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Comparison of Predictive Models for Photovoltaic Module Performance

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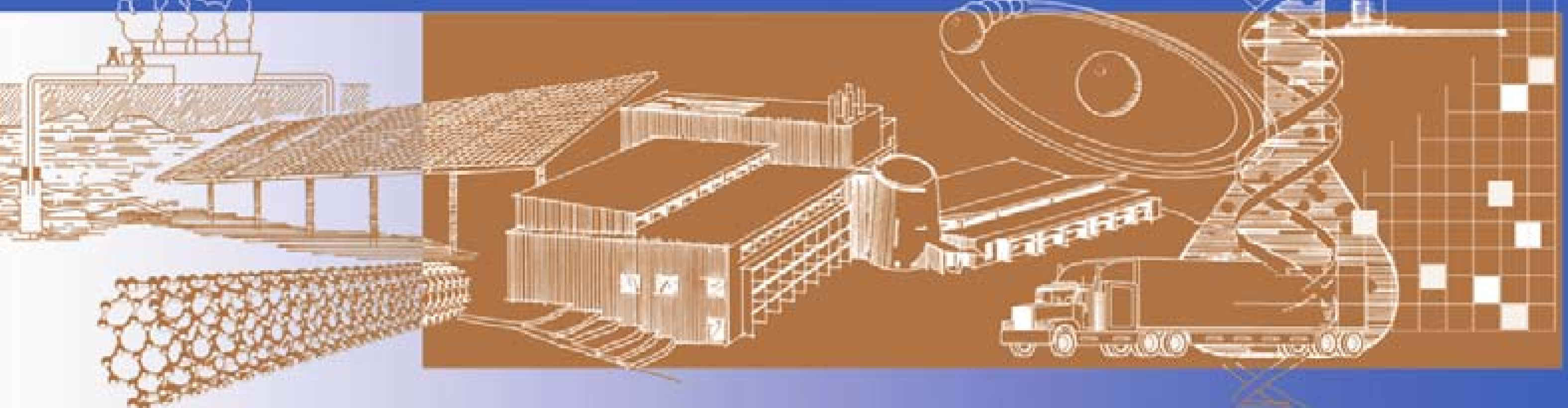

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COMPARISON OF PREDICTIVE MODELS FOR PHOTOVOLTAIC MODULE PERFORMANCE

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ABSTRACT

This paper examines three models used to estimate the performance of photovoltaic (PV) modules when the irradiances and PV cell temperatures are known. The results presented here were obtained by comparing modeled and measured maximum power (P_m) for PV modules that rely on different technologies. The models evaluated for estimating P_m are (1) the power temperature coefficient model, (2) the PVFORM model, and (3) the bilinear interpolation model. These range from simple models with few input parameters to more complex models with more extensive PV module characterization procedures. NREL researchers determined modeling error statistics by comparing model estimates with measured PV performance data. A modification to the power temperature coefficient model was also evaluated that provided improved accuracy.

INTRODUCTION

Models are a key element for predicting the performance of PV systems and for use in standards that assign a PV module an energy rating. This paper examines three models used to estimate the 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.

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 short-circuit current (I_{sc}). The equation assumes that I_{sc} is proportional to the irradiance if T and the spectral distribution of the irradiance are constant. Zero subscripts denote performance at Standard Reporting Conditions (SRC), which consists of an irradiance of 1,000 W/m^2 with a spectral distribution conforming to the air mass (AM) 1.5 spectrum [1] and a PV cell temperature of 25°C.

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

where

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

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.

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

where

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

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 [2,3].

For $E_e \le 125$ W/m^2,

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

THE 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 [4]. 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 [5].

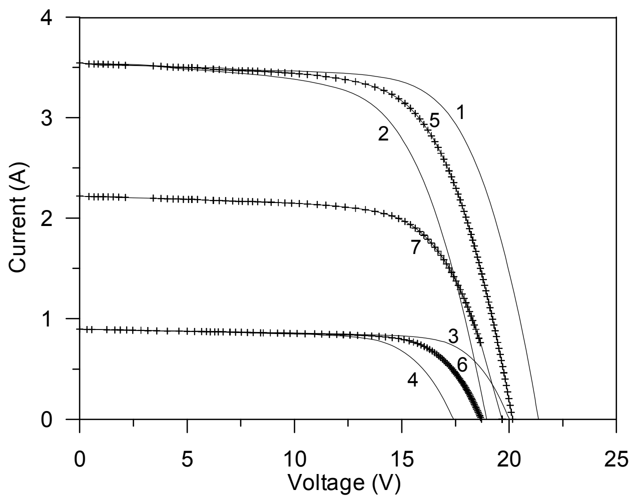

Fig. 1. Numbering of I-V curves for bilinear interpolation model

Figure 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. I-V curves 1 and 2 were measured at the same nominal irradiance, as were I-V curves 3 and 4. I-V curves 1 and 3 were measured at the same nominal PV cell temperature, as were I-V curves 2 and 4. The term *nominal* is used in referring to irradiance and temperature settings because the method's equations accommodate unintended variations in settings that might occur. 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 irradiance and PV cell temperature.

Equations 4 and 5 are used to determine values of I_{sc} and V_{oc}. Subscripts with a value of one denote performance for reference I-V curve 1.

$$I_{sc} = \frac{E_e}{E_1} \cdot I_{sc_1} \cdot \left[1 + \alpha \cdot \left(T - T_1\right)\right] \qquad (4)$$

and

$$V_{oc} = V_{oc_1} \cdot \left[1 + \beta \cdot \left(T - T_1\right)\right] \cdot \left[1 + \left(m \cdot T + b\right) \cdot \ln\left(E_e / E_1\right)\right]. \qquad (5)$$

where

β = open circuit voltage correction factor for temperature, °C^{-1}
m = open circuit voltage correction factor for irradiance, °C^{-1}
b = open circuit voltage correction factor for irradiance, dimensionless.

VALIDATION DATA

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°C per 1,000 W/m^2 irradiance to the PV module back-surface temperatures.

Data were screened to eliminate data recorded under the following conditions (which would cause inaccurate measurements): (1) days with recorded snow on PV modules and pyranometers; (2) periods of the day during and after rainfall as indicated by accumulated rainfall measurements at the nearby Solar Radiation Research Laboratory (SRRL); and (3) unstable irradiance resulting from the presence of cloud movement in the vicinity of the sun. This last condition could be detected when the next PV module's I-V curve measurement showed a change in irradiance of more than 10 W/m^2. The PERT measures I-V curves in sequence, with each PV module's I-V curve requiring 3 to 4 seconds. Missing data and the data-screening criteria reduced the available data by about 30%.

PV MODULE CHARACTERIZATION

To obtain the information required by the models, their 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). For the four I-V curves selected, the corresponding measurement times, nominal irradiances, and PV module temperatures were as follows: 7:15 a.m., 220 W/m^2 and 0°C; 10:15 a.m., 1040 W/m^2 and 35°C; 2:00 p.m., 1040 W/m^2 and 50°C; 5:00 p.m., 220 W/m^2 and 20°C.

Using the I-V curve data and their coincident measurements of irradiance and PV module temperature, the procedures outlined by Marion and coworkers were used to determine the PV module coefficients α, β, m, and b [5]. Performance at SRC was determined using these module coefficients and the bilinear interpolation model. For the power temperature coefficient model and the PVFORM model, the two I-V curves measured at 10:15 a.m. and 2:00 p.m. were used to determine γ values.

Tables 1 and 2 list the PV modules by their technology and serial number (S/N), their performance at SRC, and their derived temperature and irradiance coefficients.

Table 1. PV Module Performance at SRC

Technology	Module S/N	I_{sc} (A)	V_{oc} (V)	I_m (A)	V_m (V)	Fill-Factor (%)	P_m (W)
Multi-crystal Si	4978	2.831	21.57	2.496	16.80	68.7	41.94
Multi-crystal Si	9366	2.358	20.95	2.095	16.78	71.1	35.16
Single-crystal Si	585-2164	4.580	21.38	4.317	17.22	75.9	74.34
Single-crystal Si	270-2301	4.113	20.87	3.759	16.37	71.7	61.54
Single-crystal Si	0442	4.104	21.24	3.675	16.50	69.6	60.65
a-Si/x-Si HIT	21226001	3.517	66.16	3.258	52.48	73.5	170.97
a-Si/a-Si/a-Si:Ge	1736	2.511	21.27	1.981	14.86	55.1	29.43
CdTe	14407	0.880	87.16	0.713	59.55	55.3	42.44

Table 2. PV Module Temperature and Irradiance Coefficients

Technology	Module S/N	α (°C^{-1})	β (°C^{-1})	m (°C^{-1})	b	γ (°C^{-1})
Multi-crystal Si	4978	3.88E-04	-3.70E-03	2.40E-04	6.02E-02	-4.66E-03
Multi-crystal Si	9366	3.65E-04	-3.48E-03	4.40E-04	5.23E-02	-4.28E-03
Single-crystal Si	585-2164	6.50E-04	-3.56E-03	2.43E-04	3.38E-02	-4.58E-03
Single-crystal Si	270-2301	5.00E-04	-3.69E-03	2.66E-04	3.36E-02	-4.70E-03
Single-crystal Si	0442	6.00E-04	-3.96E-03	8.35E-05	4.98E-02	-5.20E-03
a-Si/x-Si HIT	21226001	1.60E-04	-2.76E-03	6.91E-05	4.85E-02	-2.78E-03
a-Si/a-Si/a-Si:Ge	1736	5.95E-04	-4.09E-03	4.96E-04	4.44E-02	-2.05E-03
CdTe	14407	5.97E-04	-3.10E-03	2.38E-04	4.09E-02	-1.09E-03

CALCULATING 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. RMSE, MBE, and MAE are defined by Eqs. 6, 7, and 8, which calculate the errors as a percentage of the average measured value. 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.

$$\text{RMSE} = 100\% \times \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{1/2} \div \left[\frac{1}{n}\sum_{i=1}^{n} x_i\right] \quad (6)$$

$$\text{MBE} = 100\% \times \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)\right] \div \left[\frac{1}{n}\sum_{i=1}^{n} x_i\right] \quad (7)$$

$$\text{MAE} = 100\% \times \left[\frac{1}{n}\sum_{i=1}^{n}|y_i - x_i|\right] \div \left[\frac{1}{n}\sum_{i=1}^{n} x_i\right], \quad (8)$$

where

y_i = the ith modeled value
x_i = the ith measured value
n = the number of measured or modeled values.

MODELING ERRORS FOR P_M

Table 3 gives modeling error statistics for P_m by model and PV module. The Number of Data Points column lists, by PV model, the number of measured I-V curves that were compared with model estimates. There are fewer I-V curves for the CdTe PV module because the period of data collection was shorter. The Ave column shows the average P_m of the measured data by PV module. Overall, the bilinear interpolation model performed best with the lowest errors. All models appear to adequately account for PV module temperature. The main differences were seen in the model estimates at lower irradiances, as shown graphically in Fig. 2. The figure uses a scatterplot to illustrate modeled versus measured P_m for the multi-crystal Si PV module S/N 4978 when the power temperature coefficient model is used. This PV module is used for illustration purposes because it exhibited the largest departure from linearity with respect to irradiance. As a consequence, it also had the largest MBE. The scatterplot includes a diagonal line with a slope of one for ease in comparing modeled and measured values. If modeled and measured values are in perfect agreement, the data points reside on the diagonal line. Data points above the line indicate model overestimates and data points below the line indicate model underestimates.

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 3 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

Table 3. MBE, MAE, and RMSE Statistics for P_m by Model and PV Module

Technology	Module S/N	Number of Data Points.	Ave. (W)	Power Temperature Coefficient Model			PVFORM Model			Bilinear Interpolation Model		
				MBE (%)	MAE (%)	RMSE (%)	MBE (%)	MAE (%)	RMSE (%)	MBE (%)	MAE (%)	RMSE (%)
Multi-crystal Si	4978	11816	19.50	3.9	4.3	5.5	2.8	3.4	4.8	-0.3	0.7	1.6
Multi-crystal Si	9366	11830	16.66	3.2	3.4	4.0	2.1	3.0	3.6	0.1	0.7	1.2
Single-crystal Si	585-2164	11844	36.12	0.0	1.5	1.8	-1.1	1.7	2.1	-0.4	1.4	1.7
Single-crystal Si	270-2301	11870	29.86	0.4	1.6	1.9	-0.7	1.6	1.9	0.2	1.5	1.8
Single-crystal Si	0442	12468	28.92	0.9	2.2	2.8	-0.2	2.1	2.7	-0.8	1.2	2.0
a-Si/x-Si HIT	21226001	11878	84.72	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	1736	11878	15.31	-2.6	3.2	4.5	-3.5	3.9	4.9	-2.0	3.3	4.4
CdTe	14407	3415	25.78	-1.6	2.3	3.0	-2.2	2.8	3.4	-0.9	1.9	2.5

about the same amount. Accounting for this seasonal change in PV module efficiency would improve model performance when applied to a-Si technologies.

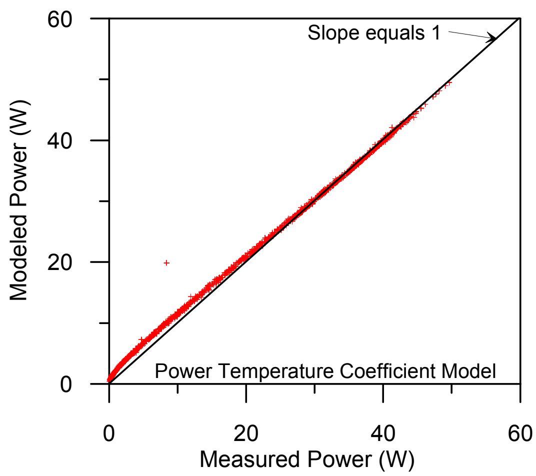

Fig. 2. Modeled versus measured P_m for the multi-crystal Si PV module S/N 4978 when using the power temperature coefficient model.

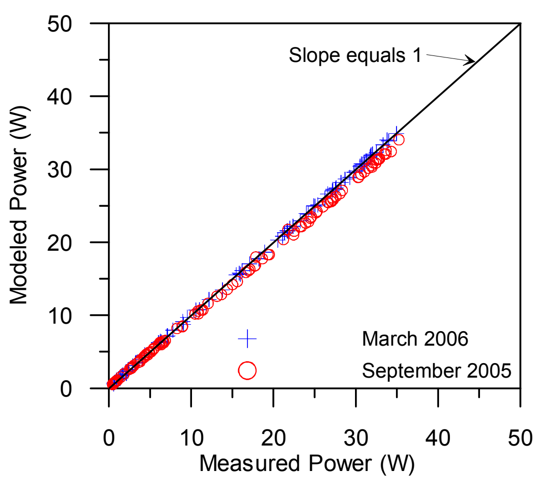

Fig. 3. Modeled versus measured P_m for the a-Si/a-Si/a-Si:Ge PV module S/N 1736 showing the effect of annealing for September 2005 and March 2006 for the power temperature coefficient model.

AN IMPROVED MODEL

The power temperature coefficient model yielded surprisingly good results for some of the PV modules, notably the single-crystal silicon and the a-Si/x-Si HIT PV modules. Because these PV modules maintained their efficiency at low irradiance levels, the model's assumption that P_m was linear with respect to the effective irradiance if the temperature is constant was valid.

If, however, the PV module does not maintain its efficiency at lower irradiance levels, the model will overestimate performance. This is illustrated in Figure 4 for the multi-crystal Si PV module S/N 4978, with the model error expressed as a percentage of the measured value and plotted as a function of irradiance to demonstrate how irradiance level affects model accuracy.

Figure 4 should be used with caution for ascertaining the overall impact on energy production because a large percentage error at a low irradiance may have less impact on energy production than a smaller percentage error at a high irradiance. Figure 5 presents the results in units of the error in modeled power divided by P_m at SRC. This results in better information on the error in overall energy

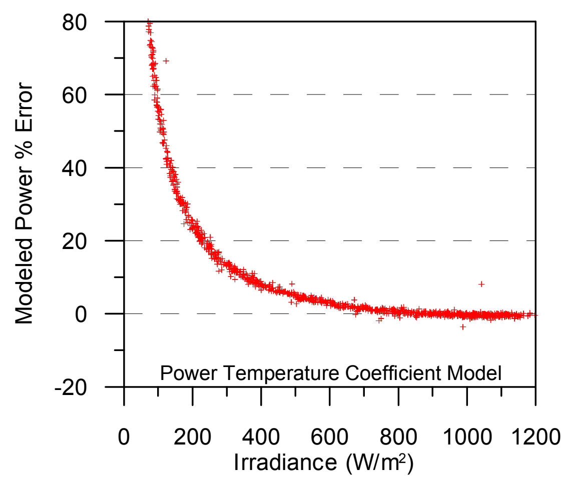

Fig. 4. Percentage error in modeled P_m for the multi-crystal Si PV module S/N 4978 when using the power temperature coefficient model.

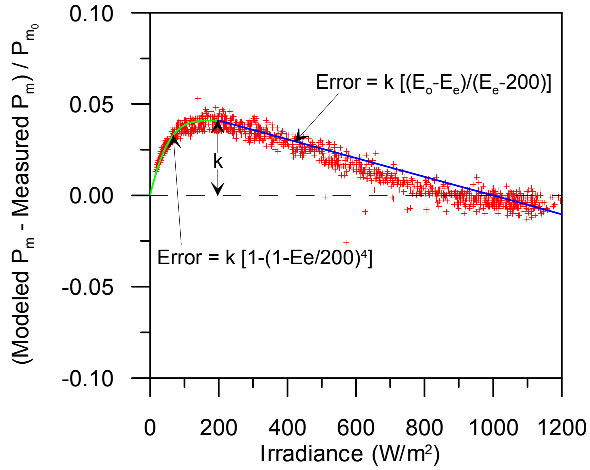

Fig. 5. Normalized error in modeled P_m for the multi-crystal Si PV module S/N 4978 when using the power temperature coefficient model, and graphical representation of functions to correct for non-linearity of P_m with respect to irradiance.

production, and it also offers insight about how a correction factor might be applied to minimize the model error at low irradiance. This is also graphically represented in Figure 5.

To correct for the modeling error as a function of irradiance, a model was developed that considers the error in two irradiance regions: ≤ 200 W/m^2 and > 200 W/m^2. For irradiance levels ≤ 200 W/m^2, the correction is a function of an irradiance term raised to the 4th power. For irradiance levels > 200 W/m^2, the correction is linear with respect to irradiance. The correction functions have a maximum value of k when E_e = 200 W/m^2, and a value of zero for E_e = 0 or 1,000 W/m^2.

Based on experimental observations, the correction functions yield results that are closer to measured performance for PV modules whose P_m is nonlinear with respect to the effective irradiance. 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.

The irradiance correction factor, k, is determined with Eq. 9:

$$k = \frac{P_m(E_L,T) - P_{meas}(E_L,T)}{P_{m_0}}, \qquad (9)$$

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.

Equations 10 and 11 represent the improved power temperature coefficient model with an irradiance nonlinearity correction:

For E_e > 200 W/m^2

$$P_m = P_{m_0} \cdot \left[\frac{E_e}{E_0} \cdot [1 + \gamma \cdot (T - T_0)] - k \cdot \frac{E_0 - E_e}{E_0 - 200} \right]. \qquad (10)$$

For E_e ≤ 200 W/m^2

$$P_m = P_{m_0} \cdot \left[\frac{E_e}{E_0} \cdot [1 + \gamma \cdot (T - T_0)] - k \cdot \left[1 - \left(1 - \frac{E_e}{200} \right)^4 \right] \right]. \qquad (11)$$

A significant development for this approach is on the horizon. Beginning in January 2009, manufacturers will be furnishing data corresponding to $P_{meas}(E_L,T)$ and based on IEC 61215 and 61646, to the California Energy Commission so that the manufacturers' PV modules can be listed by the Commission as eligible components for incentive programs [6]. Consequently, this will allow the new method to be implemented with manufacturer-supplied information without the need for further characterization measurements. 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.

To evaluate Eqs. 10 and 11 for the PV modules being assessed, k values for each PV module were determined using Equation 9 and the low irradiance I-V curve data recorded on March 14, 2006 (and previously used to determine temperature and irradiance coefficients for the bilinear interpolation model). The effective irradiance was about 220 W/m^2, sufficiently close to 200 W/m^2 that it would not impact the value of k because the change in error value is relatively constant near 200 W/m^2 (see Fig. 5). This is another attribute of the improved model. Table 4 lists the two values of k for each PV module. Both morning and afternoon data yielded approximately the same k values. Two of the PV modules have negative k values, meaning that module efficiency at low irradiance levels increases relative to their efficiencies at SRC.

Table 4. Values of k from March 14, 2006 Data

Technology	Module S/N	k (T~0°C)	k (T~20°C)
Multi-crystal Si	4978	0.046	0.041
Multi-crystal Si	9366	0.029	0.029
Single-crystal Si	585-2164	0.003	0.003
Single-crystal Si	270-2301	0.002	0.002
Single-crystal Si	0442	0.022	0.018
a-Si/x-Si HIT	21226001	0.012	0.009
a-Si/a-Si/a-Si:Ge	1736	-0.002	-0.005
CdTe	14407	-0.016	-0.012

For evaluating this new model, Eqs. 10 and 11 were used to model P_m for each of the PV modules. Then, the results were compared to measured P_m values using the methodology described previously. Values of k from the last column of Table 4 were used because the temperatures for these values were closest to the temperature for SRC. Table 5 presents the results, showing that the modeling errors are comparable to those presented in Table 3 for the bilinear interpolation model.

Table 5. MBE, MAE, and RMSE Statistics for P_m for the Power Temperature Coefficient Model with Correction for Irradiance Nonlinearity.

Technology	Module S/N	MBE (%)	MAE (%)	RMSE (%)
Multi-crystal Si	4978	-0.4	0.8	1.7
Multi-crystal Si	9366	0.2	0.6	1.1
Single-crystal Si	585-2164	-0.3	1.4	1.7
Single-crystal Si	270-2301	0.2	1.5	1.9
Single-crystal Si	0442	-0.9	1.4	2.2
a-Si/x-Si HIT	21226001	0.2	0.7	1.1
a-Si/a-Si/a-Si:Ge	1736	-2.0	3.3	4.4
CdTe	14407	-0.8	1.8	2.4

SUMMARY

Error statistics were determined for PV models that estimated the performance of PV modules of various technologies operated at NREL from April 1, 2005 through March 31, 2006. For modeling P_m using an effective irradiance and cell temperature, error statistics 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. Results for the bilinear interpolation model were consistent with other evaluations by NREL and other organizations [7, 8, 9]. 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 evaluated 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. Though equivalent in accuracy to the bilinear interpolation model, this model proved to be simpler and require less module-specific characterization data. 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 manufacturers will make the last parameter available in the near future. Consequently, this model has advantages in terms of its simplicity, accuracy, and readily available input parameters.

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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14. ABSTRACT *(Maximum 200 Words)*
This paper examines three models used to estimate the performance of photovoltaic (PV) modules when the irradiances and PV cell temperatures are known. The results presented here were obtained by comparing modeled and measured maximum power (Pm) for PV modules that rely on different technologies. The models evaluated for estimating Pm are (1) the power temperature coefficient model, (2) the PVFORM model, and (3) the bilinear interpolation model. These range from simple models with few input parameters to more complex models with more extensive PV module characterization procedures. NREL researchers determined modeling error statistics by comparing model estimates with measured PV performance data. A modification to the power temperature coefficient model was also evaluated that provided improved accuracy.

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PV; module; measured maximum power; power temperature coefficient; bilinear interpolation; PVFORM model; irradiance; short-circuit current;

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