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# Validation of a Photovoltaic Module Energy Ratings Procedure at NREL

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## ABSTRACT

A procedure was developed to assign energy ratings to a photovoltaic (PV) module for five reference days that represent different climates. The procedure uses indoor tests to characterize the electrical performance of a PV module and hourly meteorological conditions from the reference days to model PV module energy. PV performance measurements from NREL's Outdoor Test Facility during the calendar year 1998 were used to validate the procedure by comparing modeled and measured energy for seven PV modules representing different technologies.

## 1. Introduction

This paper is a brief summary of work [1] performed to develop and validate a PV module energy rating procedure for incorporation into IEEE PAR1479, "Recommended Practice for the Evaluation of Photovoltaic Module Energy Production." The energy rating procedure may be applied to five reference days that represent a range of climatic conditions for the United States. The reference day names depict their type: Hot Sunny, Hot Cloudy, Cold Sunny, Cold Cloudy, and Nice (Cool Sunny).

The procedure uses indoor tests to characterize the electrical performance of a PV module and to determine factors to correct for non-linear performance when the irradiance and PV module temperature vary. Meteorological data from the reference days are used to calculate PV module irradiances and temperatures, from which PV module current-voltage (I-V) curves are generated, one for each hour of a reference day. The calculated PV module irradiances and temperatures are used to account for the PV module's spectral response and thermal characteristics.

## 2. Energy Rating Methodology

Three technical areas address implementing the procedure: (1) determining PV module temperature and irradiance correction factors and functions, (2) determining the irradiance and PV module temperature for each reference day hour, and (3) translating a reference I-V curve to the irradiance and PV module temperature conditions.

Based on Annex A2 of ASTM E1036-96 [2], the PV module temperature and irradiance correction factors and functions are determined from a matrix of short-circuit current (Isc) and open-circuit voltage (Voc) values resulting from I-V curve measurements over a range of six irradiances and six operating temperatures. Three correction factors and functions are determined: $\alpha$, the Isc correction factor for temperature; $\beta(E)$, the Voc correction for temperature as a function of irradiance, E; and $\delta(T)$, the Voc correction for irradiance as a function of the PV module temperature, T.

The solar radiation and meteorological data for the reference days are used to model hourly values of the incident irradiance and the PV module temperatures. The incident irradiance is determined by:

$$E = \frac{\int_a^b E_{INC}(\lambda) SR(\lambda) d\lambda}{\int_a^b E_{REF}(\lambda) SR(\lambda) d\lambda} \cdot 1000\ \mathrm{W/m^2} \qquad (1)$$

where:

| | | |
|---|---|---|
| $\lambda$ | = | wavelength |
| $E_{INC}(\lambda)$ | = | incident spectral irradiance |
| $E_{REF}(\lambda)$ | = | AM1.5 spectral irradiance [3] |
| $SR(\lambda)$ | = | module spectral response per [4] |

For series-connected multi-junction modules, the spectral response of the junction that gives the smallest numerator (current at actual conditions) is used to evaluate the numerator, and the spectral response of the junction that gives the smallest denominator (current at reference conditions) is used to evaluate the denominator. Spectral responses for two junctions are required to evaluate equation 1 if one junction is the current limiting factor at reference conditions and the other junction is the current limiting factor at actual conditions. The model SEDES2 [5] is used to calculate the incident spectral irradiance.

A model developed by Fuentes [6] for use in the simulation program PVFORM is used to determine PV module temperature.

Using the incident irradiance and the PV module temperature, Isc and Voc are calculated and a reference I-V curve is translated to determine maximum power and the current at a fixed voltage. These procedures are based on modifications to ASTM E1036-96 and use equations 2 and 3 for Isc and Voc. In equations 2 and 3, the zero subscripts denote Standard Reporting Conditions (SRC).

$$Isc = \frac{E}{E_0} \cdot Isc_0 \cdot \left[1 + \alpha \cdot (T - T_0)\right] \qquad (2)$$

$$Voc = Voc_0 \cdot [1+\beta(E_0)\cdot(T-T_0)][1+\delta(T)\cdot\ln(E/E_0)] \qquad (3)$$

For determining the I-V curve for desired conditions, a reference I-V curve is selected for translation from the matrix of I-V curves measured to determine the correction factors and functions. The I-V curve selected for the reference is the one measured under the conditions of irradiance and temperature closest to those desired. This minimizes errors caused by the I-V curve translation not accounting for changes in fill factor with changes in temperature and irradiance.

Each I-V data pair of the reference I-V curve is then translated to the desired conditions using equations 4 and 5. The subscript R refers to the reference I-V curve, and Isc and Voc are determined with equations 2 and 3.

$$I = I_R \cdot \frac{Isc}{Isc_R} \qquad (4)$$

$$V = V_R \cdot \frac{Voc}{Voc_R} \qquad (5)$$

Because the translation procedure does not change the fill factor, the reference I-V curve data pair for maximum power becomes the translated I-V curve data pair for maximum power. To determine the current at a specified voltage, the current may be interpolated using the two adjacent I-V curve data pairs from the translated I-V curve with voltages above and below the specified voltage.

## 3. Comparison of Modeled and Measured Energy

The energy rating procedure was validated by comparing modeled and measured values of energy for seven PV modules for the calendar year 1998. The PV modules are located on the lower roof of NREL's Outdoor Test Facility, face south with a tilt from horizontal of 40°, and are operated at their peak-power point.

Table 1 provides root-mean-square-error (RMSE) and mean-bias-error (MBE) statistics for comparing hourly values of modeled and measured PV module energy production. RMSEs and MBEs are expressed as a percent of the average. The RMSEs are indicative of modeling accuracy for hourly data. Twice the RMSE gives a 95% confidence interval. The MBEs indicate the modeling accuracy for the year.

Table 1. RMSEs and MBEs for Modeled Hourly Energy

| PV Module | Energy | |
|---|---|---|
| | RMSE (%) | MBE (%) |
| a-Si/a-Si/a-Si:Ge, S/N 1736 | 9.5 | 4.5 |
| CdS/CuInGaSSe , S/N 5165 | 5.4 | -1.8 |
| CIS, S/N 114 | 5.7 | 1.2 |
| Mono-Crystal Si, S/N 0442 | 5.8 | -1.7 |
| Multi-Crystal Si, S/N581836 | 5.4 | -1.6 |
| a-Si/a-Si:Ge, S/N SYS49 | 5.6 | -1.2 |
| CdS/CdTe, S/N 14407 | 5.4 | 1.5 |

Comparison of daily values of modeled and measured energy is the best indicator of the suitability of the procedure for rating PV modules for daily energy production. These comparisons were performed for the 1998 days that were similar to the reference days. The results (Table 2) were used to estimate the uncertainty of the procedure in predicting the relative performance of PV modules of different technologies. Uncertainties are higher when the a-Si PV modules are included because of the increased difficulty in modeling their spectral dependencies. Also, the procedure does not account for annealing effects and long-term degradation that may have occurred during the test period.

Table 2. Estimated Percent Uncertainty in Predicting Relative Performance by Reference Day Type

| PV Module Group | Cold Cloudy | Cold Sunny | Nice | Hot Cloudy | Hot Sunny |
|---|---|---|---|---|---|
| All | 7 | 11 | 8 | 3 | 6 |
| Not a-Si | 3 | 4 | 3 | 1 | 5 |

Because different facilities will probably perform the characterization tests and energy ratings, the overall uncertainty estimate should account for the reproducibility limit of 6.7% [2] in the measurement of electrical performance by different facilities. By defining the overall uncertainty as the square root of the sum of the squares of the reproducibility limit and the maximum uncertainties from Table 2, a statement such as the following applies: "Because of errors in measurements and energy-rating methodology, differences of 8% or less in the energy ratings of two PV modules are not significant. If one of the PV modules is amorphous silicon, differences of 13% or less in the energy ratings of two PV modules are not significant."


## 4. Acknowledgments

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