Study on measurement of temperature coefficient of different types of PV modules in outdoor operating conditions in India

Module performance | Temperature coefficient has a well-known bearing on the performance of PV modules. Based on analysis of field data gathered from operational modules in India, Satish Pandey, Rajesh Dhuriya, Gaurav Mishra and Rakshita Mhatre reveal how in actual operating conditions the temperature coefficient of modules is deviating from values provided in manufacturer datasheets, potentially impacting on project financial modelling

The increasing market and profile of photovoltaics means that more applications than ever before are "photovoltaically powered". These applications range from power stations of several megawatts to solar chargers of a few volts. PV modules are incorporated in systems and the customers are interested in a high energy yield from those the systems. The energy yield from PV systems cannot be determined on the basis of the nominal power of the module. Under outdoor conditions irradiance and ambient temperatures are constantly varying, and at non-standard conditions the characteristics of the modules are often not known [1]. In this paper we try to evaluate the temperature coefficient of electrical parameters to determine the performance of PV modules in outdoor conditions typically found in India. In order to evaluate energy yield at actual and datasheet-mentioned temperature coefficients for two regions – Andhra Pradesh (latitude 13.82°N/longitude 78.09°E) and Rajasthan (latitude 27.4°N/ longitude 72.3°E) we have performed PVsyst (V6.41) simulations for corresponding regions. The temperature coefficients as per the manufacturer datasheet are shown in Table 1.

Experimental setup and approach

Real-time measurement of irradiance, module surface temperature and electrical parameters of modules was carried out in Rajasthan, India; five types of modules (two types of thin film CdTe modules and three polycrystalline silicon modules from two different suppliers) were used to compare the temperature coefficient of electrical parameters in real world conditions. All the modules were cleaned before performing the test to avoid the effect of soiling on the measurement. The irradiance at plane of module was measured using a pyranometer. The surface temperature of each module was measured using a PT100 temperature sensor attached to the rear side of the module. Data from the pyranometer and temperature sensor was automatically recorded in a data logger. The electrical parameters (voltage & current) of each module were measured in continuous mode using an I-V tracer, with each measurement taking around nine seconds. All the data was automatically recorded within an interval of one minute. Details of the equipment used are listed in Table 2 and Figure 1 shows the set up.

As per the module characteristic, the efficiency of the module is almost constant

Instrument	Measurement	Make (Model)	Specification	Accuracy
Pyranometer	Irradiance	Kipp & Zonen (CMP11)	0 to 2000 W/m2 285 to 2800nm -40°C to 80°C	+/- 2.0%
Temperature sensor	Module surface temperature	RTD PT100 (110 PV)	-0°C to 148°C	±0.1°C
Portable I-V curve tracer	PV module – electrical parameters	PV-engineering (PVPM100040C)	P: 0-4kW V: 0-1000V I: 0-40A	P: +/- 5% V & I: +/- 1%
Data logger	Data recording	Campbell Scientific (CR1000)		

Table 2. Instruments used for experiment and their specification

Sr. No	Supplier	Manufacturing year	No. of years since operation (years)	Country of origin	Technology	Datasheet temperature coefficient (%/°C)		
						Pmax	Voc	Isc
1	Supplier 1 Model 1	2013	4	China	Poly-Si	-0.43	-0.32	0.06
2	Supplier 1 Model 2	2013	4	China	Poly-Si_ PID free	-0.40	-0.30	0.06
3	Supplier 2 Model 1	2014	3	USA	Thin film-CdTe	-0.29	-0.28	0.04
4	Supplier 2 Model 2	2012	5	USA	Thin film-CdTe	-0.25	-0.27	0.04
5	Supplier 3 Model 1	2011	6	India	Poly-Si	-0.45	-0.35	0.05

Table 1. Experimental procedure parameters

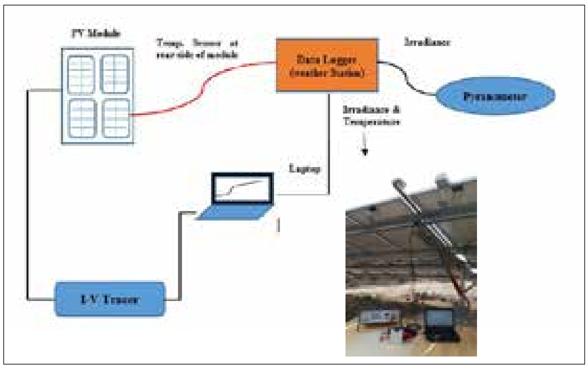

Figure 1. Block diagram of experimental set up with visual representation

for the irradiance level greater than 500W/m² [2]. To avoid the effect of irradiance level on the evaluation of temperature coefficient of electrical parameters of the modules, measurements with the I-V tracer were considered only for irradiance levels greater than 600W/m2 to 1,000W/m2. Further, to minimise the effect of fluctuating irradiance during I-V tracing, the measurements were carried out on a clear sky day.

The temperature coefficient of the electrical parameter was derived from the slope of the plot of measured electrical parameters versus module temperature as follows:

Voltage The measured voltage was plotted against measured module surface temperature and its slope was calculated.

Power The measured power was normalised with respect to measured irradiance. The normalised power was then plotted against measured module surface temperature and its slope was calculated.

The measured I-V characteristic is not affected by the resistance of the measurement cables, as it is carried out by a four-terminal measuring method [3]. In four-terminal measurement, the additional resistances like stray load loss and coupling resistance are avoided, and also the cable terminal resistance is significantly low. The measured values are reported at standard test conditions using translation as per IEC 60891:2009 PV devices procedure for temperature and irradiance correction to measured IV characteristics [4]. Using the measured parameters following curves are plotted:

Irradiance and temperature versus time:

Figure 2 shows the variation of irradiance and temperature with respect to time. The ideal time for testing can be determined from this curve. The time period is selected from the curve for which there is a linear increment in module temperature with increase in irradiance.

Linearity test current versus irradiance:

According to solar cell physics, current is directly proportional to irradiation. So the curve should be linear. Observing the curve in Figure 3, it can be determined what portion of the module characteristic is linear.

Normalised power versus module surface temperature:

The output power of the module linearly decreases as the module temperature increase, as shown in Figure 4.

Normalised Vmpp versus module surface temperature:

It is observed from Figure 5 that the maximum power point voltage linearly decreases as the module temperature increases.

Normalised Voc versus module surface temperature:

Open circuit voltage linearly decreases as the module temperature increases. As shown in Figure 6 the temperature coefficient is determined by the slope of the trend lines.

Observations

The values of temperature coefficient were different in field testing than the standard testing conditions (STC, IEC 60904–3) i.e., irradiation 1,000W/m², air mass 1.5 and the module temperature 25°C [5]. However during operation in the field PV modules spend a very short span of time under STC conditions. Thus an important characteristic for a module is to ensure an adequate performance in the field at different temperature and irradiance conditions. For the set of PV modules under test, the values as a function of the temperature for maximum power point, the open-circuit voltage and the maximum power point voltage are taken into account whereas the temperature coefficient of short circuit current (Isc) is very little so not taken into consideration. The power output of these modules is largely determined by the local climatic conditions where they are installed, hence it becomes important to obtain information on their actual field performance.

The plot between irradiance and temperature is shown in Figure 2. According to this graph, the area under the timing 08:41-11:53 is ideal to perform the test. The curve is linear in this region, meaning the temperature increases linearly with increases in irradiance. Along with ambient temperature the module's temperature is also very important for the test.

Results

Output power reduces as PV module temperature increases

According to Figure 4, the slope of Supplier 1 Model 1 is steepest hence the power output given by this module is decreasing rapidly with increasing temperature. Supplier 2 Model 2 has least slope, so its output power is decreasing slowly with increasing temperature.

Equation for evaluation of temperature coefficient (slope value) of power:

Y= Parameter on Y axis (i.e. normalised power in Figure 4)

X= Parameter on Y axis (i.e. module temperature in Figure 4).

R2= Correlation coefficient between x & y

Supplier 1 Model 1: $y = -0.0056x + 1.0987$, $R^2 = 0.9881$

Supplier 1 Model 2: $y = -0.0049x + 1.1329$, $R^2 = 0.9829$

Supplier 2 Model 1: $y = -0.0032x + 1.1078$, $R^2 = 0.9814$

Supplier 2 Model 2: $y = -0.0026x + 1.105$, $R^2 = 0.9645$

Supplier 3 Model 1: $y = -0.0041x + 1.0588$, $R^2 = 0.9671$

Output voltage at maximum power point (Vmpp) reduces as PV module temperature increases

According to Figure 5, Supplier 2 Model 2 shows least linear decrement in output voltage with increase in module temperature and the Supplier 1 Model 1 shows the highest decrement in normalised Vmpp per unit with increased module temperature.

Equation for evaluation of temperature coefficient of voltage at maximum power point:

Supplier 1 Model 1: $y = -0.0051x + 1.0833$, $R^2 = 0.9843$

Supplier 1 Model 2: $y = -0.0045x + 1.0896$, $R^2 = 0.9843$

Supplier 2 Model 1: $y = -0.0039x + 1.1752$, $R^2 = 0.9854$

Supplier 2 Model 2: $y = -0.0025x + 1.0272$, $R^2 = 0.9839$

Supplier 3 Model 1: $y = -0.0048x + 1.1114$, $R^2 = 0.9898$

The equation shows that the slope of Supplier 1 Model 1 is highest so the decrement of maximum power point voltage is rapid for this module with increases in temperature. The slope of Supplier 2 Model 2 is lowest hence the decrement of maximum power point voltage is slow for this module with increases in temperature.

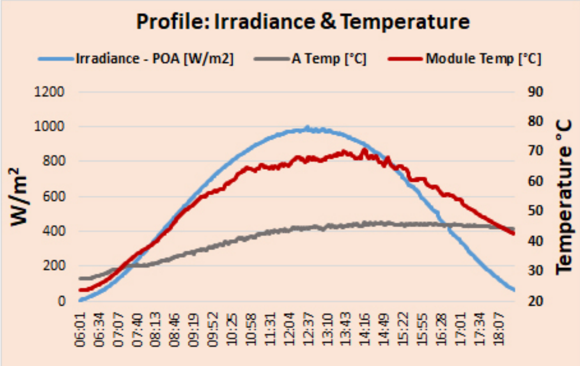

Figure 2. Graph representing linear region in irradiance & temperature curve

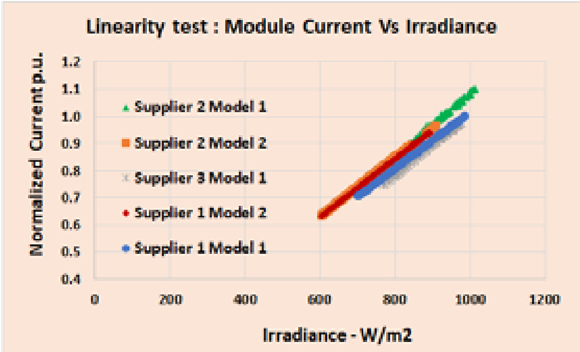

Figure 3. Normalised module current versus irradiance (linearity test)

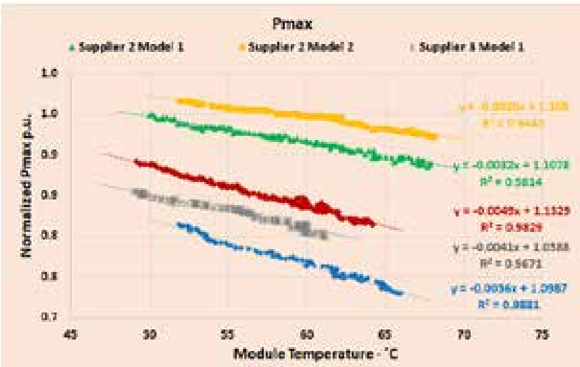

Figure 4. Normalised Pmax versus module temperature

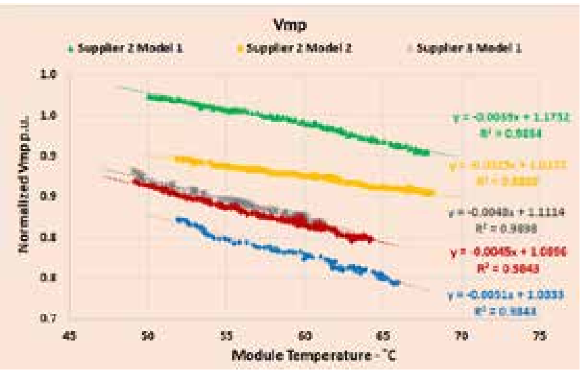

Figure 5. Normalised maximum voltage output versus module temperature

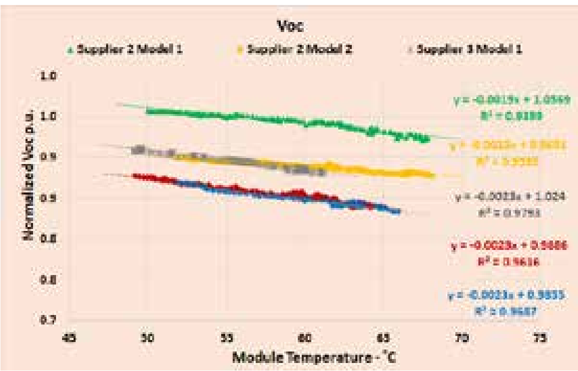

Figure 6. Normalised Voc versus module temperature

Output open circuit voltage (Voc) reduces as PV module temperature increases

Equation for evaluation of temperature coefficient of open circuit voltage:

Supplier 1 Model 1: $y = -0.0023x + 0.9855$, $R^2 = 0.9687$

Supplier 1 Model 2: $y = -0.0023x + 0.9886$, $R^2 = 0.9616$

Supplier 2 Model 1: $y = -0.0019x + 1.0569$, $R^2 = 0.9399$

Supplier 2 Model 2: $y = -0.0013x + 0.9651$, $R^2 = 0.9535$

Supplier 3 Model 1: $y = -0.0023x + 1.024$, $R^2 = 0.9793$

The equations show that, the slope of Supplier 1 Model 1 is highest so the decrement of open circuit voltage is rapid for this module with increases in temperature. The slope of Supplier 2 Model 2 is lowest so the decrement of open circuit voltage is slow for this module with increase in temperature.

Table 3 shows the values of the parameters like maximum power, Vmpp and the open circuit voltage for the various PV modules.

Observations from Table 3 are as follows:

Measured temperature coefficients of power are higher than the manufacturers' datasheets, except for Supplier 3. A possible reason may be due to low quality of wafer/cell processing.

Measured temperature coefficients of Vmpp (voltage at maximum power) are approximately close to temperature coefficients of Pmax; the same is claimed by different module manufacturers.

Measured temperature coefficients of open circuit voltage (Voc) are lower than manufacturers' datasheets.

Table 4 shows predicted temperature losses for respective module suppliers for two locations (Andhra Pradesh and Rajasthan); we have calculated the loss in energy for evaluation of impact of temperature coefficient.

Table 5 shows the energy losses predicted by PVsyst for respective module suppliers due to temperature coefficients given on manufacturer datasheets and those measured in the field in two locations (Andhra Pradesh and Rajasthan).

Table 6 shows the annual revenue loss at tariff US$0.07/kWh calculated on energy loss due to TMod predicted by PVsyst for two locations (Andhra Pradesh and Rajasthan).

Conclusion

It is observed that, in the field, the measured temperature coefficient (Tcpmax) of power is higher than the manufacture datasheet whereas the measured temperature coefficients of Vmpp and Voc are approximately close to datasheet. It is a known phenomenon of PV modules that a higher Tcpmax leads to higher losses in energy yield compared to a lower one. For prediction of energy, Tcpmax plays a vital role as financial models are based on predicted energy during the design stage;

Make & Model	Supplier 1 Model 1			Supplier 1 Model 2			Supplier 2 Model 1			Supplier 2 Model 2			Supplier 3 Model 1		
Temp coefficient (%/°C)	Pmax	Vmpp	Voc	Pmax	Vmpp	Voc	Pmax	Vmpp	Voc	Pmax	Vmpp	Voc	Pmax	Vmpp	Voc
Manufacturer datasheet	-0.43		-0.32	-0.40		-0.30	-0.29		-0.28	-0.25		-0.27	-0.45		-0.35
Measured	-0.56	-0.51	-0.23	-0.49	-0.45	-0.23	-0.32	-0.39	-0.19	-0.26	-0.25	-0.11	-0.41	-0.48	-0.23
Variation from datasheet	-0.13		0.09	-0.09		0.07	-0.03		0.09	-0.01		0.16	0.04		0.12
Observed TC of Pmax	-0.38 to -0.63			-0.34 to -0.54						-0.17 to - 0.35			-0.27 to -0.51		

Table 3.Temperature coefficients of various PV modules. Note figures in red highlight where the measured value is greater than the one given by the manufacturer

PVsyst measured reference temperature	Location	Temperature losses due to temperature coefficient	Units of Measurement	Supplier 1 Model 1	Supplier 1 Model 2	Supplier 2 Model 1	Supplier 2 Model 2	Supplier 3 Model 1
46.54	Andhra Pradesh, India	Manufacturer	%	-9.30%	-8.60%	-6.20%	-5.40%	-9.70%
		Measured on Field	%	-12.10%	-10.60%	-6.90%	-5.60%	-8.80%
		Absolute Delta	%	-2.80%	-1.90%	-0.60%	-0.20%	0.90%
48.43	Rajasthan, India	Manufacturer	%	-10.10%	-9.40%	-6.80%	-5.90%	-10.50%
		Measured on Field	%	-13.10%	-11.50%	-7.50%	-6.10%	-9.60%
		Absolute Delta	%	-3.00%	-2.10%	-0.70%	-0.20%	0.90%

Table 4. Predicted temperature losses of respective module suppliers

	Location	Temperature losses due to temperature coefficient	Units of measurement	Supplier 1 Model 1	Supplier 1 Model 2	Supplier2 Model1	Supplier 2 Model2	Supplier 3 Model 1
Energy loss due to PVsyst Predicted Tmod (kWh)	Andhra Pradesh, India	Manufacturer	kWh/kWp/Year	-164	-153	-111	-96	-168
		Measured on Field	kWh/kWp/Year	-213	-188	-123	-100	-153
		Absolute Delta	kWh/kWp/year	-49.54	-34.51	-11.5	-3.83	14.91
	Rajasthan, India	Manufacturer	kWh/kWp/Year	1719	1719	1778	1788	1663
		Measured on Field	kWh/kWp/Year	1666	1682	1765	1784	1678
		Absolute Delta	kWh/kWp/Year	-53.04	-36.46	-12.25	-4.07	15.86

Table 5. Energy loss due to TMod predicted by PVsyst. Note, negative sign Indicates that manufacturer given losses are lower than actually measured losses in the field

	Location	Temperature Losses Due to Temperature coefficient	Units of Measurement	Supplier 1 Model 1	Supplier 1 Model 2	Supplier2 Model1	Supplier 2 Model2	Supplier 3 Model 1
Annual Revenue loss(-)/gain(+) per MWp at tariff USD 0.07/kWh	Andhra Pradesh, India	Difference	kWh/MWp	-49535.4	-34507.0	-11502.3	-3827.6	14914.3
		Revenue loss	USD/MWp	-$3,429	-$2,389	-$796	-$265	$1,033
	Rajasthan, India	Difference	kWh/MWp	-53035.6	-36465.0	-12251.9	-4071.0	15862.0
		Revenue loss	Rs/MWp	-$3,672	-$2,524	-$848	-$282	$1,098

Table 6. Annual revenue loss at tariff USD¢7/kWh

if the Tcpmax is not as per committed value then generated energy will be lower than the predicted energy, which can disrupt a project's financial modelling. Considering the fact that in the field PV modules spend a very short period at standard test conditions and almost 96% of the time at non-STC condition, which can lead to lower generation of electrical yield, PV module manufacturers must therefore precisely determine Tcpmax values for different operating temperatures, not only standard test conditions.

As per Table 6, the maximum annual revenue loss is US$3,672 and US$3,429 for 1MW plant in Rajasthan and Andhra Pradesh respectively with Supplier 1 Model 1 which is a significant revenue loss that could disrupt the financial model. If we consider 1GW of solar PV portfolio in Rajasthan & Andhra Pradesh, the expected revenue loss would be US$3.67 & US$3.43 million per year for maximum potential and US$1.25 & US$1.17 million per year for average potential respectively. If we consider 25 years of operation for the developer then resulted revenue loss will be huge.

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