It has made the project engineer spend a lot of time doing the calculation manually. Thus, the GCPV Design Tool played a vital role in simplifying the process of getting the result for the GCPV system sizing. Even though there are many kinds of PV system simulation software in the market, that software is sold at a very high price. The proposed design tool has been developed by using Microsoft Excel Visual Basic. The proposed design tool can be used to identify the sizing of the GCPV system and conduct the performance, environmental and economic analysis on the recommended GCPV system. The case study has been conducted by using both the proposed design tool and PVsyst to design a GCPV system for the user at Johor Bahru. The result of PV panel and inverter sizing obtained by the proposed design tool is similar to PVsyst software.

**Keywords:** Grid-Connected Photovoltaic System, GCPV Design Tool, PVsyst, Microsoft Excel Visual Basic

### 1. Introduction

Nowadays, the participation of solar energy in the power industry has developed day by day [1]. The PV system can be categorized into a stand-alone and grid-connected photovoltaic (GCPV) system [2]. The complexity of the grid-connected photovoltaic system sizing calculation is very high. It has made the project engineer spend a lot of time doing the calculation manually [3]. Thus, the GCPV System Simulation Tool played a vital role in simplifying the process of getting the result for the GCPV system sizing. Even though there is a lot of PV system simulation software in the market, but that software is basically sold at a very high price. At the end of this project, the low-cost photovoltaic system design tool will be developed by using Microsoft Excel with Visual Basic Application. The

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students, lecturers, or even professional engineers can use this software to design the grid-connected photovoltaic system.

PV system designing process is very complicated since this process has included the energy consumption, sizing of the PV system and its components, and the performance analysis. The innovation of PV system design and simulation software has eased the process of PV system designing and so on. There is analysis has been done depending on the different PV system design software as shown in Table 1 [4] – [9]. As shown in Table 1, most of the professional PV system design software such as PV\*SOL and PVsyst is difficult to be used by the new user, and that professional PV system design software is sold at very high prices annually. The PV system design tool developed by using Microsoft Excel VBA is almost free and easy to be used. Thus, this proposed design tool can ease the process of PV system designing and it can be used by the user from different background.

**Table 1: Comparison of PV System design and simulation software**

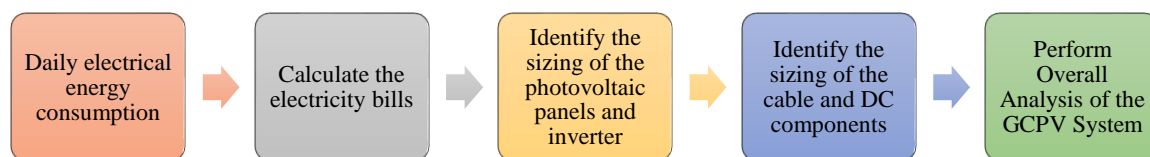
Characteristics	Complexity	Cost	Performance	Accuracy
PV*SOL [4] [5]	Complex	1092USD	Complete	Moderate
HelioScope [6]	Complex	950USD	Complete	High
PVsyst [7]	Complex	668USD	Complete	Moderate
Microsoft Excel VBA [8] [9]	Simple	Free	Moderate	Moderate

## 2. Methodology

The main content of the methodology for this project is focusing on the development of the Grid-Connected Photovoltaic System by using Microsoft Excel Visual Basic for Application. There are few general steps to identify the sizing of the GCPV system and conduct the analysis on it. While due to the page limitation of the content, only the most important equation will be elaborated.

### 2.1 Design of the Grid-Connected Photovoltaic (GCPV) System simulation software

Determine the sizing of the component used in the photovoltaic system is a vital process before purchasing and installing the photovoltaic system. In this case, this project has been planned to develop a GCPV System design and analysis software. The process of the GCPV system sizing is shown in Figure 1. Besides, the proposed Grid-Connected Photovoltaic System Simulation Tools has been named YHM Grid-Connected PV System Design Tool. The detail explanation for each GCPV design procedure will be discussed in next subtopic.



**Figure 1: Process of the GCPV system sizing**

#### 2.1.1 Identify the Load Calculation

The total connected load can be identified by using the power rating and quantity of all the loads applied by the end user. The calculation on the sizing of the GCPV system components required the value of the total maximum demand. It is defined by following Eq. 1.

$$E_{MD} = P_{load} \times Qty \times Usage\ Hour \quad Eq. 1$$

where  $E_{MD}$  is the total energy maximum demand and *Usage Hour* is the operation hour of the loads that used by the end user.

### 2.1.2 Identify Sizing of the Photovoltaic Array

Before the calculation of the PV Modules sizing, the peak wattage that produced by the PV modules are required to be obtained by using Eq. 2 [10].

$$P_{pv\_peak\_est} = \frac{E_{MD}}{PSH_{daily} \times \eta_{DC\_cable} \times \eta_{inv}} \quad Eq. 2$$

$PSH_{daily}$  is the daily peak sun hour data,  $\eta_{DC\_cable}$  is the efficiency of the cable and  $\eta_{inv}$  is the efficiency of the selected inverter.

After the  $P_{pv\_peak\_est}$  have been obtained, the estimate total numbers of PV panels required can be identified by using Eq. 3 [10].

$$N_{tot\_est} = \text{round up} \left( \frac{P_{pv\_peak\_est}}{P_{mp\_stc}} \right) \quad Eq. 3$$

where  $N_{tot\_est}$  is the total estimate number of PV modules and  $P_{mp\_stc}$  is the maximum power of the PV modules at standard condition.

### 2.1.3 Identify Sizing of the Inverter

The system upsizes (almost 20%) should be considered during the selection of the inverter. Formula to calculate the power rating of the inverter is shown in Eq. 4.

$$P_{rate,inv} = P_{pv\_peak\_est} * (100\% + \%_{upsize,sys}) \quad Eq. 4$$

where  $P_{rate,inv}$  is the power rating of the inverter,  $P_{pv\_peak\_est}$  is the estimated peak power of the PV modules and the  $\%_{upsize,sys}$  is the percentage of the system upsizes.

### 2.1.4 Identify the Sizing of the Cable

The suitable sizing of the cables in the PV system is very important. The minimum cross-sectional area required of the DC cable for the PV module can be identified by using the Eq. 5 [11].

$$A_{min\_string\_dc\_cable} = \frac{2 \times L_{dc\_cable} \times I_{mp\_stc} \times \rho}{Loss \times V_{min\_string}} \quad Eq. 5$$

where the  $A_{min\_string\_dc\_cable}$  is the minimum cross-sectional area of the cable for string,  $L_{dc\_cable}$  is the length of the longest string cable (m),  $I_{mp\_stc}$  is the maximum operating current in the cable (A),  $\rho$  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).

### 2.1.5 Identify the Sizing of the Fuse

When the full-load current is higher than the fuse sizing, the fuse may burn up when the full load current passes through the system. The safety factor should be considered. So, the normal fuse sizing must be 135% greater than the normal full-load current [4] & [12]. The current rating of the fuse should be followed the Eq.6 and the minimum voltage rating of the fuse shown in Eq. 7.

Fuse Current Rating Range:

$$1.5 \times I_{sc\_pv\_stc} \leq I_{fuse} \leq 2.0 \times I_{sc\_pv\_stc} \quad Eq. 6$$

where the  $I_{fuse}$  is the minimum fuse current rating required for the system, while the  $I_{sc\_pv\_stc}$  is the short circuit current of the PV panel at standard test condition.

Minimum voltage rating for the fuse:

$$V_{fuse} \geq 1.2 \times N_{pvs} \times V_{oc_{pv_{stc}}} \quad Eq. 7$$

where the  $V_{fuse}$  is the minimum fuse voltage rating required by the system,  $V_{oc_{pv_{stc}}}$  is the open circuit voltage of the PV panel at standard test condition and the  $N_{pvs_{act}}$  is the number of PV panels connected in series.

### 2.1.6 Identify the Sizing of the DC Surge Protection Device (SPD) and DC Breaker

Fuse is not the only protection device that will be used inside the PV system. For instance, the DC breaker and DC surge protection device (SPD) also have been used to protect the system from damaged by a different kind of fault. Eq. 8 shows the formula used to identify the minimum voltage rating of the DC SPD and DC Breaker while the Eq. 9 shows the minimum current rating of the DC SPD and DC breaker [13].

Minimum voltage rating for the DC components:

$$V_{DC_{Comp}} > V_{oc_{pv_{stc}}} \times 1.15 \times N_{pvs_{act}} \quad Eq. 8$$

where  $V_{DC_{Comp}}$  is the minimum voltage rating for the DC components,  $V_{oc_{pv_{stc}}}$  is the open circuit voltage of the PV panel and the  $N_{pvs_{act}}$  is the actual number of PV panels connect in series.

Minimum current rating for the DC components:

$$I_{DC_{Comp}} > I_{sc_{pv_{stc}}} \times 1.25 \times N_{pvp_{act}} \quad Eq. 9$$

where  $I_{DC_{Comp}}$  is the minimum current rating for the DC components,  $I_{sc_{pv_{stc}}}$  is the short circuit current of the PV panel and the  $N_{pvp_{act}}$  is the actual number of PV panels connect in parallel.

### 2.1.7 Performance Analysis

For the performance analysis, the proposed software can estimate the monthly energy generated and the carbon dioxide emission reduction by the PV system suggested by the proposed software.

#### 2.1.7.1 Identify the Performance Ratio

The performance ratio (PR) shows the quality of component used in the system. For a good GCPV system in Malaysia, the performance ratio should be higher than 75%. The Eq. 10 shown the formula to identify the performance ratio of the purposed GCPV system [13].

$$PR = \frac{E_{Exp_{sys\_Monthly}}}{P_{array_{stc}} \times PSH_{Monthly}} \quad Eq. 10$$

where the  $PR$  is the performance ratio,  $E_{Exp_{sys\_Monthly}}$  is the expected monthly energy generated by the proposed PV system,  $P_{array_{stc}}$  is the expected power generated by the PV array at standard test condition and the  $PSH_{Monthly}$  is the monthly peak sun hour (Hour).

#### 2.1.7.2 Identified the Specific Yield

For a good GCPV system in Malaysia, the specific yield should be higher than 1200Wh/Wp per annum. The Eq. 11 shown the formula to calculate the specific yield [13].

$$SY = \frac{E_{Exp_{sys\_Monthly}}}{P_{array_{stc}}} \quad Eq. 11$$

where the  $SY$  is the specific yield of the system (Wh/Wp),  $E_{Exp_{sys\_Monthly}}$  is the expected monthly energy generated by the proposed PV system (kW) and the  $P_{array_{stc}}$  is the expected power generated by the PV array at standard test condition (kW)

### 2.1.7.3 Identify the Carbon Dioxide Emission Reduction

According to the SEDA Official Website, the ratio of carbon dioxide emission be different between Peninsular Malaysia and East Malaysia and the carbon dioxide emission can be predicted with the ratio shown as below [14]:

- Peninsular: 0.694 tCO<sub>2</sub>/MWh
- Sabah and Sarawak: 0.536 tCO<sub>2</sub>/MWh

### 2.1.8 Economic Analysis: Estimated Cost Required for the Suggested GCPV System

The economic analysis can be done by identify the estimated cost required for the suggested GCPV system installation fee and its component fee. According to the GCPV system cost index, there will be 5 Ringgit per Watt for the Grid-Connected PV system including the PV panels, inverter and the other components. The Eq. 12 shown the formula to calculate the estimated cost for the PV system installation.

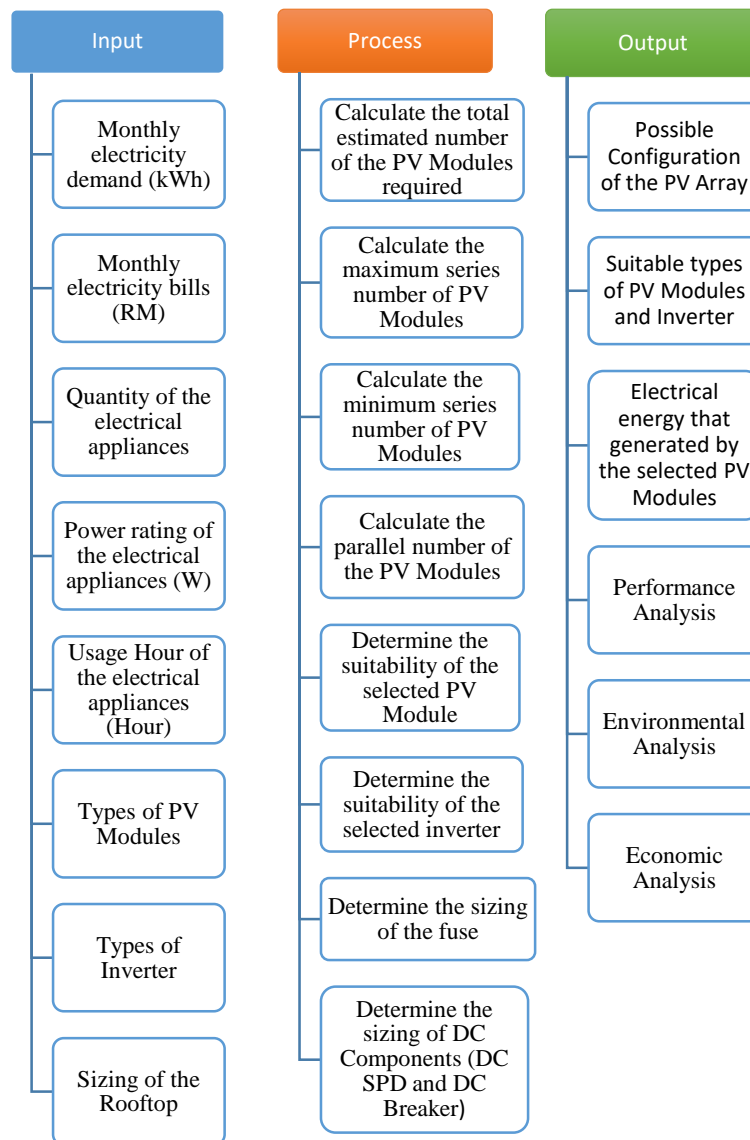
$$\text{Estimated Cost} = N_{Tot\_act} \times P_{mp\_pv\_stc} \times C.I \quad \text{Eq. 12}$$

where the *Estimated Cost* is the estimated cost for whole GCPV system, *C.I* is the *GCPV system cost index*  $\left(\frac{RM}{Wp}\right) \sim (RM5/Wp)$ ,  $N_{Tot\_act}$  is the total actual number of the PV panels used and the  $P_{mp\_pv\_stc}$  is the maximum power generated by the PV panel at the standard test condition.

## 2.2 System configuration of Grid-Connected Photovoltaic System simulation software

The system configuration of the Grid-Connected Photovoltaic System Simulation Software can be illustrated in **Figure 2**. The block diagram can be categorized into three parameters which are input, the process of calculation, and output.

- **Input:** For the input of the proposed software, the user may choose either one dataset to be inserted. The first dataset which is required the end-user to insert their monthly electricity demand in kWh and electricity bills as the main input of the proposed software. The user may insert another dataset which is the quantity, power rating, and usage hour of electrical appliances as the input of the system. Next, no matter which mode of the user select, they are required to insert their rooftop sizing, location of installation the PV system and select the PV module and inverter they prefer into the proposed design tool.
- **Process:** In the process section, the proposed design tool will use the dataset inserted by the end-user to calculate the sizing of the PV Array. The proposed software will calculate the maximum and the minimum number of the PV modules in series and parallel. Next, the proposed design tool will identify the sizing of the cable, sizing of the fuse, and sizing of the DC SPD and DC breaker.
- **Output:** The proposed software will show the possible configuration of the PV modules in series and parallel. The end-user needs to select the possible configuration of the PV array and it will determine the suitability of the PV modules and the inverter. The proposed software will identify the electrical energy generated by the selected configuration of the PV array. Lastly, the proposed software can conduct the performance analysis, environmental analysis, and economic analysis of the GCPV system.



**Figure 2: Block diagram of the proposed software parameters**

### 3. Results and Discussion

This section has been categorized into two main subtopics. The first subtopic is the structure of the YHM Grid-Connected PV System Design Tool. The second subtopic is the case study done by using both the proposed design tool and PVsyst software.

#### 3.1 Structure of the Proposed YHM Grid-Connected PV System Design Tool

There are 10 pages of the worksheet in this proposed design tool. While due to the limitation of the thesis paper page numbers, only some of the most important worksheet will be described in fellow subtopic.

##### 3.1.1 User Interface of the GCPV system simulation tools

Figure 3 shows the user interfaced of the YHM Grid-Connected PV System Design Tool. In this page, there are three modes to be selected by the user depend on the which dataset that user have.

For the first mode which is the New User mode, this mode is for the user only know the quantity and the usage hours of the electrical appliances but do not know the power rating in their house. Next, the second mode is the Experience User mode. This mode is for the user who know all the power rating,

quantity, usage hours of their electrical appliances. For the third mode also recognize as the recommend mode for the user which is called as Electricity Bills mode. This mode is for the user who have the past twelve months' electricity bills.



Figure 3: User Interface of the GCPV system simulation tools

### 3.1.2 Electricity Bills Mode

For the most recommended mode to be selected by the use which is the Electricity Bills Mode as shown in Figure 4. Since the main input dataset in this mode is the user's monthly electrical consumption, thus the calculation based on this input data will be more accurate. After the user has insert the data above, the system will show the total electricity bills per year, total energy consumption per year, average monthly and daily energy consumption. The user may press the NEXT button and the system will direct the user to the Rooftop Sizing and PV System Installed Location Page.

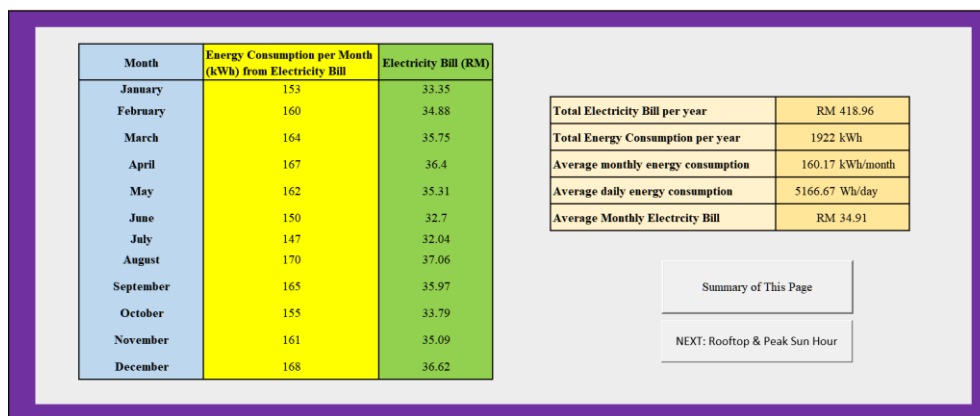


Figure 4: Electricity Bills and Electrical Consumption Data Input Page

### 3.1.3 Rooftop sizing and PV system installed location page

Figure 5 shows the rooftop sizing and PV system installed location page. The user need to insert the rooftop sizing and select the location to install the PV system. After that, the user can press the next button and proceed to PV Module and Inverter Sizing Page.

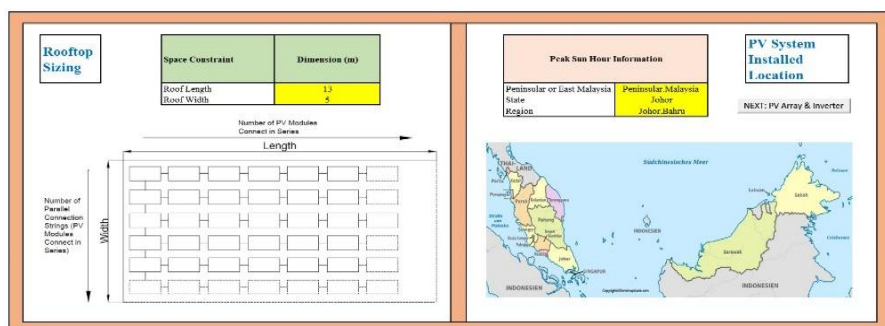


Figure 5: Rooftop sizing and PV system installed location page

### 3.1.4 PV Module and Inverter Sizing Page

Figure 6 shows the PV module and inverter sizing page. The user required to select the model of the PV modules and conductor material they prefer in this page first. Then, the system will display the estimated total number of the PV modules required and the possible configuration of the PV modules in series and parallel. The user required to select the combination of series and parallel number of PV panel. The proposed design tool will display the suitability of the selected configuration of the PV modules in series and parallel. Next, the user can refer the minimum power rating required for the inverter before they select the model of inverter. If the selected inverter is not suitable, the proposed design tool will display the error message and user need to re-select the model of inverter again.

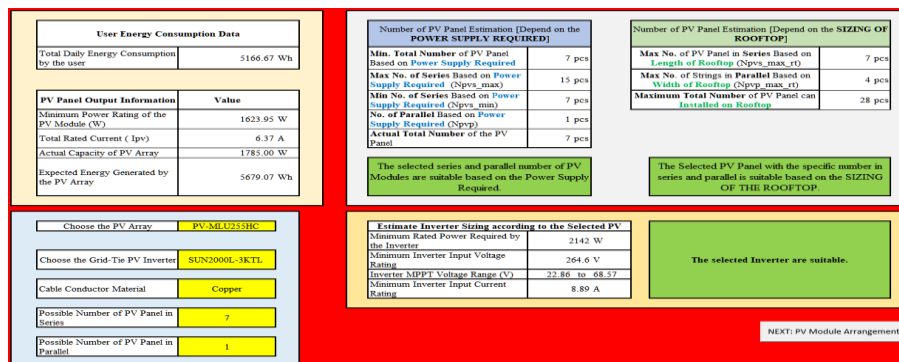


Figure 6: PV Module and Inverter Sizing Page

### 3.1.5 Component sizing and sample single line diagram page

Figure 7 shows the component sizing and sample single line diagram page. The user will obtain the sizing of the DC breaker and the DC surge protection device (SPD). In addition, the sizing of the cable can also be found on this page and there is one sample single line diagram of the PV system shows inside this page.

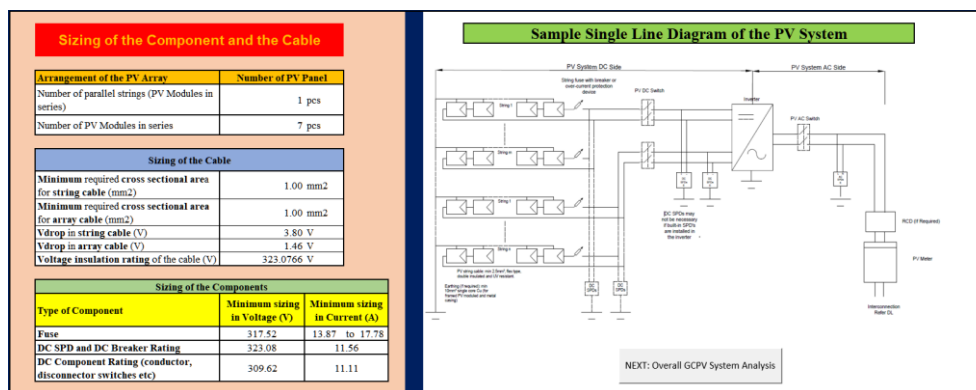


Figure 7: Component sizing and sample single line diagram page

### 3.1.6 Overall GCPV system analysis page

Figure 8 shows the overall GCPV system analysis page. The result of the performance analysis, economic analysis and environmental analysis are all shown in this worksheet. The user may press the print button to print the result or save the result in PDF file type.



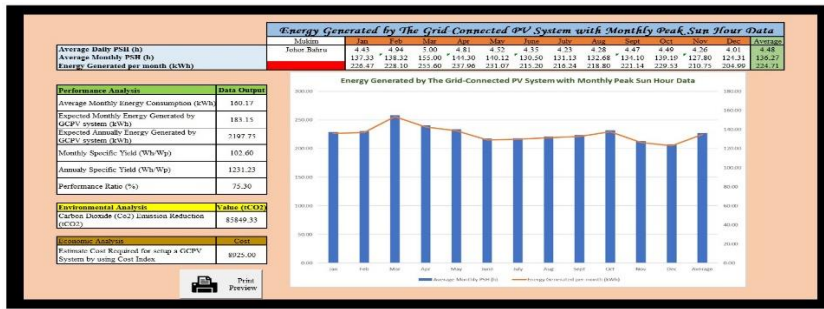


Figure 8: Overall GCPV system analysis page

### 3.2 Case Study: Proposed GCPV System for Double Storey Low-Cost Terrace House

The case study has been conducted to analyse and compare the performance of the proposed software with the PVsyst software. The case study will be the double-storey low-cost terrace house in Johor Bahru, Johor.

The owner of the double-storey low-cost terrace house for this case study has provided the monthly electricity consumption, monthly electricity bill as shown in Table 2.

Table 2 : Monthly electricity consumption and electricity bill

Month	Monthly Electrical Consumption (kWh)	Electricity Bill (RM)
January	153	33.35
February	160	34.90
March	164	35.75
April	167	36.40
May	162	35.30
June	150	32.70
July	147	32.00
August	170	37.05
September	165	35.00
October	155	33.80
November	161	35.10
December	168	36.70

Table 3 shows the comparison the result of both proposed design tool and PVsyst. The same model of PV modules and inverter have been selected in both software to compare the difference of the analysis result by using both software. The result from the aspect of the performance analysis of both software are almost the same, this prove that the proposed design tool can simulate the result almost same to the commercial software.

But there are some advantages of the proposed design tool compared to the PVsyst software. The proposed design tool has considered the required number of the PV panel not only from the energy required aspect but the rooftop sizing has also been considered. While the PVsyst software only can choose either plane power required or surface area of the rooftop as the parameter to conduct the PV system designing. The YHM Grid-Connected PV System Design Tool has been successfully identifying the sizing of cable, fuse, DC SPD, and DC Breaker, while the PVsyst software does not have the function to identify the sizing of these components.

Table 3: Comparison the result of both proposed design tool and PVsyst

PVsyst	Comparison of the Suggested GCPV System Design by using Both Software	YHM Grid-Connected PV System Design Tool
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Mitsubishi Electric PV-MLU255HC	<b>PV Modules</b>	Mitsubishi Electric PV-MLU255HC
Huawei Technologist SUN2000L-3KTL	<b>Inverter</b>	Huawei Technologist SUN2000L-3KTL
7/1	Number of module/inverters	7/1
7	Number of PV Module In series	7
11.6	PV Module Surface Area ( $m^2$ )	13.51
1785	Power Rating of PV Array (W)	1785
	<b>Sizing of Cable</b>	
-	Minimum cross-sectional area of the string and array cable ( $mm^2$ )	1.00
-	Minimum voltage drop in string and array cable (V)	3.80 and 1.46
-	Minimum voltage insulation rating of the cable (V)	323.07
	<b>Sizing of the Fuse</b>	
-	Minimum sizing in Voltage (V)	317.52
-	Minimum sizing in Current (A)	13.78 to 17.78
	<b>DC SPD and DC Breaker Rating</b>	
-	Minimum sizing in Voltage (V)	323.08
-	Minimum sizing in Current (A)	11.56
	<b>Performance Analysis</b>	
2315	Annually Energy Generated (kWh/year)	2232
1253	Annually Specific Yield (Wh/Wp/year)	1251
80.93	Performance Ratio (%)	76.46
-	Carbon Dioxide Emission Reduction ( $tCO_2$ )	85849.33
-	Estimation Cost (RM)	8925

#### 4. Conclusion

This paper proposed a Grid-Connected PV system design tool for residential buildings that have been developed within one-year period. The Microsoft Excel with Visual Basic Application has been used to develop the proposed tool and named the “YHM GCPV Simulation Software”. The proposed design tool can do the function such as PV system designing based on energy consumption required and rooftop sizing limitation. Besides, the proposed design tool can also be used to conduct the performance, environmental and economic analysis of the suggested GCPV system. The proposed design tool is free of charge and user-friendly. Users from different backgrounds can use this proposed design tool to conduct the GCPV system design either they are students, lecturers, or even professional engineers.

The recommendation and the function that might can be improved for future work has been listed as below:

- Adding the function of display the picture of PV module and inverter to the proposed design tool.
- Adding the function of calculate the power loss and display the power loss diagram in the proposed design tool.
- Adding other function to the proposed design tool from the economic analysis aspect such as the periodic cost and annual cost.

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