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Performance of Grid-Connected Photovoltaic System in Equatorial Rainforest Fully Humid Climate of Malaysia

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ABSTRACT

This paper presents a result obtained from a comparative study of three different photovoltaic (PV) module technologies for grid-connected (GC) system under Malaysia's operating conditions. From the results obtained, the performance ratio (PR) showed slightly different from the three PV technologies for polycrystalline was about 78.2%, 94.6% for a-Si thin film and 81% for monocrystalline during the four years of monitoring. Outdoor assessment shows that a-Si thin-film PV modules had demonstrated high performance and better in terms of final yield, performance ratio and array/system efficiency of the GC system over the entire monitored period. On the other hand, a-Si thin-film PV modules exhibit higher energy production, reliability and better conversion of system performance in Malaysia.

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1. INTRODUCTION

Nowadays, many types of different photovoltaic (PV) modules are commercially available in the market. There are three main types of PV module technology which are monocrystalline silicon, polycrystalline silicon and amorphous silicon thin-film (a-Si TF). More efficient PV modules will lead to smaller PV array installations, generally comes from crystalline silicon with high power generation as well as the conversion efficiency vary up 12% to 24.2% [1]. In contrast, the PV module made from thin-film PV technology is low cost manufacturing, high optical absorption coefficient, non-toxic, robust and reliability in performance. However, the disadvantage of this type of TFPV technology is instability in initial higher output that need several considerations in system design [2] as well as the efficiency of TFPV module typically lies in range from 5% to 12% [3].

Research studies published by K. Akhmad et al. 1997 [4] indicated that a-Si TFPV modules are more suited if installed in the tropical regions. This finding is also supported by N. Amin et al. 2009 [5] found that a-Si and CIS solar cells shown better in the performance ratio compared to c-Si solar cell under Malaysia's condition. Mostly, TFPV technology has worked better in a hotter temperature due to smaller power temperature coefficient, whereas c-Si PV technology responds more efficiently in average lower temperature under cold climate.

This finding is proven in recent studies by P. Kamkird et al. 2012 [6] who have carried out three comparisons on PV technology in terms of temperature coefficients involving a-Si, p-Si and HiT PV modules in Thailand which is known for its equatorial savannah with winter dry climate (Aw) [7]. They have concluded that a-Si TFPV modules have lower impacts due to temperature coefficients in terms of current, voltage, power outputs and also lowest in negative coefficients for the long-term performances. This finding is consistent with a study conducted by S. Shaari et al. 2009 [8] under Malaysian climate using the similar linear regression, which claimed a-Si TFPV modules show are better performance with less dependence on operating array temperatures compared to c-Si PV technology.

This study covers the performance of the different types of PV module technology under the equatorial rainforest fully humid climate such as existing in Malaysia country. The measured parameters are: output energy from the inverter, operating temperature and solar irradiance. The performance indices and the conversion efficiencies of two types of crystalline and thin-film PV technology are also presented in this study due to lack of study and experience related to performance and understand the behavior of GC system, especially in TFPV technology under Malaysian environment. The outdoor performance results of three different PV module technologies, e.g. polycrystalline (mc-Si), amorphous-Silicon (a-Si), and monocrystalline (sc-Si) PV modules using GC systems implemented for a period of four continuous years under Malaysian climate is included.

2. RESEARCH METHOD

a. Malaysian characteristic

The study was conducted on a grid-connected (GC) PV system located at latitude of 2 °N 101°E in Selangor, Malaysia under equatorial rainforest fully humid climate (Af) according to the Köppen-Geiger climate classification [7]. Naturally, the characteristic features of the climate of Malaysia are uniform temperature, high relative humidity and heavy rainfall throughout the year. According to Malaysia's latitude, the annual solar irradiation is estimated to be an approximately of 1,643 kWh/m^2 with an annual daily irradiation of 4.21 to 5.56 kWh/m^2 [9]. The maximum irradiation was estimated at 6.8 kWh/m^2 while the average daily temperature was at 35°C and 25°C for the day and night, respectively, in between of August and November. The minimum irradiation occurred in December with the average ambient temperature during the day was at 33°C and 23°C during the night time. Most locations in Malaysia experienced a relative humidity between 80% and 88%, rising up to almost 90% in the upland areas at higher elevations and average wind speed of about 1.5 m/s [10].

b. Characteristics of PV module technology

The selected PV module technology is namely group A for polycrystalline (mc-Si), group B for amorphous silicon single junction (a-Si) and monocrystalline (sc-Si) for group C. Three different PV module technologies are tested; polycrystalline and monocrystalline PV module of the highest module efficiencies in the range of 13.0 - 13.7%, whereas a-Si thin-film module efficiency is about 6.7%. The different characteristics of three GC systems with different PV technology is described in Table 1.

Table 1. The characteristics of GC systems at Standarad Test Conditions

Group	A	B	C
PV Technology	Poly-crystalline (mc-Si)	amorphous-Siliocn (a-Si)	Mono-crystalline (sc-Si)
Maximum Peak Power (Wp)	120	64	180
Module Efficiency (%)	13	6.7	13.7
Inverter	Fronius IG 15	Fronius IG 60	Fronius IG 300
Nominal Output Power	1.3 kW	4.6 kW	24 kW
Maximum Efficiency	94.2 %	94.3 %	94.3 %

This green building is divided into four GC systems and equipped with a total peak power of 92 kWp from different types of PV module technologies. In order to carry out the performance test, three different PV modules have been selected in this study as tabulated in Table 2.

Table 2. Features selected GC systems with different PV module technology

Group	PV technology type	PV array power (kWp)	Array configuration	Inclination (º)	Mounting
A	Polycrystalline (mc-Si)	1.92	16 p x 1 s	7 º	BIPV
B	Amorphous Silicon (a-Si)	6.08	19 p x 5 s	5 º	BIPV
C	Monocrystalline (sc-Si)	27.0	10 p x 15 s	5 º	rooftop

Two types are used for crystalline PV technology which a total of 16 units for each 120 Wp polycrystalline PV module for group A and 150 units for each 180 Wp monocrystalline PV module for group

C using Fronius IG15 and IG 300 inverters, respectively. Meanwhile, group B using a-Si TFPV modules connected to Fronius IG60, with a total of 95 PV modules, divided into 19 strings of 5 modules each.

The monitoring system complies to meet the requirements of IEC 61724 international standard [11] and within the International Energy Agency Photovoltaic Power System (IEA-PVPS) Program Task 2 framework. Three performance parameters are used to define the overall performance with respect to the energy production per kWp, overall effect of system losses and efficiency; e.g. the final yield, performance ratio and PV array/system efficiencies. These performance indicators are relevant since they can provide a basis to determine which GCPV systems can be compared under various operating climatic conditions.

The following parameters are measured; the electrical parameters recorded by the Fronius system monitoring which located in the control room involves DC/AC voltage, current, power and energy production, whereas, the meteorological parameters such as solar irradiance via monocrystalline-Si sensor, ambient and PV module temperatures using PT 1000.

The final yield Y_f is defined as the annual, monthly or daily net energy output of the entire PV system which is supplied by the PV array per kW of installed PV array (kWh/kWp).The final yield can be calculated as follows;

$$Y_f = \frac{E_A}{P_{PV,rated}} \tag{1}$$

Where:

E_A Output AC energy from the inverter, kWh

$P_{PV,rated}$ PV array power rating at STC, kWp

Besides that, reference yield defines the total irradiation is divided by the reference irradiance (G_{stc} = 1 kW/m^2). The reference yield can be expressed in unit of h and defined as;

$$Y_r = \frac{H_t}{G_{stc}} \tag{2}$$

where H_t is total in-plane irradiation, kWh/m^2. The performance ratio, PR is used to access the quality of PV installation which is widely reported on a daily, monthly or yearly basis. PR typically expressed in percentage to describe the overall losses on the PV system's rated output and can be defined by the following equation (3) as;

$$PR = \frac{Y_f}{Y_r} \tag{3}$$

The monthly conversion for PV array efficiency is calculated as:

$$\eta_{PV,m} = \frac{E_{D,m}}{H_{t,m} A_a} \times 100\% \tag{4}$$

where $E_{D,m}$ is the total DC energy generated by PV array in the month, kWh and $H_{t,m}$ is defined as the total monthly irradiation received in the month. In addition, the monthly system efficiency is given as follows:

$$\eta_{sys,m} = \frac{E_{A,m}}{H_{t,m} A_a} \times 100\% \tag{5}$$

where $E_{A,m}$ represents the total AC energy output from inverter in the month, kWh and A_a is the total active of PV array area, m^2. About 55053 continuous dataset was taken from the GC system with an average sample interval of every 15 minutes. All datasets were collected in a period of four years from January 2008 to December 2011.

3. RESULTS AND DISCUSSION

In this section, a comparative study was conducted according to three performance indicators: the final yield, performance ratio and PV array/system efficiencies. All datasets were processed for each month and summarized into annual performance. For this reason, it is necessary to identify the PV module technology in Malaysian climate by offering the maximum yield, reliability and stability in performance output.

a. Annual Final Yield

Figure 1 illustrates that group B has higher energy production among the other PV module technologies. The annual final yield of group B (1392.6 kWh/kWp.y) is higher than groups A (1220.2 kWh/kWp.y) and C (1158.6 kWh/kWp.y) by about ~12% and ~17%, respectively, for the first year of operation. However, groups B and C showed the lowest final yield in 2010 due to the inverter breakdown for seven and six months, respectively, while for group A's inverter does not operate for three months. Over four years, the higher energy production is predominant to group B (a-Si TF) from the early production. This made the a-Si TFPV technology is the best choice technology under Malaysian climate. It is also proven by numerous research publications that indicated that the TFPV technology is the most appropriate technology under warm and tropical climate [4],[12],[13] because of its unique characteristics in terms of temperature dependence, low irradiance behavior, spectral response, and the metastability nature in electrical properties of TFPV performance.

In addition, for the four-year monitoring, the annual average final yield of group B is higher about 1057.6 kWh/kWp per year compared to groups A and C. For groups A and C, the annual final yield is about 985.5 and 811.5 kWh/kWp.yr respectively, calculated under a similar climatic condition.

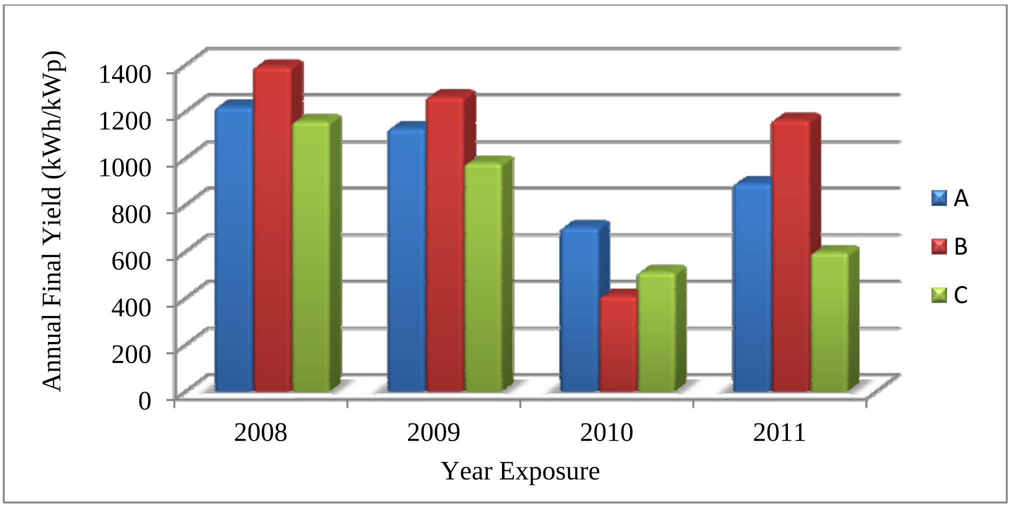

Figure 1. Annual final yield of the mc-Si (A), a-Si (B) and sc-Si (C) groups over the monitored period.

b. Annual Performance Ratio

From a view of annually datasets in terms of the performance ratio, three characteristics of the PV modules tested show that significantly different under Malaysian climate. Figure 2 indicates that the group A shows a drastic decreased in the annual performance ratio measured from 89.8% to 69.2% over the monitored period. For group B with TFPV technology, a slight decrease was observed over the time. For the first year of operation, TFPV technology has degraded by approximately 6.0% attributed to the light-induced degradation (LID) effect [14]. It also shows that the degradation of a-Si PV modules has reduced slowly by 6.0%, 5.8%, and 2.4% for the first, second and third years, respectively. As published in [12],[13],[15], the metastability nature of TFPV technology that the behavior commonly occurs in the first or second year after the PV modules exposed under outdoor exposure and show a stable behavior over the following years after LID phenomenon has stabilized. For the group C (sc-Si), the value shown a fairly consistent at about ~84% for the first three years; however, an approximately 13% decrease can be observed after the final year continuous period.

For groups A and C, Figure 2 shows that there is deterioration by 23% and 15.3%, respectively, with reference to the initial year value. Group C depicts a more stable for annual performance ratio amongst the three PV module technologies, whereas a-Si TFPV modules have demonstrated a stable performance after two years of operation. Although a-Si TFPV modules tend to be degraded with respect to time due to LID phenomenon, the study shown that the annual performance ratio value of group B (a-Si TF) was higher than both of performance ratio values for group C (sc-Si) and group A (mc-Si) with 94.6%, 81%, and 78.2%, respectively, over four years period under Malaysia’s outdoor conditions.

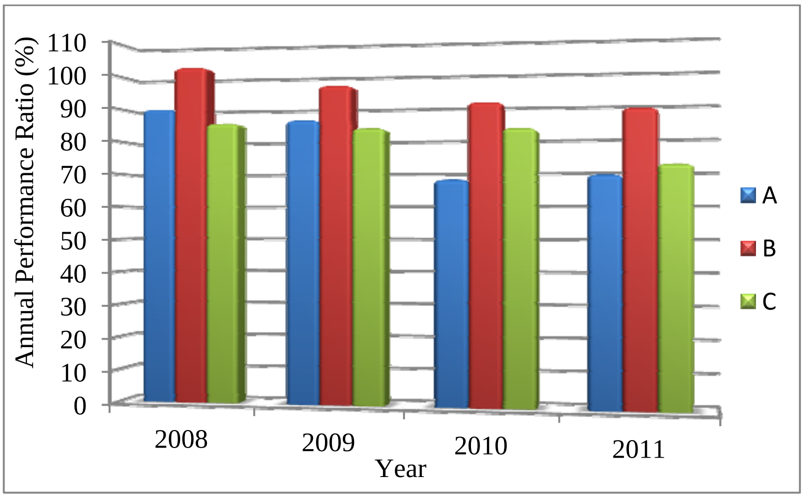

Figure 2. Annual performance ratio of three different PV module technologies; mc-Si (A), a-Si (B), and sc-Si (C) under outdoor measurements

c. System Efficiency

Figure 3 illustrates the monthly system efficiency curves for three groups of PV technology. For the first two years shows that the crystalline PV modules exhibit a quite consistent in performance with the values of system efficiency from 11% to 12%. However, after two years of operation, group A showed a decrease in annual relative percentage of 24% in the final year compared with the initial year in the system efficiency performance. In addition, the results indicated that the monthly average system efficiency of group B looks more stable, whereas group A has exhibited a significant decrease after 24 months of operation. In addition, group C also showed a decrease in its performance after the two-year of operation.

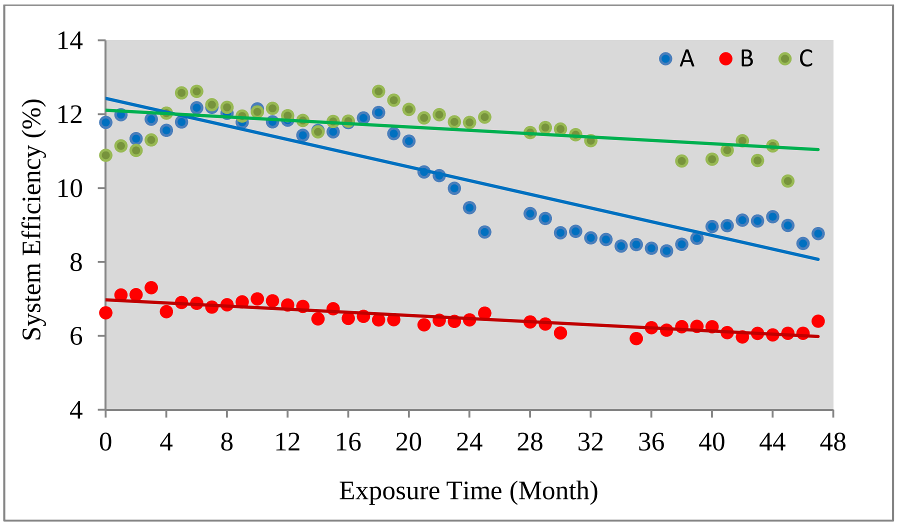

Figure 3. Monthly system efficiency of the mc-Si (blue dots), a-Si (red dots) and sc-Si (green dots) groups over 48 months monitored period.

Table 3 summarizes the system performance indices for annual performance of three different PV module technologies after outdoor exposure over four years of monitoring. The highest producer in the energy output is group B about 4230.2 kWh/kWp over the monitored period, followed by group A and C with a total final yield generated of 3941.8 and 3246.1 kWh/kWp, respectively.

Table 3. Comparison of PV module technology for annual system performance under Malaysian climate

Group		A				B				C			
Year		1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
1	Y_f	1220.2	1127.5	703.1	891.0	1392.6	1263.1	410.4	1164.1	1158.6	979.6	511.5	596.4
2	PR	89.8	86.0	67.8	69.2	102.5	96.3	90.8	88.6	85.3	83.4	83.0	72.2
	AD		-4.3	-21.1	+1.9		-6.0	-5.8	-2.4		-2.2	-0.5	-13.0
3	η_{sys}	11.8	11.2	8.8	9.0	6.9	6.5	6.1	6.1	11.7	11.5	11.4	9.9

Y_f = Final Yield (kWh/kWp)
PR = Performance Ratio (%)
AD = Annual difference of PR (%)
η_{sys} = System Efficiency (%)

d. PV Array Efficiency

All PV module technology will demonstrate a slight decrease in the efficiency by increasing irradiance level. A significant increase in efficiency usually occurs rapidly for each PV technology at lower irradiance levels. It can be seen on both crystalline PV technology for mc-Si and sc-Si which shows more inclined and tilted than a-Si TFPV technology, as shown in Figure 4. In addition, mc-Si showed a greater decrease in array efficiency and significant than other PV technologies. This trend occurred where the array efficiency for mc-Si has declined dramatically about 9.8% with irradiance levels greater than 600 W/m^2. The second influential technology was sc-Si PV technology measured at 11.8%.

In contrast, a-Si TFPV technology show stable values measured efficiency of 6.5% under outdoor exposure even it has the lowest conversion efficiency. Crystalline PV technology seems more influenced by the temperature effect when compared with TFPV technology. Obviously, a-Si TFPV technology has greater benefits in terms of delivering a stable conversion efficiency and reliable at high temperature and irradiance.

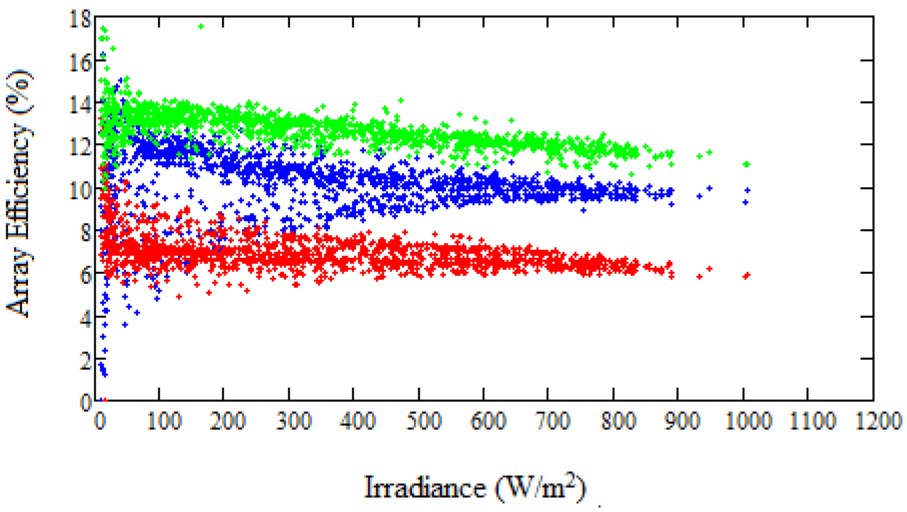

Figure 4. The instantaneous PV array efficiency against irradiance for three different PV technologies; mc-Si (blue dots), a-Si (red dots), sc-Si (green dots) in the month of January 2010

Figure 5 depicts the normalized PV array efficiency against filtered irradiance at selected irradiance above 600 W/m^2 in order to eliminate the environmental effects toward datasets. The instantaneous normalized PV array efficiency for three types of PV technology is calculated on the basis of 15 minutes per day for the month of January 2010, demonstrate that the group B (red dots) is good stability in the conversion efficiency which is close to the nominal value of the efficiency at STC rating. Second best conversion efficiency was group C (green dots) and followed by group A (blue dots) as illustrated in Figure 5. Therefore, a-Si TFPV technology provides more advantages in terms of delivering superior stability in performance efficiency under Malaysian climate.

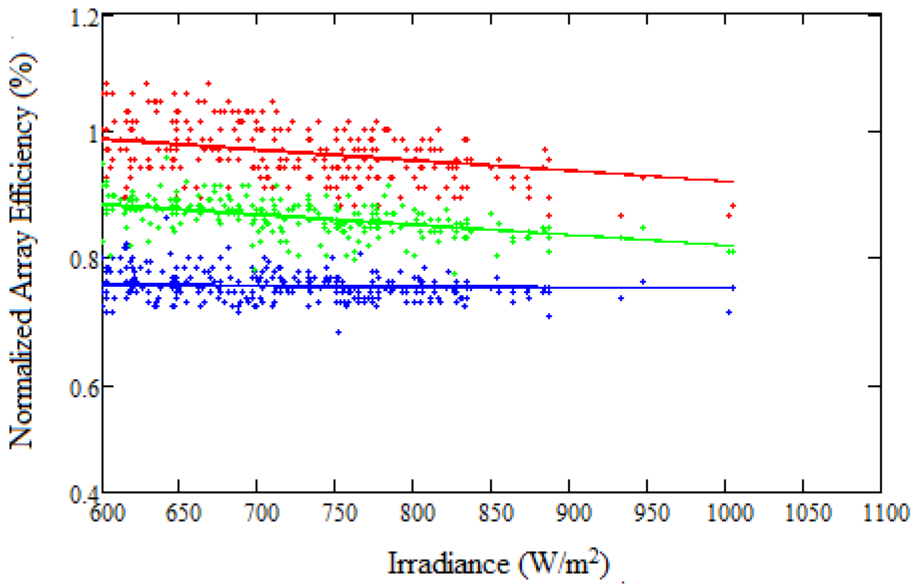

Figure 5. Normalized PV array efficiency against irradiance for each day in January 2012 to mc-Si (blue dots), a-Si (red dots) and sc-Si (green dots)

e. Monthly Performance Ratio- Degradation Rate

A linear trend of degradation rate or also known as aging factor for the three different types, which are given in terms of annual performance, where it can be determined using a simple linear correlation analysis by evaluating the monthly performance ratio during the monitored period [16]. The sum of the annual degradation rates can be derived in equation 6. The percentage of degradation rate per year (% Rd) method, which the existing approaches used in [17],[18], is given by the following equation as:

$$\%R_d = \frac{(m \times 12)}{C} \times 100\% \tag{6}$$

Where, m represents the slope of the equation line and C is the intercept along the Y-axis shows the performance ratio in the beginning of the measurement period. The initial dataset 16 months were excluded in the degradation rate analysis to ensure that the LID effect of a-Si TFPV technology had fully stabilized. The degradation rate should be determined after the PV modules are fully stabilized or calculated from the first two years, three years and above, as described in [19].

Figure 6 represents the annual degradation rates for the groups A, B and C were found to be -8.7%/yr, -2.5%/yr and -2.6%/yr, respectively. In the first 16 months, the major degradation rate of group B (a-Si) was about -4.6%/yr. After that, the continuous degradation has been reduced by about -2.5% per year until the end of the monitored period.

For the group A, the greater of degradation rate was observed at -8.7%/yr, which can be indicated as the system is facing problems due to the long-term stability issues, as reported in [20],[21]. Further investigation will be conducted in order to identify the exact problem.

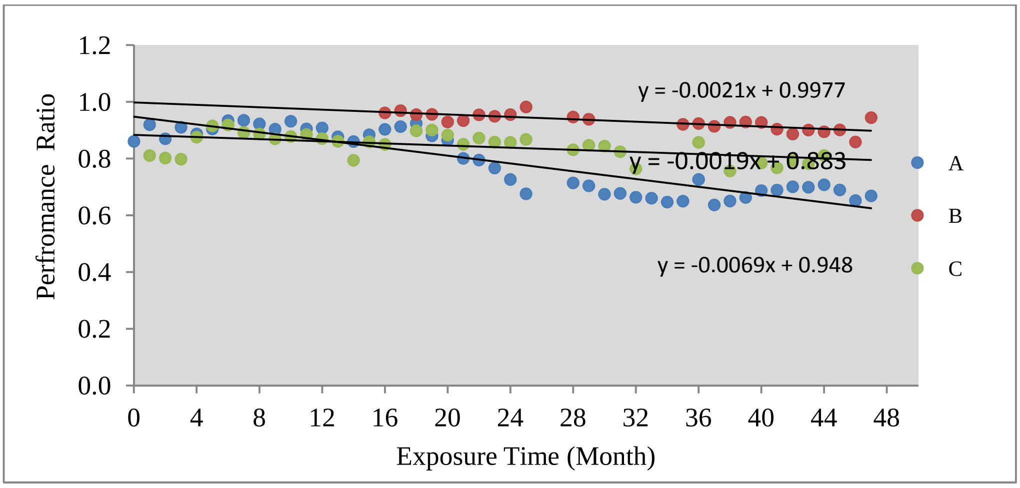

Figure 6. Linear degradation trend for three PV technologies; mc-Si (blue dots), a-Si (red dots), sc-Si (green dots) over 48-month monitored period

f. Performance Ratio- Degradation Rate

Annual degradation rate of system efficiency for three different PV technologies was -8.7%/yr, -1.8%/yr and -2.0%/yr for groups A, B and C respectively, as shown in Figure 7. The group B exhibit stable reliability with the lowest degradation rate per year of about -1.8% per year among other PV technologies.

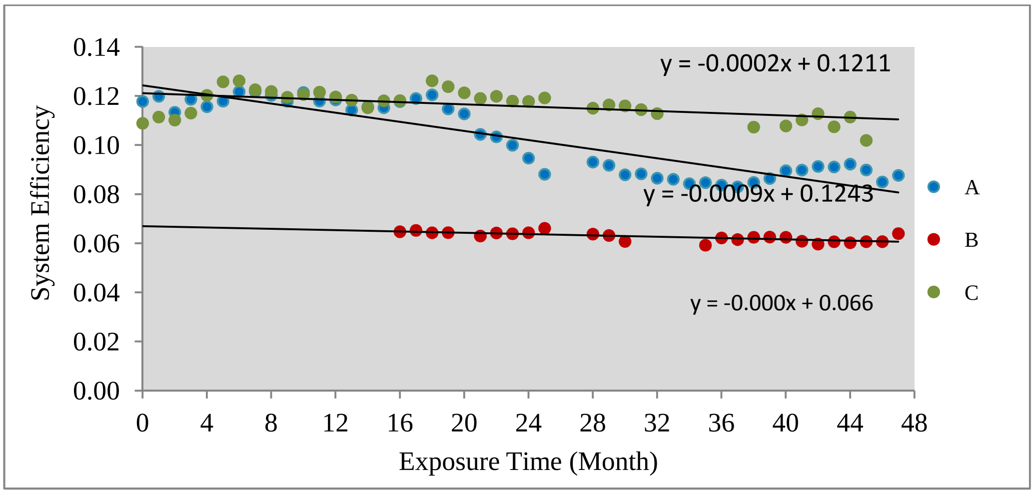

Figure 7. Monthly system efficiency of the mc-Si (blue dots), a-Si (red dots) and sc-Si (green dots) groups

4. CONCLUSION

Outdoor performance of three different PV technologies has been investigated under field conditions during the four years of monitoring. In the period of time studied, the annual performance ratio of a-Si was about 14% and 21% better than the performance ratio for sc-Si and mc-Si PV technologies, respectively.

This study describes a comparative study of different PV technologies where a-Si TFPV technology have demonstrated a steady efficiency, reliability as well as higher final yield for long-term performance in the GC system under Malaysian climate. Using the above parameters, it is possible to make a comparative study of different conversion systems in determining PV module technology that can offer a better energy production, conversion efficiency and reliability of the output performance.

As described in the results, the four-year monitoring period under Malaysia's environment has revealed that the PV module technology can provide the greater yield production, reliability and stability is a-Si TFPV technology, which in the future, hopefully can help in creating awareness and exploit the potential of this kind in Malaysia's PV applications, especially for the purpose of BIPV applications operating at high temperature.

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