PV Performance Modeling with PVfit
Workflows that balance cost, complexity, and accuracy.

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Agenda

PVfit’s Approach to Photovoltaic Modeling

2021 Blind PV Modeling Comparison

PV-Based Sensing and Other Opportunities
PVfit’s Single-Diode Model (SDM)

6-parameter SDM for photovoltaic (PV) direct current (DC)\(^2\)—

\[
0 = I_{ph} - I_{rs} \left( e^{\frac{q(V+IR_s)}{N_snkB}} - 1 \right) - G_p (V + IR_s) - I,
\]

with auxiliary equations—

\[
I_{ph} = I_{rs} \left( e^{\frac{qI_{sc}R_s}{N_snkB}} - 1 \right) + G_p I_{sc} R_s + I_{sc},
\]

\[
I_{rs} = I_{rs0} \left( \frac{T}{T_0} \right)^3 e^{\frac{qE_{g0}}{nkB} \left( \frac{1}{T_0} - \frac{1}{T} \right)},
\]

\[
n = n_0, \quad R_s = R_{s0}, \quad G_p = G_{p0}, \quad I_{sc} = FI_{sc0}.
\]

“Irradiance” \( F = \frac{I_{sc}}{I_{sc0}} \) and PV cell temperature \( T \) (junction).

\(^2\text{Current conservation under homogeneity assumptions.}\)
Performance w.r.t. Irradiance and Temperature

6-Parameter SDM Fit to IEC 61853-1 Data Using PVfit (HIT05667)

- $P_{mp}$ depends strongly on $F$ and $T$
- $I_{sc}$ depends strongly on $F$
- $V_{oc}$ depends strongly on $T$

Increasing $F$

Increasing $T$
Parameter Inference (aka. Model Calibration)

Given sufficient measurements of observables—

\[ V, I, T, \text{ and } F, \]

then infer six model parameters at reference condition (RC)—

\[ I_{sc0}, I_{rs0}, n_0, R_s0, G_p0, \text{ and } E_g0, \]

using a minimization-based solver with rescalings and careful choice of initial conditions—`scipy's least_squares (dogbox)` or `odr`.

PVfit's formulation accommodates various measurement types. However—

- How do we work with \( F \) instead of traditional irradiance?
- Is “the” temperature given for PV cell(s), or back of module, or ambient, or ...?
Observing Irradiance and Temperature

- Calibration labs measure dense I-V curves using a PV reference device, where for each point—

\[
F = \frac{I_{sc}}{l_{sc0}} = M \frac{I_{sc,\text{ref}}}{l_{sc,\text{ref}0}},
\]

and the spectral correction \( M \) depends on the temperature-dependent spectral responsivity of both devices.

- IEC 61853-1 matrix provides several 3-point I-V curves (one at RC\(^3\)), where for each curve with short-circuit current \( I_{sc} \)—

\[
F = \frac{I_{sc}}{l_{sc0}}.
\]

\( T \) is too loosely defined in IEC 61853-1 (my opinion).

*Module and cell temperatures may, or may not, be close, e.g., continuous vs. flashed irradiance.*

\(^3\)Here, RC is the standard test condition (STC).
Performance Simulation (a.k.a. Model Prediction)

Given values of operating-condition (OC) observables—

\[ F \text{ and } T, \]

then predict maximum power—

\[ P_{mp} = I_{mp} \cdot V_{mp}. \]

However—

- \( F \) is traditionally observed using a reference device, with (mis)match depending on several conditions.
- \( T \) of the PV cell is rarely the observed temperature.
Using Meteorological (MET)-Station Data

Sandia Array Performance Model (SAPM) defines an effective irradiance, $E_e$—

$$E_e = \frac{l_{sc}}{l_{sc0} \left(1 + \alpha_{sc}(T - T_0)\right)},$$

so that—

$$F = \frac{l_{sc}}{l_{sc0}} = E_e \left(1 + \alpha_{sc}(T - T_0)\right).$$

$E_e$ (unitless) is readily calculated from MET-station data.\(^4\)

\(^4\)Technically, $\alpha_{sc}$ depends on spectrum of OC.
Calculation of Effective Irradiance

\[ E_e \text{ is computed from plane-of-array (POA) irradiance, } E_{\text{POA}} — \]

\[ E_e = f_{\text{AM}_a} \frac{E_{\text{POA}}}{E_0} = f_{\text{AM}_a} \left( \frac{f_{\text{IAM}} E_b + f_d E_d}{E_0} \right). \]

- \( E_0 \): irradiance at RC (1000 W/m\(^2\) at STC)
- \( E_b \): beam irradiance
- Incident angle modifier: \( f_{\text{IAM}} = f_{\text{IAM}}(\text{AOI}) — \text{PCHIP}\)\(^5\) of IEC 61853-2 data or physical model, with AOI from \text{pvlib}\)
- \( E_d \): diffuse irradiance — sum of sky and ground components (e.g., isotropic and monthly albedo, respectively)
- Simple diffuse fraction model: \( f_d = 1 \) (non-concentrating)
- \( E_b \) and \( E_d \) from given GHI, DNI, and DHI using \text{pvlib}\)
- No absolute air-mass correction: \( f_{\text{AM}_a} = 1 \) (insufficient info)

\(^5\)Piecwise-Cubic Hermite Interpolating Polynomial
Incident Angle Modifier

PCHIP is smooth, while respecting data’s extrema.\(^6\)

\(^6\)Zero “tail” is separate.
Temperature from MET Data

Faiman model for module temperature, $T_m$, using POA irradiance, $E_{POA}$, ambient temperature, $T_a$, and wind speed, $WS$—

$$T_m = T_a \frac{E_{POA}}{U_0 + U_1 \cdot WS}.$$ 

$T_m$ can be further transformed into cell temperature, $T$, using, e.g., SAPM—

$$T = T_m + \frac{E_{POA}}{E_0} \Delta T.$$ 

$U_0$, $U_1$, and $\Delta T$ are installation- and module-dependent.\(^7\)

\(^7\)Because $F \approx \frac{E_{POA}}{E_0}$, one could recast models in terms of $F$. 
Degradation and Other Losses

Warranty degradation using time since commissioning (worst case).

Soiling, mismatch, wiring, etc. not included (best case).
Agenda

PVfit’s Approach to Photovoltaic Modeling

2021 Blind PV Modeling Comparison

PV-Based Sensing and Other Opportunities
Considered three of six scenarios, omitting tracked and bifacial.

Albuquerque, NM, USA—
1: Panasonic 325W monofacial HIT, $N_s = 72$, 12 panels
2: Canadian Solar 275W monofacial mono-Si, $N_s = 60$, 12 panels

Roskilde, Denmark—
5: Trina Solar 305W monofacial mono-Si, $N_s = 60$, 88 panels
Scenarios (2 of 2)

For Panasonic & Canadian Solar in Albuquerque—
- IEC 61853-1 provided I-V matrix (assume $T = T_m$) and $\alpha_{sc}$
- IEC 61853-2 measurements for $U_0$, $U_1$, and IAM

For Trina Solar in Roskilde—
- Datasheet had $I_{sc}$, $I_{mp}$, $V_{mp}$, & $V_{oc}$ at STC & NOCT\(^8\) and $\alpha_{sc}$
- $U_0$ and $U_1$ estimated, physical model for IAM

For all scenarios—
- Only Faiman temperature model ($\Delta T = 0$, not provided)
  \[
  T = T_m + \frac{E_{PQA}}{E_0} \Delta T
  \]

\(^8\)Nominal operating cell temperature NOCT), not nominal module operating temperature (NMOT).
Panasonic 325W monofacial HIT (Albuquerque)
Panasonic 325W Monofacial HIT (Albuquerque)

Fit parameters (seconds to solve)—

<table>
<thead>
<tr>
<th>$I_{sc0}$</th>
<th>$I_{rs0}$</th>
<th>$n_0$</th>
<th>$R_{s0}$</th>
<th>$G_{p0}$</th>
<th>$E_{g0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.903 A</td>
<td>1.314e-12 A</td>
<td>1.304</td>
<td>0.7820 Ω</td>
<td>0.001893 S</td>
<td>1.575 eV</td>
</tr>
</tbody>
</table>

$P_{mp}$ errors for model calibration ($\frac{P_{mp,fit} - P_{mp,meas}}{P_{mp,meas}}$, in %)—

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>-10.0</td>
<td>-2.8</td>
<td>0.22</td>
<td>0.57</td>
<td>0.57</td>
<td>0.68</td>
<td>—</td>
</tr>
<tr>
<td>25</td>
<td>-9.1</td>
<td>-2.8</td>
<td>0.084</td>
<td>0.40</td>
<td>0.36</td>
<td>0.26</td>
<td>0.112</td>
</tr>
<tr>
<td>50</td>
<td>-8.1</td>
<td>-2.5</td>
<td>-0.21</td>
<td>0.28</td>
<td>0.188</td>
<td>-0.100</td>
<td>-0.30</td>
</tr>
<tr>
<td>75</td>
<td>-5.7</td>
<td>-0.86</td>
<td>0.61</td>
<td>0.41</td>
<td>0.24</td>
<td>-0.064</td>
<td>-0.183</td>
</tr>
</tbody>
</table>

Yearly PV-array energy from hourly powers: 134.841 kWh
Calculation of $F = \frac{I_{sc}}{I_{sc0}}$ (1 of 2)

$I_{sc}$ (A) from IEC 61853-1 matrix—

<table>
<thead>
<tr>
<th>$T$ ($^\circ$C)</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.595</td>
<td>1.183</td>
<td>2.354</td>
<td>3.532</td>
<td>4.706</td>
<td>5.891</td>
<td>–</td>
</tr>
<tr>
<td>25</td>
<td>0.599</td>
<td>1.183</td>
<td>2.365</td>
<td>3.542</td>
<td>4.718</td>
<td><strong>5.903</strong></td>
<td>6.488</td>
</tr>
<tr>
<td>50</td>
<td>0.602</td>
<td>1.199</td>
<td>2.379</td>
<td>3.567</td>
<td>4.754</td>
<td>5.944</td>
<td>6.528</td>
</tr>
<tr>
<td>75</td>
<td>0.606</td>
<td>1.207</td>
<td>2.399</td>
<td>3.593</td>
<td>4.784</td>
<td>5.976</td>
<td>6.578</td>
</tr>
</tbody>
</table>

$I_{sc0} = 5.903$ A is in red — divisor for $F = \frac{I_{sc}}{I_{sc0}}$. 
Calculation of $F = \frac{I_{sc}}{I_{sc0}}$ (2 of 2)

$F = \frac{I_{sc}}{I_{sc0}}$ from IEC 61853-1 matrix—

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.1008</td>
<td>0.200</td>
<td>0.399</td>
<td>0.598</td>
<td>0.797</td>
<td>0.998</td>
<td>–</td>
</tr>
<tr>
<td>25</td>
<td>0.1015</td>
<td>0.200</td>
<td>0.401</td>
<td>0.600</td>
<td>0.799</td>
<td>1</td>
<td>1.099</td>
</tr>
<tr>
<td>50</td>
<td>0.1020</td>
<td>0.203</td>
<td>0.403</td>
<td>0.604</td>
<td>0.805</td>
<td>1.007</td>
<td>1.106</td>
</tr>
<tr>
<td>75</td>
<td>0.1026</td>
<td>0.204</td>
<td>0.406</td>
<td>0.609</td>
<td>0.810</td>
<td>1.0124</td>
<td>1.114</td>
</tr>
</tbody>
</table>

Shows that $F \neq \frac{E_{POA}}{E_0}$, merely $F \approx \frac{E_{POA}}{E_0}$. 
Canadian Solar 275W Monofacial Mono-Si (Albuquerque)
Canadian Solar 275W Monofacial Mono-Si (Albuquerque)

Fit parameters (minutes to solve)—

<table>
<thead>
<tr>
<th>$I_{sc0}$</th>
<th>$I_{rs0}$</th>
<th>$n_0$</th>
<th>$R_{s0}$</th>
<th>$G_{p0}$</th>
<th>$E_{g0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.299 A</td>
<td>1.133e-09 A</td>
<td>1.088</td>
<td>0.2303 Ω</td>
<td>0.0 S</td>
<td>1.138 eV</td>
</tr>
</tbody>
</table>

$P_{mp}$ errors for model calibration ($\frac{P_{mp,fit} - P_{mp,meas}}{P_{mp,meas}}$, in %)—

<table>
<thead>
<tr>
<th>$E_{POA}$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ (°C)</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>75</td>
</tr>
</tbody>
</table>

Yearly PV-array energy from hourly powers: 114.361 kWh
Trina Solar 305W Monofacial Mono-Si (Roskilde)

6-Parameter SDM Fit to STC & NOCT Data Using PVfit (Trina Monofacial Fixed)

No info for low $F$ & high $T$. 
Trina Solar 305W Monofacial Mono-Si (Roskilde)

Fit parameters (seconds to solve)—

<table>
<thead>
<tr>
<th>$I_{sc0}$</th>
<th>$I_{rs0}$</th>
<th>$n_0$</th>
<th>$R_{s0}$</th>
<th>$G_{p0}$</th>
<th>$E_{g0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.85 A</td>
<td>3.488e-15 A</td>
<td>0.7299</td>
<td>0.3520 Ω</td>
<td>0.007732 S</td>
<td>1.272 eV</td>
</tr>
</tbody>
</table>

$P_{mp}$ errors for model calibration ($\frac{P_{mp,\text{fit}} - P_{mp,\text{meas}}}{P_{mp,\text{meas}}}$, in %)—

<table>
<thead>
<tr>
<th>$E_{POA}$ (W/m²)</th>
<th>$T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>800</td>
</tr>
<tr>
<td>25</td>
<td>–</td>
</tr>
<tr>
<td>44</td>
<td>0.039</td>
</tr>
</tbody>
</table>

CAUTION: Good fit does not guarantee good model!  

Yearly PV-array energy from hourly powers: 478.868 kWh

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9 This scenario’s fit changed considerably when scipy.odr used instead.
Are We There Yet?

“All models are wrong, but some are useful.”

–George E. P. Box

Key IEC 61853-1 measurement questions—
- Module vs. cell temperature?
- Matched reference device (spectral & angular response)?
- Representative module sample? Variability estimates?

Is complexity of PVsyst, double-diode model, ... worth it?
- Photo-conductive shunt in SDM, e.g., $G_p = F \cdot G_{p_0}$?
- The Future™ is bifacial, or perovskite, or ...?

When do other factors swamp measurement & fitting errors?
- $\Delta T = 0$ led to overestimated energy? (unblind hourly data)
- 2–4% energy increase switching isotropic to haydavies!
- Degradation, soiling, shading, mismatch, line losses, ...
- Weather uncertainty, variability, availability, ...

Inter-comparisons needed to tease all this out...thank you PVPMC!
Agenda

PVfit’s Approach to Photovoltaic Modeling

2021 Blind PV Modeling Comparison

PV-Based Sensing and Other Opportunities
Recasting the Inference Problem

**Why not think/work directly in terms of \( F \) and \( T \)?**

Given a well-calibrated PV device with known parameters—

\[ l_{sc0}, l_{rs0}, n_0, R_{s0}, G_{p0}, \text{ and } E_{g0}, \]

and sufficient measurements of observables at one OC—

\[ V \text{ and } I, \]

then infer the two model parameters—

\[ F \text{ and } T. \]

A minimally observed I-V curve could be simply \( l_{sc} \) and \( V_{oc}. \)\(^{10}\)

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\(^{10}\)Note absence of temperature-coefficients.
PV-Based Sensing of Irradiance and Cell Temperature

6-Parameter SDM Fit to IEC 61853-1 Data Using PVfit (HIT05667)

- $P_{mp}$ depends strongly on $F$ and $T$
- $I_{sc}$ depends strongly on $F$
- $V_{oc}$ depends strongly on $T$
- Increasing $F$
- Increasing $T$
Combine $F$ and $T$ with $T_m$ measurements to infer $\Delta T$!
Soiling-measurement systems have matched reference devices—

- Simply (?) add $V_{oc}$ measurement with $I_{sc}$ to infer $T$
- Combine with $T_m$ measurement (and $F$) to infer $\Delta T$

$$T = T_m + \frac{E_{POA}}{E_0} \Delta T \approx T_m + F \cdot \Delta T$$

-Photo credit: NRGSystems
PVfit: Because Measurements Cost Money

Model calibration at https://pvfit.app or via REST API

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### PVfit: Single Diode Model (SDM)

<table>
<thead>
<tr>
<th>FIT</th>
<th>INFO</th>
<th>API</th>
</tr>
</thead>
</table>

#### SDM Calibration over a Range of Irradiance and Temperature

**Input: I-V Curve Data**

- **LOAD EXAMPLE DATA**
- 60-cell mono x-Si module
- 72-cell poly x-Si module
- 216-cell CdTe module

**IEC 61853-1 Matrix**

Input IEC 61853-1 matrix data, then click COMPUTE FIT (standard test conditions (STC) are 1000 W/m² and 25°C, with grey cells optional).

<table>
<thead>
<tr>
<th>Irradiance (W/m²)</th>
<th>Module Temperature (°C)</th>
<th>15</th>
<th>25</th>
<th>50</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td></td>
<td>I_sc (A)</td>
<td>P_mp (W)</td>
<td>I_sc (A)</td>
<td>P_mp (W)</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>V_mp (V)</td>
<td>V_oc (V)</td>
<td>V_mp (V)</td>
<td>V_oc (V)</td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td>I_sc (A)</td>
<td>P_mp (W)</td>
<td>I_sc (A)</td>
<td>P_mp (W)</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>V_mp (V)</td>
<td>V_oc (V)</td>
<td>V_mp (V)</td>
<td>V_oc (V)</td>
</tr>
</tbody>
</table>

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Open-source simulation code at https://github.com/markcampanelli/pvfit
References