Performance of a-Si, p-Si, and HIT PV Technological Comparison under Tropical Wet Climate Condition

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ABSTRACT

The main problem in photovoltaic (PV) performance measurement is that energy output from actual condition is lower than Standard Testing Condition (STC). The purpose of this study was therefore to compare the performance of amorphous silicon (a-Si), poly-crystalline silicon (p-Si) and hybrid solar cell (HIT) PV technologies under Tropical Wet Climate Condition of Phitsanulok, Thailand. The Array Yield (Y_a) of three different technologies of PV arrays had been analyzed. The results showed that the elevated irradiance and temperature in each season were more affected on the p-Si than HIT and a-Si modules. Nevertheless, relative humidity and wind speed also affected on Y_a of all modules with low level.

Keywords: *PV Performance, PV Technological Comparison, Tropical Wet Climate Condition*

1. INTRODUCTION

The main problem in photovoltaic (PV) performance measurement arises from the fact that solar cells have a highly selective spectral response and are therefore very sensitive to the spectral composition of the incident radiation. Outdoor, it varies considerably with location, weather, season and daytime. Indoors, it depends on various types of simulator. Unless measurement procedures take account of these variations and other difficulties, such as the make temperature dependence of solar cells, the result can be grossly erroneous [1].

The evaluation and assessment of the performance of photovoltaic (PV) cells requires the measurement of the current as a function of voltage, temperature, solar radiation intensity, wind speed, and radiation spectrum. Most noticeable of these parameter is PV conversion efficiency η (defined as the maximum electrical power P_{max} produce by the PV cell divided by the incident condition refer to the solar spectrum (AM 1.5), solar radiation intensity (1,000 W/m^2), cell temperature (25 ± 2 °C) and wind speed (2 mph)). Tests under the standard testing condition (STC) are carried out in laboratory-controlled environment. The STC combine the irradiance of a clear summer day, the cell/module temperature of a clear winter day and the solar spectrum of a clear spring day. These measurement conditions obviously do not represent real operating conditions of PV devices at the site of installation. For the optimum design of PV power systems, it is desirable to measure their long term performances at the site of installation [2].

The PV has been applied in Thailand over 30 years. The problems of PV in Thailand were various natural parameters such as solar irradiance, ambient temperature, wind speed, and relative humidity. Thailand has a tropical climate dominated by monsoon and characterized in general by three seasons per year, which are summer from March to May, rainy season from June to October and winter from November to February [3, 4, 5].

Therefore, the aim of this study was performance comparison of a-Si, p-Si and HIT PV technologies under Tropical Wet Climate Condition of Phitsanulok, Thailand.

2. EXPERIMENTAL SET UP

The location of the study was the 10 kW PV systems was installed and operated in the Energy Park at the School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok, Thailand.

2.1. Photovoltaic generator

The photovoltaic generator was consisted of three different types of photovoltaic technologies. First, a-Si 3,672 *W*, 54 *W* x 68 modules was connected into 17 strings, 4 modules each. Second, p-Si 3,600 *W*, 80 *W* x 45 modules was connected into 3 strings, 15 modules each. Finally, HIT 2,880 *W*, 180 *W* x 16 modules was connected into 2 strings, 8 modules each. The photovoltaic generator array of a 10 kW_P PV system after installed as shown in Figure 1, which from right to left was a-Si, p-Si and HIT panel, respectively [6].

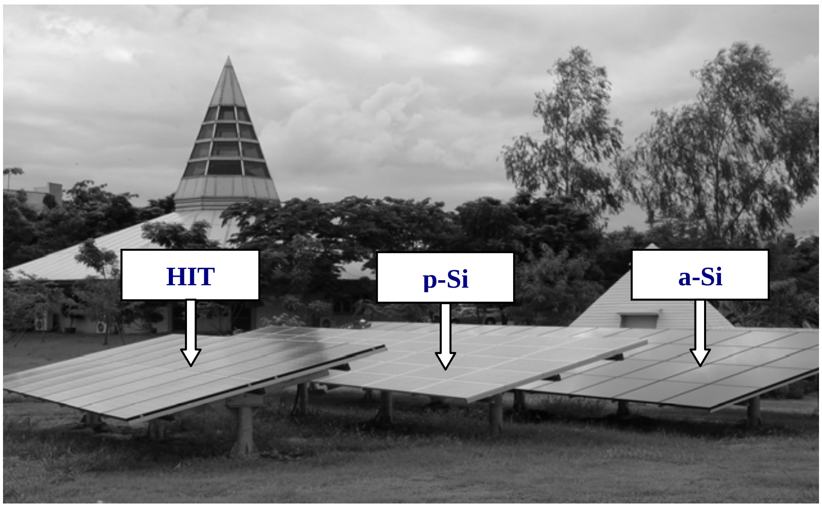


Fig. 1 The three different types of photovoltaic generator technologies

2.2. Monitoring system

The testing period was one year from January to December, 2006. Net DC energy output in kWh was measured from the system and used to calculate the Array Yield (Y_a). Total plane of array irradiance in kWh/m^2 was calculated base on meteorological data at SERT and consequent calculated the Reference Yield (Y_r). Therefore, Y_a and Y_r were used to calculated the Capture Losses (L_c) and Array Efficiency (η_a)[7]. For the general data acquisition, a multi-function measuring device measures the parameters are shown in Table 1:

Table1 Monitoring system of 10 kW PV systems

Electrical Parameters:	**Meteorological Parameters**
DC voltage of PV array	Total irradiance (Kipp & Zonen CM11)
DC current of PV array	Tilt irradiance (Kipp & Zonen CM11)
Power of PV array	Ambient temperature
Energy of PV array	Wind speed
Daily energy	Relative Humidity
Monthly energy	
Yearly energy	

2.3. Photovoltaic Performance Analysis

Parameters describing energy quantifies of the PV System and its components have been established by the International Energy Agency (IEA) Photovoltaic Power Systems TASK 2 [8,9,10] and are described in the IEC Standard 61724 [11]. Four of the IEC Standard 61724 performance parameters, which are Y_r, Y_a, L_c, and η_a, maybe used to define the PV array with respect to the energy production, solar resource, and overall effect of system losses. These parameters could define the overall performance of a PV array with respect to the same way.

2.3.1. Reference Yield (Y_r)

Y_r was the total in-plane irradiance (H_i) divided by the PV reference irradiance (G_{STC}). It represents the equivalent amount of hours necessary for the array to receive the reference irradiance. Y_r defined the solar radiation resource for PV array. It is a function of a location orientation and month-to-month weather variability. Therefore, value of Y_r was calculated by equation (1).

$$Y_r = H_i / G_{STC} \tag{1}$$

2.3.2. Array Yield (Y_a)

Y_a was array net DC energy output (E_a) divided by array rated power (P_O). Y_a was the portion of the output daily energy of the photovoltaic array per kilowatt peak of installed photovoltaic array. Thus, it was a convenient way to compare the energy of PV array in difference size. Therefore, value of Y_a was calculated by equation (2).

$$Y_a = E_a / P_O \tag{2}$$

2.3.3. Array Efficiency (η_a)

η_a was array net DC energy output (E_a) divided by total plane of array irradiance (H_i) multiply by area of PV array in m^2 (A_a). Therefore, value of η_a was calculated by equation (3).

$$\eta_a = E_a / H_i A_a \tag{3}$$

3. RESULTS AND DISCUSSION

This section presents the 12 months data analysis from January to December 2006 and results of the performance comparison of different PV technologies, which were a-Si, p-Si and HIT, under tropical wet climate conditions.

3.1 The parameters in winter

On every month in winter, *Irr* was the same trend. It slowly increased from 6 AM to 1 PM and then slowly decreased in the afternoon. We found the highest *Irr* at 12 AM to 1PM but the lowest at 6 AM to 7 AM. We also found that *Irr* in the morning of November and December was higher than January and February. In contrast, *Irr* in the afternoon of November, December and January were lower than February.

In winter, every month T_{amb} shows the same trend. It slowly increased from 6 AM to 1 PM and then stabilized at about 27 °C. In addition, T_{amb} in the morning on November was higher than December, January and February. However, T_{amb} in the afternoon on February was higher than other.

RH all day long in winter from high to low were November, December, January and February, respectively. The highest *RH* was found at 6 AM and then slowly decreased until lowest at 1 PM. Then, it slowly increased but still lower than *RH* in the morning.

WS in winter was lowest at 6 AM and then slowly increased until highest at 1 PM. Then, it slowly decreased but still higher than in early morning.

In addition, module temperatures in winter from high to low are a-Si, p-Si and HIT, respectively. The highest module temperature is fund on November and the rest are February, December and January, respectively.

Furthermore, Y_a of all modules in each month in winter from high to low are November, December, February and January, respectively. Finally, Y_a of the modules from high to low are a-Si, HIT and p-Si, respectively.

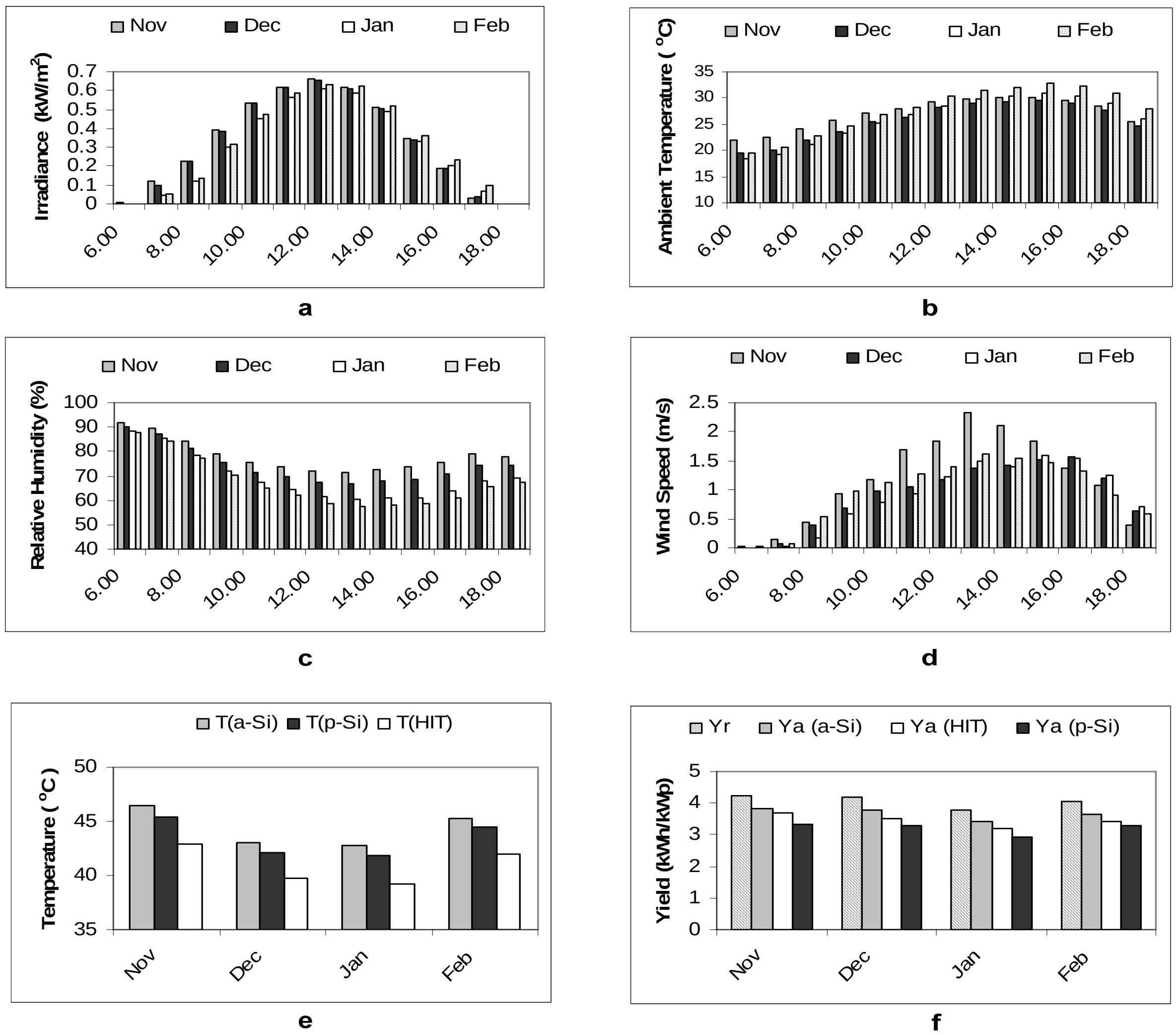


Fig. 2 The natural parameters, modules temperature and Y_a of different PV technologies in winter

3.2 The parameter in summer

In the months of summer, *Irr* showed the same trend. It slowly increased from 6 AM to 1 PM and then slowly decreased in the afternoon. We found the highest *Irr* at 12 AM to 1PM but the lowest at 6 AM to 7 AM. We also found that *Irr* in May and April was higher than March.

In summer, every month T_{amb} shows the same trend. It slowly increased from 6 AM to 1 PM and then stabilized at about 31 °C. However, T_{amb} in April was higher than March and May.

RH all day long in winter from high to low were May, April and March, respectively. The highest *RH* was found at 6 AM and then slowly decreased until lowest at 1 PM. Then, it slowly increased but still lower than *RH* in the early morning.

WS in winter was lowest at 6 AM and then slowly increased until highest at 1 PM. Then, it slowly decreased but still higher than in early morning.

In addition, module temperatures in summer from high to low are a-Si, p-Si and HIT, respectively. The highest module temperature is fund on April and the rest are March and May, respectively.

Furthermore, Y_a of all modules in each month in summer from high to low are May, April and March, respectively. Finally, Y_a of the modules from high to low are a-Si, HIT and p-Si, respectively.

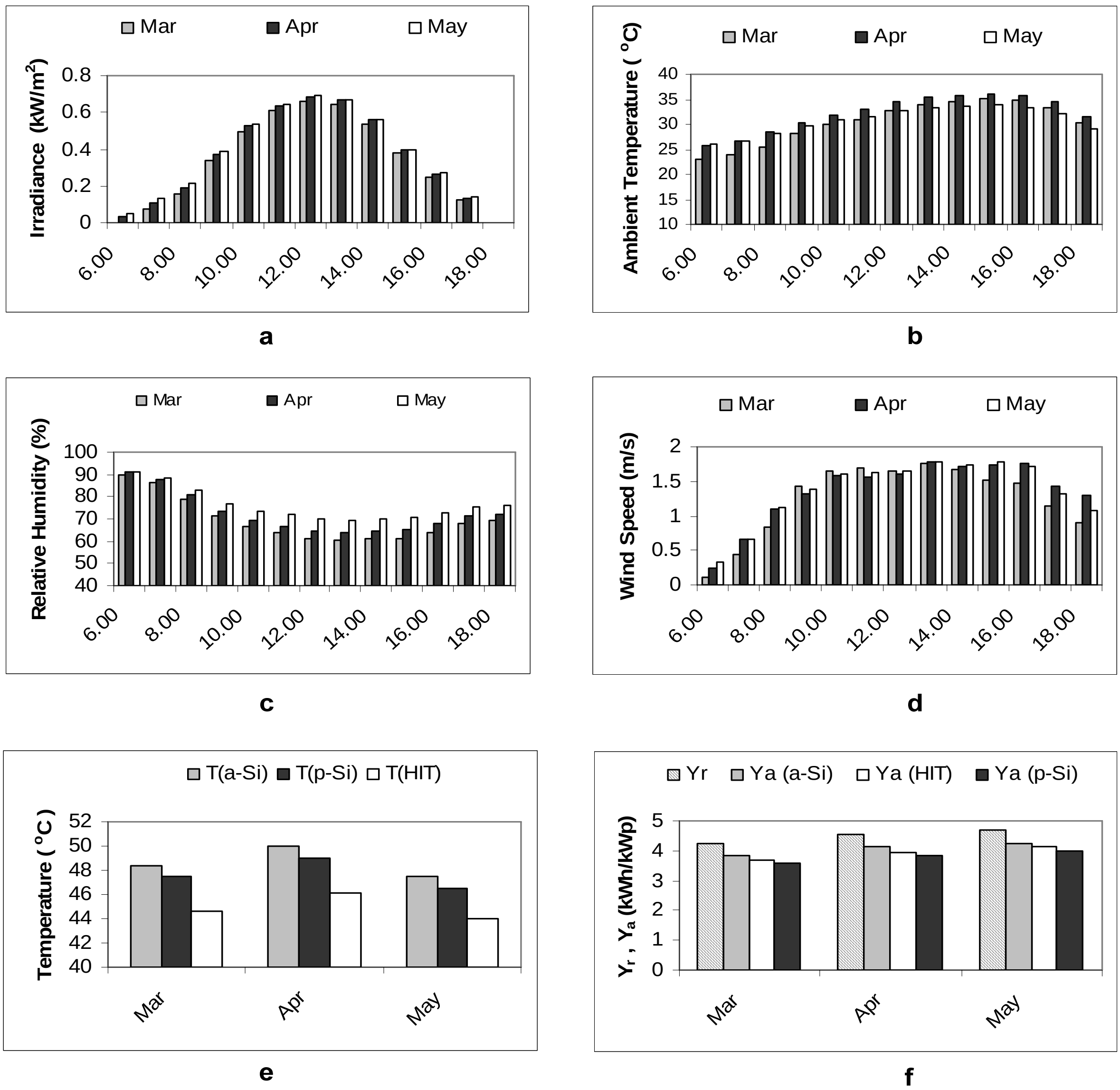


Fig. 3 The natural parameters, modules temperature and Y_a of different PV technologies in summer

3.3 The parameter in rainy season

In the month of rainy season, *Irr* showed the same trend. It slowly increased from 6 AM to 1 PM and then slowly decreased in the afternoon. We found the highest *Irr* at 12 AM to 1PM but the lowest at 6 AM to 7 AM. We also found that *Irr* from high to low were June, July, August, September and October, respectively.

In rainy season, every month T_{amb} shows the same trend. It slowly increased from 6 AM to 1 PM and then stabilized at about 29 °C. In addition, T_{amb} on June was highest and October was lowest.

RH all day long in rainy season from high to low were October, September, August, June and July, respectively. The highest *RH* was found at 6 AM and then slowly decreased until lowest at 1 PM. Then, it slowly increased but still lower than *RH* in the early morning.

WS in rainy season was lowest at 6 AM and then slowly increased until highest at 1 PM. Then, it slowly decreased but still higher than in early morning.

In addition, module temperatures in rainy season from high to low are a-Si, p-Si and HIT, respectively. The highest module temperature is fund on June and the rest were October, September, July and August, respectively.

Furthermore, Y_a of all modules in each month in rainy season from high to low are June, July, August, September and October, respectively. Finally, Y_a of the modules from high to low are a-Si, HIT and p-Si, respectively.

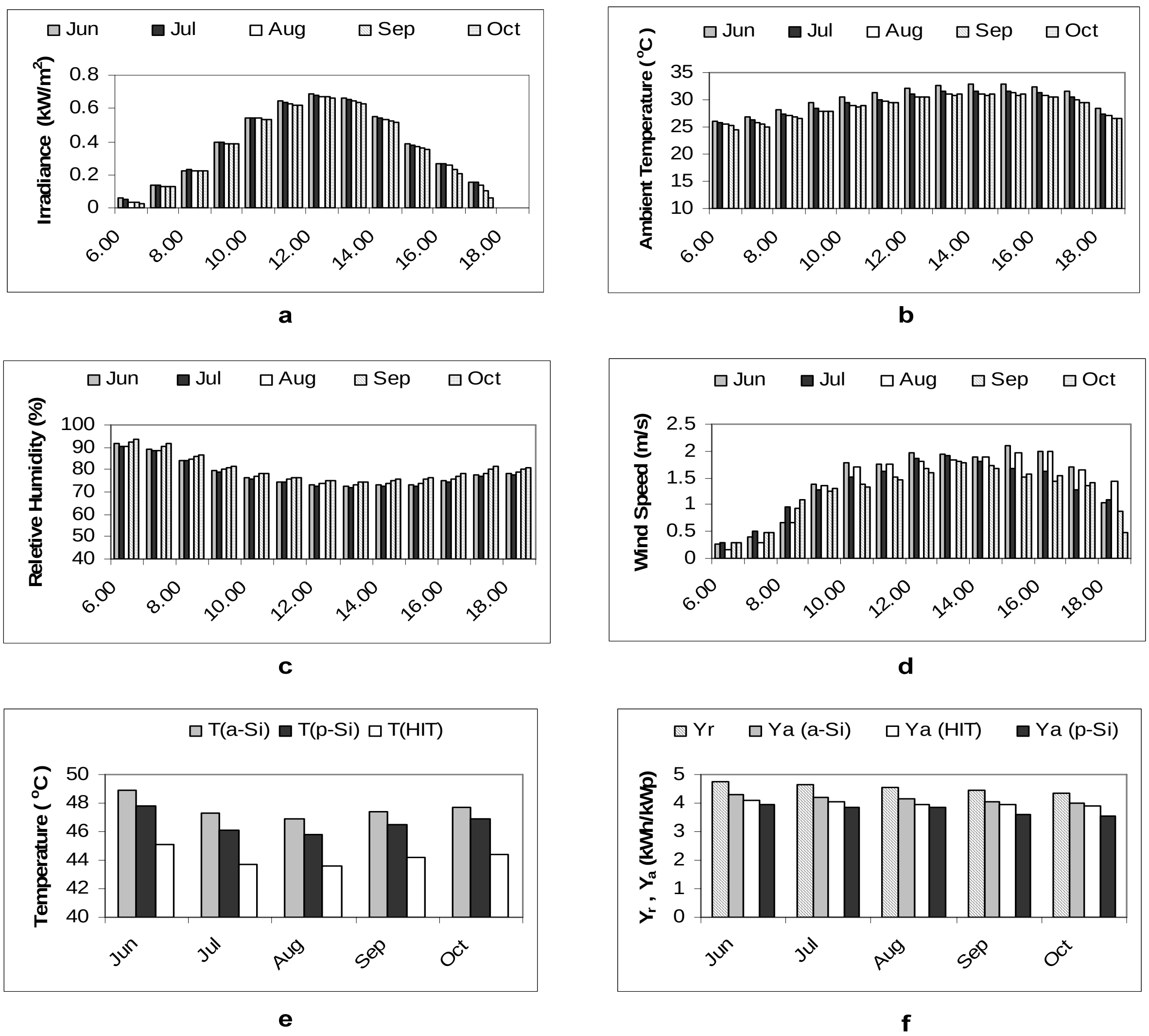


Fig. 4 The natural parameters, modules temperature and Y_a of different PV technologies in rainy

3.4 The different PV technologies was affected by these parameters

As shown in Figure 5(a), the low *Rad* showed in winter and the lowest *Rad* was found in January. On the other hand, the high *Rad* showed in summer and the highest *Rad* was found in June. The low T_{amb} showed in winter and the lowest T_{amb} was found in December. In contrast, the high T_{amb} showed in summer and the highest T_{amb} was found in April, as shown in figure 5(b).

Figure 5(c) showed that the low *RH* was found in winter and the lowest *RH* was found in February but the high *RH* showed in rainy season and the highest *RH* was found in October. Moreover, the low *WS* showed in winter and the lowest *WS* was found in January but the high *WS* showed in rainy season and the highest *WS* was found in June, as shown in Figure 5(d).

Furthermore, the low module temperature of all modules showed in winter and the lowest module temperature was found in January. In contrast, the low module temperature showed in summer and the highest module temperature was found in April, as shown in Figure 5(e). The module temperature depended on T_{amb}, so high T_{amb} resulted in high module temperature. Finally, Y_a producing from all modules were low in winter and the lowest Y_a was found in January. On the other hand, the high Y_a showed in rainy season and the highest Y_a was found in June, as shown in figure 5(f).

From these data, in winter when *Rad* was low, thus it results in the Y_a also low. In contrast, in rainy season with high Y_a, not much high T_{amb}, high *RH* and *WS*, therefore, they made suitable module temperature to produce the highest Y_a in June. However, in summer with high T_{amb}, not much high *RH* and *WS*, so they made to high module temperature that unsuitable to produce the high Y_a. Therefore, the Y_a in summer was a bit lower than rainy season.

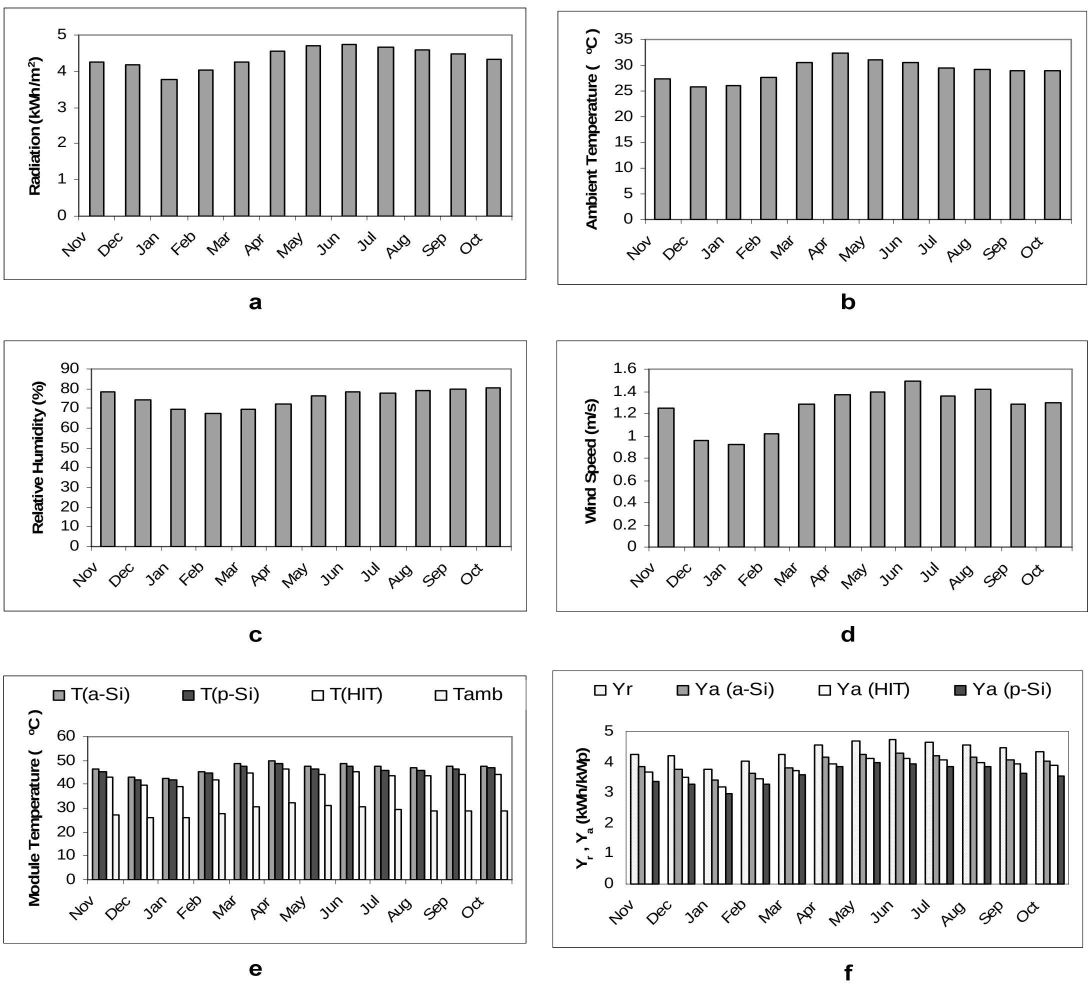


Fig. 5 The natural parameters, modules temperature and Y_a of different PV technologies

3.5 The relation of natural parameters and array yields of different PV technologies

As shown in Figure 6 and Table 2, the relations between Y_a (a-Si), Y_a (p-Si), Y_a (HIT) and natural parameters; *Irr*, T_{amb}, *RH* and *WS*, under Tropical Wet climate condition were described in this section.

Figure 6(a-c) shows that the relations between Y_a (a-Si), Y_a (p-Si), Y_a (HIT) and *Irr* from high to low in each season are summer, winter and rainy season, respectively. This relation of all seasons is positive linear relationship. However, the weather condition in rainy season is more affect to *Irr* of all modules than in summer and winter. As shown in Table 2, the relation between Y_a and *Irr* was linear relationship. The r^2 value of a-Si, p-Si and HIT were 0.9854, 0.9487 and 0.9654, respectively. From the r^2 value reveals that *Irr* is the most and directly affected to Y_a in all three PV when compared with other parameters. In summary, a-Si and HIT modules are better absorbing *Irr* in weather condition of summer and winter than rainy season. On the other hand, p-Si module is better absorbing *Irr* in rainy season than other seasons. Finally, the relations between *Irr* and Y_a of different modules under tropical wet climate condition from high to low are p-Si, HIT and a-Si, respectively.

Figure 6(d-f) shows that the relations between Y_a (a-Si), Y_a (p-Si), Y_a (HIT) and T_{amb} from high to low in each season are rainy season, summer and winter, respectively. This relation of all seasons was polynomial relationship. In addition, T_{amb} is more affected to Y_a (a-Si), Y_a (p-Si) and Y_a (HIT) in rainy season and summer than winter. As shown in Table 2, the relation between Y_a and T_{amb} was polynomial degree 6 relationship. The r^2 value of a-Si, p-Si and HIT were 0.7318, 0.8544 and 0.7683, respectively. From the r^2 value reveals that T_{amb} affected to Y_a in all three PV and affected to Ya of p-Si more than 80%. In conclusion, T_{amb} is more directly affect to p-Si and HIT than a-Si. And T_{amb} in rainy season directly affected to Y_a of all modules. Finally, the relations between T_{amb} and Y_a of different modules under tropical wet climate condition from high to low are p-Si, HIT and a-Si, respectively.

Figure 6(g-i) shows that the relations between Y_a (a-Si), Y_a (p-Si), Y_a (HIT) and *RH* from high to low in each season are rainy season, summer and winter, respectively. This relation of all seasons was polynomial relationship. The *RH* affect to Y_a (a-Si), Y_a (p-Si) and Y_a (HIT) in rainy season with negative curvilinear relationship but in summer and winter are positive curvilinear relationship. As shown in Table 2, the relation between Y_a and *RH* was polynomial degree 6 relationship. The r^2 value of a-Si, p-Si and HIT were 0.6546, 0.4566 and 0.6185, respectively. From the r^2 value reveals that *RH* had a few affected to Y_a in all three PV but it still affected to Y_a of a-Si and HIT more than 60%. In contrast, *RH* had a little affected to Y_a of p-Si with only 45%. In summary, *RH* affect to modules in different seasons. In winter, *RH* is more affect to Y_a (HIT) than other seasons. In rainy season, *RH* is more directly affect to p-Si than other modules and show that when *RH* value increase then it cause Y_a value decrease.

Figure 6(j-l) shows that the relations between Y_a (a-Si), Y_a (p-Si), Y_a (HIT) and *WS* from high to low in each season are summer, winter and rainy season, respectively. This relation of all seasons is polynomial relationship. The *WS* affect to Y_a (a-Si), Y_a (p-Si) and Y_a (HIT) in winter and rainy season with negative curvilinear relationship but in summer is positive curvilinear relationship. As shown in Table 2, the relation between Y_a and *WS* was polynomial degree 6 relationship. The r^2 value of a-Si, p-Si and HIT were 0.7833, 0.7398 and 0.8546, respectively. From the r^2 value reveals that *WS* affected to Y_a in all three PV. In addition, *WS* affected to Y_a of HIT more than 80% and it also affected to Y_a of a-Si and p-Si 78% and 74%, respectively. In conclusion, *WS* affect to all modules in all seasons. In summer, *WS* affect to Y_a of all modules in positive curvilinear relationship. But in winter and rainy season, *WS* affect to Y_a of all modules in negative curvilinear relationship and show that when *WS* value increase then it cause Y_a value decrease.

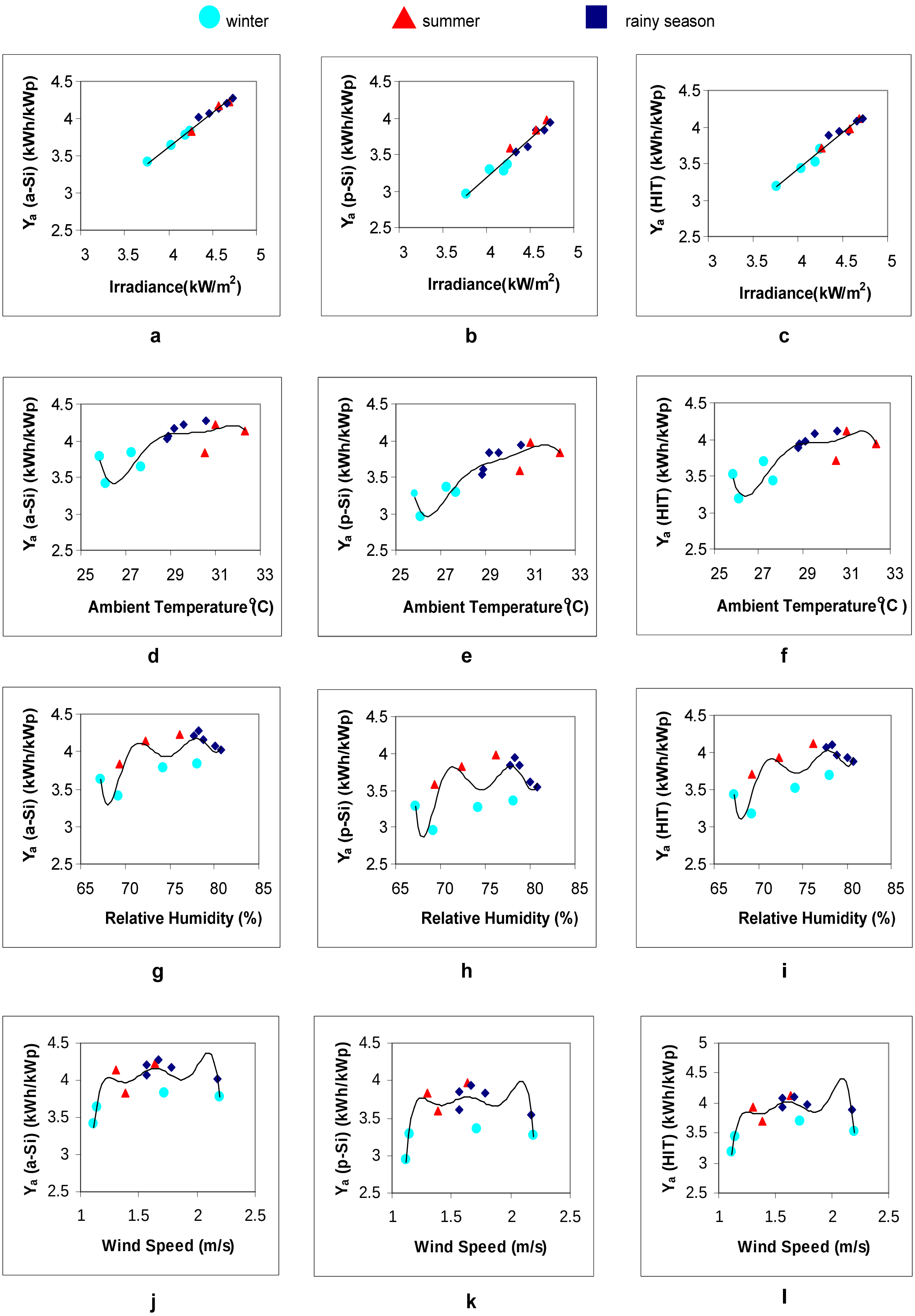


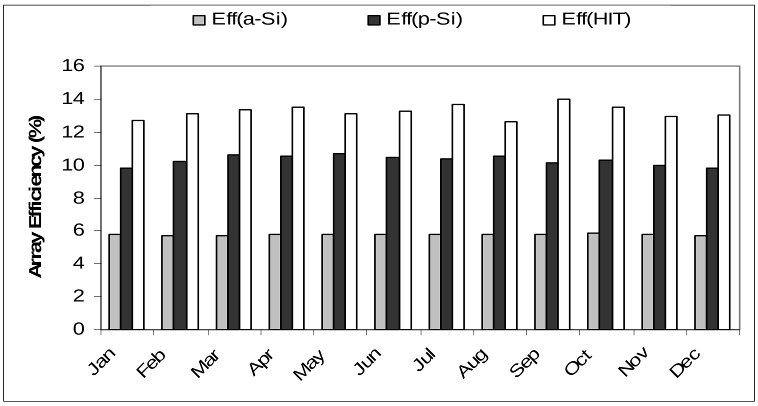
Fig. 6 The relation of natural parameters & array yields of three different PV technologies

Table 2 The R-squared of different PV technologies under natural parameters.

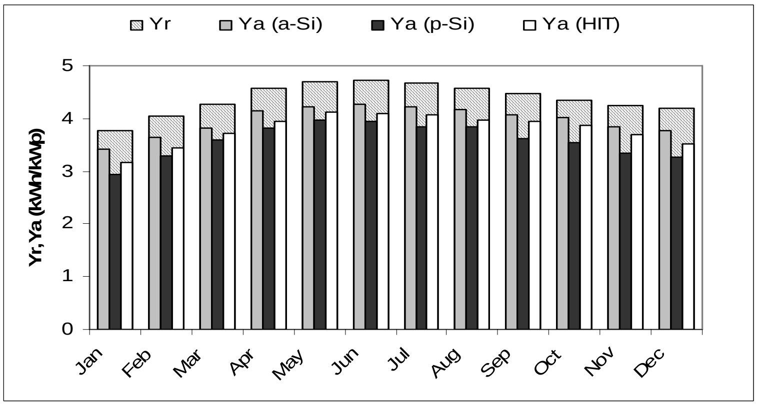
Natural parameters	a-Si		p-Si		HIT	
	Y_a	R^2	Y_a	R^2	Y_a	R^2
Irr	$0.9191Irr - 0.058$	0.9854	$0.9965Irr - 0.9774$	0.9487	$0.09675Irr - 0.5705$	0.9654
T_{amb}	$0.0002T_{amb}^6 - 0.0459 T_{amb}^5 + 3.6072 T_{amb}^4 - 150.56 T_{amb}^3 + 3517.6 T_{amb}^2 - 43633 T_{amb} + 224564$	0.7318	$0.0005T_{amb}^6 - 0.086 T_{amb}^5 + 6.5026 T_{amb}^4 - 261.68 T_{amb}^3 + 5911.5 T_{amb}^2 - 71081 T_{amb} + 355413$	0.8544	$-8E\text{-}05T_{amb}^6 + 0.0092 T_{amb}^5 - 0.3595T_{amb}^4 + 1.7043T_{amb}^3 + 232.77T_{amb}^2 - 5869.5T_{amb} + 43810$	0.7683
RH	$-4E\text{-}05RH^6 - 0.00188 RH^5 + 3.507RH^4 - 347.74RH^3 + 19378RH^2 - 575422RH + 7E{+}06$	0.6546	$6E\text{-}05RH^6 - 0.0259RH^5 + 4.8122RH^4 - 476.65RH^3 + 26533RH^2 - 787040RH + 1E{+}07$	0.4566	$5E\text{-}05RH^6 - 0.0214RH^5 + 3.9712RH^4 - 393.15RH^3 + 21875RH^2 - 648542RH + 8E{+}06$	0.6185
WS	$-190.87WS^6 + 1884.8WS^5 - 7684.5WS^4 + 16557WS^3 - 19883WS^2 + 12618WS + 3302.4$	0.7833	$-195.87WS^6 + 1938.2WS^5 - 7924.3WS^4 + 17134WS^3 - 20664WS^2 + 13178WS - 3468.4$	0.7398	$-227.53WS^6 + 2226.9WS^5 - 8998.9WS^4 + 19218WS^3 - 22877WS^2 + 14395WS - 3737.4$	0.8546

3.6 The data of different PV technologies analyzed in 2006 at SERT

Figure 7 shows array efficiency and Y_a producing from all modules every month in 2006. The highest array efficiency is hybrid array efficiency and the lowest array efficiency is amorphous array efficiency. However, Y_a of a-Si in all seasons is higher than p-Si and HIT.



a



b

Fig. 7 (a) array efficiency of three different PV technologies, (b) array yield & reference yield

4. CONCLUSION

The Y_a of three different technologies of PV arrays had been analyzed. The results showed that the elevated irradiance and temperature in each season were more affected on the p-Si than HIT and a-Si modules. Nevertheless, relative humidity and wind speed also affected on Y_a of all modules with low level. The p-Si yielded the lowest Y_a but a-Si yielded the highest Y_a in these conditions.

In conclusion, the a-Si produced more energy than p-Si and HIT under tropical wet climate condition for these studies. However, the modules degradation and other natural parameters especially solar spectrum also affected on Y_a of all modules.

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Nomenclature

Abbreviation	Definition
A_a	Area of PV array (m^2)
a-Si	Amorphous silicon
DC	Direct current
E_a	Array net DC energy output (kWh)
Eff(a-Si)	Efficiency of amorphous silicon (%)
Eff(HIT)	Efficiency of hybrid solar cell (%)
Eff(p-Si)	Efficiency of poly-crystalline silicon (%)
G_{STC}	Reference irradiance (kW/m^2)
H_i	Total plane of array radiation (kWh/m^2)
HIT	Hybrid solar cell
Irr	Irradiance (kW/m^2)
P_o	Array rated power (kWp)
p-Si	Poly-crystalline silicon
Rad	Radiation (kWh/m^2)
RH	Relative Humidity (%)
STC	Standard Test Condition
T(a-Si)	Module temperature of amorphous silicon (°C)
T(HIT)	Module temperature of hybrid solar cell (°C)
T(p-Si)	Module temperature of poly-crystalline silicon (°C)
T_{amb}	Ambient temperature (°C)
WS	Wind speed (m/s)
Y_a	Array Yield (kWh/kWp)
$Y_a(a\text{-}Si)$	Array yield of amorphous silicon (kWh/kWp)
$Y_a(HIT)$	Array yield of hybrid solar cell (kWh/kWp)
$Y_a(p\text{-}Si)$	Array yield of poly-crystalline silicon (kWh/kWp)
Y_r	Reference yield (kWh/kWp)

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