PERFORMANCE OF A GRID-CONNECTED PHOTOVOLTAIC SYSTEM IN MALAYSIA

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ABSTRACT

The performance of a 5.76 kWp grid-connected photovoltaic (PV) system has been obtained at the Universiti Kebangsaan Malaysia (UKM), Bangi. In this system, an array of PV modules have been configured to generate direct current (DC) and converted to alternating current (AC) via an inverter. The PV system exports power into the grid when generation exceeds demand but imports power at night time and during times when the demand exceeds the generation. The grid-connected PV system at UKM recorded an average module temperature of 39.5 ± 0.6 oC, generated energy at 17.1 ± 0.6 kWh per day, received an incident solar irradiation of 195.8 ± 7.4 kWh per day, exported energy into the grid at 15.6 ± 0.5 kWh, received solar irradiation of 4.1 ± 0.2 kWhm-2 per day, operated at an array efficiency of 8.8 ± 0.2 %, operated at an inverter efficiency of 91.2 ± 0.4 %, operated at a system efficiency of 8.1 ± 0.2 %, has a final yield of 949.0 ± 0.5 kWhkWp-1 and has a Performance Ratio of 63.6 ± 1.0 %. In addition, the peak production of electricity by a PV system coincides with the peak load of the public grid in Malaysia. Therefore, a PV system could be concluded to offer great potential in the Malaysian urban areas.

Keywords: *grid-connected, photovoltaic system, inverter, efficiency, global solar radiation, performance ratio.*

INTRODUCTION

The applications of solar energy can be broadly classified into two categories: a) thermal systems that convert solar energy into thermal energy and; b) photovoltaic (PV) systems which convert solar energy directly into electrical energy. Presently, research and development programmes in developing countries are oriented towards the applications of solar energy for domestic hot water systems, solar distillation of sea and brackish water, water pumping, drying of agricultural produce, solar industrial process heat, and photovoltaic for remote applications [1]. However, in the developed countries extensive work have been carried out on space heating and cooling (passive and active design), Building integrated Photovoltaic (BiPV) systems and products, grid-connected Renewable Energy (RE) systems including biomass and PV systems, daylighting, solar thermal electricity generation, and solar refrigeration [2-5].

A PV system can be classified into three types: a) stand-alone system; b) hybrid system and; c) grid-connected system. A stand-alone system comprises of a PV array which is built up of a number of modules to make up the peak power capacity; and the Balance-Of-System (BOS) comprising of: a charge controller for controlling and managing the charging and discharging of the accompanying battery bank as well as the load demands; and a set of fuses and connecting wires. A hybrid system comprises of the stand-alone system plus additional power generating system/s; such as a diesel generator, or a wind turbine. The hybrid system is capable of supplying power without interruption since the system could be programmed to operate at intervals to maintain optimum state of charge of the battery bank. Hybrid systems may also combine a number of electricity production and storage faiclities to meet the energy demands of a given facility or community. A grid-connected system comprises of the modules and an inverter. The inverter converts the direct current (DC) electricity generated by the PV array into alternating current (AC) electricity that is synchronized with the mains electricity so that excess electricity generated at any time is fed into the grid. The owner of a grid-connected PV system could import and/or export electricity provided that there is an agreement. Used this way, the utility backs up the photovoltaic like batteries do in stand-alone systems, thus eliminating the need for a battery bank which adds to the cost of the system. At the end of the month, credit for electricity sold gets deducted from charges for electricity purchased. Therefore, the grid or utility acts as an infinite energy sink.

Grid-connected PV systems in Malaysia is actually in the pilot stage, going on into the demonstration stage [1]. In view of this trend, data regarding its performance must be studied. Thus a pilot grid-connected PV system was installed at Malaysia to experience the design tasks, operation and obtain indicative performance indices of such systems specifically in the local climate conditions. This is because the energy produced by a grid-connected PV system depends on local climate factors such as; incident solar radiation and module working temperature; inverter characteristics such as; yield, working point and operation threshold; and the coupling system to the grid, which depends on the characteristics of the energy produced by the inverter on grid stability and availability. In this installation, the measured data were the ambient temperature, module temperature, DC voltage, DC current, inverter output energy and solar radiation. From these data, the performance indices were obtained with regards to DC power, energy produced by the PV modules, solar irradiation, module conversion, inverter and system efficiencies, final yield and Performance Ratio (PR). These indices would enable normalised comparisons be made with other more established systems.

SYSTEM SPECIFICATIONS

Schematic Diagram

Figure 1 shows a schematic diagram of the pilot grid-connected PV system installed in the ‘Solar Energy Research Park’ at the Universiti Kebangsaan Malaysia (UKM) in Bangi, Malaysia with latitude 4 ^{o}N and longitude 105 ^{o}E of Greenwich Meridian. The electricity generated by this system is coupled at a nearby transformer located within the UKM ring circuit and was commissioned in autumn 1998.

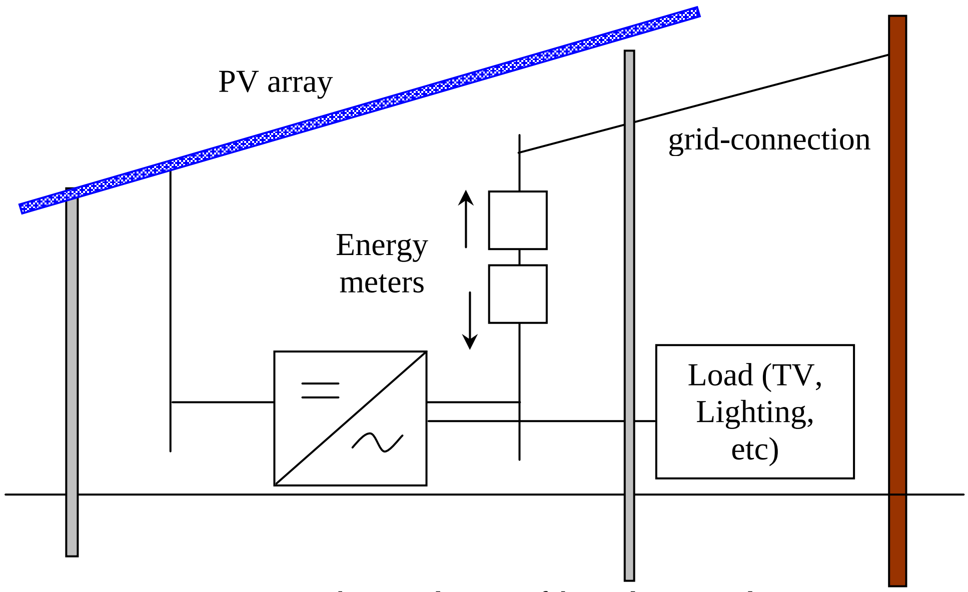

Figure 1: Schematic diagram of the grid-connected PV system.

The PV Array

The PV array consists of 72, BP280F modules, with the BOS comprising of; an inverter, two energy meters, supporting structures, cables and a surge arrestor. The PV modules were configured in an array of 9 strings with each string comprising of 8 modules connected in series and the whole structure is supported by galvanised iron frames. The strings were combined in parallel at the string combiner box. The nominal power of each module is 80 Wp and therefore the system peak power is 5.76 kWp. The area of the whole array is about 45.36 m^2. The PV modules were tilted at 10^o facing due South.

The Inverter

The inverter is a ‘Solar Grid Interactive Sine wave Inverter’ rated at 5 kW and 110 V DC input and gives an output of 240 V AC at 50 Hz single phase. The inverter automatically synchronizes with the grid when it is present and within the allowed specification. It is fully automatic and under normal operating conditions required no operator input. The inverter automatically starts when the solar irradiance is sufficient and the grid supply is present.

Environmental Monitoring System

For measuring and monitoring purposes an Environmental Monitoring System (EMS) was installed. The EMS comprised of: two 'Eppley' black and white pyranometers have been used along with four type K thermocouples, a voltage divider to measure the incoming DC voltage, a shunt resistor to measure the DC current, two energy meters for import and export and a ten channel 'Yokogawa DR130' hybrid recorder. The error in solar radiation and temperature measurements is about 2% and 1.8% respectively.

MATHEMATICAL MODELING

The performance analysis of the grid-connected system has been carried out. To calculate the efficiencies, the assumption made is that the energy received when the inverter is in operation and the energy incident on the PV array have been considered. To achieve this, the following equations have been used [5].

The daily ($\eta_{PV,d}$), monthly ($\eta_{PV,m}$) and annual ($\eta_{PV,a}$) PV array efficiencies are given by the following equations respectively:

$$\eta_{PV,d} = \frac{E_{PV,d}}{E_{r,d}} \qquad \eta_{PV,m} = \sum_{d=1}^{D}\left(\frac{\eta_{PV,d}}{D}\right) \qquad \eta_{PV,a} = \sum_{d=1}^{T}\left(\frac{\eta_{PV,d}}{T}\right) \tag{3}$$

where D and T are number of days with recorded data in the month and number of days with recorded data in the year respectively, $E_{PV,d}$ is the daily energy (kWh) supplied by the modules and is given by the following equation:

$$E_{PV,d} = \int_{t_i}^{t_f} (V_{DC} I_{DC}) dt \tag{4}$$

where V_{DC} and I_{DC} is the DC voltage (V) and DC current (A) respectively, t_i and t_f are the initial and final times respectively (h), $E_{r,d}$ is the available daily energy (kWh), defined as the daily irradiation on the plane of the array surface during the time the inverter is connected to the grid and is given as:

$$E_{r,d} = \sum_{i=o}^{n} (E_i \times C) = \int_{t_i}^{t_f} (S \times A) dt \tag{5}$$

where C = 0 if the inverter is out and C =1 if the inverter is operating, n is the total number of values recorded daily and E_i is the total energy received on the plane of the array surface during one measured interval (kWh), S is the solar irradiance (Wm^{-2}) and A is the area of the PV array (m^2).

Therefore, if C = 0 for E_i < the inverter threshold then the inverter is disconnected from the grid.

The daily $\eta_{inv,d}$, monthly $\eta_{inv,m}$, and annual $\eta_{inv,a}$ inverter efficiencies are calculated as follows:

$$\eta_{inv,d} = \frac{E_{grid,d}}{E_{pv,d}} \qquad \eta_{inv,m} = \sum_{d=1}^{D}\left(\frac{\eta_{inv,d}}{D}\right) \qquad \eta_{inv,a} = \sum_{d=1}^{T}\left(\frac{\eta_{inv,d}}{T}\right) \tag{6}$$

where E_{grid} is the output of the AC energy (kWh) obtained the import and export meters ($E_1 - E_2$, where E_1 is the meter reading at the beginning of daily data acquisition and E_2 is the meter reading at the end of the daily data acquisition), $E_{grid,d}$ is also the daily active energy at the output of the inverter (kWh) and consequently, to the grid.

The daily $\eta_{sys,d}$, monthly $\eta_{sys,m}$ and annual $\eta_{sys,a}$ system efficiencies can be evaluated using the following equations:

$$\eta_{sys,d} = \frac{E_{grid,d}}{E_{r,d}} \qquad \eta_{sys,m} = \sum_{d=1}^{D}\left(\frac{\eta_{sys,d}}{D}\right) \qquad \eta_{sys,a} = \sum_{d=1}^{T}\left(\frac{\eta_{sys,d}}{T}\right) \qquad (7)$$

In order to compare the yield of different PV systems, two other parameters are needed namely; the final yield Y_f and the Performance Ratio (*PR*).

The final yield Y_f is defined as the annual or daily system energy output divided by $W_{p,c}$, where $W_{p,c}$ denotes the previous estimated peak power of the array under Standard Testing Conditions (STC). Thus the daily, monthly and annual final yields are calculated as follows:

$$Y_{f,d} = \frac{E_{grid,d}}{W_{p,c}} \qquad Y_{f,m} = \sum_{d=1}^{D}\left(\frac{Y_{f,d}}{D}\right) \qquad Y_{f,d} = \sum_{d=1}^{T}\left(\frac{Y_{f,d}}{T}\right) \qquad (8)$$

The daily Performance Ratio (PR_d) is defined as the ratio between the daily final yield to the daily global irradiation on the plane of the array surface $E_{i,d}$ as is given by:

$$PR_d = Y_{f,d} \times \frac{G_{STC}}{E_{i,d}} \qquad PR_m = \sum_{d=1}^{D}\left(\frac{PR_d}{D}\right) \qquad PR_a = \sum_{d=1}^{T}\left(\frac{PR_d}{T}\right) \qquad (9)$$

where G_{STC} is the irradiance under STC. The *PR* allows comparison between performances of different PV systems taking into account all parameters such as: location, tilt angle, orientation, nominal power, shading dust, etc.

RESULTS AND DISCUSSIONS

ANALYSIS OF RESULTS

Analyses of results from the 5.76 kWp grid-connected PV system in this study are summarised as shown in Tables 1, 2 and 3 as follows.

Table 1: Ambient data and energy outputs in daily values.

Month	T_a (°C)	T_m (°C)	$E_{i,d}$ (kWhm^{-2})	$E_{pv,d}$ (kWh)	$E_{grid,d}$ (kWh)
May 2000	34.5	43.6	4.3	16.2	15.4
Jun 2000	33.7	44.1	4.1	15.1	13.4
Aug 2000	32.3	41.9	4.1	15.6	14.2
Sep 2000	31.6	40.3	4.5	17.3	15.6
Dec 2000	32.1	41.0	4.0	16.3	15.0
Jan 2001	31.3	40.8	3.7	14.7	13.4
Feb 2001	31.6	41.2	3.9	15.8	14.4
Mar 2001	33.6	44.6	4.6	21.4	19.5
Apr 2001	31.7	39.9	3.7	16.4	14.9
May 2001	32.0	39.5	4.0	17.6	16.2
Jul 2001	34.2	43.6	4.6	19.7	18.0
Aug 2001	34.5	44.7	4.3	18.9	15.6

As shown in Table 1, the parameters recorded were ambient temperature T_a, the PV module temperature T_m, daily solar irradiation $E_{i,d}$, daily energy generated by PV array $E_{pv,d}$ and daily energy from inverter output $E_{grid,d}$. The average T_a was between 31.3 °C to 34.5 °C and the average T_m was between 39.5 to 44.6 °C. The average values of $E_{i,d}$ were between 3.7 kWhm^{-2} per day and 4.6 kWhm^{-2} per day with the highest value during the month of July 2001. The $E_{pv,d}$ was between 14.7 kWh and 21.4 kWh and the $E_{grid,d}$ in the range of 13.4 kWh to 19.5 kWh.

Table 2: Performance indices of the system in monthly values.

Month	$\eta_{pv,m}$ (%)	$\eta_{inv,m}$ (%)	$\eta_{sys,m}$ (%)	$Y_{f,m}$ ($kWhkW_p^{-1}$)	PR_m (%)
May 2000	8.4	94.9	8.0	2.7	62.8
Jun 2000	8.2	88.5	7.3	2.3	57.1
Aug 2000	8.5	91.5	7.8	2.5	61.1
Sep 2000	8.5	90.0	7.7	2.7	60.6
Dec 2000	9.0	91.5	8.2	2.6	64.9
Jan 2001	8.9	91.0	8.1	2.3	63.8
Feb 2001	9.1	91.6	8.4	2.5	65.9
Mar 2001	9.3	91.1	8.5	3.1	67.4
Apr 2001	9.0	91.0	8.1	2.3	64.5
May 2001	8.9	91.2	8.3	2.6	65.5
Jul 2001	8.5	91.5	7.8	2.8	61.5
Aug 2001	8.8	91.9	8.1	2.7	64.3

Table 2 shows the monthly average values of the PV module efficiency $\eta_{pv,m}$, inverter efficiency $\eta_{inv,m}$, system efficiency $\eta_{sys,m}$, energy yield $Y_{f,m}$ and Performance Ratio PR_m. The $\eta_{pv,m}$ ranges between 8.2 to 9.3%, $\eta_{inv,m}$ from 88.5% to 94.9 % and the $\eta_{sys,m}$ ranges between 7.3 to 8.5 %. The highest $\eta_{pv,m}$ of 9.3 % was obtained in March 2001 and the lowest $\eta_{pv,m}$ of 8.2 % was obtained in June 2000. The inverter $\eta_{inv,m}$ varies between 88.5% to 94.9%. The values of $Y_{f,m}$ were between 2.3 $kWhkW_p^{-1}$ and 3.1 $kWhkW_p^{-1}$ with highest values obtained in March 2001. And lastly, the values of the PR_m ranges between 57.1% and 67.4%.

Table 3: Summary of the annualised performance indices of the 5 .76 kWp PV grid-connected system.

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Performance parameter	Unit	Value
Average ambient temperature T_a	^oC	32.5 ± 0.4
Average module temperature $T_{m,a}$	^oC	39.5 ± 0.6
Energy generated by PV array $E_{pv,a}$	kWh per day	17.1 ± 0.6
Incident solar irradiation on PV array $E_{r,a}$	kWh per day	195.8 ± 7.4
Energy exported into the grid $E_{grid,a}$	kWh per day	15.6 ± 0.5
Solar irradiation $E_{i,a}$	$kWhm^{-2}$ per day	4.1 ± 0.2
Efficiency of array $\eta_{pv,a}$	%	8.8 ± 0.2
Efficiency of inverter $\eta_{inv,a}$	%	91.2 ± 0.4
Efficiency of system $\eta_{sys,a}$	%	8.1 ± 0.2
Final yield Y_a pa	$kWhkW_p^{-1}$	949.0 ± 0.5
Performance Ratio PR_a pa	%	63.6 ± 1.0

Table 3 shows the annualised values of the performance parameters. The annual average ambient and PV array temperatures were 32.5 ^oC and 39.5 ^oC respectively. The annual photovoltaic yield, $E_{pv,a}$ was 17.1 kWh. The incident solar irradiation on the PV array before being converted into electricity $E_{r,a}$ has been recorded by the pyranometer at a value of 195.8 kWh. The PV system supplied an annual electricity $E_{grid,a}$ of 15.6 kWh to the UKM grid. This represents the demand for three residential houses with 5 to 7 people with connection to the grid. The annual PV efficiency $\eta_{pv,a}$, annual inverter efficiency $\eta_{inv,a}$ and the annual system efficiency $\eta_{sys,a}$ were 8.8%, 91.2% and 8.1% respectively. The annual final yield $Y_{f,a}$ was 949.0 $kWhkWp^{-1}$ and the PR_a was 63.6 %.

RESULTS & DISCUSSIONS

Temperature dependence

One of the outstanding issues regarding PV applications in Malaysia is the temperature effects on module performance. In this project, using linear regression, the temperature dependence correlation between the difference of module temperature T_m, the ambient temperature T_a against the solar irradiance S was found to be related as follows:

$$T_m - T_a = 1.08 + 0.02S \qquad (10)$$

Equation 10 was obtained using a scatter plot of ($Tm – Ta$) and plotted versus S, as shown in Figure 2. It is quite apparent that the temperature difference is proportional to solar irradaince. However from past experiences, we found out that the module efficiency decreased by 0.06 per $^{\circ}$C with an increase of module temperature exceeding 25 ^{o}C [7].

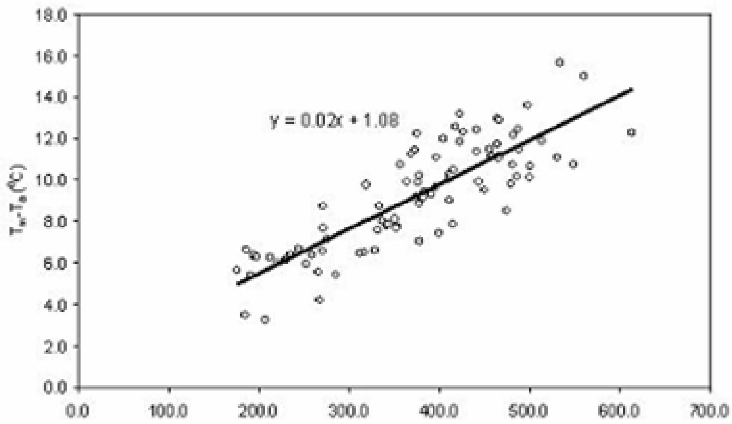

Figure 2: Temperature difference ($T_m – T_a$) as a function of solar irradiance S.

Array Efficiency

The daily photovoltaic array efficiency $\eta_{pv,d}$ has the closest relationship with the available solar energy and module power [8]. Figure 3 shows a scatter plot of array efficiency $\eta_{pv,d}$ versus solar irradiance S.

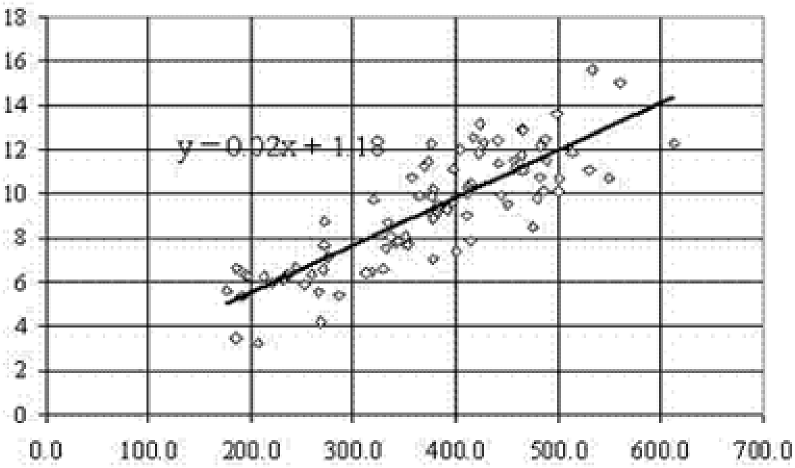

Figure 3: Scatter plot of array efficiency $\eta_{pv,d}$ versus solar irradiance S.

The $\eta_{pv,d}$ is quite low compared to the value claimed by the supplier of 12.4%. The decrease of $\eta_{pv,d}$ may be due to: a) reflection due to cover glass and solar cells; b) increase of module temperatures; c) wiring losses; d) mismatch losses; e) series connection modules and parallel connection of strings and; f) efficiency of Maximum Power Point (MPP) tracking [9].

Inverter Output

The solar radiation threshold for this system at UKM, Bangi was 24.1 Wm^{-2}. Therefore, it would not contribute a great loss to the system overall losses. The annual average daily energy output, $E_{grid,a}$ for the system was 15.6 kWh. It is thus estimated that the system could generate approximately 5,500 kWh per year. The $E_{grid,d}$ is a value that includes the influence of $\eta_{pv,d}$ and $\eta_{inv,d}$. If we were able to optimise the system, this would lead to a higher daily energy output and in the future grid-connected PV system might be one of the main energy contributors for Malaysia. Figure 4 shows a scatter plot of inverter efficiency versus solar irradiation.

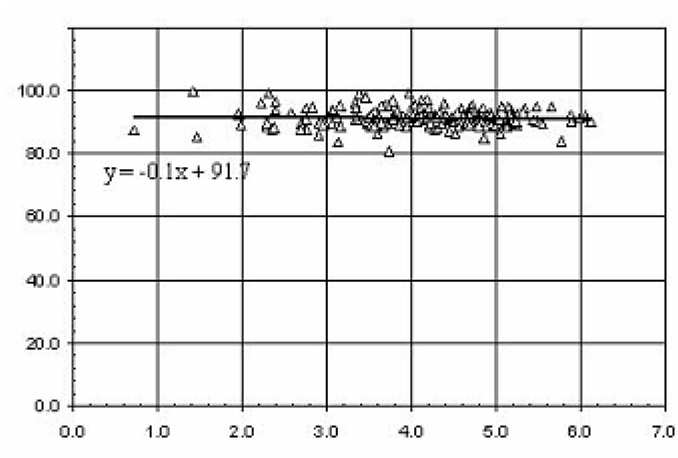

Figure 4: Scatter plot of inverter efficiency versus available solar irradiation.

Performance Ratio

In a grid-connected PV system, the PR characterizes the efficiencies of the solar modules and inverter and also their relative dimensions or matching within the total system [10]. Figure 5 shows a scatter plot between the PR_d and the final yield Y_{fd}. It is apparent that the PR ranges between 60 to 70% whilst the yield ranges between 2 to 3 $kWhkWp^{-1}$.

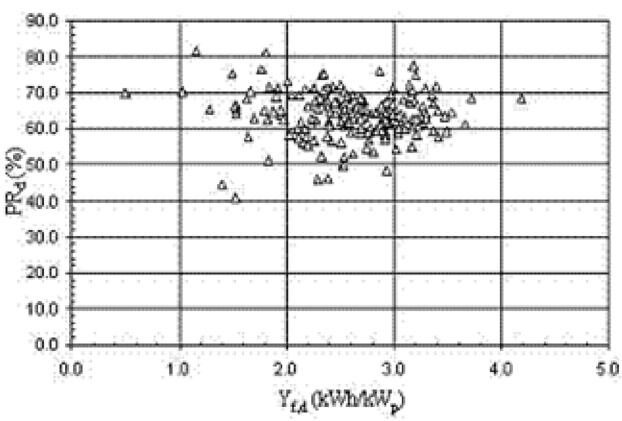

Figure 5. Scatter plot between the PR_d and the final yield Y_{fd}

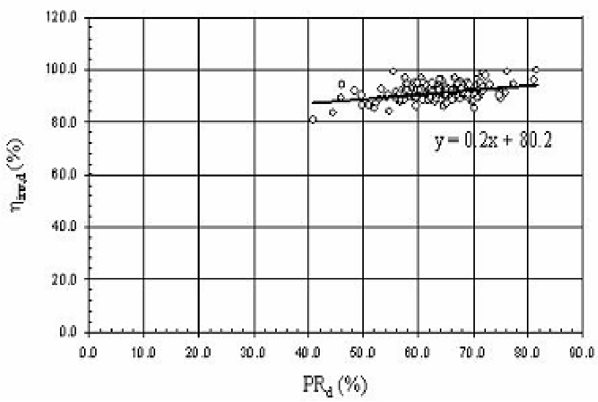

Figure 6 shows a scatter plot between inverter efficiency $\eta_{inv,d}$ against PR_d.

It is apparent that there is a direct proportional relationship between them. The PR_d values for the system mainly ranges from 56% to 69% with the $\eta_{inv,d}$ falling within 85.0 to 93.0%. The inverter appeared to be behaving with narrow ranges of inverter efficiency. High PR_{ds} could only be obtained in a system with a higher inverter

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efficiency. In comparison with hybrid and stand-alone systems, grid-connected PV systems show the highest PR_{ds}. The reasons for this are: a) omitting the needs of battery (thus avoiding associated losses) and; b) the energy is not wasted (surplus energy will be contributed to the grid) [8].

CONCLUSIONS

The average daily, monthly and annualised performance of a 5.76 kWp grid-connected PV system installed in the 'Solar Energy Research Park', UKM, Bangi, in Malaysia has been presented. The main objective of the system was to experience the design tasks, operation and obtain indicative performance indices of such systems specifically in the Malaysian climate conditions. From the study, it was found that the PV grid-connected system:

- Experiences an average module temperature of 39.5 ± 0.6 ^{o}C
- Generated PV energy of 17.1 ± 0.6 kWh per day
- Received an incident solar irradiation of 195.8 ± 7.4 kWh per day
- Exported energy into the grid at 15.6 ± 0.5 kWh
- Received solar irradiation at 4.1 ± 0.2 kWhm^{-2} per day
- Operated at an array efficiency of 8.8 ± 0.2 %
- Operated at an inverter efficiency of 91.2 ± 0.4 %
- Operated at a system efficiency of 8.1 ± 0.2 %
- Has a final yield of 949.0 ± 0.5 kWhkW$_p^{-1}$
- Has a Performance Ratio of 63.6 ± 1.0 %

In essence, it could be concluded that the applications of a PV grid-connected system is very suitable in the Malaysian climate due to results presented in this paper, besides the fact that the peak production is synchronous with the peak demand in power in Malaysia. There are still a few reasons that might attribute to the reduction of the inverter efficiencies. Among the many reasons are possibly: a) prolonged inverter operation at part/low loads; b) oversizing of the inverter to supply loads with high starting currents and; c) inverter control circuitry with high power consumption. Thus it is recommended that more long term data be monitored and results reassessed. A major advantage of grid-connected PV systems in Malaysia is the synchronous occurrence of peak demand and peak power generation by the system. In Malaysian climate, we experience the high solar radiation conditions usually from 11.00 am to 3.00 pm which coincides with the peak production of electricity by PV. The consumption of energy for air condition in houses and business premises would expectedly increase during this period. Therefore the implementation of grid-connected PV system will be able to ease the peak demand of electricity and can be considered as very appropriate for Malaysia.

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NOMENCLATURE

A	area of the PV array	(m^2)
D	number of days with recorded data in the month	($W.m^{-2}.K^{-1}$)
T	number of days with recorded data in the year	($W.m^{-1}.K^{-1}$)
$E_{PV,d}$	daily energy	(kWh)
$E_{r,d}$	available daily energy	(kWh)
E_i	total energy received on the plane of the array surface during one measured interval (kWh)	
E_{grid}	output of the AC energy	(kWh)
$E_{grid,d}$	daily active energy at the output of the inverter	(kWh)
I_{DC}	DC current	(A)
G_{STC}	irradiance under STC (standard testing condition)	($kWhm^{-2}$)
$\eta_{inv,m}$	daily inverter efficiencies	
$\eta_{inv,d}$,	monthly inverter efficiencies	
$\eta_{inv,a}$	annual inverter efficiencies	
$\eta_{sys,d}$	daily system efficiencies	
$\eta_{sys,m}$	monthly system efficiencies	
$\eta_{sys,a}$	annual system efficiencies	
PR	Performance Ratio	
PR_d	daily Performance Ratio, $PR_d = Y_{f,d} \times \frac{G_{STC}}{E_{i,d}}$	
S	solar irradiance	(Wm^{-2})
t_i and t_f	initial and final times respectively	(h)
T_a	ambient temperature	(^0C)
T_m	PV module temperature	(^0C)
Y_f	final energy yield, $Y_{f,d} = \frac{E_{grid,d}}{W_{p,c}}$	($kWhkW_p^{-1}$)
V_{DC}	DC voltage	(V)