

# Outdoor Energy Rating Measurements of Photovoltaic Modules

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## ABSTRACT

Photovoltaic (PV) modules are currently rated for power (W) under standard test conditions (STC). The overall objective of this work is to rate the PV modules for the energy (Wh) production per IEEE1479 and IEC61853 draft standards, and per user defined site specific conditions. The primary difference between the previous works and this work is the use of outdoor (natural sunlight) based equipment rather than the indoor (solar simulator) based equipment. This paper presents key information on this outdoor equipment including: the design characteristics of thermal test bed (TTB) installed on a 2-axis tracker outdoor; the capability of this TTB to control the module temperatures between 5°C and 60°C; the means to change the irradiances on the test module; and the technique to carry out spectral mismatch measurements. The results obtained from these measurements, on a typical PV module, are analyzed, modeled and presented.

## 1. Introduction

Major advantages of using natural sunlight for the energy rating of photovoltaic (PV) modules include: elimination of expensive solar simulator, usage of actual solar spectra and high level of spatial light uniformity. However, the challenges of using natural sunlight include: attaining equilibrium/stabilized module temperature in an uncontrolled ambient temperature with continuous solar gain, avoiding condensation of water on the surface of the modules at low temperatures, and accounting for the global irradiance, spectral irradiance and angle of incidence change over the period of measurements. The primary objective of this research work is to investigate the feasibility of performing energy rating of PV modules using natural sunlight with a temperature controlled test bed installed on a two-axis tracker. The results obtained from this investigation are analyzed, modeled and presented in this paper.

## 2. Methodology

The test set up used in this investigation is located in Mesa, Arizona. This is a very dry location receiving a total normal insolation of about 8.9 kWh/m<sup>2</sup>/day. Major issues related water condensation and irradiance fluctuation are addressed by carrying out the

measurements on very clear days at this selected location. The issue related to minor irradiance fluctuation, if any, during the measurement period is addressed using a reference cell installed coplanar to the module. The angle of incidence (AOI) effect is eliminated by installing the test bed/module on a two-axis tracker. The spectral mismatch error is virtually eliminated because of the use of matched reference cell and the negligible difference between the reference spectrum and test spectra collected on clear days between 9 AM and 3 PM at this location. After eliminating all the above variables, the challenge boils down to attaining equilibrium/stabilized module temperature only. This stabilized module temperature issue is addressed by using a well insulated test bed/box in conjunction with an air conditioning unit as shown in Figure 1. To change the irradiances, several perforated black mesh screens are used as neutral density filters as shown in Figure 2.

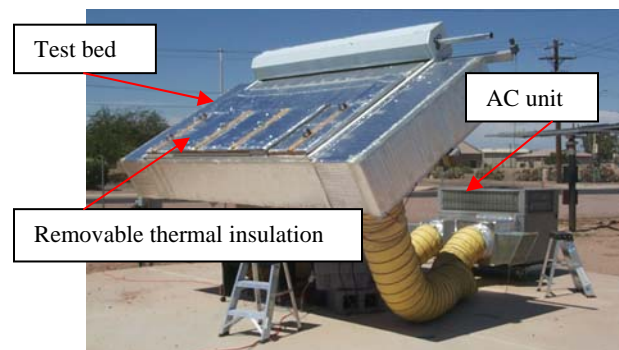


Figure 1: Photograph of thermal test bed installed on a 2-axis tracker

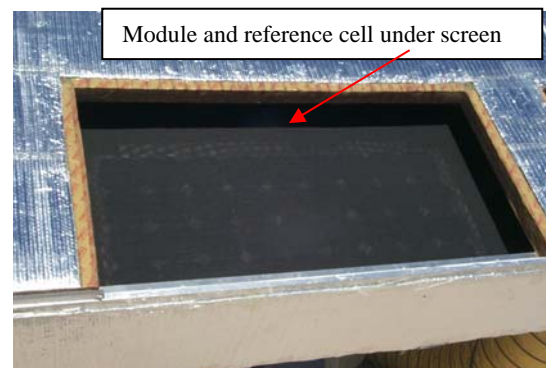


Figure 2: Photograph of a module and reference cell covered by a screen

Electrical performance data (I-V curves) of a test module were collected at different module temperatures (5 to 65°C) and irradiances (130, 250, 600, 700, 1000 W/m<sup>2</sup>). Mathematical models were then developed based on the collected data for the prediction of the module electrical performance (I<sub>sc</sub>, V<sub>oc</sub>, I<sub>mp</sub>, V<sub>mp</sub> and P<sub>max</sub>) at a given module temperature and irradiance.

### 3. Results and Accomplishments

#### 3.1 Spectral mismatch analysis

Spectral mismatch errors for different PV technologies were obtained based on the spectral response of the test device, reference device, onsite spectra (collected between 9 AM and 3 PM using a spectral radiometer) and the reference spectrum<sup>1</sup>, and the maximum errors, in percentage, are shown in Table 1. The mismatch error for mono-Si investigated in this study is practically negligible, 0.23%.

Table 1: Maximum spectral mismatch errors obtained for different PV technologies

Reference Cell Technology	Module Technology	Mismatch (%)
mono-Si	CdTe	2.03
	GaAs	2.50
	mono-Si	0.23
	poly-Si	0.74
GaAs	CdTe	1.30
	mono-si	2.58
	poly-Si	3.32

#### 3.2 Model Development

A simple linear model and a complex nonlinear model were developed to obtain various important parameters of an I-V curve at an unknown module temperature and irradiance. The simple model works very well for I<sub>sc</sub>, V<sub>oc</sub>, I<sub>mp</sub> and V<sub>mp</sub>, but not for P<sub>max</sub> (Figure 3). The complex model works well for all the above parameters including P<sub>max</sub> (Figure 4). MATLAB's neural network toolbox was used to develop these models.

##### 3.2.1 Simple linear model

Equation 1 provides the simple model:

$$Y = c_1 * (T - 25) + c_2 * E + c_3 \quad (1)$$

where Y is the modeled data for I<sub>sc</sub> (A), V<sub>oc</sub> (V), I<sub>mp</sub> (A), V<sub>mp</sub> (V) or P<sub>max</sub> (W); T is the module temperature (°C); E is the irradiance (W/m<sup>2</sup>); c<sub>1</sub>, c<sub>2</sub>, c<sub>3</sub> are coefficients.

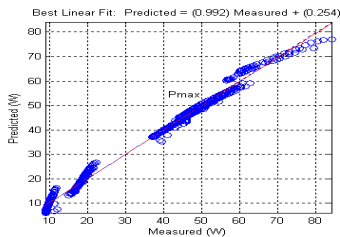


Figure 3: Simple model – Predicted vs. Measured P<sub>max</sub>

##### 3.2.2 Complex nonlinear model

The nonlinear complex model is shown by equations (2) through (5):

$$T_n = 2 * \frac{(T - T_{min})}{(T_{max} - T_{min})} - 1 \quad (2)$$

$$E_n = 2 * \frac{(E - E_{min})}{(E_{max} - E_{min})} - 1 \quad (3)$$

$$Y_n = c_1 * \left( \frac{1}{1 + \exp[-(a_1 * T_n + a_2 * E_n + a_3)]} \right) + c_2 * \left( \frac{1}{1 + \exp[-(b_1 * T_n + b_2 * E_n + b_3)]} \right) + c_3 \quad (4)$$

$$P = 0.5 * (Y_n + 1) * (M_{max} - M_{min}) + M_{min} \quad (5)$$

where T<sub>n</sub> and E<sub>n</sub> are the preprocessed data of module temperature and irradiance; T<sub>min</sub> (°C), T<sub>max</sub>, E<sub>min</sub> (W/m<sup>2</sup>) and E<sub>max</sub> are the minimum and maximum values of module temperature and irradiance among all the measured data; a<sub>1</sub>, a<sub>2</sub>, a<sub>3</sub>, b<sub>1</sub>, b<sub>2</sub>, b<sub>3</sub>, c<sub>1</sub>, c<sub>2</sub>, c<sub>3</sub> are coefficients; P is the modeled data for I<sub>sc</sub> (A), V<sub>oc</sub> (V), I<sub>mp</sub> (A), V<sub>mp</sub> (V), or P<sub>max</sub> (W); M<sub>min</sub> and M<sub>max</sub> are minimum and maximum value of measured I<sub>sc</sub>, V<sub>oc</sub>, I<sub>mp</sub>, V<sub>mp</sub> and P<sub>max</sub>.

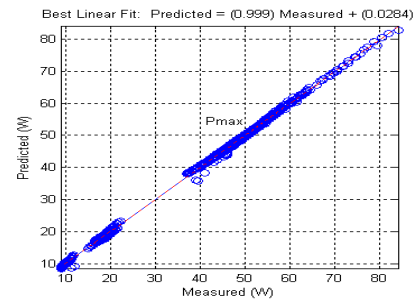


Figure 5: Complex model - Predicted vs. Measured P<sub>max</sub>

### 4. Conclusions

The results shown in this study indicate that it is feasible to carry out energy rating of PV modules using natural sunlight with a temperature controlled test bed installed on a two-axis tracker. The error related to spectral mismatch could be reduced to negligible level by using natural sunlight and a reference cell of matched technology. The complex model developed in this investigation works well for a mono-Si module. However, this model needs to be validated for other modules and technologies by generating module-dependent coefficients involved in this model. By combining this complex model with the thermal model developed in a previous work<sup>2</sup>, it is possible to predict the module performance parameters using just three input parameters from ambient conditions (ambient temperature, POA irradiance measured with a reference cell of matched technology, and wind speed).

### REFERENCES

- [1] ASTM G159: *Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37 Tilted Surface*
- [2] G. TamizhMani, L. Ji, Y. Tang, L. Petacci and C. Osterwald, *Photovoltaic Module Thermal/Wind Performance: Long -Term Monitoring and Model Development for Energy Rating*, NCPV Meeting, 2003.