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TEST OF A PV MODULE UNDER INSTALLED CONDITION TO OBSERVE REALISTIC MODULE POWER OUTPUT

TONY GAN ANG, TANAPAT HEMASUK AND FRANCE LASNIER*
Energy Technology Division, Asian Institute of Technology, Bangkok, Thailand.

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ABSTRACT

Module I-V curves were measured on a 45 W_p module at stable irradiance levels throughout a specified period of several weeks of daily measurement. 140 characteristic curves ranging from 300 W/m^2 to 900 W/m^2, with different irradiance levels coming in at different times of the day and associated with different module temperature, were processed. Results indicate that a single measurement of I-V characteristic at each irradiance level does not provide a wide enough viewing frame to observe the behavior of module performance under the stimuli of both random and deterministic parameters in its surroundings. Many controlled measurements (clouds of points) make the evaluation conclusive with acceptable accuracy. Graphical tools based on analyses conducted are presented for quick prediction of module response variables (TC, V_{oc}, V_{max}, I_{sc}, I_{max}, P_{max}, E_{max}) knowing the irradiance level (RAD) and the ambient temperature (TA) for conditions similar to those prevailing in the Energy Park at AIT. Maximum power available from the test module was found to be around 26 watts at 900 W/m^2 50° C. This only indicates a 25% power reduction of the module due to differences in the operating conditions to which the same module is subjected, out of the manufacturer's laboratory. Even at 25° C 1000 W/m^2, the empirical model for maximum efficiency (E_{max}) predicts a maximum 9% module efficiency. At a more realistic module temperature of 52° C, the module efficiency is likely to drop down to around 7% of the nominal figure at 25° C.

INTRODUCTION

Financial and technical feasibility of a photovoltaic power system has materialized into a commercial market in some specific regions and within specific applications. Among the many factors involved in making an investment decision in favor of PV power system (PVPS), two most likely common questions are : "How reliable is this new system ?" and "How much does it cost to produce a certain kWh ?"

Let us look at reliability first. The simplest measure of reliability by a user (who are usually from remote areas) is the answer to his question "Will my appliances run as they used to ?" Electronic equipments that go into a PVPS have been the focus of much product development and technical refinement for various specific operating conditions for the past few years and much improvement in terms of reliability, robustness and serviceability has been achieved. What is of interest now is whether the amount of energy in kWh promised by the system so designed is going to be fulfilled throughout the useful lifetime of the system. By fulfilling this designed kWh energy output, any appliances connected to the system are going to operate as required ; failing to do so will cause some of the connected appliances to stop running due to insufficient energy output from the PVPS. This sizing problem due to poor reliability has a lot to do with how design engineers understand the energy output from the installed PV module ; not to oversize to optimize cost and not to undersize to optimize reliability. An accurate prediction of the energy output from a PV module subjected to the prevailing conditions at the installation site is vital to this end.

Another common concern of a user is the cost of the system. The cost of a PVPS is always related to the energy output expected from the system. Electronic equipments of higher power carrying capability cost more. Overall system cost per rated kW will be much more when they are underutilized if there is an unexpected drop in module output. Even PV modules are priced and compared by the user in terms of $/W$_p$. More often, the manufacturer's measured module power output is not duplicated in every installation site. Price per W$_p$ of power output will certainly shoot up when irradiance is less and temperature higher in the field compared to the test conditions of the manufacturer.

The approach taken here is to obtain an accurate prediction of the PV module performance at the site of installation. This involved taking series of measurements of module performance subjected to characteristic environmental stress of the site. Investigation will be made on the irradiance condition of the site, module temperature behavior and its effects, performance of the module as a function of the environmental stress, and finally to present graphical curves to predict module performance.

AN OVERVIEW OF THE SYSTEM

A complete computerized system for the characterization and performance testing of photovoltaic (PV) modules under natural sunlight and ambient condition was designed and installed in AIT. The system automates daily testing of PV modules. Data handling capability, tabular and graphic presentation of results and a numerical solution to a theoretical model are coded into a software package (PVMOD) providing a useful tool for evaluation and assessing the field performance of a PV module. The PV Module Test-Bed is a two-axis tracking structure installed with sixteen PV module input terminals and sixteen surface-temperature sensors, including meteorological instrumentation.

Outdoor performance testing of photovoltaic modules requires a compilation of vast amounts of data in order that module characterization can be reliable and statistically acceptable. During testing in AIT, regular as well as sudden shift in sky condition throughout the day within a month is a common occurrence. Clouds can be thick or thin, scattered or uniform from day to day. The spectral energy distribution of the global radiation varies according to these changing sky conditions even at the same irradiance intensity. Therefore, more than a single day of performance testing is required to characterize a module in this type of meteorological condition.

PV MODULE TEST (PVMOD)

A single crystal photovoltaic module was tested in the ET energy park of AIT, from the 8th of June to the 4th of July 1988. The module was installed on an open frame, with 78 cm height of open space above the ground, tilted at 15° south. 36 cells of 10 cm diameter are connected in series comprising a total module area of 0.43326 m^2.

Module performance is monitored in terms of module current, voltage and module back surface temperature. The I-V characteristics of the module under constant global irradiance from 300 W/m^2 to 900 W/m^2 at 100 W/m^2 interval were compiled. The response variables,

a) V_{oc} – open-circuit voltage
b) I_{sc} – short-circuit current
c) V_{max} – voltage at maximum power
d) I_{max} – current at maximum power
e) P_{max} and E_{max} – maximum power and efficiency
f) Fill factor, FF%

were correlated to measured ambient conditions in terms of ambient temperature, global and diffuse irradiance on the plane of the module and wind speed. Some of the response variables were strongly dependent on the module temperature, which is in turn a function of irradiance, ambient temperature and module thermal inertia.

General performance of the module

Table 1 tabulates the response variables at each global irradiance level. They are average values computed from several sets of I-V characteristic curve at each irradiance level. Standard deviation within each irradiance level, except WS and TC, is on more than 6% of the average value.

The variances of ambient temperature TA between irradiance levels and within each irradiance level do not differ significantly. In other words, as observed, variations in TA cannot be statistically explained by variations in irradiance levels, but may be due to other variables or measurement precision around its average value. Therefore, a model to explain the variations in ambient temperature will not be pursued in the following discussions.

Theoretical considerations indicate that TC, I_{sc}, I_{max} and subsequently P_{max} are dependent on irradiance levels, and the rest of the parameters insensitive to irradiance levels, except their apparent effects through the cell temperature. The average module temperature increases with increasing irradiance level, thereby making V_{oc}, V_{max}, E_{max} and FF% seem to vary with irradiance level as well.

Module temperature

Partial correlation analyses of module temperature TC in response to ambient parameters show that irradiance level explained 64% of the variation in TC and ambient temperature explained 34.9% of the variation in TC (Table 2) ; and a regression line fitted to observed data with irradiance level and ambient temperature as independent variable has a coefficient of determination value of 0.737 (73.7% variation in TC explained by the regression line).

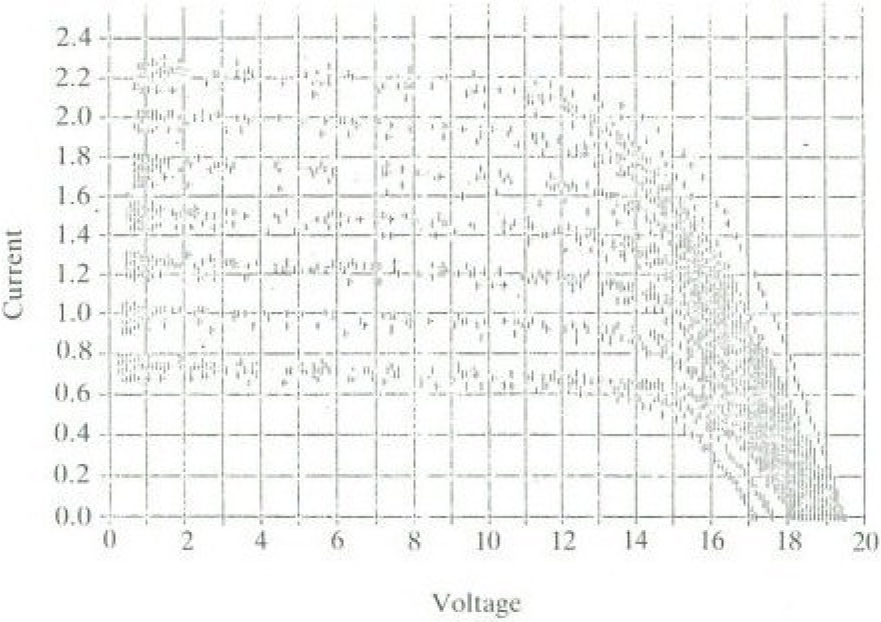

Fig. 1A I-V characteristics observed from 300 W/m^2 to 900 W/m^2

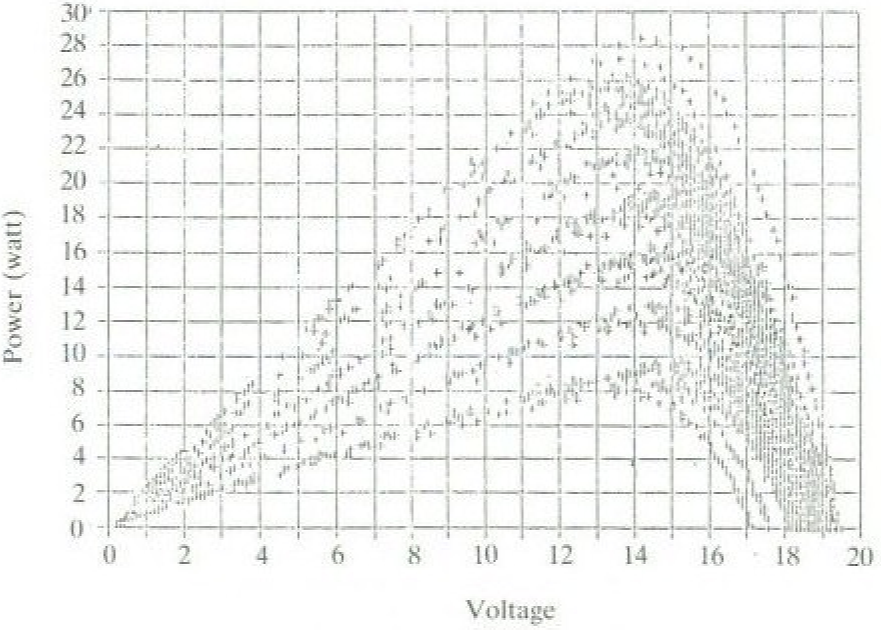

Fig. 1B Module power against module voltage, indicating movement of V$_{max}$ due to TC and not directly a function of irradiance level

TABLE 1
SUMMARY OF AVERAGE MODULE PERFORMANCE UNDER NATURAL CONDITION FROM 8 JUNE TO 4 JULY 1988. MODULE AREA IS 0.43326 M^2 OF 36 CELLS IN SERIES.

W/m^2	# of EXPT	TC °C	TA °C	WS m/s	V_{oc} V	I_{sc} Amp	V_{max} V	I_{max} Amp	P_{max} W	E_{max} %	FF%
300	35	38.7	32.4	0.9	18.6	0.74	14.8	0.61	9.0	7.0	65.8
400	18	40.1	32.7	0.9	18.8	1.00	14.9	0.84	12.6	7.2	66.5
500	26	42.1	32.6	0.9	18.8	1.26	14.6	1.07	15.8	7.2	66.2
600	21	43.8	33.0	1.1	18.8	1.51	14.5	1.29	18.6	7.2	65.6
700	13	45.7	32.3	1.3	18.8	1.77	14.2	1.51	21.6	7.1	64.7
800	10	47.8	33.0	1.2	18.6	2.01	13.9	1.73	24.1	6.9	63.7
900	15	50.4	33.3	1.1	18.6	2.23	13.4	1.94	26.1	6.7	62.5

*TC – module back surface temperature in °C
TA – ambient temperature in °C

TABLE 2

MODULE TEMPERATURE TC AS A FUNCTION OF RAD AND TA

I. Partial correlation : (TC response variable)

	R	R^2 (%)
RAD	0.80020	64.0 %
DIFFUSE	0.09440	0.9 %
TA	0.59085	34.9 %
WS	0.01714	0.3 %

II. Stepwise multiple regression of TC = f (RAD, TA)

R^2 = 0.737
F-ratio = 189.0686 with 133 degrees of freedom
A (Constant) = 30.006 ± 2.085 at 95% confidence interval
B (RAD coefficient) = 0.0175 ± 0.0022 at 95% confidence interval
C (TA coefficient) = 1.14 ± 0.268 at 95% confidence interval

Therefore, the empirical model for TC = f (RAD, TA) is

$$TC = A + B\,(RAD\text{-}300) + C\,(TA\text{-}25)$$

$$TC = 30.006 + 0.0175 * (RAD-300) + 1.14 * (TA-25)$$

$$TC = 30.006\,[1+5.832 \times 10^{-4} * (RAD-300) + 0.038 * (TA-25)] \ldots (1)$$

and these coefficients are specific to this particular module tested. A more complex model for TC involving heat transfer analysis of the module and ambient may give us a more physically meaningful coefficient than the empirical model.

Table 3 lists the temperature window at 80% and 90% confidence level. The average observed TC from Table 1 is included to check values predicted by equation 1. In every irradiance level the predicted value varies no more than 2% from the average observed TC.

A module may have a TC of 52°C at 900 W/m2, but when cloud effects decrease the global irradiance from 900 W/m^2 to 300 W/m^2 for 3–5 min, module temperature TC will not decrease instantaneously; neither will ambient temperature TA. Such cases are not predicted by the empirical model since equation 1 is an instantaneous model dependent on the instantaneous value of RAD and TA. Such cloud effects can only be predicted through a thermodynamic simulation within a day, using a heat transfer energy balance model.

TABLE 3
TEMPERATURE RANGE AT 80% AND 90% CONFIDENCE LEVEL OF FINDING TC AT EACH IRRADIANCE LEVEL.

RAD (W/m^2)	**Confidence level of finding TC**		**Average observed °C**	**Calculated eqn 1 °C**
	80%	**90%**		
300	35-40 ° C	35-43 ° C	38.7	38.5
400	36-43	36-44	40.1	40.5
500	40-44	40-46	42.1	42.2
600	42-46	41-47	43.8	44.4
700	45-47	44-47	45.7	45.3
800	44-50	44-51	47.8	47.9
900	50-53	49-53	50.4	50.0

The empirical model of TC = f(RAD, TA) in equation 1 is used in the last column. Refer to Table 1 for average TA values at each irradiance level. Equation 1 gives less than 2% error compared to average observed TC in every irradiance level.

Module response to ambient parameters

Table 4 is a partial correlation result of the module response variables to ambient parameters. Based from the data gathered, irradiance and module temperature explain a high percentage of variation in all the module response variables. Module current and power are sensitive to irradiance level, while voltage and efficiency are sensitive to module temperature. It is interesting to note that the irradiance level induced a positive response from the module, which is of no surprise ; while module temperature tends to degrade module performance. The other three ambient parameters (TA,WS,DIFF) do not exhibit any direct significant effects on the response of the module.

Among the response variables, I_{sc}, I_{max} and P_{max} are almost totally controlled (explained 98% to 99%) by the irradiance level. P_{max} (product of V_{max} and I_{max}) being highly sensitive to irradiance is mostly due to a higher correlation of I_{max} to irradiance compared to a lower correlation of V_{max} to TC. On the other hand, since I_{max} is almost proportional to irradiance, E_{max} becomes highly correlated to TC. Furthermore, irradiance has very little effect on V_{max}, while module temperature has very little effect on I_{sc} and I_{max}.

TABLE 4
PARTIAL CORRELATION OF RESPONSE VARIABLES TO AMBIENT PARAMETERS.

$R^2 \times 100\%$	Ambient parameter				
	RAD	**DIFF**	**TC**	**TA**	**WS**
V_{oc}	83.5	7.8	−85.8	−2.9	0.8
I_{sc}	99.5	0.3	0.007	−34.4	−7.9
V_{max}	−0.02	0.2	−39.1	0.8	1.5
I_{max}	98.7	0.4	0.1	−12.9	−1.7
P_{max}	97.9	3.9	−22.8	−5.0	−0.3
E_{max}	19.5	2.0	−36.3	−10.8	−3.8

$R^2 \times 100\%$ refers to the percentage of the variation of the response variables explained by the corresponding ambient parameters.

In order to determine the rate of variation of the response variables of Table 4 with respect to irradiance and module temperature, a linear model,

$$Y = A + B(RAD-300) + C(TC-25) \qquad \ldots(2)$$

is fitted to the observed data. The coefficient B and C is then the rate of variation with respect to irradiance and module temperature respectively. A better fit was achieved for V_{oc} and E_{max} when they are expressed as a logarithmic function of irradiance.

$$Y = A + B \cdot LN(RAD-100) + C(TC-25) \qquad \ldots(3)$$

Table 5 tabulates the result of a stepwise multiple linear regression. R^2 expressed in percent is the coefficient of multiple determination indicating the percentage of response variation explained by the regression model.

TABLE 5
STEPWISE MULTIPLE LINEAR REGRESSION

	A (Constant)	B (RAD coeff)	C (TC coeff)	R^2 (%)	MSE	F-ratio	
						RAD	TC
V_{oc}	15.518 (±0.190)	0.841 (±0.040)	−0.100 (±0.00389)	95.1	0.0056	39.52	2603.66
I_{sc}	0.797 (±0.021)	0.002569 (±0.000036)	−0.003458 (±0.001462)	99.7	0.0007	47,697	22.03
V_{max}	16.457 (±0.236)	–	−0.11181 (±0.01270)	69.2	0.134	–	304.89
I_{max}	0.650 (±0.026)	0.002255 (±0.000044)	−0.002157 (±0.001799)	99.5	0.001	24,628	5.64
P_{max}	11.373 (±0.425)	0.031445 (±0.000132)	−0.137871 (±0.029818)	99.1	0.297	15,209	83.43
E_{max}	5.527 (±0.462)	0.489 (±0.096)	−0.077 (±0.00945)	66.4	0.033	8.90	264.37

$Y = A + B(RAD-300) + C(TC-25)$

$Y = A + B * LN(RAD-100) + C(TC-25)$ For V_{oc} and E_{max}

V_{max} degrees of freedom = 136; others 135. 95% confidence interval estimated under each coefficient enclosed by a bracket.

The numeric value under each coefficient in Table 5 indicates the range of 95% confidence interval around the estimated coefficient. Therefore we are 95% confident that I_{sc} increased by 0.25 to 0.26 Ampere per every 100 W/m^2 rise in irradiance level ; and 95% confident that V_{oc} decreased by 96 mV to 109 mV per degree centigrade rise in module temperature. The sums-of-squares in Table 6 are computed as $\Sigma \text{RAD} = 300^{900}$ (OBS-PRED)^2. The sum-of-squares error for P_{max} ($V_m \times I_m$) improves by 63% when manual computation using V_{max} (PRED) and I_{max} (PRED) is compared to predicted value P_{max} (PRED) from the model in Table 5. This same advantage does not apply to E_{max}.

Module performance evaluation

The performance of the test module was evaluated in terms of its response variables (V_{oc}, V_{max}, I_{sc}, I_{max}, P_{max}, E_{max}). Ambient parameters that stimulate much of their responses (refer to Table 4) were the irradiance level and the thermal component of the surroundings, quantified not in terms of the ambient temperature which this report was not able to characterize, but rather quantified in terms of the module temperature measured at its back surface.

TABLE 6
A COMPARISON BETWEEN OBSERVED (OBS) (TABLE 1) AND PREDICTED (PRED) VALUES MODELLED FROM TABLE 5

		V_{oc}		I_{sc}		V_{max}		I_{max}		P_{max}			E_{max}	
RAD	TC	OBS (V)	PRED (V)	OBS (Amp)	PRED (Amp)	OBS (V)	PRED (V)	OBS (Amp)	PRED (Amp)	OBS (W)	PRED (W)	$V_m * I_m$	OBS (%)	PRED (%)
300	38.7	18.6	18.6	0.74	0.75	14.8	14.9	0.61	0.62	9.0	9.5	9.3	7.0	7.1
400	40.1	18.8	18.8	1.00	1.00	14.9	14.8	0.84	0.84	12.6	12.4	12.4	7.2	7.2
500	42.1	18.8	18.8	1.26	1.25	14.6	14.5	1.07	1.06	15.8	15.3	15.5	7.2	7.1
600	43.8	18.8	18.9	1.51	1.50	14.5	14.4	1.29	1.28	18.6	18.2	18.4	7.2	7.1
700	45.7	18.8	18.8	1.77	1.75	14.2	14.1	1.51	1.51	21.6	21.1	21.1	7.1	7.1
800	47.8	18.6	18.7	2.01	2.00	13.9	13.9	1.73	1.73	24.1	24.0	24.0	6.9	7.0
900	50.4	18.6	18.6	2.23	2.25	13.4	13.6	1.94	1.95	26.1	26.7	26.7	6.7	6.8
Sum-of-squares			0.029	0.000983			0.107	0.000259			1.338	0.490	0.0431	

Figures 5 and 6A to 6F are graphical tools based on analyses conducted in PV MODULE TEST section of this paper. They can be used for quick prediction of the module response variables (TC, V_{oc}, V_{max}, I_{sc}, I_{max}, P_{max}, E_{max}) knowing the irradiance level (RAD) and the ambient temperature (TA) for conditions similar to those prevailing in the Energy Park at AIT.

I_{sc}, I_{max} and P_{max} are highly sensitive to the irradiance level (Table 4, Figures 6C, 6D, 6E). The effect due to the thermal component of the surrounding measured through TC, the module temperature, becomes comparable to the effect due to the irradiance component in the case of V_{oc}, V_{max} and E_{max} (Figures 6A, 6B, 6F). V_{max} was found to be independent of the irradiance level (refer to Table 4, Figure 6B).

MAXIMUM POWER POINT WINDOW

Identification of the maximum power point and eventually fixing the system operating voltage at or near this point will optimize the energy production cost of the system. It is essential to investigate the behavior of the maximum power point (MPP) of the module during the operating period of the system ; the objective of which is to match the MPP variations of the module through the day as close as possible to the voltage requirement of the load, particularly when a tracker is not utilized.

The V_{max} window can be identified in Figure 2. From 300 W/m^2 to 900 W/m^2, V_{max} varies within a voltage window of 13 to 16 volts. The cloud of points at each irradiance level is due to module temperature (TC) negative effects, not so much an effect of irradiance level (Table 4). Therefore, controlling TC will help stabilize V_{max} throughout the day.

Figure 3 is a plot of the frequency distribution of V_{max} within this V_{max} window. Cumulative probability at every 0.5V interval is also indicated. There is a 44.6% probability of finding V_{max} between 14.5 to 15.5V within a day, while there is 50.3% probability that V_{max} is between 14 to 15V within a day. Therefore, when the system operating voltage varies between 14 to 15V during the day, 50.3% of the time from 8.00 a.m. to 5.00 p.m., the system is operating at the maximum power point, therefore maximum efficiency. Figure 3 can be used to measure how well the system voltage matches the MPP of this particular module. The peak of the V_{max} distribution for this particular module is 14.5V. Additional data will make the plot more symmetrical around 14.5V, and more accurate. If a maximum power point tracker is utilized, then Figure 3 will still guide us to find the operating voltage during the day.

Figure 4 shows us how the maximum efficiency varies during the day. A higher Emax is achieved in the morning than in the afternoon due to lower TC in the morning. Generally, global irradiance is almost symmetrical around noon even during cloudy days in the test site. Module temperature, however, tends to be higher in the afternoon, thereby affecting Vmax and Emax, negatively, by shifting their clouds of points downward in the afternoon.

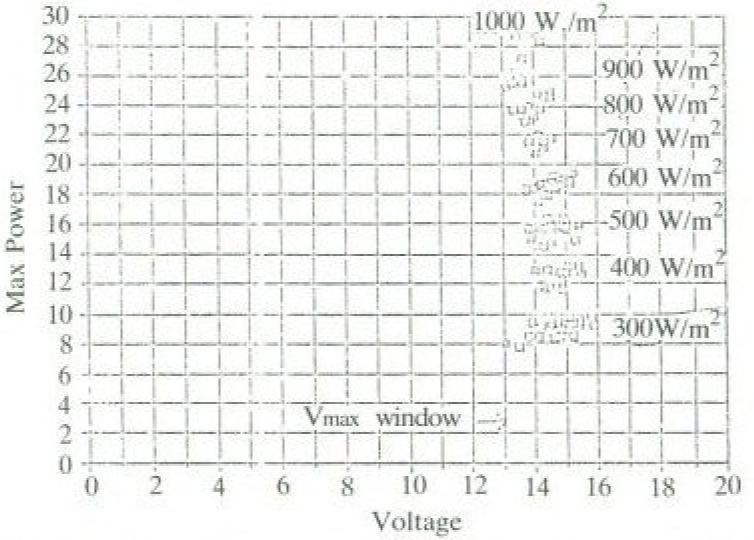

Fig. 2 Behavior of maximum power Pmax and maximum voltage Vmax at different irradiance levels, 300 W/m^2 to 1000 W/m^2

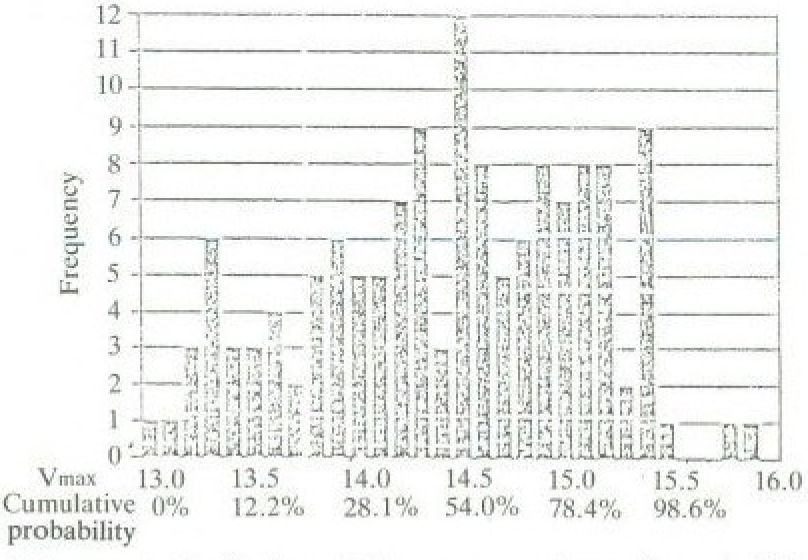

Fig. 3 Frequency distribution of Vmax to approximate the probability of the system operating at maximum power point if the system voltage is within the Vmax window (13–16 volts)

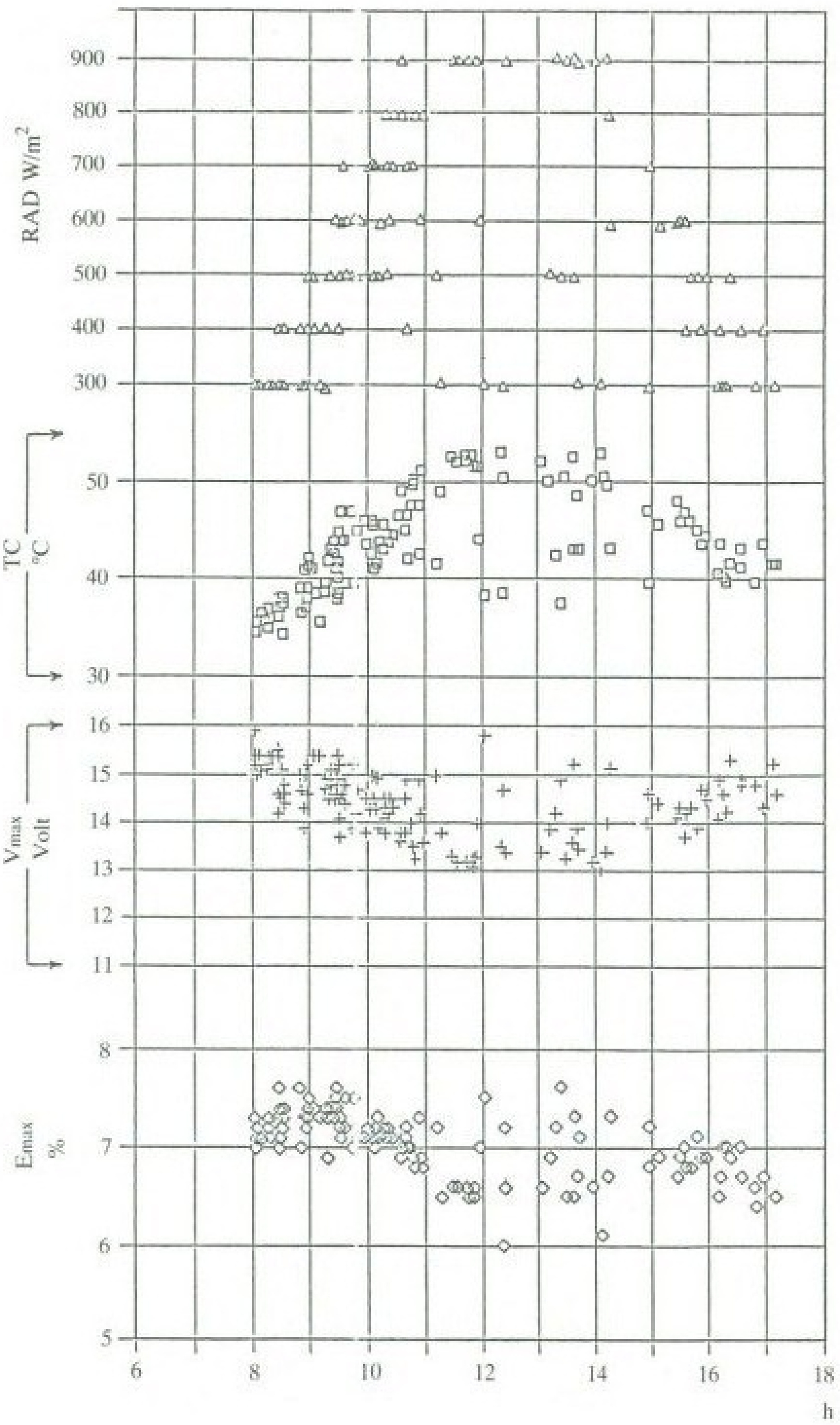

Fig. 4 Performance of the module on an average day. A higher efficiency is achieved in the morning due in large part to lower module temperature.

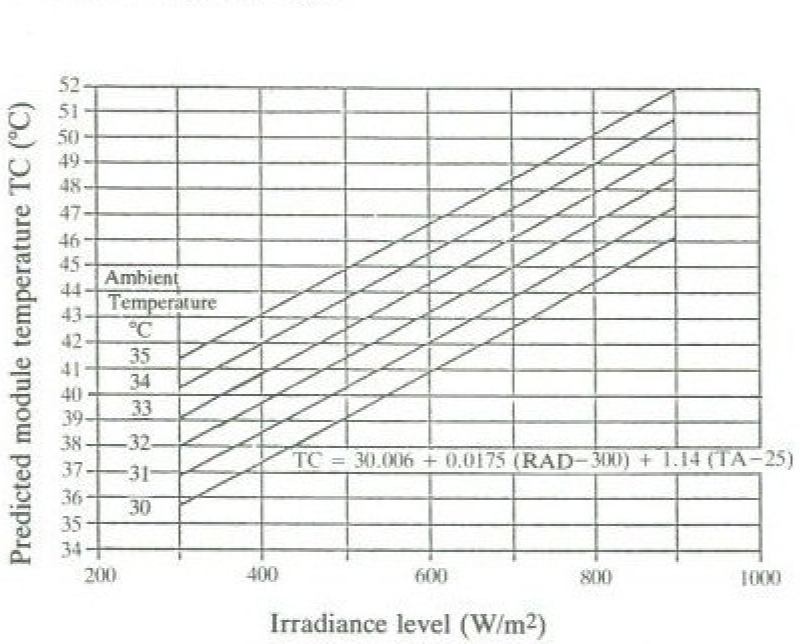

Fig. 5 Predict the module temperature by locating the irradiance level and ambient temperature. Once TC is predicted, other response variables can be predicted from Figures 6 A to 6 F

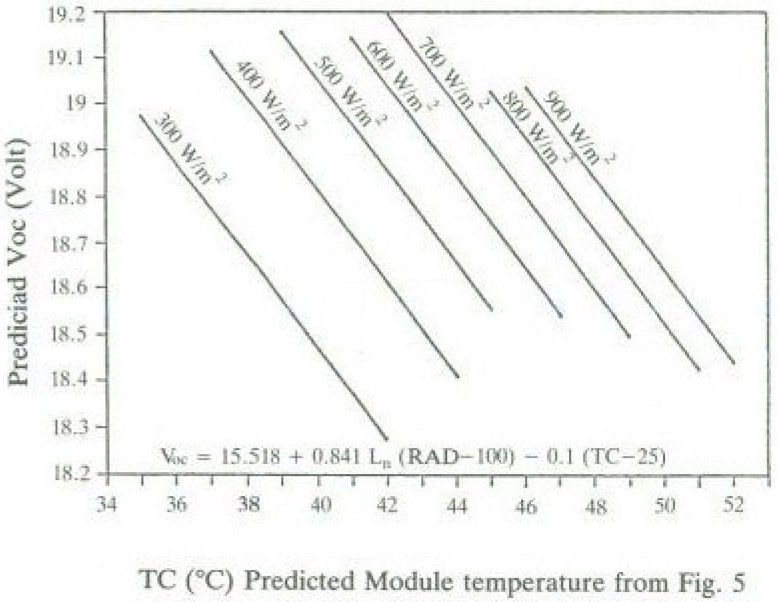

Fig. 6A TC (°C) Predicted module temperature from Fig. 5

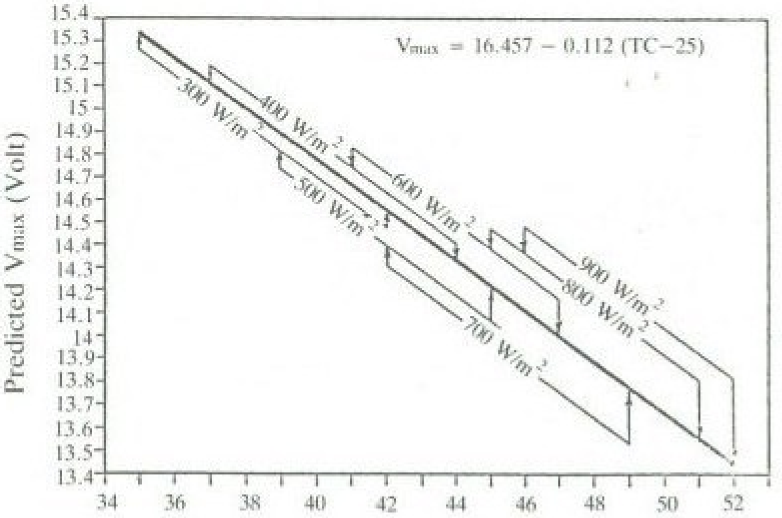

Fig. 6B TC(C°) Predicted module temperature from Fig. 5

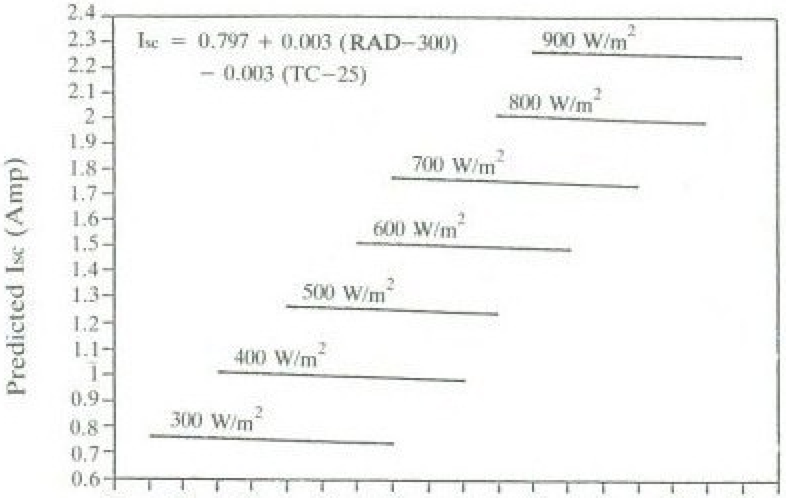

Fig. 6C TC (°C) Predicted module temperature from Fig. 5

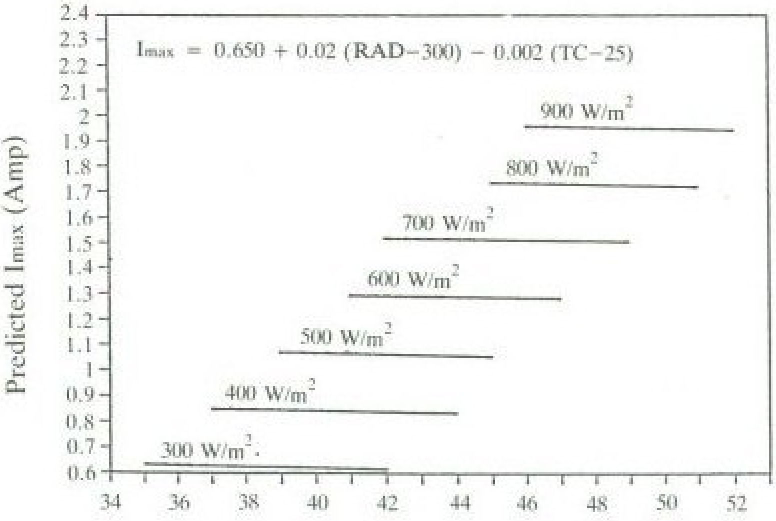

Fig. 6D TC (°C) Predicted module temperature from Fig. 5

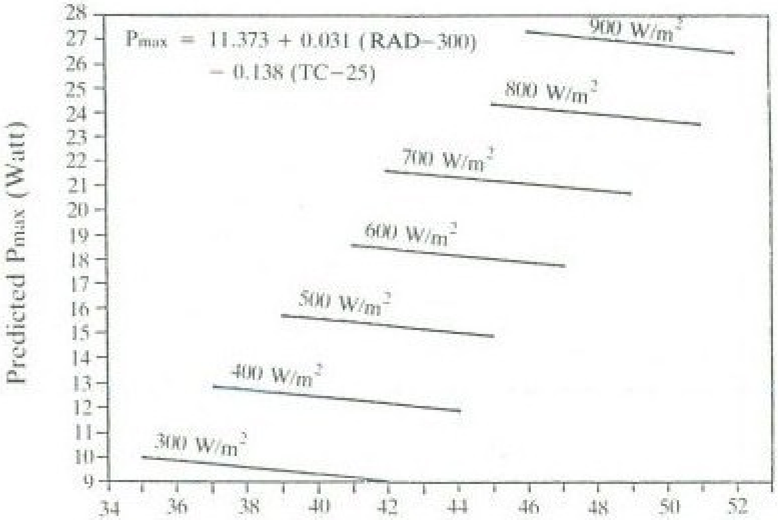

Fig. 6E TC (°C) Predicted module temperature from Fig. 5

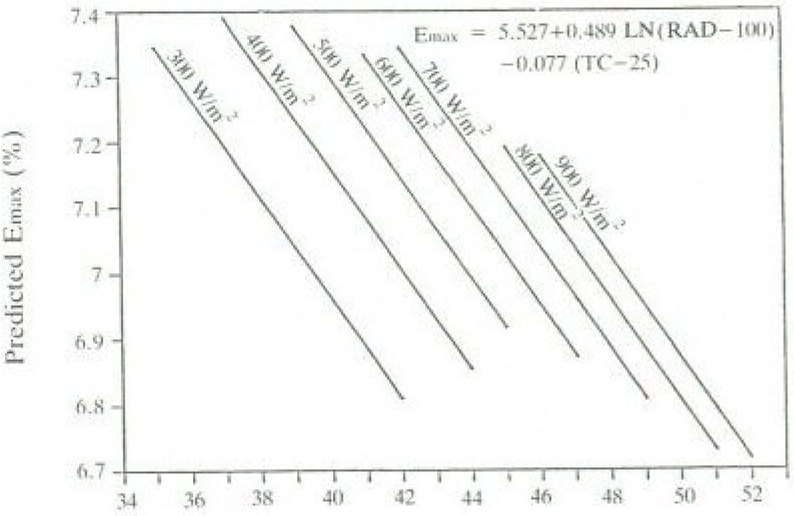

Fig. 6F TC (°C) Predicted module temperature from Fig. 5

CONCLUSION

Maximum power available from the test module was found to be around 26 watts at 900 W/m² 50°C (Table 6). The module will most probably produce not more than 30 watts at 1000 W/m² based on projection from Figure 6E. This is a 25% reduction from the power rating (45 W_p ± 10% @ 25°C) reported by the manufacturer. In financial terms, a user will be paying 35% more for power that does not exist in his system using this particular test module. However, caution must be taken there : the data available can only indicate a 25% power reduction of the module due to differences in the operating conditions to which the same module is subjected, out of the manufacturer's laboratory. They are not conclusive to reflect the quality or indicate a deterioration of the module. Nevertheless, this still points to a very important fact : If installed operating conditions are very different from those where the manufacturer's specifications were measured, a field test of the module in question will be necessary, unless financial constraint can allow an overdesign by more than 25% or an additional capital outlay of about 35%.

According to the empirical model for the maximum efficiency (E_{max}), even at 25°C 1000 W/m², the attainable maximum module efficiency will only be around 9%. At a more realistic module temperature of 52°C, the module efficiency is likely to drop down to around 7% of the nominal figure at 25°C.

NOMENCLATURE

AIT = Asian Institute of Technology
Amp = Ampere, a unit of current
D.F. = Degrees of freedom
DIFF = Diffuse irradiance, W/m^2
E_{max} = Module efficiency at maximum power point, %
FF% = Fill factor expressed as $(V_{max} * I_{max}) / (V_{oc} * I_{sc}) * 100\%$
I = Module current, Amp
I-V = Current against voltage
I_{max} = Module current at maximum power point, Amp
I_{sc} = Module short-circuit current, Amp
LN = Natural logarithmic function
MPP = Maximum power point
MSE = Mean sum-of-square error
OBS = Observed values
P_{max} = Module power at the maximum power point, watts
PRED = Predicted values
PV = Photovoltaic
PVPS = Photovoltaic power system
RAD = Irradiance, W/m^2
TA = Ambient temperature, °C
TC = Module back-surface temperature, °C
V = Volts, unit of voltage
V_{max} = Module voltage at the maximum power point, volts
V_{oc} = Module open-circuit voltage, volts
W = Watts, unit of electrical power
W_p = Watt peak, module electrical power output measured at standard conditions having the reference spectral distribution for irradiance at 1000 W/m^2 and at a cell temperature of 25°C
WS = Wind speed, m/s