National Renewable Energy Laboratory
Innovation for Our Energy Future

Comparison Of Predictive Models for PV Module Performance

Bill Marion

1. Introduction

This paper examines three models used to estimate the maximum power (P_m) of PV modules when the irradiance and PV cell temperature are known: (1) the power temperature coefficient model, (2) the PVFORM model, and (3) the bilinear interpolation model. A variation of the power temperature coefficient model is also presented that improved model accuracy.

For modeling values of P_m, an "effective" plane-of-array (POA) irradiance (E_e) and the PV cell temperature (T) are used as model inputs. Using E_e essentially removes the effects of variations in solar spectrum and reflectance losses, and permits the influence of irradiance and temperature on model performance for P_m to be more easily studied. Eq. 1 is used to determine E_e from T and the PV module's measured short-circuit current (I_{sc}). Zero subscripts denote performance at Standard Reporting Conditions (SRC).

$$E_e = \frac{I_{sc} \cdot E_0}{I_{sc_0} \cdot [1 + \alpha \cdot (T - T_0)]} \qquad (1)$$

where

I_{sc} = short-circuit current, A
E = POA irradiance, W/m^2
α = short-circuit current correction factor for temperature, ^{0}C^{-1}
T = PV cell temperature, ^{0}C.

2. Power Coefficient & PVFORM Models

The Power Temperature Coefficient Model - This model applies a temperature correction to P_m to account for departures in cell temperature from those at SRC. P_m is assumed to be linear with respect to the effective irradiance if the temperature is constant. Eq. 2 represents this model. Zero subscripts denote performance at SRC.

$$P_m = \frac{E_e}{E_0} \cdot P_{m_0} \cdot [1 + \gamma \cdot (T - T_0)] \qquad (2)$$

where

γ = maximum power correction factor for temperature, ^{0}C^{-1}.

The PVFORM Model - The PVFORM model is the same as the power temperature coefficient model for irradiance levels greater than 125 W/m^2, but PVFORM uses a different formulation for irradiance levels of less than 125 W/m^2 to account for reductions in output observed for crystalline silicon modules by Sandia National Laboratories, the originators of this model.

For Ee ≤ 125 W/m^2,

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$$P_m = \frac{0.008 \cdot {E_e}^2}{E_0} \cdot P_{m_0} \cdot [1 + \gamma \cdot (T - T_0)] \qquad (3)$$

3. Bilinear Interpolation Model

This model is based on work by Hishikawa and colleagues which developed translation equations for interpolating, with respect to the irradiance, a current-voltage (I-V) curve from two I-V curves at the same PV cell temperature. Marion and colleagues expanded this work by developing a method in which four I-V curves could be used to bilinearly interpolate an I-V curve with respect to both irradiance and PV cell temperature.

Fig. 1 illustrates the bilinear interpolation methodology. I-V curves 1 through 4 are the reference I-V curves measured for combinations of two PV cell temperature and two irradiance settings. To perform the bilinear interpolation, I-V curves 5 and 6 are interpolated with respect to open-circuit voltage (V_{oc}) from I-V curves 1 and 2, and 3 and 4, respectively, and I-V curve 7 is interpolated with respect to I_{sc} from I-V curves 5 and 6. I-V curve 7 is the translated I-V curve for the desired conditions of E_e and T.

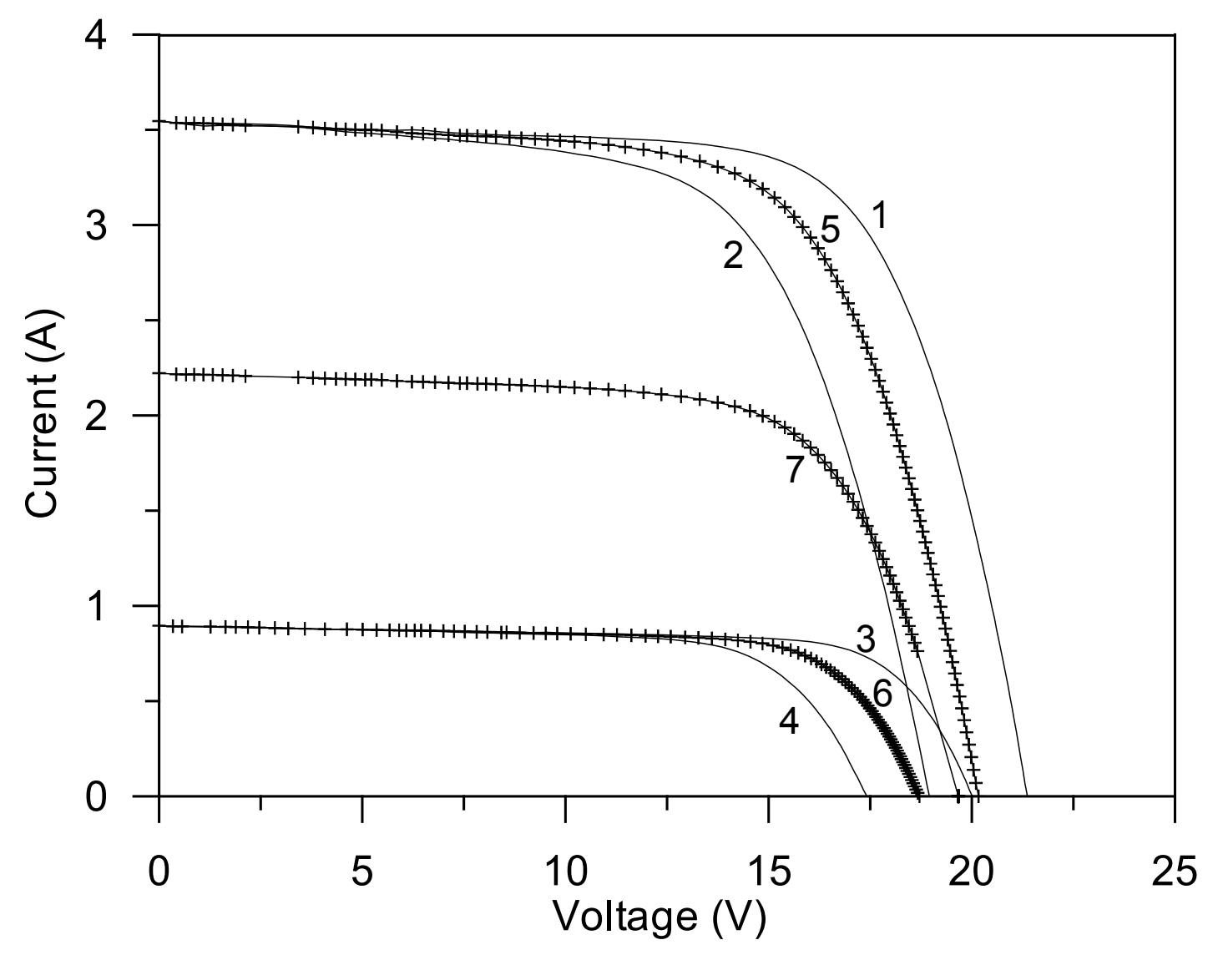

Fig. 1. Numbering of I-V curves for bilinear interpolation

4. Data and PV Module Characterization

NREL's Performance and Energy Rating Testbed (PERT) supplied the data used to evaluate model performance. These data were collected from April 1, 2005 through March 31, 2006, except for the CdTe PV module, on which data were available only from 11 November, 2005 through March 31, 2006. The data include I-V curves measured at 15-minute intervals with coincident measurements of POA irradiance and PV module back-surface temperatures. To reduce data uncertainty, pyranometer calibration data were used to correct irradiance measurements for cosine response. In addition, cell temperatures were estimated by adding 2.5^{0}C per 1,000 W/m^2 irradiance to the PV module back-surface temperatures.

To obtain the input information required by the models, PV module performance was characterized using PERT I-V curve data measured on March 14, 2006, a day with clear skies and a fairly large temperature differential between morning and afternoon. These conditions afforded the opportunity to select four reference I-V curves that met the criteria for the bilinear interpolation method (two irradiance levels and two temperatures for an irradiance level). Using the I-V curve data and their coincident measurements of irradiance and PV module temperature, the PV module coefficients were determined.

5. Model Error Statistics

Model estimates and measured data were compared using root-mean-square-error (RMSE), mean-bias-error (MBE), and mean-absolute-error (MAE) statistics. RMSE provides information on the variation of the modeled values from the measured values, MBE provides the average deviation of the modeled values from the measured values, and MAE provides the average absolute deviation of the modeled values from the measured values. RMSE and MAE are always positive, whereas MBE can be either positive or negative.

Although the word "error" is used, "difference" would be more accurate because the true values are not known and because the differences between measured and modeled values are being reported.

Table 1 gives modeling error statistics for P_m by model and PV module. The Ave column shows the average P_m of the measured data by PV module. The error statistics are presented as a percentage error of the average P_m.

Overall, the bilinear interpolation model performed best with the lowest errors, followed by the PVFORM model which yielded slightly lower errors than the power temperature coefficient model.

6. Tabular Results for Model Errors

Table 1. MBE, MAE, and RMSE Statistics for P_m by Model and PV Module. The bilinear interpolation model provided the smallest errors. The PVFORM model errors were slightly less than those for the power temperature coefficient model.

Technology	Ave. (W)	Power Temperature Coefficient Model			PVFORM Model			Bilinear Interpolation Model		
		MBE (%)	MAE (%)	RMSE (%)	MBE (%)	MAE (%)	RMSE (%)	MBE (%)	MAE (%)	RMSE (%)
Multi-crystal Si	19.5	3.9	4.3	5.5	2.8	3.4	4.8	-0.3	0.7	1.6
Multi-crystal Si	16.7	3.2	3.4	4.0	2.1	3.0	3.6	0.1	0.7	1.2
Single-crystal Si	36.1	0.0	1.5	1.8	-1.1	1.7	2.1	-0.4	1.4	1.7
Single-crystal Si	29.9	0.4	1.6	1.9	-0.7	1.6	1.9	0.2	1.5	1.8
Single-crystal Si	28.9	0.9	2.2	2.8	-0.2	2.1	2.7	-0.8	1.2	2.0
a-Si/x-Si HIT	84.7	1.1	1.4	1.7	0.1	1.7	2.1	0.2	0.7	1.0
a-Si/a-Si/a-Si:Ge	15.3	-2.6	3.2	4.5	-3.5	3.9	4.9	-2.0	3.3	4.4
CdTe	25.8	-1.6	2.3	3.0	-2.2	2.8	3.4	-0.9	1.9	2.5

7. a-Si Seasonal Degradation-Recovery

For the a-Si/a-Si/a-Si:Ge PV module, the data show about a 5% reversible degradation-recovery cycle from late winter (degradation) to late summer (annealing). Figure 2 shows this as increased modeling error for September 2005 when compared to March 2006. PV module performance was characterized using data measured at the beginning of the recovery cycle. For September, relative PV module performance had improved by about 5%, and the models underestimated the performance by about the same amount.

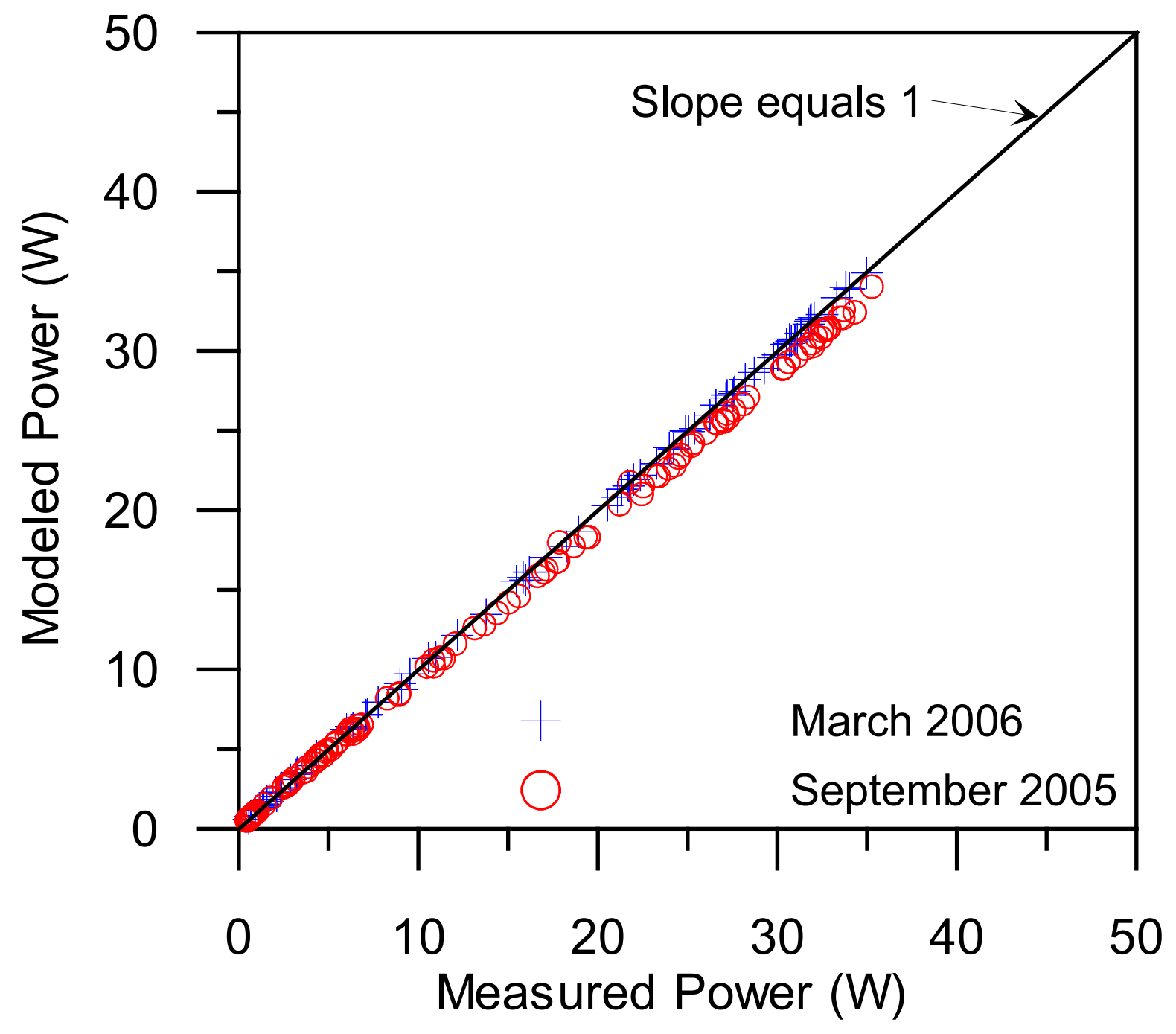

Fig. 2. Modeled versus measured P_m showing the effect of annealing for the a-Si/a-Si/a-Si:Ge PV module.

8. Influence of Irradiance

The power temperature coefficient model only uses characterization data at SRC; consequently, if the PV module does not maintain its efficiency at lower irradiance levels, the model will overestimate performance. This is illustrated in Fig. 3 for a multi-crystal Si PV module with the model error expressed as a percentage of irradiance to illustrate how irradiance level affects model accuracy. (Note: A large percentage error at a low irradiance may have less impact on energy production than a small percentage error at a high irradiance.)

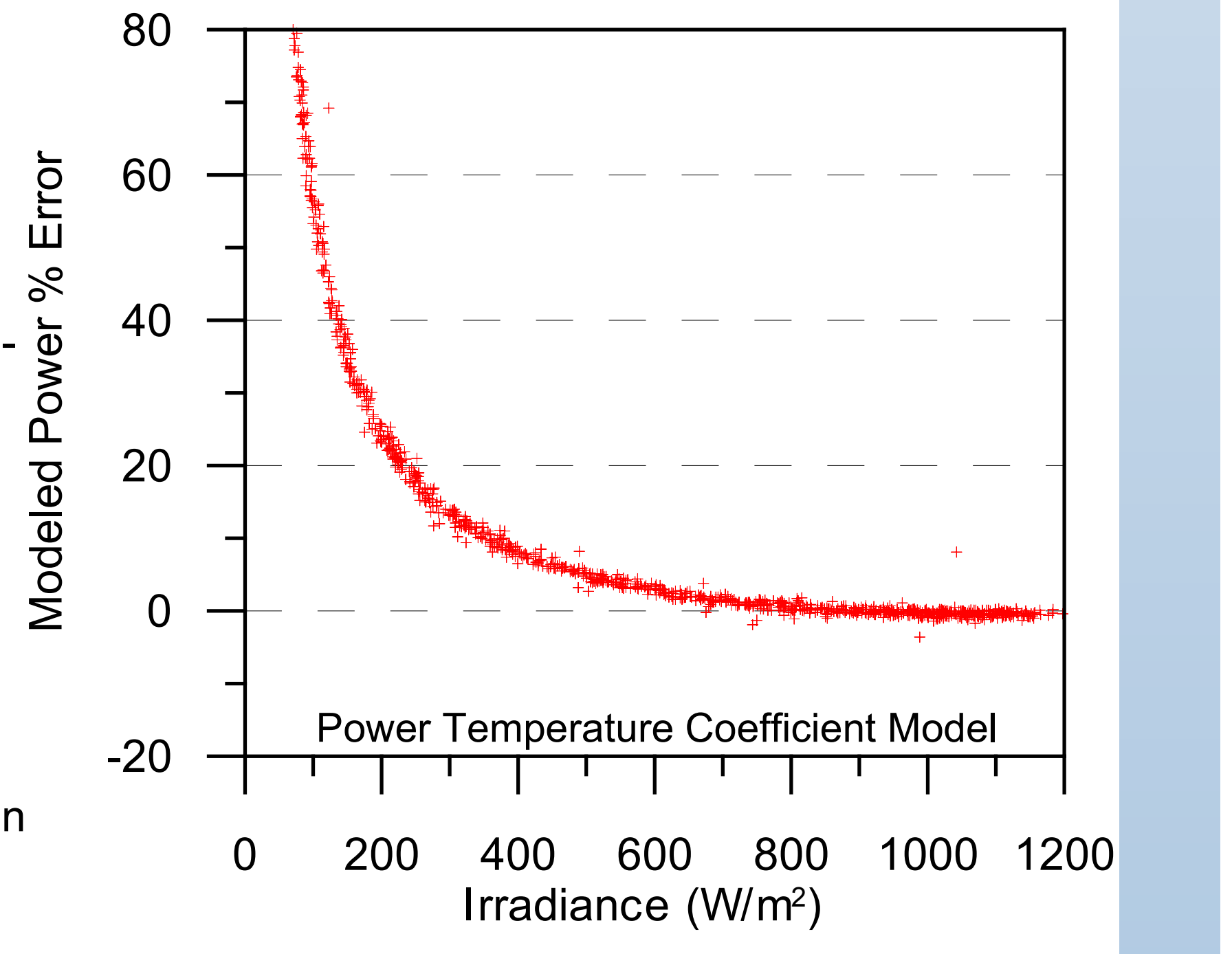

Fig 3. Percentage error in modeled P_m for the multi-crystal Si PV module with greatest model error

9. Correction for Irradiance

For the same PV module and model in Fig. 3, Fig. 4 presents the error in units of the error in modeled P_m divided by the P_m at SRC. By representing the error with the two functions in Fig. 4, an error term may be subtracted from modeled P_m if the value of k, the irradiance correction factor, is known.

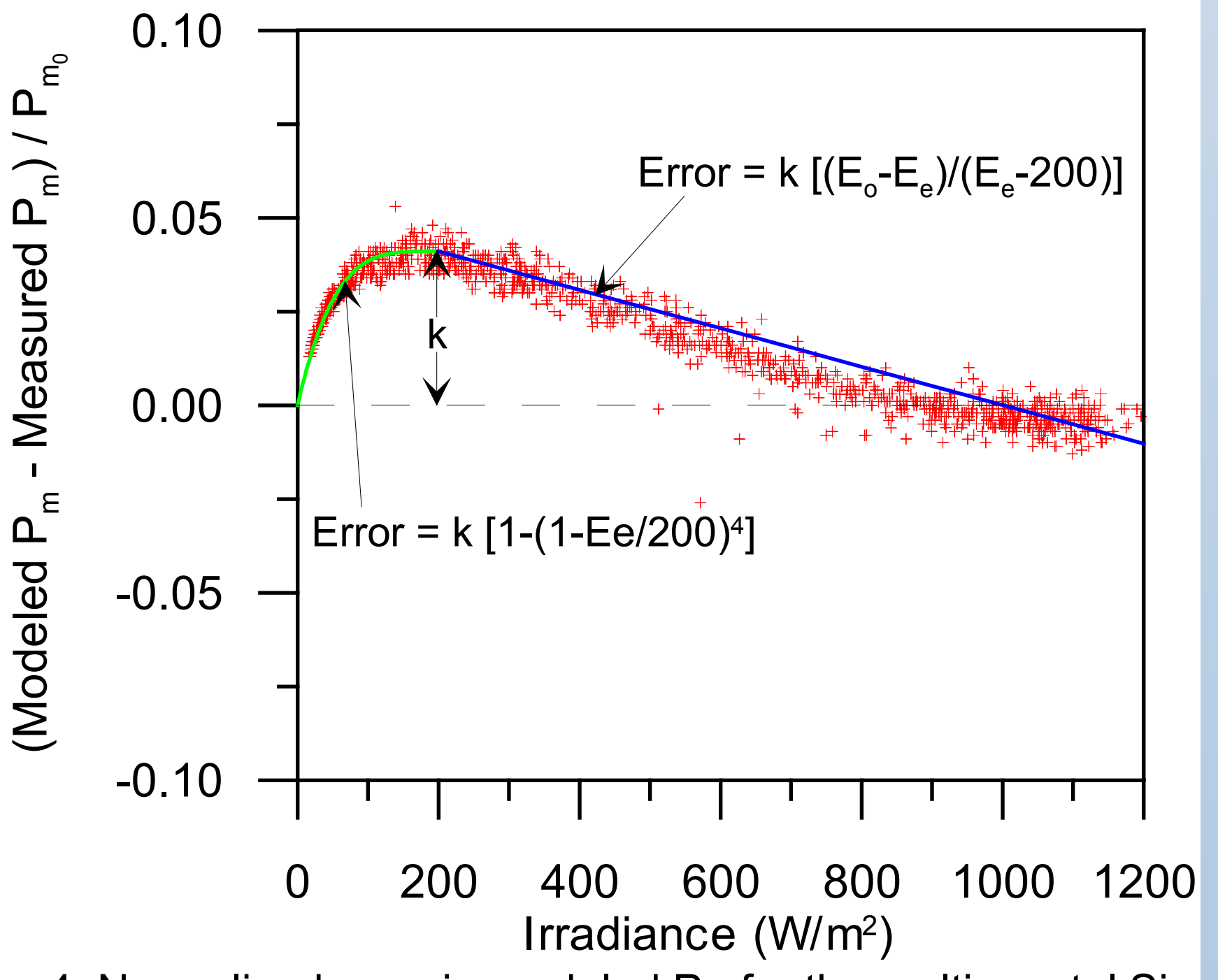

Fig. 4. Normalized error in modeled P_m for the multi-crystal Si PV module and error functions to correct for P_m nonlinearity.

10. Equations for P_m Nonlinearity

The new model adds an irradiance correction term to the power temperature coefficient model to account for nonlinearity of P_m with irradiance level. The new model is represented by Eqs. 4, 5, and 6.

$$k = \frac{P_m(E_L, T) - P_{meas}(E_L, T)}{P_{m_0}} \qquad (4)$$

where

E_L = effective low irradiance, ~ 200 W/m^2
$P_m(E_L,T)$ = P_m from Eq. 2 for E_L and T conditions
$P_{meas}(E_L,T)$ = measured P_m for E_L and T conditions.

For E_e > 200 W/m^2

$$P_m = P_{m_0} \cdot \left[\frac{E_e}{E_0} \cdot [1 + \gamma \cdot (T - T_0)] - k \cdot \frac{E_0 - E_e}{E_0 - 200}\right] \qquad (5)$$

For E_e ≤ 200 W/m^2

$$P_m = P_{m_0} \cdot \left[\frac{E_e}{E_0} \cdot [1 + \gamma \cdot (T - T_0)] - k \cdot \left[1 - \left(1 - \frac{E_e}{200}\right)^4\right]\right] \qquad (6)$$

11. Results for the New Model

The new model was evaluated using the same measured data sets and error statistic methodology as for the other models. The resulting error statistics for the new model are essentially the same as the results for the bilinear interpolation model shown in Table 1. (Compared to the bilinear interpolation model results in Table 1, MBEs were within 0.1%, and MAEs and RMSEs were within 0.2%.)

Besides accuracy, other attributes of the new model are:

- Simplicity – The equations are of the same form as the power temperature coefficient model, with an additional term for nonlinearity of P_m with irradiance level. Conversely, if a PV module's P_m is linear with respect to the effective irradiance, the value of k is zero and—in effect—no correction is applied.

- Availability of PV module data – Required module characteristic data are reduced to three parameters: P_{m_0}, γ, and $P_{meas}(E_L,T)$. PV manufacturers currently provide the first two parameters, and the third parameter will be available in January 2009 when the California Energy Commission begins requiring PV module data to be supplied based on IEC 61215 and 61646. Some manufacturer data sheets already contain this information as "reduction in efficiency under low irradiance (200 W/m^2)." For example, a reduction in efficiency value by 10% would correspond to k = 0.10 x 200/1000 = 0.020.

12. Summary

Error statistics for modeling P_m were determined for the following models (listed in order of overall performance): (1) the bilinear interpolation model, (2) the PVFORM model, and (3) the power temperature coefficient model. Using characterization data at a low irradiance (~200 W/m^2) in the bilinear interpolation model helped it to account for the nonlinearity of P_m with irradiance level.

This work also presented a model that addressed the inability of the power temperature coefficient model to account for nonlinearity of P_m with respect to irradiance that is seen in some PV modules. This model proved to be as accurate as the bilinear interpolation model, yet simpler and requiring less module-specific characterization data.

In this work, the analysis was restricted to studying the accuracy of the models when using inputs of measured PV temperatures and of irradiances calculated from measured I_{sc}. This is analogous to measuring the irradiance with a calibrated reference cell that matched the optical and spectral characteristics of the PV module. Modeling errors would have been increased if (1) the irradiance had been measured with a pyranometer or modeled; (2) the PV cell temperature had been modeled; or (3) P_m at SRC had been determined independently of the PERT measurements or by another laboratory (because of uncertainties associated with the reproducibility of measurements among laboratories).

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