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# Modeling Current-Voltage Curves Using Bilinear Interpolation

## Preprint

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**Modeling Current-Voltage Curves Using Bilinear Interpolation**

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## ABSTRACT

Current-voltage (I-V) curves for photovoltaic (PV) modules representing all PV technologies were modeled by bilinearly interpolating the I-V curves from a PV module's four reference I-V curves. The interpolation was performed first with respect to open-circuit voltage to account for PV module temperature, and second with respect to short-circuit current to account for irradiance. The modeled I-V curves compared closely with measured I-V curves for 26 PV modules located at the National Renewable Energy Laboratory.

## BACKGROUND

Expanding on work by Hishikawa et al.[1] that developed translation equations for interpolating with respect to irradiance a current-voltage (I-V) curve from two I-V curves at the same photovoltaic (PV) module temperature, Marion et al.[2] developed a method where four I-V curves could be used to bilinearly interpolate an I-V curve with respect to both irradiance and PV module temperature.

Figure 1 illustrates the bilinear interpolation methodology. I-V curves 1-4 are the reference I-V curves measured for combinations of two PV module temperature and two irradiance settings. I-V curves 1 and 2 are measured at the same nominal irradiance, likewise for I-V curves 3 and 4. I-V curves 1 and 3 are measured at the same nominal PV module temperature, likewise for I-V curves 2 and 4. The term nominal is used when referring to irradiance and temperature settings because the method's equations accommodate unintended variations in settings that might occur. From the four reference curves, temperature and irradiance correction factors for short-circuit current (Isc) and open-circuit voltage (Voc) are determined: $\alpha$, the Isc correction factor for PV module temperature ($°C^{-1}$); $\beta$, the Voc correction factor for PV module temperature ($°C^{-1}$); $mT + b$, the Voc correction for irradiance as a linear function of PV module temperature T, where m ($°C^{-1}$) is the slope and b (dimensionless) is the y-intercept.

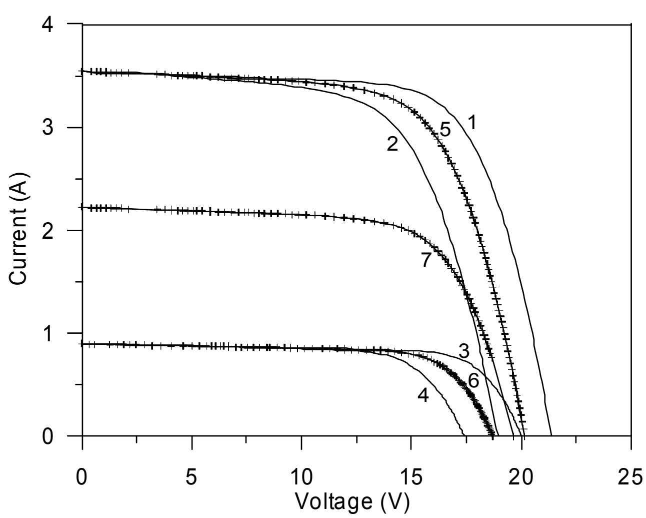


Figure 1. Numbering of I-V curves for bilinear interpolation

To perform the bilinear interpolation, I-V curves 5 and 6 are interpolated with respect to Voc from I-V curves 1 and 2, and 3 and 4, respectively, and I-V curve 7 is interpolated with respect to Isc 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 module temperature. The method was evaluated[2] for seven PV module technologies by comparing modeled and measured I-V curves. I-V curve measurements were performed both indoors using a solar simulator and outdoors under clear skies. The indoor and outdoor results were favorable with root-mean-square-errors (rmse) of 1.5% or less for the I-V curve parameters of Isc, Voc, maximum power (Pm), voltage at maximum power (Vmp), and current at maximum power (Imp). For fill factor (FF), the rmse was 2%. Mean-bias-errors (mbe) were less than 1%.

This paper presents additional evaluation results for the method by using I-V curve measurement data from the Performance and Energy Rating Test bed (PERT) located at the National Renewable Energy Laboratory (NREL).

## COMPARISON OF MODELED AND MEASURED I-V CURVES

The PERT contains numerous PV modules of various technology and manufacture. Each PV module faces south and is tilted from the horizontal at an angle of 40º, which approximates the local latitude. The PV modules are operated at their peak-power point to provide energy performance data, except once every 15 minutes they are temporarily disconnected in order that a complete I-V curve can be measured. Supporting data include incident solar irradiance measured with a pyranometer and PV module back-surface temperature measured with a thermocouple.

From a day with clear skies (September 22, 2003 for the majority of the PV modules, but August 14, 2003 for a few), four I-V curves per PV module were selected for use as the reference I-V curves. The remaining I-V curves for the day were used to compare with bilinearly interpolated/extrapolated I-V curves for the same conditions of irradiance and PV module temperature.

Reference I-V curves were typically selected for times of 7:00 (reference I-V curve 3), 10:00 (reference I-V curve 1), 13:45 (reference I-V curve 2), and 16:45 hours (reference I-V curve 4). This resulted in irradiance values of 920-940 W/m$^2$ for reference I-V curves 1 and 2 and 200-220 W/m$^2$ for reference I-V curves 3 and 4. PV module back-surface temperatures were typically 48ºC for reference I-V curve 1, 58ºC for reference I-V curve 2, 12ºC for reference I-V curve 3, and 32ºC for reference I-V curve 4. When using in-situ data of this nature, achievable differences in temperature between reference curves 1 and 2 are a function of the rise in ambient air temperature over the mid portion of the day, which is climate dependent. A more humid climate with a smaller hourly variation in temperature would result in a smaller temperature differential than the 10°C achieved at NREL's location. The reference I-V curves for previous evaluations[2] had greater temperature differentials of 25° to 30°C. Typically, a greater temperature differential is desirable for general application of the method because it lessens the need to extrapolate performance and the resulting impact on accuracy.

Besides the relatively small temperature difference between reference I-V curves 1 and 2, their temperature range is not the same as I-V curves 3 and 4, in fact, they do not even overlap. Consequently, for any desired I-V curve temperature, one or both of the intermediate I-V curves 5 and 6 will be extrapolated. I-V curve 7 will also require extrapolation for irradiances above 940 $W/m^2$ (midday values as great as 1080 $W/m^2$) and below 200 $W/m^2$ (morning and evening values as small as 30 $W/m^2$). Although the references I-V curves are not optimum for the temperature and irradiance conditions for which they are applied, they do provide a rigorous test of the method's ability to extrapolate I-V curves outside reference I-V curve temperature and irradiance ranges.

For comparison with the remaining I-V curves measured on the clear day, modeled I-V curves were bilinearly interpolated for the same conditions of PV module temperature and irradiance. To account for the temperature gradient between the PV module cell and the PV module back-surface, 2.5°C per 1000 $W/m^2$ irradiance was added to the PV module back-surface temperature to establish the PV module temperature.[3] Irradiance was determined from the measured Isc and PV module temperature.[2] This minimized errors associated with spectral response differences between the pyranometer and the PV modules, orientation misalignment between the pyranometer and the PV modules, and differences in their angular response.

Comparisons of modeled (bilinearly interpolated) and measured I-V curves were made using rmse and mbe statistics to show differences between the modeled and measured I-V curve parameters Voc, Pm, Vmp, Imp, and FF. Statistics are not provided for Isc because the manner in which the irradiance was determined results in no error when modeling Isc. Consequently, the results portray translation and measurement errors not related to irradiance or spectral mismatch errors. The rmse provides information on the variation of the modeled values from the measured values, while the mbe provides the average deviation of the modeled values from the measured values.

The statistical results are shown in Table I for 26 PV modules. As indicated by the low errors in the tables, the method performed well for all the PV module technologies. On average, rmses were 0.6% for Voc, 0.8% for Pm, 0.7% for Vmp, 0.5% for Imp, and 1.1% for FF. The average mbes ranged from -0.2% to +0.1%. The poorest results were for the CdS/CdTe #485005 PV module from manufacturer (Man.) D where the model estimates of Voc for irradiances below 100 $W/m^2$ were too large, thereby increasing the rmse for Voc, and also for FF. Modeling for two other PV modules, the CdS/CdTe #14407 and single-crystal Si #270-2301 PV module, overestimated the FF for irradiances below 100 $W/m^2$ and this resulted in larger FF rmses. At low irradiances, the FF of these PV modules decreased more than the extrapolated FF.

For nine PV modules with known stable performance, comparisons between modeled and measured I-V curves were made for the period July-December 2003. Table II includes the results for this comparison and shows that the approximately 6000 I-V curves for each PV module were successfully modeled from four reference I-V curves. Error statistics were increased only slightly when compared to those in Table I even though the range of irradiances and PV module temperatures were larger than that occurring on the day the reference I-V curves were measured.

Figure 2 uses the July-December data to contour the Pm bias error of the single-crystal Si #270-2301 PV module, which had the highest errors, as a function of irradiance and PV module temperature. In Figure 2, the irradiance and temperature conditions for the reference I-V curves are represented by the location of the bold numbers 1-4 and for measured I-V curves (only 10% shown for clarity) by the location of the + symbols. Errors are smallest near reference I-V curve conditions, underestimate Pm by 0-3%

between the reference I-V curve irradiance levels, and increasingly overestimate Pm (as a percentage) at lower irradiances. The contours near reference I-V curves 1 and 2 locations show a positive bias error with increasing temperature and a negative bias error with decreasing temperature. The temperature difference between reference I-V curves 1 and 2 is only 8°C; if the reference I-V curves had been measured with a larger temperature difference the change in bias error with temperature would likely have been less. For the other PV modules in Table II, contours of Pm bias errors were more favorable, particularly at low irradiance, than those shown in Figure 2.

Table I. Model root-mean-square-error (rmse) and mean-bias-error (mbe) as a percentage of the average Voc, Pm, Vmp, Imp, or FF using single day data. (~ 45 I-V curves per module)

| PV Module | Man. | $V_{oc}$ | | $P_m$ | | $V_{mp}$ | | $I_{mp}$ | | FF | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | rmse | mbe | rmse | mbe | rmse | mbe | rmse | mbe | rmse | mbe |
| a-Si #47-37 | A | 0.3 | 0.1 | 0.6 | 0.0 | 0.3 | 0.1 | 0.4 | -0.1 | 0.7 | -0.2 |
| a-Si #51-13 | A | 0.3 | 0.2 | 0.4 | 0.0 | 0.3 | 0.0 | 0.2 | 0.0 | 0.7 | -0.3 |
| a-Si/a-Si #6766 | B | 0.3 | -0.1 | 0.9 | -0.2 | 0.4 | -0.2 | 0.7 | 0.0 | 0.9 | -0.2 |
| a-Si/a-Si #6760 | B | 0.4 | -0.1 | 1.3 | -0.2 | 0.7 | -0.2 | 0.7 | -0.1 | 1.3 | -0.3 |
| a-Si/a-Si #390M-14 | C | 0.1 | 0.0 | 0.4 | -0.1 | 0.4 | 0.0 | 0.2 | -0.1 | 0.4 | -0.1 |
| a-Si/a-Si #390M-9 | C | 0.2 | 0.0 | 0.4 | 0.0 | 0.5 | -0.2 | 0.2 | 0.1 | 0.4 | -0.1 |
| a-Si/a-Si:Ge #49 | D | 0.6 | 0.4 | 0.5 | 0.2 | 0.8 | 0.5 | 0.4 | -0.3 | 0.5 | -0.2 |
| a-Si/a-Si/a-Si:Ge #74 | B | 0.5 | 0.2 | 0.6 | -0.1 | 0.6 | 0.0 | 0.4 | -0.1 | 0.6 | -0.3 |
| a-Si/a-Si/a-Si:Ge #1736 | B | 0.2 | -0.1 | 0.4 | -0.2 | 0.2 | 0.0 | 0.3 | -0.2 | 0.6 | -0.2 |
| a-Si/a-Si/a-Si:Ge #16912 | B | 0.3 | 0.0 | 0.4 | -0.1 | 0.4 | 0.0 | 0.3 | 0.0 | 0.7 | -0.1 |
| a-Si/a-Si/a-Si:Ge #011 | E | 0.3 | 0.1 | 0.4 | -0.1 | 0.2 | 0.1 | 0.4 | -0.1 | 0.7 | -0.2 |
| CdS/CdTe #485005 | D | 6.3 | 1.2 | 2.2 | 0.0 | 1.7 | -1.1 | 3.5 | 1.3 | 4.1 | -1.3 |
| CdS/CdTe #K98012825 | F | 0.8 | 0.0 | 1.1 | 0.1 | 1.1 | 0.2 | 0.7 | 0.1 | 0.8 | 0.0 |
| Cds/CdTe #14407 | F | 0.6 | -0.1 | 2.2 | -0.8 | 1.9 | -0.7 | 0.9 | -0.3 | 3.2 | -0.9 |
| CdS/Cu(Ga,In)(S,Se) #4079 | G | 0.3 | -0.1 | 0.4 | -0.2 | 0.3 | -0.2 | 0.2 | -0.1 | 0.4 | -0.2 |
| CdS/Cu(Ga,In)(S,Se) #5165 | H | 0.2 | -0.1 | 0.3 | 0.0 | 0.2 | 0.0 | 0.2 | 0.1 | 0.3 | 0.0 |
| Multi-crystal Si #0162 | I | 0.1 | 0.0 | 0.6 | 0.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.6 | -0.2 |
| Multi-crystal Si #0194 | I | 0.1 | 0.0 | 0.7 | -0.4 | 0.6 | -0.4 | 0.3 | -0.1 | 1.0 | -0.6 |
| Multi-crystal Si #4978 | J | 0.8 | -0.1 | 1.0 | -0.2 | 0.9 | -0.2 | 0.3 | 0.0 | 0.7 | -0.2 |
| Multi-crystal Si #9365 | D | 0.1 | 0.1 | 0.4 | 0.2 | 0.3 | 0.1 | 0.1 | 0.0 | 0.3 | 0.0 |
| Multi-crystal Si #9366 | D | 0.2 | 0.0 | 0.4 | -0.3 | 0.2 | 0.0 | 0.4 | -0.3 | 0.4 | -0.3 |
| Single-crystal Si #270-2301 | D | 0.4 | 0.1 | 1.4 | -0.2 | 2.1 | 0.2 | 0.9 | -0.2 | 4.0 | 0.4 |
| Single-crystal Si #585-2316 | D | 0.1 | 0.0 | 0.6 | -0.2 | 0.4 | -0.2 | 0.2 | -0.1 | 0.8 | -0.3 |
| Single-crystal Si #585-2164 | D | 0.1 | 0.0 | 0.6 | 0.1 | 0.6 | 0.0 | 0.2 | 0.2 | 0.8 | 0.2 |
| Single-crystal Si #270-2577 | D | 0.5 | 0.0 | 1.1 | 0.0 | 1.7 | 0.0 | 0.9 | 0.4 | 1.6 | -0.3 |
| Single-crystal Si #0442 | H | 0.5 | 0.2 | 0.9 | 0.1 | 0.9 | 0.1 | 0.3 | 0.0 | 0.8 | -0.1 |
| Average | | 0.6 | 0.1 | 0.8 | -0.1 | 0.7 | -0.1 | 0.5 | 0.0 | 1.1 | -0.2 |

Table II. Model root-mean-square-error (rmse) and mean-bias-error (mbe) as a percentage of the average Voc, Pm, Vmp, Imp, or FF using July-December 2003 data. (~ 6000 I-V curves per module)

| PV Module | Man. | $V_{oc}$ | | $P_m$ | | $V_{mp}$ | | $I_{mp}$ | | FF | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | rmse | mbe | rmse | mbe | rmse | mbe | rmse | mbe | rmse | mbe |
| CdS/Cu(Ga,In)(S,Se) #5165 | H | 0.4 | 0.0 | 1.0 | -0.1 | 0.9 | -0.2 | 0.4 | 0.0 | 1.1 | -0.4 |
| Multi-crystal Si #0162 | I | 0.4 | 0.1 | 1.0 | -0.2 | 0.8 | -0.1 | 0.7 | -0.1 | 1.3 | -0.2 |
| Multi-crystal Si #0194 | I | 0.2 | 0.1 | 1.3 | -0.2 | 0.7 | -0.2 | 0.7 | -0.1 | 1.3 | -0.3 |
| Multi-crystal Si #9365 | D | 0.3 | 0.1 | 0.7 | 0.1 | 0.5 | 0.0 | 0.6 | 0.1 | 1.0 | 0.0 |
| Multi-crystal Si #9366 | D | 0.4 | 0.1 | 0.8 | -0.3 | 0.8 | 0.1 | 0.8 | -0.4 | 0.8 | -0.3 |
| Single-crystal Si #270-2301 | D | 0.6 | 0.3 | 2.0 | 0.0 | 3.6 | 0.7 | 1.5 | -0.1 | 7.2 | 2.2 |
| Single-crystal Si #585-2316 | D | 0.4 | 0.2 | 1.0 | 0.3 | 1.5 | 0.5 | 0.6 | 0.2 | 3.2 | 1.3 |
| Single-crystal Si #585-2164 | D | 0.4 | 0.2 | 1.5 | 0.7 | 1.5 | 0.3 | 1.0 | 0.6 | 4.3 | 1.9 |
| Single-crystal Si #270-2577 | D | 1.5 | 1.3 | 2.1 | 0.9 | 1.8 | -0.8 | 2.6 | 1.9 | 3.5 | 0.7 |
| Average | | 0.5 | 0.3 | 1.3 | 0.1 | 1.3 | 0.0 | 1.0 | 0.2 | 2.6 | 0.5 |

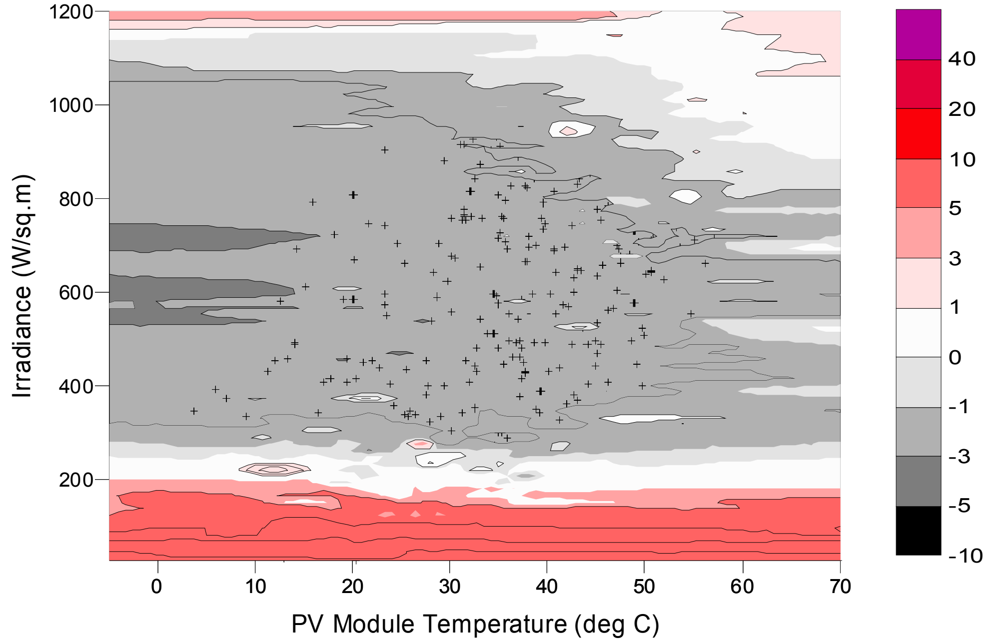


Figure 2. Contour map for the single-crystal Si #2301 PV module (which had the highest errors) showing percent bias in $P_m$ when translated from reference I-V curves measured for conditions represented by the location of the bold numbers 1-4. Map based on July-December 2003 data (~6000 I-V curves), + symbols show ranges of temperature and irradiance for the period.

## SUMMARY AND DISCUSSION

For 26 PV modules at NREL, I-V curves were modeled, by bilinearly interpolating from four reference I-V curves, and then compared with measured I-V curves for a clear day. The method performed well for all the PV module technologies. On average, rmses were 0.6% for Voc, 0.8% for Pm, 0.7% for Vmp, 0.5% for Imp, and 1.1% for FF. The average mbes ranged from -0.2% to +0.1%. For nine of the PV modules, a more extensive evaluation was performed using approximately 6000 I-V curves per PV module for July-December 2003. Error statistics increased only slightly from the clear day error statistics. Because irradiance values were derived from Isc, the error statistics portray model and measurement errors not related to spectral or angular response. Increased errors would have resulted if irradiances were from pyranometer measurements.

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Current-voltage (I-V) curves for photovoltaic (PV) modules representing all PV technologies were modeled by bilinearly interpolating the I-V curves from a PV module's four reference I-V curves. The interpolation was performed first with respect to open-circuit voltage to account for PV module temperature, and second with respect to short-circuit current to account for irradiance. The modeled I-V curves compared closely with measured I-V curves for 26 PV modules located at the National Renewable Energy Laboratory.

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