Overview of the PV Module Model in PVWatts

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Model Used in PVWatts

Model based on PVFORM Version 3.3 (1988)
- Provides estimate of maximum power, $P_m$
- For irradiance $> 125 \text{ W/m}^2$

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

where,

$E = \text{POA irradiance, W/m}^2$
$T = \text{PV cell temperature, } ^\circ\text{C}$
$\gamma = P_m \text{ correction factor for temperature, } ^\circ\text{C}^{-1}$

Zero subscripts denote performance at SRC, the $e$ subscript denotes an “effective” irradiance, which in the case of PVWatts means corrected for AOI but not spectrum.
A different formula is used at low irradiances to account for reductions in output observed by Sandia for crystalline silicon PV modules.

- For irradiance \( \leq 125 \text{ W/m}^2 \)

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

- PVWatts also applies an AOI correction.
AOI Correction

The King-Sandia AOI function is used to correct direct beam radiation for incident angles greater than 50 degrees.

Other equivalent methods are shown in the figure.
Not used in PVWatts, but the method of Martin and Ruiz may allow for better predictions if the soiling amount is known. (Progress in PV, 2005; 13:75-84)
Analysis of data collected at NREL and FSEC indicates no benefit for applying spectral corrections in PVWatts for x-Si and m-Si PV modules.

- For a group of 5 x-Si and m-Si PV modules at NREL, use of a spectral model and spectral response data reduced the RMSE in $I_{sc}$ by only 0.1%, use of the Sandia AM$_a$ function increased the RMSE by 0.3%.

- For amorphous silicon PV modules, both methods reduced errors in estimating $I_{sc}$, and the most favorable results were for the CREST air-mass function.
AOI and Spectral Correction Results

**Graph 1:**
- Y = 0.0002862 * X
- Number of data points used = 11562
- Average X = 527.6 W/m²
- Average Y = 1.503 A
- RMSE = 0.048 A or 3.2% of average

**Graph 2:**
- Y = 0.0002883 * X
- Number of data points used = 11562
- Average X = 519.9 W/m²
- Average Y = 1.503 A
- RMSE = 0.028 A or 1.9% of average

**Graph 3:**
- Y = 0.0002888 * X
- Number of data points used = 11562
- Average X = 520.7 W/m²
- Average Y = 1.503 A
- RMSE = 0.033 A or 2.2% of average

**Graph 4:**
- Y = 0.0002925 * X
- Number of data points used = 11562
- Average X = 513.6 W/m²
- Average Y = 1.503 A
- RMSE = 0.023 A or 1.6% of average
The traditional linear expression for PV power using irradiance, temperature, and a power correction factor for temperature was published by Evans and Florschuetz in 1977 (Solar Energy 19, 255-262).

- Is it appropriate for today’s PV modules?
- How do it’s predictions compare with later models when using the same inputs of irradiance and temperature?
Comparison with Sandia Model

For the three modules and data sets for this workshop study, PVWatts module power estimates were compared with those using the Sandia model.

For PVWatts:

- $P_{m0}$ determined using the Sandia model for SRC.
- $P_{m}$ correction factor for temperature determined using the Sandia model for SRC and for 1000 W/m$^2$ and 55 C.
- This ensured agreement at 1000 W/m$^2$ and allowed differences at other irradiances to be more readily observed.
PVWatts versus Sandia for the Mobil Module

Differences at low irradiances from PVWatts using a different algorithm below 125 W/m².

PVWatts Average = 99.7% of Sandia Average

1:1 slope
PVWatts versus Sandia for SunPower

PVWatts Average = 99.9% of Sandia Average

1:1 slope
PVWatts versus Sandia for Shell

PVWatts Average = 103.0% of Sandia Average
Correction for Irradiance Nonlinearity

Previous work (Marion, 2008 PVSC) presented a method for correcting for irradiance nonlinearity.

Scatter plot and percent error graph showing nonlinearity with respect to Irradiance for a multi-crystalline PV module.
Correction for Irradiance Nonlinearity

Error function applies a non-linear correction below 200 W/m² and a linear correction above 200 W/m²

- k is determined using a power measurement at 200 W/m² (now required by IEC 61215 and 61646)

\[
k = \frac{0.2 \cdot P_{m0} - P_{200}}{P_{m0}}
\]

- Results in a model using 3 parameters: \(P_{m0}\), \(\gamma\), and \(P_{200}\)

- \(k=0.011\) for Mobil, 0.009 for SunPower, 0.030 for Shell

Error in watts normalized by \(P_{m0}\)
3-Parameter versus Sandia for Mobil Module

3-Parameter Average = 100.0% of Sandia Average
3-Parameter versus Sandia for SunPower

The graph shows a linear relationship between the 3-Parameter Model and the Sandia Model. The 3-Parameter Model average is 100.1% of the Sandia Model average, indicating a strong correlation with a 1:1 slope.
3-Parameter versus Sandia for Shell

3-Parameter Average = 100.7% of Sandia Average

1:1 slope
Summary

The historical PV model in PVWatts is acceptable for estimating the energy production of PV systems.

– Even larger nonlinearities with respect to irradiance only impact estimates on the order of 3%, which may be inconsequential considering other sources of error: resource data, manufacturer’s ratings, long-term degradation, shading, availability, etc.

– The addition of a 3rd parameter to the model could reduce errors associated with nonlinearity if the additional data proved reliable.