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Solar Array and Battery Sizing for a Photovoltaic Building in Malaysia

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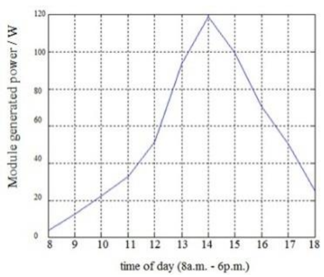
Graphical abstract



Abstract

Renewable energy plays an important role in the national energy policy especially in reducing greenhouse gas emissions. For a photovoltaic (PV) system, one important consideration is the cost of the system. One needs to select the best PV array from a range of selection, that is, the one which is the most efficient and with a best price. This article illustrates a method to compute the size and cost of a required PV array, and then after to compute the required battery for the case of a photovoltaic building in Malaysia. The computation is simulated using Matlab integrated with suitable mathematical equations. The generated current and power of the PV array are calculated for daily solar irradiation in Malaysia. The computation enables the user to quickly compute the initial cost needed to be spent if a given PV system is to be installed. A typical building requiring 12 kWh daily energy with 6 kW peak demand load was shown to need at least 114 solar modules at a cost of about RM53k. It is noted that the main cost of the whole PV system is mainly contributed by the cost of the chosen PV array. Hence, the right choice of a PV module is vital in achieving the minimum cost.

Keywords: Component; photovoltaic; array; crystalline; solar irradiation; matlab software; sizing; economic

Abstrak

Tenaga boleh diperbaharui memainkan peranan yang penting dalam dasar tenaga negara terutamanya dalam mengurangkan pelepasan gas rumah hijau. Bagi sistem photovoltaic (PV), salah satu pertimbangan yang penting adalah kos sistem. Salah satu keperluan untuk memilih yang terbaik susunan PV dari pelbagai pilihan, di mana ia adalah satu cara yang paling berkesan dan dengan harga yang terbaik. Artikel ini menunjukkan satu kaedah untuk mengira saiz dan kos pelbagai PV yang diperlukan, dan kemudian selepas mengira bateri yang diperlukan untuk kes sebuah bangunan photovoltaic di Malaysia. Pengiraan adalah menggunakan simulasi Matlab bersepadu dengan persamaan matematik yang sesuai. Arus penjanaan dan kuasa susunan PV dikira untuk sinaran solar harian di Malaysia. Pengiraan ini membolehkan pengguna mengira dengan cepat kos permulaan yang diperlukan untuk dibelanjakan jika sistem PV yang diberikan dipasang. Sebuah bangunan tipikal memerlukan 12 kWh tenaga harian dengan 6 kW puncak beban permintaan telah ditunjukkan memerlukan sekurang-kurangnya 114 modul solar pada kos kira-kira RM53k. Ia menyatakan bahawa kos utama keseluruhan sistem PV disumbangkan oleh kos pelbagai PV yang dipilih. Oleh itu, pilihan modul PV yang tepat adalah penting dalam mencapai kos minimum.

Kata kunci: Komponen; photovoltaic; aturan; kristal; sinaran suria; matlab software; saiz; ekonomi

1.0 INTRODUCTION

In the near future, development of a wide range of renewable energy sources such as wind and solar power is necessary for environmental sustainability. Renewable energy plays an important role in the national energy policy and in reducing greenhouse gas emissions. The sun is a source of clean and renewable energy without the problems of greenhouse gases or hazardous wastes. It is also the original source of most other renewable energies such as those that can be extracted from wind and ocean waves. Among several kinds of available renewable energies, the wind and solar energies are considered to have greatest potential. Many researchers are working to improve the solar technologies and also to reduce the cost of photovoltaic system.

Due to the increase in consumption, the price of traditional fuel such as oil and coal has increased. For example, the price of raw oil has risen from US$2 to US$93 per barrel during the last 30 years [1-2]. During the same period, solar energy had received more attention because of its many advantages compared to other renewable energy sources. Malaysia is a country located in the tropical region. Hence, its average daily solar irradiation is more than those for many other countries which makes the solar energy a great potential source to meet its energy needs [3-5].

A photovoltaic (PV) system is a technology that can be used to directly convert solar radiation into electricity. The energy conversion system has no moving parts and produces minimum noise and pollution. The source itself is free and abundance. The photovoltaic systems can be either stand alone or grid connected. In the standalone system, a battery is needed for storing of energy during daylight and then for using the stored energy during night or cloudy times. On the other hand, no battery storage is needed for the grid connected system due to the utility power supply support [6-8]. However, the cost of photovoltaic system is still high since the required components for the system such as the solar array, battery, converter, and inverter are expensive. Among the components of the photovoltaic system, the solar array is the most important component due to its cost. Different types of solar or PV arrays are available in the market, each with different efficiency, cost and performance. Thus, by selecting an appropriate solar array with high performance and at a reasonable price, the overall photovoltaic system cost can be reduced. In this paper, a simulation program is developed to enable the computation of the cost of the required solar arrays and battery for a stand alone photovoltaic system.

2.0 DATA REVIEW OF PHOTOVOLTAIC SYSTEM

2.1 Overview of PV System in Malaysia

In Malaysia, the first grid-connected PV was installed in July 1998 [7]; this system was on the rooftop of the College of Engineering, Universiti Tenaga Nasional (UNITEN). TNB Research Sdn Bhd (TNBR) initiated the system installation as part of a pilot research project funded by Malaysia Electricity Supply Industry Trust Account (MESITA) and Tenaga Nasional Berhad (TNB). The system is connected to the 3-phase system of the building with a rated capacity of 3.15 kWp. This installation provided the first Malaysian practical experience on grid-connected PV, and as such the system was rather simple and basic. The system is still working, albeit with technical problems. During the same year, another two grid connected PV systems were installed by BP Malaysia and Universiti Kebangsaan Malaysia (UKM) [7, 8, 9]. An 8 kWp PV system was installed at a BP petrol station along the KESAS highway, and a 5.5 kWp PV at the Solar Energy Research Park in UKM. However, both the UKM and BP PV systems have since been removed.

In August 2000, the family of a TNB senior officer became the first Malaysian family to experience BIPV when a 3.15 kWp BIPV system was installed at their house in Port Dickson. Subsequently, another two BIPVs were installed at public residences in Shah Alam (3.24 kWp in November 2000) and Subang Jaya (2.8 kWp in November 2001). These BIPV installations however, were done as retrofits and installed on top of existing roof tiles. Until now the Subang Jaya system has been working fine since its commissioning without any problem. These residential BIPV installations have provided valuable practical experiences to the respective homeowners as well as the BIPV project developers.

While majority of BIPVs in Malaysia is installed on existing roofs or retrofitted, several installations have roof integrated PV. One such installation is a bungalow (used as a PV research center) built within the compound of TNB Research, in October 1999. PV modules of 3.6 kWp capacities were used as the roof of the bungalow [7, 10, 11]. Other examples include the BIPV installations found at TNB Research's nursery, several local universities, and at a private school in Damansara. In late 2004, BIPVs had also been installed in CETDEM's office in Petaling Jaya and in the MEWCLEO building. In addition, Success Electronics Sdn Bhd and Transformer Manufacturer Sdn Bhd had set up their own private solar parks which comprise of an 8 kWp grid-connected PV system with Leonics inverters (Thailand made) in August 2005 [7].

2.2 Common Types of Solar Arrays

A PV cell or a solar array is the most important component of a photovoltaic system since it determines the efficiency and overall cost of the system. Photovoltaic cells are usually made from semiconductor materials such as silicon. The amount of electricity that one single PV cell can produce is just around 2 watts, which is too small even for a small calculator or watch [8-10]. Therefore a series of PV cells are connected together and this series of PV cells is called a module. Figure 1 diagrammatically shows the configuration of a PV cell, a PV module and a PV array. Figure 2 shows the current-voltage relationship of a PV module [11, 12]. For maximum efficiency and output power, the operating point of the PV cell in the current-voltage curve should be at the knee point.

Several types of solar arrays are available in the market. The crystalline silicon and thin films are the two most common types. The crystalline silicon can be either mono-crystalline silicon (M-Si) or poly-crystalline silicon (P-Si). Other types may be made from non-crystalline or amorphous silicon or from other materials such as in the case of gallium arsenide (GaAs) PV modules, .

The high cost of PV arrays is the main impediment of the wide application of solar PV for renewable energy. The high cost is largely due to the expensive solar cell manufacturing process. A high demand for the PV arrays by the users can help to make the PV price more competitive and reasonable. Over the last two decades, the cost of PV had significantly reduced and the price will continue to decrease due to research and development in advanced material and manufacturing techniques. Figure 3 [13] shows the continual reduction in PV price since 1990.

2.3 Solar Radiation in Malaysia

A PV cell can generate DC electricity from sunlight. The amount of power generated is dependent on the sunlight irradiation as well as the ambient temperature. Typically, a solar module with an 80 Wp rating would produce 80 Wd.c power under standard test condition (STC). The STC is specified as a condition where the solar radiation is 1000 W/m^2 and the ambient temperature is 25°C [14, 15, 16]. Differences between a standard condition and the maximum solar radiation is usually between 800 W/m^2 to 1000 W/m^2 . But the ambient temperature could be as high as 40°C at noon. Figure 5 shows the PV cell temperature during daytimes. And also the output generated power of the PV cell consider to the temperature. Malaysia is located between 1° and 8°N latitudes, and between 99° and 120°E longitudes.

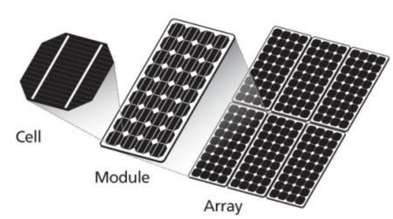


Figure 1 Solar panel figuration, cell, module, array

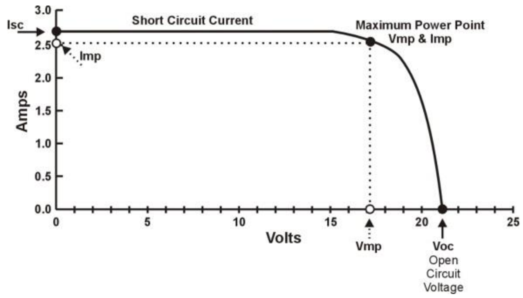


Figure 2 I-V Characteristic of PV module

According to the Ministry of Energy Communications and Multimedia (MECM), Malaysia is in the equatorial region with an average daily solar radiation of 4,500 kWh/m^2 and with sunshine duration of about 10 hours. The ambient temperature stays high during the year at 27°C to 33°C. The average humidity is 80% – 88%, and is nearly 90% in highland areas, and is never falling below 60% [16-19]. A PV installation in Kuala Lumpur receives 1.3 times higher global solar irradiance than that in Germany.

3.0 METHODOLOGY

3.1 Solar Radiation Data

In this work, the required meteorological data were obtained from the Meteorology Headquarters, Petaling Jaya, and from NASA's Surface Meteorology and Solar Energy (http://eosweb.larc.nasa.gov). The data consist of the solar radiation level, mean relative humidity, and the maximum temperature for the area under study.

The latitude and longitude of the area being studied are 4° 31' N and 101° 6' E respectively. For this area, the sun irradiation duration was given as 10 hours and the irradiation level varies from 30 W/m^2 to 1000 W/m^2. Then, based on this irradiation condition, the generated cell current and power can be calculated. Figure 4 shows the variation of the irradiation during daylight. The maximum power of the PV array (at 1000 W/m^2) is observed to be generated right in the middle of the day due to the strong sun irradiation during that period. It is also noted that the electricity generation is much less at the beginning and the end of the day and hence those times are comparatively less valuable.

3.2 PV Characteristic and Price Analysis

Mono- and poly- crystalline silicon modules make up more than 90% of the currently installed PV arrays. Major manufacturers include Sharp, Kyocera, Sanyo, BP, Siemens, Q-Cells, Sun Power, and Sun Tech. The cell efficiency is in the range of 15 to 20 % and the prices in the range of US$ 1 to US$ 2 per watt peak [20, 21].

A survey carried out by Solarbuzz in 2012 states that the lowest prices for a poly-crystalline and mono-crystalline solar modules are US$ 1.28 and US$ 1.23 per watt peak respectively. On the other hand, the lowest price for a thin film module is US$ 0.86 per watt peak. It is usual to expect that thin film modules are cheaper compared to crystalline silicon modules [20].

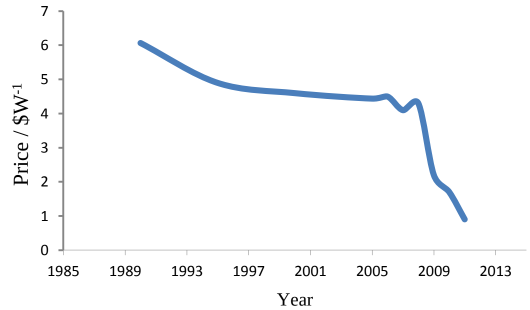


Figure 3 Variation of the PV module cost with time

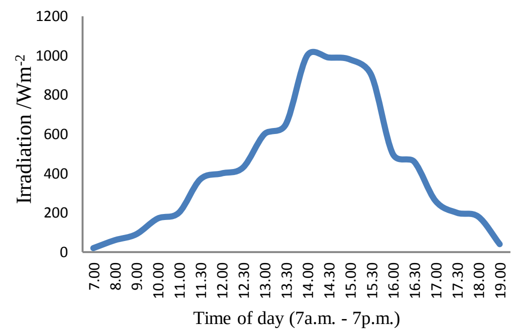


Figure 4 Variation of irradiation level during daylight [21]

Another survey undertaken by Global Solar Energy Inc. (GSE) (as reported in [23]) indicates that the lowest prices for a poly-crystalline and mono-crystalline solar modules are US 1.28 and US$ 1.23 per watt peak respectively. The lowest price for a thin film module is US$ 0.86 per watt peak.

In order to further reduce the price of the PV module, copper indium diselenide (CIS) which consists of nano sized copper, indium, gallium, and selenide can be used instead of silicon. CIS is produced using thin film technology and "roll and roll" manufacturing process [26, 27]. The 2012 Solarbuzz survey reported that the lowest CIS module price is US$ 0.93 per watt peak and the long term projected price is US$ 1 per watt peak. Major CIS companies include Nanosolar, Miasole, Heliovolt, and Honda. Volume production of CIS had already been materialized in 2007. Alternatively, cadmium telluride (CdTe) thin films produced by several manufacturers can also be used instead of silicone. Compared to CIS, CdTe thin films have the advantages of higher efficiency, simpler configuration, and cheaper price at US$ 0.86 per watt peak [20, 24].

Table 1 summarizes the price of various photovoltaic modules as discussed above. It can also be noted that it is now economically possible to integrate the PV cells with standard building materials such as roofing, windows, and etcetera due to the lower cost of array materials and thin film technology.

Table 1 Minimum price per watt peak for various PV modules [20]

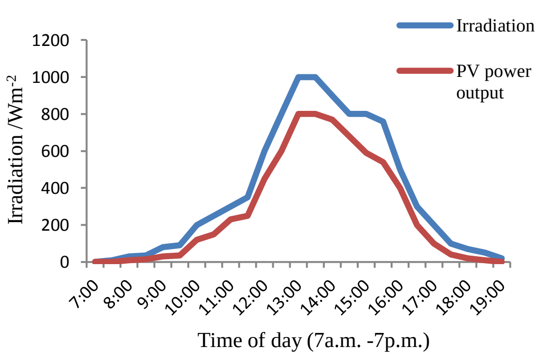
Type of PV Cell	Price per Watt Peak / US$	Price per Watt Peak / RM
Monocrystalline	1.28	13.48
Polycrystalline	1.23	13.08
Amorphous silicon	1.02	11.31
Cadmium telluride (CdTe)	0.87	10.23
Copper indium diselenide (CIS)	0.93	10.32

Table 2 Electrical characteristics of PV module (SQ85-P/80-P) [23]

	Power Max	Ultra 80-P	Ultra 85-P
Rated Power [W]	P_r	80	85
Peak power [W]	P_{mpp}	80	85
Peak Power Voltage[V]	V_{mpp}	16.9	17.2
Peak Power Current [A]	I_{mpp}	4.76	4.95
Open Circuit Voltage [V]	V_{oc}	21.8	22.2
Short Circuit Current [A]	I_{sc}	5.35	5.45
Dimensions (in/mm)	47.2×20.8 1200×507		
Weight (kg)	7.6		

3.3 Computation of Required Arrays

For this work, the estimated energy requirement for the chosen building per day is 12 kWh. Based on the irradiation variation shown in Figure 4, the ambient temperature, and using the PV module characteristics from the datasheets, the generated cell current and power can be calculated. Several equations are useful for the calculation of the generated current and power by the PV module.



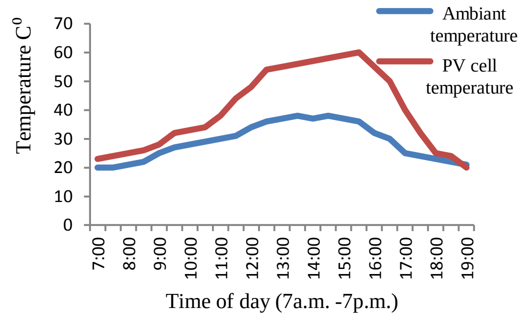


Figure 5 Solar radiation and ambient temperature

Malaysia is a tropical country and the daytime temperature varies between 25 and 36 degree Celsius. Since the ambient temperature does not significantly affect the calculated PV current, a fixed temperature of 34° C is assumed. The generated current under standard condition (25 °C) is given as $I(T_1)$

$$I(T_1) = G \times I_{sc}(T_1)/ G_{nm} \tag{1}$$

where

T_1= standard temperature for module (25 °C)
G = solar irradiation in W/m^2
I_{sc} = nominal current of the module in A
G_{nm} = nominal solar irradiation (=1000 W/m^2 or one sun)

Then, the generated current at a given temperature, I_L, can be computed using Equation 2.

$$I_L = I(T_1) \times (1 + K(T-T_1)) \tag{2}$$

where

T = temperature of the area under study
K = temperature coefficient of the module at Isc

The generated power is then given by

$$P = I_L \times V \tag{3}$$

where

V = module open circuit voltage in volts

A sample computation of the current generated under the standard condition with G = 30 W/m^2 (depending on the time of the day) is given as $I(T_1) = (30\times5.35)/1000 = 0.1605$ A. Then, using the commercial PV module SQ85-P/80-P, operating at an ambient temperature of 34 °C, the generated current on the first daytime hour, I_{L1}, is calculated as

$$I_{L1} = 0.1605 \times (1 + 0.00042(34\text{-}25)) = 0.1611 \text{ A}$$

Finally, the generated power, P_1, can be calculated using Equation 3

$$P_1 = 21.8 \times 0.1611 = 3.511 \text{ W}$$

The same computations are then repeated for the rest of the remaining day time hours. If the average generated power of a single module is given as P_{av}, and the peak demand load of the building as P_{peak}, then the required modules can be calculated as Number of required modules = (P_{peak} / P_{av})

A Matlab program was developed to assist in the computation including the price. All required data including the building size need to be provided for the computation. The program can then conveniently gives the array cost, battery size as well as the total initial capital cost.

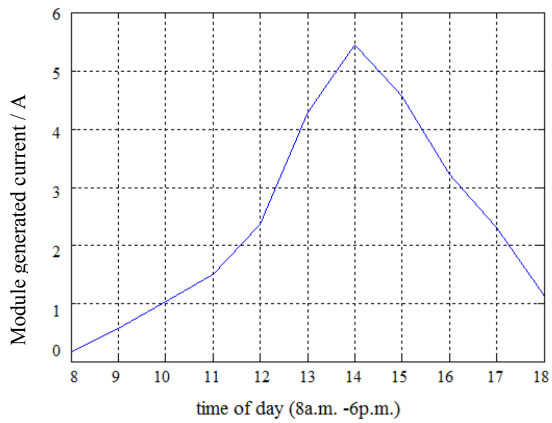


Figure 6 Computed PV module's current during day time

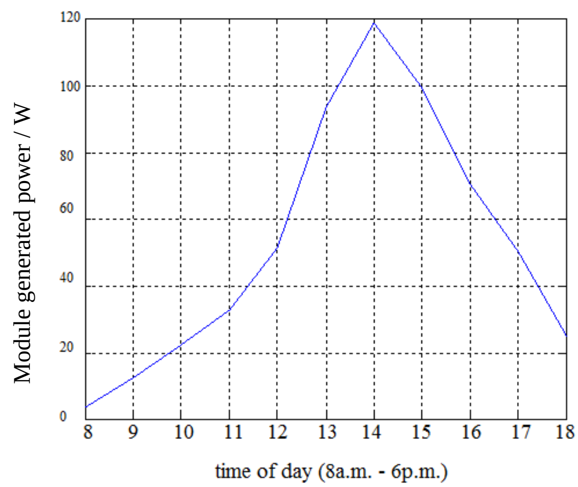


Figure 7 Computed PV module's power during daytime

Table 3 Matlab simulation results of average generated power and the corresponding number of required modules for the 6 kW PV building

Average generated power	Number of Required Module
52.6819W	114

4.0 RESULTS AND DISCUSSIONS

The results of simulation by using Matlab are shown in Figures 6 and 7. It can be clearly seen that the generated current and power variation with time follows very closely with that of the variation in temperature and sunlight irradiation. Table 3 shows computed average generated power per module as 52.68 W. Given the peak demand load, P_{peak}, for the building as 6 kW, the required modules can then be calculated as

Number of required modules = (P_{peak} / P_{av}) = 6000/52.67 = 114

4.1 Battery Size

For a typical high quality battery, the lifetime with a maximum allowable depth discharge of 50% is 10 to13 years. For battery configuration, the following two requirements are considered: an average battery's efficiency of 90%; and two autonomy days. Days of autonomy for a battery are the number of days that a fully charged battery can meet the load demand in the event of the PV system is not in operation.

In addition, the nominal battery voltage need also be specified. The battery voltages are usually specified as 6, 12, 18, 24, 36, 48 or 72 V.

The battery type used in this simulation is the valve regulated lead acid cells (VRLA) which consist of one or more battery cells, each of which is rated at 2 V. The most common configuration has six cells that are connected in series to give a nominal voltage of 12 V. The battery was sized based on the energy demand for each day. In this simulation, it was set at 12 kWh.

In the simulation, the sample battery is known as Trojan T1260. Its characteristic is shown in Table 4.

Table 4 Characteristics of Trojan T1260 battery

Parameter	Value
Type	Flooded
Voltage	12 V
20 HR Rate	140 AH
Length	12 7/8" (327mm)
Width	7 1/8" (181mm)
Height	10 11/16" (272mm)
Weight	78 Lbs
Unit Price	$0.178 per watt hour

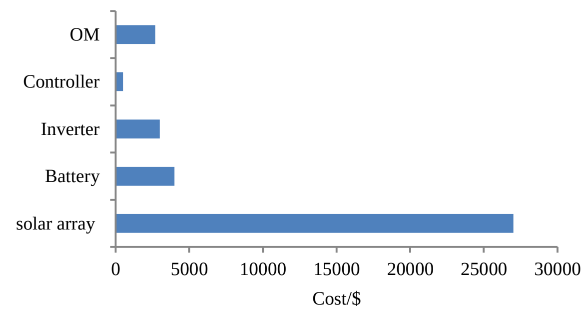


Figure 8 Comparison of component cost of PV system

Table 5 Computed prices of PV components for the chosen building

Cost of PV Array	Cost of Battery
$11673.6 (RM35020.8)	$4272 (RM12816)

4.2 Cost of PV System: PV Array and Battery

The price of the chosen array (made up of 114 modules) for the PV system was computed as follows:

Cost of array = module price × number of modules
= $102.4 × 114 = $11673.6
= RM35020.8

The initial cost of the battery bank for this PV system was computed as follows:

Cost of battery = autonomy days × required energy × price
= 2 × 12,000 × 0.178 = $4272 = RM12816

The results are summarized in Table 5.
The battery is expected to last for at least 10 years. During the projected PV system life-span of 20 years, the battery needs to be replaced at least once.

4.3 Discussion

Figure 8 shows the comparison of component cost in a typical photovoltaic system. As clearly shown in this figure, the main cost of the whole system is mainly contributed by the cost of the PV array, followed by that of the battery. In short, in order to optimize a PV system in terms of economic returns, two most important information, namely the PV array cost and the battery cost, are needed. This work had successfully provided a simulation software to facilitate an easy and quick computation of such costs.

■5.0 CONCLUSION

By using the actual irradiation and temperature data obtained from the meteorological department in Malaysia, the number of required PV modules for a typical household PV system was successfully calculated. The average daily irradiation that would fall onto a flat and horizontal photovoltaic array must be used. In addition, the effect of temperature on the generated power need also be considered in the computation. This work had successfully provided a Matlab based simulation software to facilitate an easy and quick computation of the cost of a PV system destined for a typical household building. The program takes into consideration of all required data and computation algorithms in order to give the most accurate estimate of the initial cost of the PV system. It can be concluded that the main cost of the whole PV system is mainly contributed by the cost of the chosen PV array. Hence, the right choice of a PV module is vital in achieving the minimum cost.

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