Field performance of grid-connected photovoltaic system using amorphous silicon modules

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ABSTRACT

This paper describes the field performance of a grid-connected photovoltaic (GCPV) system using single junction amorphous silicon PV modules installed in Shah Alam, Malaysia over a period of one year. The system consists of fifteen Kaneka K60 PV modules and connected to the grid by indirect-feed via an SMA Sunny Boy 1200. The system has been continuously monitored and analyzed in accordance with international standards and guidelines. The results showed that the average daily irradiation at the site ranges from 3.34 to 4.47 kWh/m^2. The average daily array and final yields were 3.83 kWh/kWp and 3.46 kWh/kWp, respectively. The array and system efficiencies were 5.93% and 5.35 % respectively. At the end of the first year of operation, the total AC energy production was 1,128 kWh and the annual performance ratio was 85%. However, there appears to be a steady decline in array and system efficiencies. Nevertheless, these performance values were among the highest compared to all other systems from the cited literature.

Keywords: *Photovoltaic (PV), Grid-connected (GC), Thin-film (TF), Amorphous-Silicon (a-Si), Single-Junction (SJ), Performance Indices.*

1. Introduction

The relatively high solar radiation conditions in equatorial climate regions have always been thought to be well suited for the use of solar photovoltaic (PV) systems generally, despite its relatively higher ambient temperature and humidity with relatively low wind speeds in most of the interiors. For the case on Malaysia, this thought is very enticing with the launch of the Feed-in Tariff (FIT) scheme in December 2012. Ever since, there has been an accelerated growth of renewable energy (RE) system technology applications in Malaysia, especially for grid-connected (GCPV) systems technology. The guaranteed FIT for solar GCPV is between 0.85 to 1.23 Ringgit Malaysia (RM) per kWh, with an investment period of FIT in 21 years [1].

Whilst many PV systems use crystalline modules in various climate regions around the globe, it is well known that thin-film (TFPV) technology has several advantages over others when operating at higher temperatures such as tropical and equatorial climates [2-5]. The major contribution is mostly attributed to the lower temperature coefficient of TFPV cells over crystalline ones. In terms of generation, this clearly appears to offer an economic advantage. In view of this, research and development (R&D) in TFPV technology has been growing faster than crystalline technology, with an estimated annual growth rate of 94%, while the crystalline transmission represents only a 63% share in 2005-2010 [6]. However, TFPV technology is not efficient in terms of space required for the installation area per unit due to its lower efficiency. Until now, numerous research publications in terms of performance are mostly associated with crystalline technology [7-10], with very few literature published on TFPV technology, especially in hot equatorial climates.

Thus, this paper presents findings on the performance of a free-standing (FS) mounted GCPV system using amorphous-silicon (a-Si) single-junction (SJ) TFPV technology in field operation. In addition, this study was conducted to observe the unique performance of a-Si technology for long-term operation in FS mode to assess its behaviour in the Malaysian environment.

2. System description

The GCPV system comprised fifteen a-Si Kaneka K60 single-junction PV modules, free-mounted on a concrete walkway, at an elevated height of 2 m above the ground. The tilt angle is 15 deg facing due south and the array is configured in five parallel strings, with each string having three modules connected in series. The total nominal power of the PV array is 900 Wp. The PV array is fed to the grid via indirect feed-in using a single-phase grid inverter; the SMA Sunny Boy rated at 1.2 kW nominal power. A detail of the system is shown in Table 1.

Table 1 Specification of system location

Subject	Description
Site	Universiti Teknologi MARA (UiTM), Shah Alam, Malaysia
Latitude / Longitude	3° 04’ North / 101° 29’ East
Inclination angle and orientation	15° from horizontal and looking South
Climate	Equatorial Rainforest, fully humid (Af)

The specifications of the PV module and inverter are listed in Tables 2 and 3.

Table 2 Specifications of the Kaneka K60 PV array

PV Array	Specification	
PV technology	a-Si single-junction	
	Initial value	Stabilized value
Maximum power (P_{max})	78.6	60.0
Open circuit voltage (V_{oc})	95.6	92.0
Short circuit current (I_{sc})	1.22	1.19
Maximum power voltage (V_{mp})	74.0	67.0
Maximum power current (I_{mp})	1.06	0.90
Module efficiency	8.30	6.30
Array configuration	5 parallel x 3 series (15 modules)	
Nominal array power	900 Wp	
Mounting type	Free-standing	

Table 3 Specifications of the SMA SB 1200 grid-inverter

Inverter	Specification
DC Input	
Maximum DC power	1,320
Maximum DC voltage	400
MPP– voltage range	100 - 320
AC Output	
Maximum AC power	1,200
Nominal AC output	1,200
Maximum efficiency / Euro-eta	92.1% / 90.9%
Operating temperature	–25°C...+60°C

3. Methodology

The system used in this study was monitored for one complete year. The availability of monitored data achieved was better than 99%. The monitoring protocol used was based on the International Electrotechnical Commission IEC 61724 [11] and International Energy Agency Photovoltaic Power Systems (IEA-PVPS) Programme Task 2 framework [12]. In all, 51,361 continuous datasets were logged during the daytime hours at 5-minute intervals. In this study, all datasets were collected and analyzed for the full monitoring period from the day it was commissioned in early June 2011 to May 2012.

Amongst the monitored parameters were: DC/AC voltages, DC/AC currents, AC power, cumulative AC energy supplied to grid, daily AC energy production; and meteorological parameters: e.g. plane-of-array (POA) irradiance, wind velocity, ambient temperature and PV module temperature. The system is appraised using performance indices such as array yield, final yield, PV module and system efficiencies, inverter efficiency, performance ratio, array capture losses and system losses.
The daily and monthly array yields are calculated as follows:

$$Y_{A,d} = \frac{E_{DC,d}}{P_0} \quad (1)$$

$$Y_{A,m} = \sum_{d=1}^{D} \left(\frac{Y_{A,d}}{D} \right) \quad (2)$$

Where;

$Y_{A,d}$	Daily array yield, kWh/kWp.d
$E_{DC,d}$	Daily net DC energy generated by PV array, kWh/d
P_o	PV array's output power at STC, kWp
$Y_{A,m}$	Monthly array yield, kWh/kWp.m
D	Number of days with availability of recorded data in the month

The daily and monthly final yields are calculated as follows:

$$Y_{F,d} = \frac{E_{AC,d}}{P_0} \quad (3)$$

and;

$$Y_{F,m} = \sum_{d=1}^{D} \left(\frac{Y_{F,d}}{D} \right) \quad (4)$$

Where;

$Y_{F,d}$	Daily final yield, kWh/kWp.d
$E_{AC,d}$	Daily net AC energy supplied to grid, kWh/d.
$Y_{F,m}$	Monthly final yield, kWh/kWp.m

The reference yield is calculated as follows:

$$Y_R = \frac{H_t}{G_{stc}} \quad (5)$$

Where;

Y_R	Reference yield, h
H_t	Total POA irradiation, kWh/m^2
G_{stc}	Reference irradiance under STC, ($1\ kW/m^2$)

The performance ratio, PR is widely used to access the quality of PV system installations that are commonly reported on a daily, monthly or yearly basis. PR can be expressed as a percentage by the following equation:

$$PR = \frac{Y_F}{Y_R} \tag{6}$$

The instantaneous PV array conversion efficiency is calculated as follows:

$$\eta_{PV} = \frac{P_{DC}}{G_{i,POA} A_a} \times 100\% \tag{7}$$

Where;

P_{DC}	DC power generated by PV array, W
$G_{i,POA}$	Instantaneous POA irradiance, W/m^2
A_a	Total active of the PV array area, m^2

The monthly system efficiency, $\eta_{sys,m}$ is calculated as follows:

$$\eta_{sys,m} = \frac{E_{AC,m}}{H_{t,m} A_a} \times 100\% \tag{8}$$

Where;

$E_{AC,m}$	Monthly net AC energy supplied to grid, kWh/m
$H_{t,m}$	Monthly total POA irradiation, kWh/m^2

The monthly inverter efficiency, $\eta_{inv,m}$ is calculated as follows:

$$\eta_{inv,m} = \frac{E_{AC,m}}{E_{DC,m}} \times 100\% \tag{9}$$

Where;

$E_{DC,m}$	Monthly net DC energy generated by PV array, kWh/m

The capture losses for the operation of the PV array is calculated as follows:

$$L_C = Y_R - Y_A \tag{10}$$

Where;

L_C	Array capture losses, h/d
Y_R	Reference yield, h
Y_A	Array yield, kWh/kWp

The system losses due to conversion of inverter during operation is calculated as follows:

$$L_S = Y_A - Y_F \tag{11}$$

Where;

L_S	System losses, h/d
Y_F	Final yield, kWh/kWp

4. Results and discussion

4.1. Operation under Malaysian climate

The following figures show results of the study. Figure 1 depicts the average daily irradiation and the operating temperatures of the system.

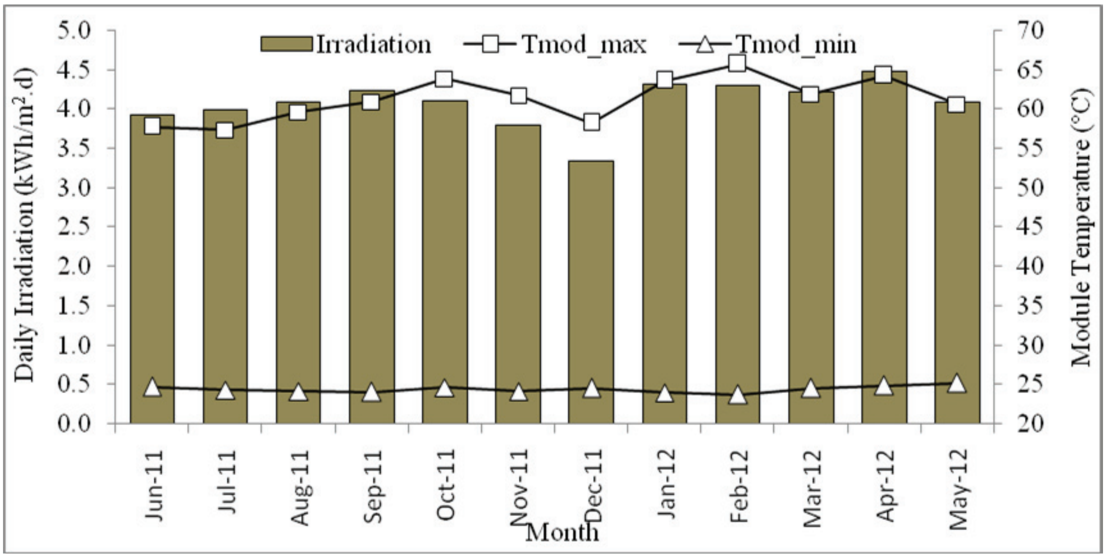

Figure 1 Values of the daily POA irradiation and operating temperatures.

As can be seen in Figure 1, the POA irradiation in terms of daily, monthly and yearly averages during the monitored period are 4.07 kWh/m^2, 123.2 kWh/m^2 and 1,478.4 kWh/m^2, respectively. The monthly average daily POA irradiation varies from 3.34 to 4.47 kWh/m^2. As shown in December 2011, the monthly average daily POA irradiation and maximum module temperature drops dramatically, due to the rainy season.

Figure 2 depicts the frequency bins of POA irradiance and operating temperatures of the system.

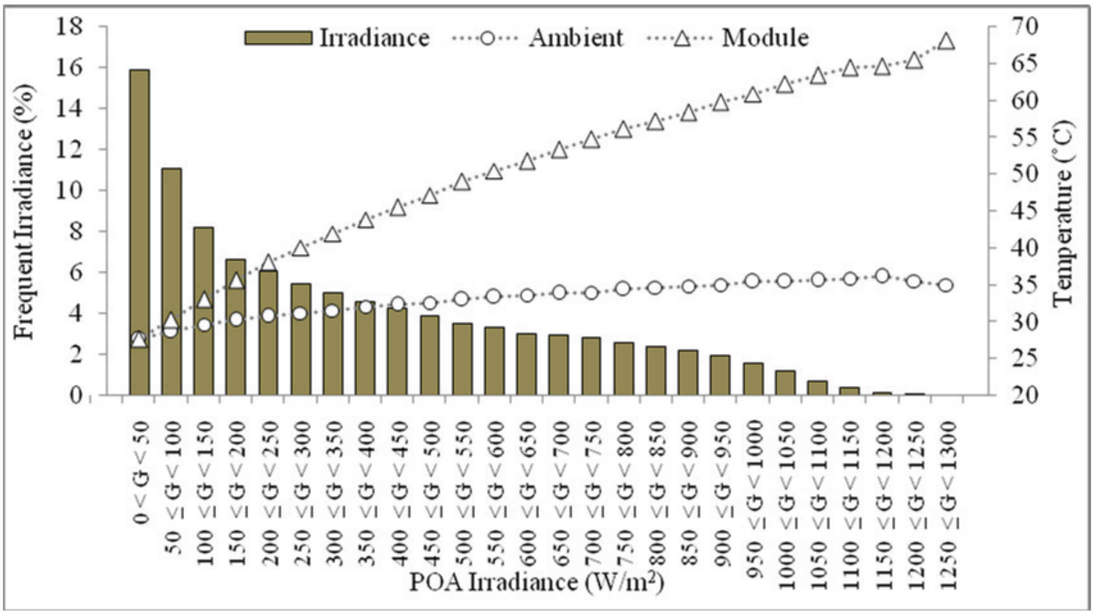

Figure 2 Percentage distribution of the averaged five-minute intervals for POA irradiance and operating temperatures.

Figure 2 shows the average operating module and ambient temperatures obtained for different levels of irradiance. Each bar represents the percentage of POA irradiance and the average temperature in bins of 50 W/m^2. It can be seen that the occurrence of POA irradiance was over 96% for values under 950 W/m^2 and only 4% occurrence for POA irradiance over 950 W/m^2. In addition, the average maximum and minimum temperatures of the PV modules measured on the back surface are 65.8°C and 23.7°C, whilst the ambient temperatures are 38.0°C and 24.5°C, respectively, which occurred in February 2012.

The following Figures 3,4,5 show sample profiles of monitored data of the system for: (a) Clear sunny day; (b) Overcast day; (c) Intermittent clear and cloudy day.

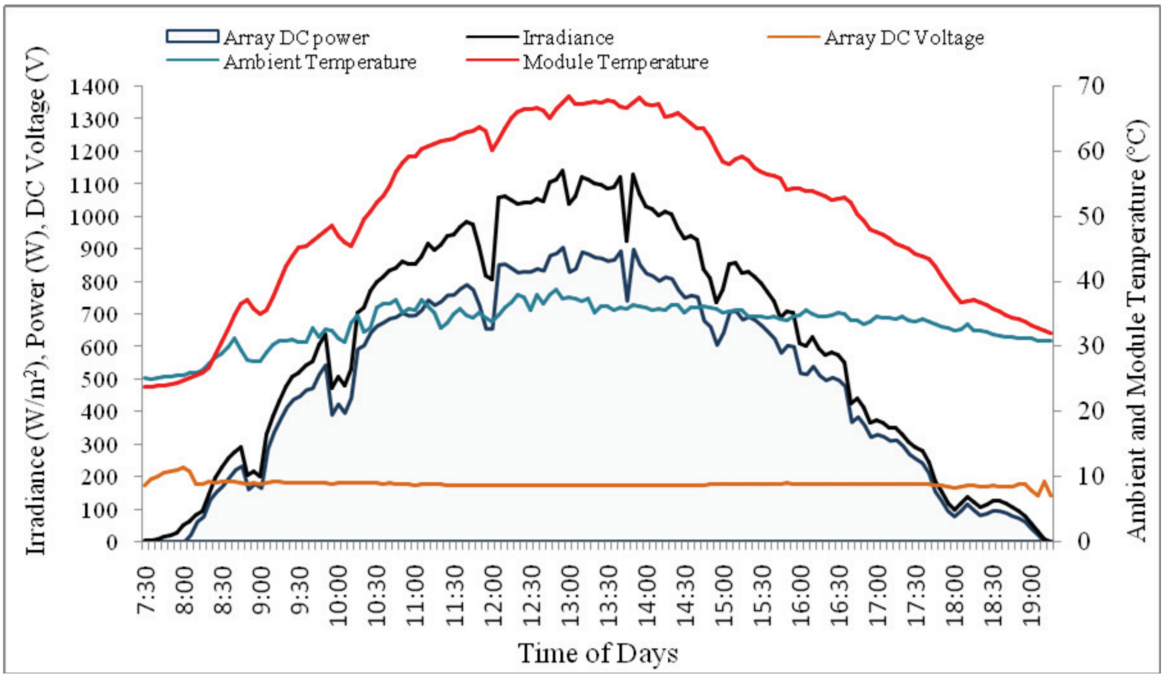

Figure 3 Clear sunny day on 16 March 2012.

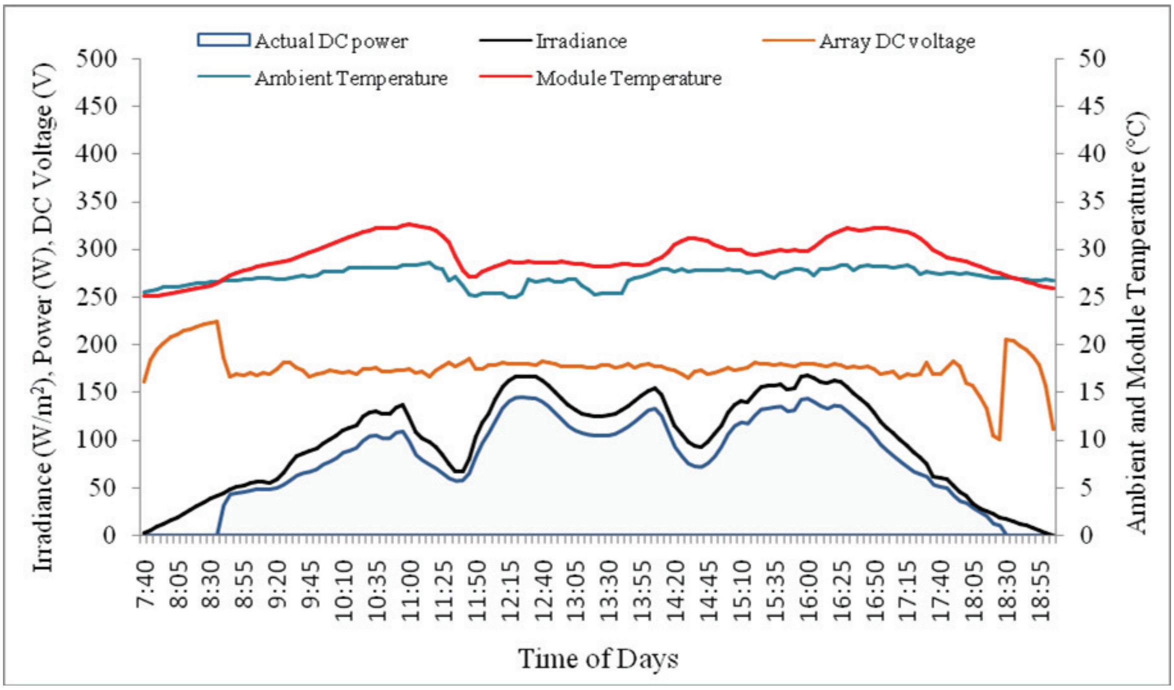

Figure 4 Overcast day on 22 December 2011.

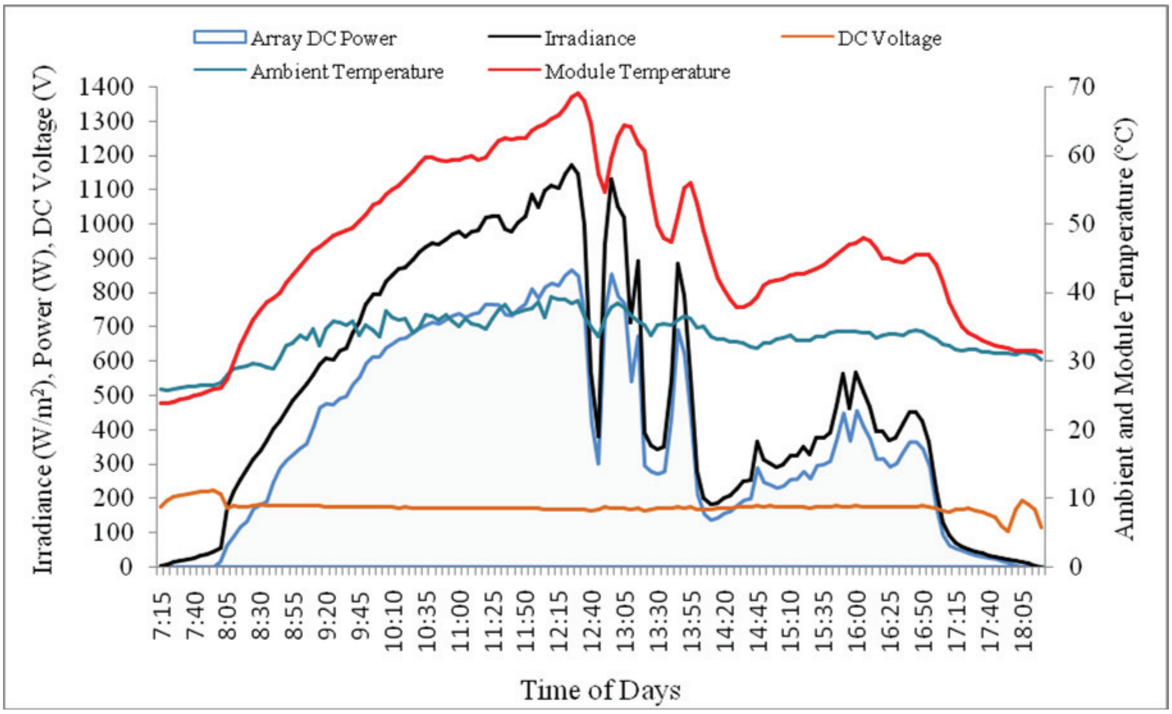

Figure 5 Intermittent clear and cloudy day on 09 October 2012.

4.2. Array yield and Final yield

For the first year of operation, the annual array yield is 1,401.0 kWh/kWp, equivalent to 3.83 kWh per day, whereas, the annual final yield is 1,261.1 kWh/kWp (3.46 kWh/kWp.d). Table 4 summarizes the monthly energy, array and final yields measurement for the first year of operation.

Table 4 Monthly array and final yields for first-year of operation

Month-year	Array Yield kWh/kWp	Final Yield kWh/kWp
Jun-2011	116.7	106.1
Jul-2011	120.0	107.8
Aug-2011	121.7	109.4
Sep-2011	120.6	108.4
Oct-2011	120.5	108.2
Nov-2011	107.3	96.2
Dec-2011	97.2	86.8
Jan-2012	123.3	110.8
Feb-2012	113.9	102.3
Mar-2012	119.8	109.1
Apr-2012	124.5	112.2
May-2012	115.5	103.8
Range	97.2 – 124.5	86.8 – 112.2

The values from Table 4 are plotted as histograms as shown in Figure 6.

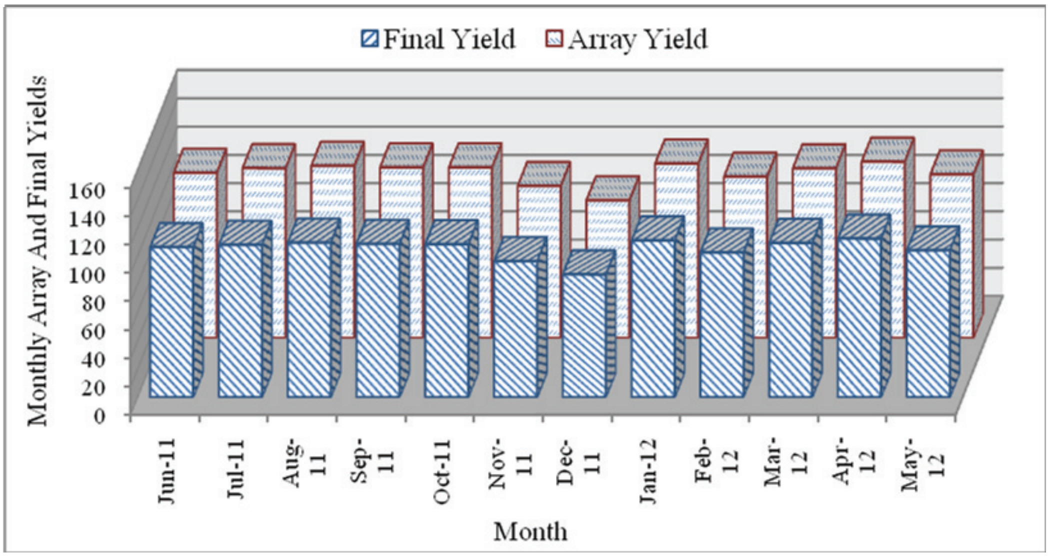

Figure 6 Monthly values of the array yield, and final yield.

Figure 7 shows the daily average final yield and all related losses.

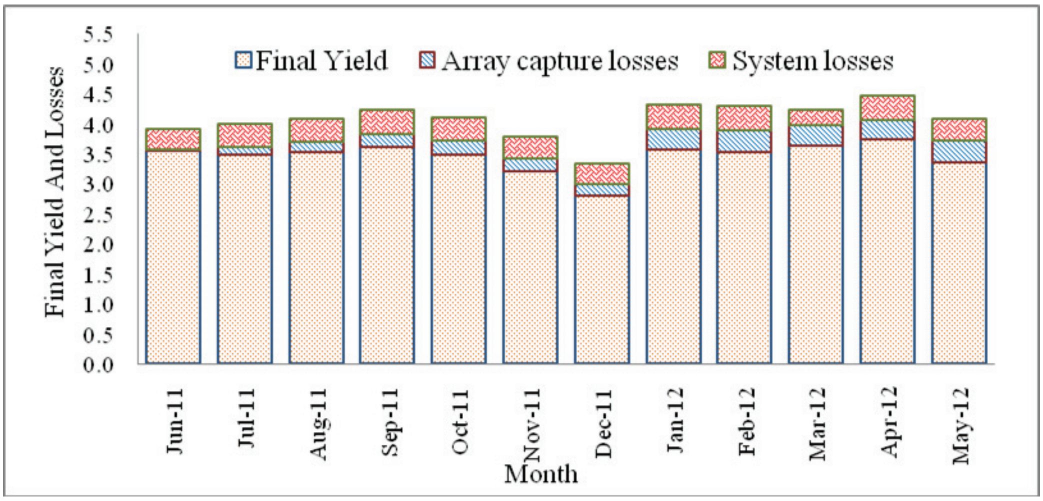

Figure 7 Monthly average daily values in terms of final yield, array capture losses and system losses.

From Figure 7, the monthly average daily final yield varies between 2.80 to 3.74 kWh/kWp. The capture losses, Lc lies between 0.03 to 0.37 h/d. the system losses, Ls lies between 0.24 to 0.41 h/d. Most of the monthly losses is attributed to system losses of 0.41 h/d during the months of September 2011 and April 2012. This means that the major losses in the inverter operation occurred during periods of high irradiation which took place in September 2011 and April 2012.

4.3. Performance ratio

Figure 8 shows the monthly performance ratio (PR) for the first year of operation.

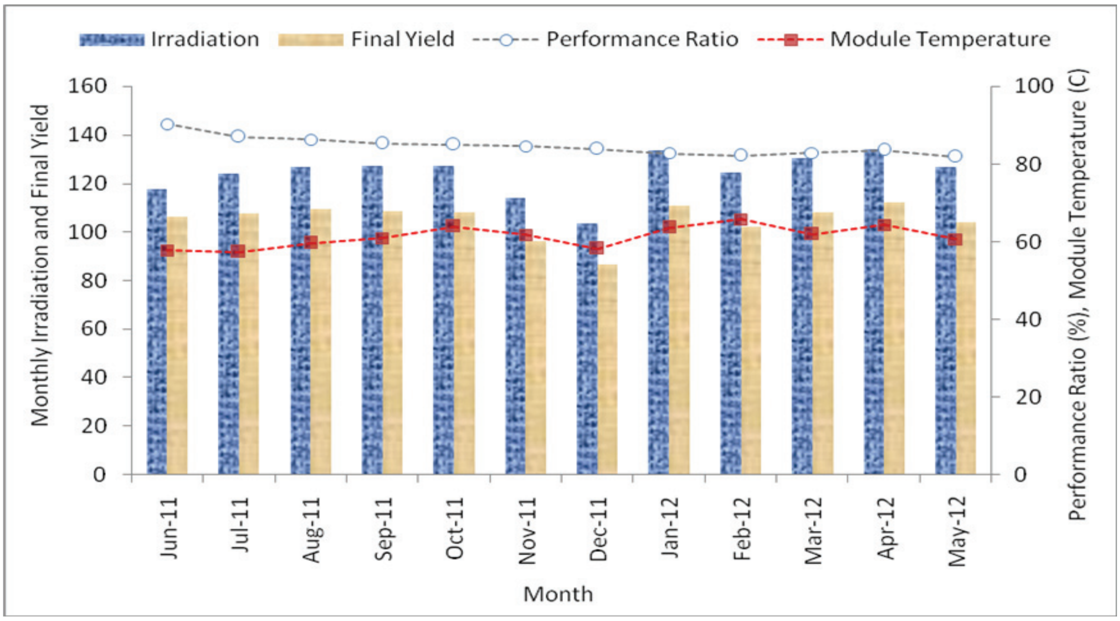

Figure 8 Monthly values in terms of irradiation, final yield and performance ratio.

From Figure 8, the monthly PR varies from 82% to 90.3% which shows the value of PR is quite consistent. A decrement of about 8.4% is observed for the final operation as compared to the initial month value. In addition, the system appears to be operating well since the annual PR value is about 85% with an availability of data at 99% over the entire period monitored. Based on literature [12], a high PR of about 60-80% indicates that the system operates in a better situation and utilizes the full potential of solar energy, while a lower PR value could be due to technical or design problems.

4.4. PV Array, System and Inverter Efficiencies

Figure 9 shows the monthly variation of the PV array, system and inverter efficiencies for the entire one-year of field operation.

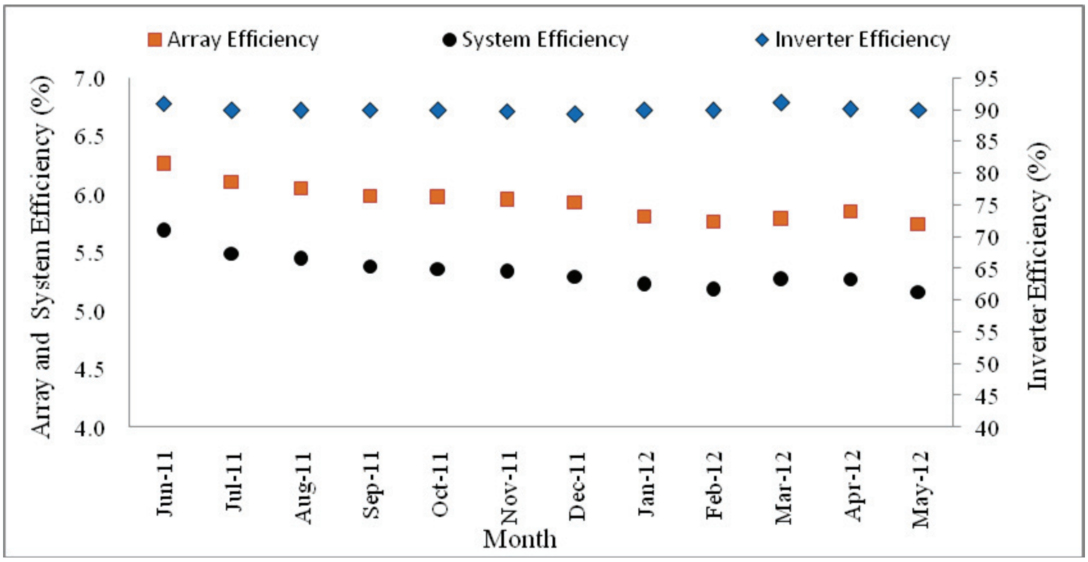

Figure 9 Monthly PV array, system and inverter efficiencies.

From Figure 9, it is apparent that there appears to be a general declining trend of array and system efficiencies over time. Looking at the data and trend very closely reveals that there may be two bumps, i.e. in November and April. These two months happen to coincide with the rainy seasons in Malaysia. In addition, the inverter efficiency appears to be stable over the period. Attention should be given to several factors, such as cell degradation, possible creeping shading, haze problem and dust accumulation as well as inverter health.

The PV array efficiency shows an excellent performance by more than 6% during the months from June 2011 to August 2011. During the first three months of exposure, the PV array efficiency varies from 6.25 to 6.06%. The maximum and minimum monthly PV array efficiencies are 6.25% and 5.75% respectively. In terms of monthly PV array efficiency, the efficiency of the PV array lies in the range of 6.25 to 5.76%, with annual PV array efficiency of about 5.93%. On the other hand, system efficiency ranges from 5.17 to 5.70% during the first year of operation. In addition, the annual efficiency of the entire PV system is about 5.35%. In terms of the monthly efficiency inverter, the DC energy output was evaluated by dividing the output AC energy. From the results obtained, the SMA inverter operated very well, ranges from 89.2 to 93.8% with an annual conversion efficiency of about 90.2%.

Table 5 shows a summary of the performance study from this work as well as from others for TFPV technology in GC systems, divided into zones based on the Köppen-Geiger climate classification.

Table 5 Performance indices for different types of TFPV technology and mounting for GC systems

Location	Climate	Technology	Duration	PR	Y_F	η_{PV}	η_{SYS}	η_{INV}	Ref
Italy, Rome	Csa	EPV-50	12-month	0.87	3.37	4.60	-	-	[13]
Malaysia, Shah Alam	Af	Kaneka K60	12-month	0.85	3.46	5.93	5.35	0.90	
Brazil, Florianopolis	Cfa	RWE-Schott	96-month	0.83	3.45	-	-	0.90	[14]
Cyprus, Nicosia	BSh	MA100T2	12-month	0.79	4.31	-	-	0.91	[15]
Egypt, Cairo	BWh	Pfixx ASI-40 B	12-month	0.78	4.35	4.22	4.02	0.94	[16]
Germany, Stuttgart	Cfb	MA100T2	12-month	0.76	3.05	-	-	0.90	[15]
Italy, Portici	Csa	BR 28	48-month	0.75	3.29	4.60	-	-	[17]
Thailand, Nonthaburi	Aw	Kaneka LSU-58	48-month	0.73	3.50	6.13	5.04	0.82	[18]
Thailand, Bangkok	Aw	Unisolar US-64	12-month	0.73	3.19	5.50	4.70	0.85	[19]
Poland, Warsaw	Dfb	MST-50 MV	12-month	0.60–0.80	2.03	4.5–5.5	4.00–5.00	0.92–0.93	[20]
Thailand, Ratchaburi	Aw	NA	12-month	0.55–0.59	2.40–3.58	4.62	3.17	0.63	[21]
UK, Oxfordshire	Cfb	ASE 30 DG-UT	12-month	-	2.65	-	-	-	[22]
UK, Oxfordshire	Cfb	Solarex Millennia	12-month	-	2.48	-	-	-	[22]
UK, Oxfordshire	Cfb	Unisolar US-64	12-month	-	2.30	-	-	-	[22]
R. Korea, Gyeonggi	Dwa	Kaneka Transparent ASI	24-month	-	1.59	-	-	-	[23]
UK, Oxfordshire	Cfb	Intersolar Gold	12-month	-	1.31	-	-	-	[22]

NA = not available

From Table 5, it can be clearly seen that the PR for the system in Rome, Italy is highest at 87% with a YF of 3.37, and Poland, Warsaw with PR of up 60 to 80% and Y_F of 2.03. These both are very interesting since they are located at a high latitude region. The system used in this study shows a PR of 85% with a Y_F of 3.46.

In addition, the performance ratio of Portici, Italy demonstrated contradicting with Rome, Italy under similar climatic conditions, even relatively close in the final yield is presented. In similar system at Ratchaburi, Thailand has a PR of 59% with a Y_F of 3.58, which appears to be conflicting and should be looked into. The lowest based on Y_F is 1.31 in the UK. Based on the reports published, it shows that the a-Si PV module performed best in the Malaysian climate.

5. Conclusion

The yield from the system used in this study during the first year of operation is 1,128 kWh or on average 3.11 kWh per day. In terms of array and final yields, these are 3.83 kWh/kWp and 3.46 kWh/kWp respectively. The PV array and system efficiencies are found to be 5.93% and 5.35%, respectively. The average PR for the entire monitored duration ranges between 82 to 90.3% with an average is about 85%. It is also found that the efficiency of the inverter ranges from 89.2 to 93.8% with an annual conversion efficiency of about 90.2%.

Thus, it can be concluded that the performance of the system used in this study shows that a-Si modules proved to produce relatively high yields. It is also interesting to find that TFPV systems in certain other countries like Italy outperform the system in Malaysia, whilst the system in Poland is also quite high. In addition, it is worth noting that the PR of system in nearby regions could be looked into further.

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Abbreviations

STC	Standard Test Conditions
Af	Equatorial rainforest, fully humid
Aw	Equatorial savannah with dry winter
BWh	Arid Desert climate, hot steppe / desert
BSh	Arid Steppe climate, hot steppe / desert
Cfb	Warm temperate climate, fully humid with warm summer
Csa	Warm temperate climate with dry, hot summer
Dfb	Snow climate, fully humid with warm summer
Dwa	Snow with dry winter, hot summer

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