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]—

$$0 = I_{\mathrm{ph}} - I_{\mathrm{rs}} \left(e^{\frac{q(V + I R_{\mathrm{s}})}{N_s n k_{\mathrm{B}} T}} - 1 \right) - G_{\mathrm{p}} \left(V + I R_{\mathrm{s}} \right) - I,$$

with auxiliary equations—

$$I_{\mathrm{ph}} = I_{\mathrm{rs}} \left(e^{\frac{q I_{\mathrm{sc}} R_{\mathrm{s}}}{N_s n k_{\mathrm{B}} T}} - 1 \right) + G_{\mathrm{p}} I_{\mathrm{sc}} R_{\mathrm{s}} + I_{\mathrm{sc}},$$

$$I_{\mathrm{rs}} = I_{\mathrm{rs0}} \left(\frac{T}{T_0} \right)^3 e^{\nu \frac{q E_{\mathrm{g}0}}{n k_{\mathrm{B}}} \left(\frac{1}{T_0} - \frac{1}{T} \right)},$$

$$n = n_0, \quad R_{\mathrm{s}} = R_{\mathrm{s0}}, \quad G_{\mathrm{p}} = G_{\mathrm{p}0}, \quad I_{\mathrm{sc}} = F I_{\mathrm{sc0}}.$$

"Irradiance" $F = \frac{I_{\mathrm{sc}}}{I_{\mathrm{sc0}}}$ and PV cell temperature T (junction).

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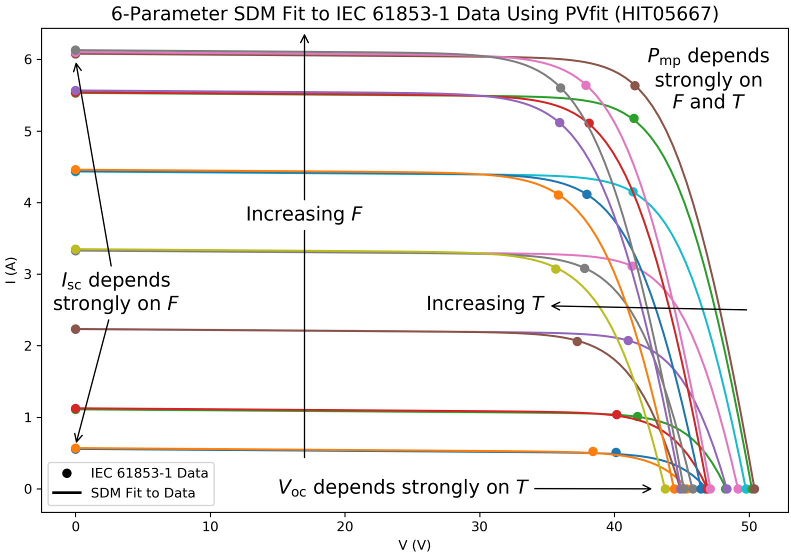
[2] Current conservation under *homogeneity assumptions*.

Performance w.r.t. Irradiance and Temperature



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*—

$$F = \frac{I_{\mathrm{sc}}}{I_{\mathrm{sc}0}} = M \frac{I_{\mathrm{sc,ref}}}{I_{\mathrm{sc,ref}_0}},$$

  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}—

$$F = \frac{I_{\mathrm{sc}}}{I_{\mathrm{sc}0}}.$$

  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—

$$P_{\mathrm{mp}} = I_{\mathrm{mp}} \cdot V_{\mathrm{mp}}.$$

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 effecitve irradiance, E_e—

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

so that—

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

E_e (unitless) is readily calculated from MET-station data.[4]

[4]Technically, α_{sc} depends on spectrum of OC.

Calculation of Effective Irradiance

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

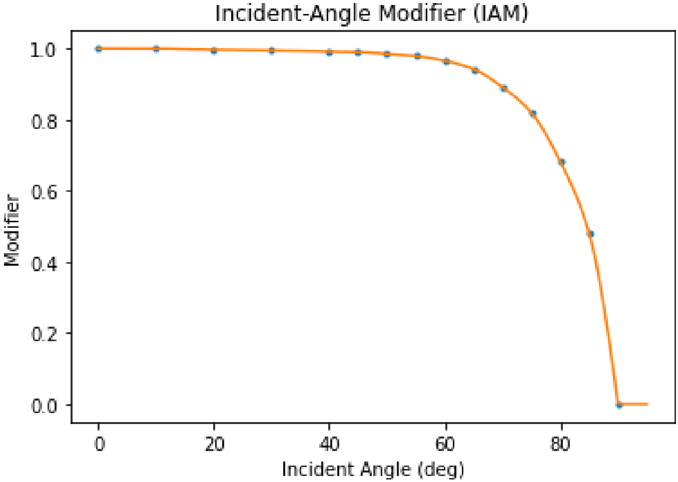
$$E_e = f_{AM_a} \frac{E_{POA}}{E_0} = f_{AM_a} \left(\frac{f_{IAM} E_b + f_d E_d}{E_0} \right).$$

- E_0: irradiance at RC (1000 W/m^2 at STC)
- E_b: beam irradiance
- Incident angle modifier: $f_{IAM} = f_{IAM}(AOI)$ — PCHIP[5] of IEC 61853-2 data or physical model, with AOI from `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 `pvlib`
- No absolute air-mass correction: $f_{AM_a} = 1$ (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—

$$T_{\mathrm{m}} = T_{\mathrm{a}} \frac{E_{\mathrm{POA}}}{U_0 + U_1 \cdot WS}.$$

T_{m} can be further transformed into cell temperature, T, using, e.g., SAPM—

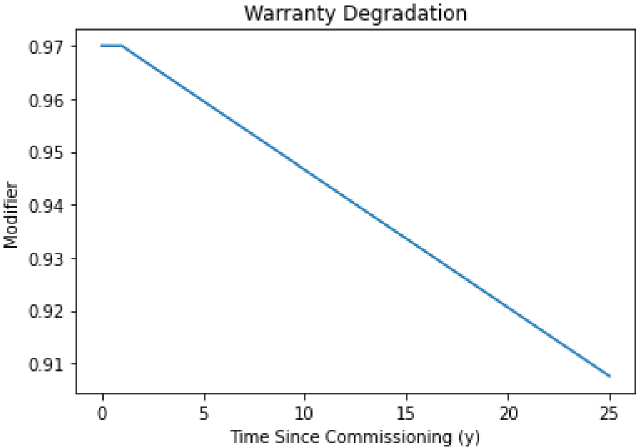
$$T = T_{\mathrm{m}} + \frac{E_{\mathrm{POA}}}{E_0} \Delta T.$$

U_0, U_1, and ΔT are installation- and module-dependent.[7]

[7] Because $F \approx \frac{E_{\mathrm{POA}}}{E_0}$, 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).

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Scenarios (1 of 2)

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 $T = T_\mathrm{m}$) and α_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 α_sc
- U_0 and U_1 estimated, physical model for IAM

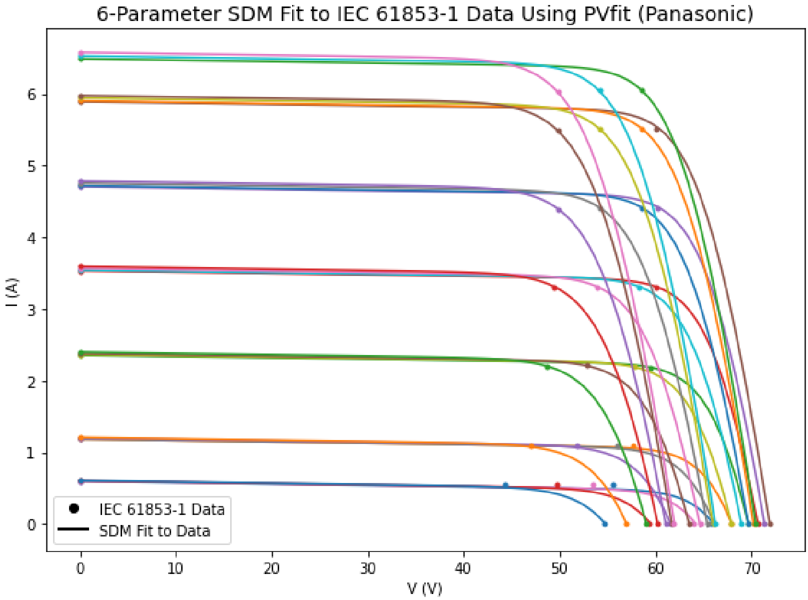
For all scenarios—

- Only Faiman temperature model ($\Delta T = 0$, not provided)

$$T = T_\mathrm{m} + \cancel{\frac{E_\mathrm{POA}}{E_0} \Delta T}$$

[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)—

I_{sc0}	I_{rs0}	n_0	R_{s0}	G_{p0}	E_{g0}
5.903 A	1.314e-12 A	1.304	0.7820 Ω	0.001893 S	1.575 eV

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

	E_{POA} (W/m^2)						
T (°C)	100	200	400	600	800	1000	1100
15	-10.0	-2.8	0.22	0.57	0.57	0.68	–
25	-9.1	-2.8	0.084	0.40	0.36	0.26	0.112
50	-8.1	-2.5	-0.21	0.28	0.188	-0.100	-0.30
75	-5.7	-0.86	0.61	0.41	0.24	-0.064	-0.183

Yearly PV-array energy from hourly powers: 134.841 kWh

Calculation of $F = I_{sc}/I_{sc0}$ (1 of 2)

Isc (A) from IEC 61853-1 matrix—

	E_{POA} (W/m^2)						
T (°C)	100	200	400	600	800	1000	1100
15	0.595	1.183	2.354	3.532	4.706	5.891	–
25	0.599	1.183	2.365	3.542	4.718	5.903	6.488
50	0.602	1.199	2.379	3.567	4.754	5.944	6.528
75	0.606	1.207	2.399	3.593	4.784	5.976	6.578

$I\text{sc}_0 = 5.903$ A is in red — divisor for $F = \frac{I_{sc}}{I_{sc0}}$.

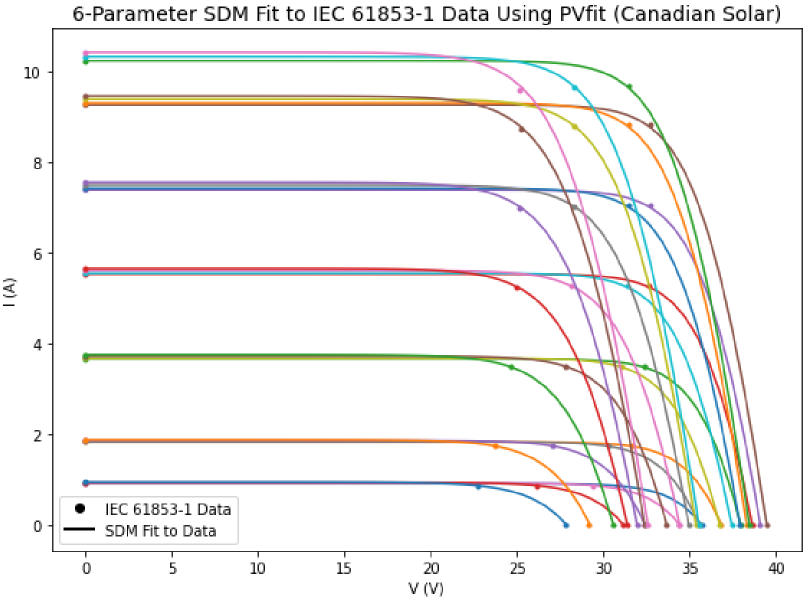
Calculation of $F = I_{sc}/I_{sc0}$ (2 of 2)

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

	E_{POA} (W/m^2)						
T (°C)	100	200	400	600	800	1000	1100
15	0.1008	0.200	0.399	0.598	0.797	0.998	–
25	0.1015	0.200	0.401	0.600	0.799	1	1.099
50	0.1020	0.203	0.403	0.604	0.805	1.007	1.106
75	0.1026	0.204	0.406	0.609	0.810	1.0124	1.114

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)—

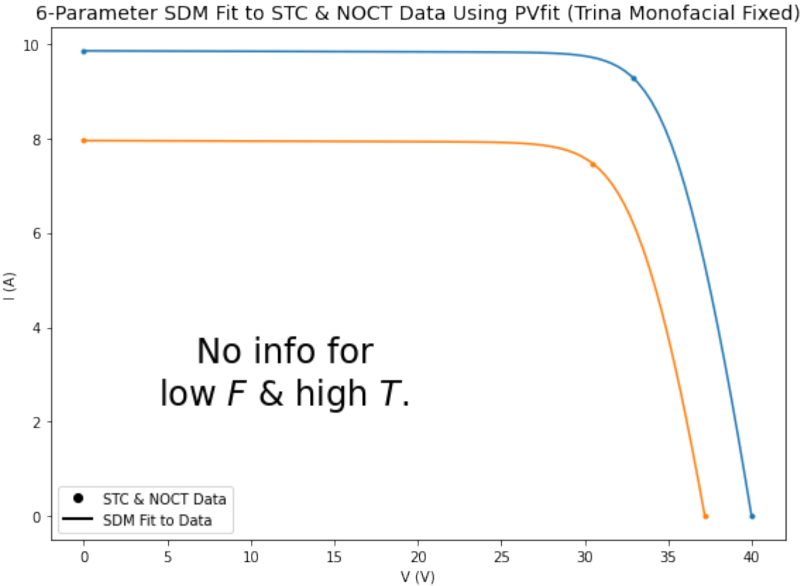
I_{sc0}	I_{rs0}	n_0	R_{s0}	G_{p0}	E_{g0}
9.299 A	1.133e-09 A	1.088	0.2303 Ω	0.0 S	1.138 eV

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

	E_{POA} (W/m^2)						
T (°C)	100	200	400	600	800	1000	1100
15	-0.70	-0.83	-0.97	-0.80	-0.69	-0.66	–
25	-0.166	-1.14	-0.88	-0.56	-0.42	-0.49	-0.50
50	0.110	-0.55	-0.30	-0.118	-0.0069	0.154	0.143
75	-0.34	-0.38	-0.118	0.37	0.51	0.72	0.85

Yearly PV-array energy from hourly powers: 114.361 kWh

Trina Solar 305W Monofacial Mono-Si (Roskilde)



Trina Solar 305W Monofacial Mono-Si (Roskilde)

Fit parameters (seconds to solve)—

I_{sc0}	I_{rs0}	n_0	R_{s0}	G_{p0}	E_{g0}
9.85 A	3.488e-15 A	0.7299	0.3520 Ω	0.007732 S	1.272 eV

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

	E_{POA} (W/m^2)	
T (°C)	800	1000
25	–	0.077
44	0.039	–

CAUTION: Good fit does *not* guarantee good model![9]

Yearly PV-array energy from hourly powers: 478.868 kWh

[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., $G_{\mathrm{p}} = F \cdot G_{\mathrm{p}_0}$?
  - The Future$^{\mathrm{TM}}$ 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

Recasting the Inference Problem

Why not think/work directly in terms of F and T?

Given a well-calibrated PV device with known parameters—

$$I_{sc0}, I_{rs0}, n_0, R_{s0}, G_{p0}, \text{ and } E_{g0},$$

and sufficient measurements of observables at one OC—

$$V \text{ and } I,$$

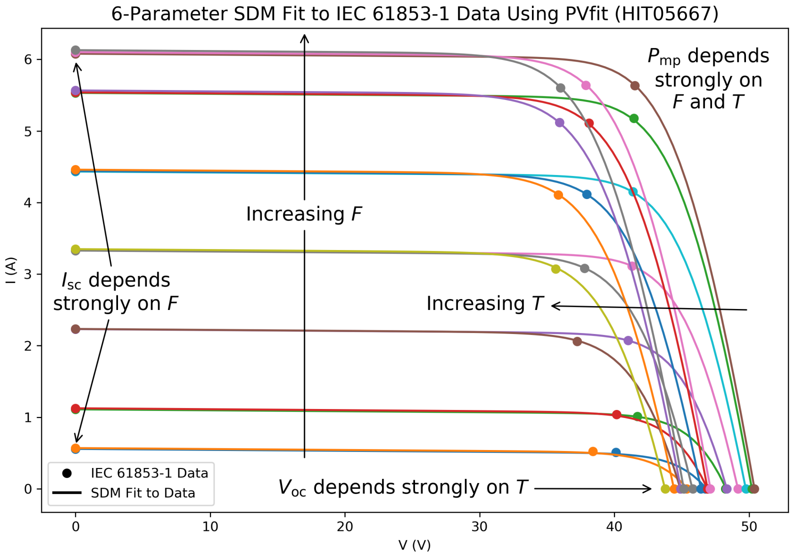
then infer the two model parameters—

$$F \text{ and } T.$$

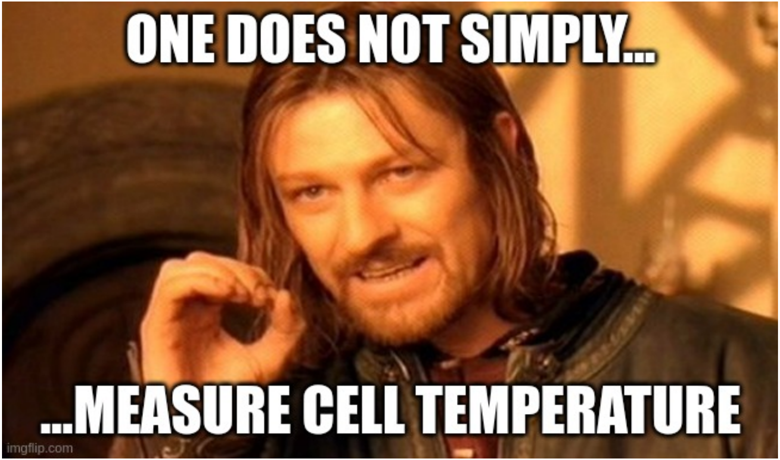
A minimally observed I-V curve could be simply I_{sc} and V_{oc}.[10]

[10] Note absence of temperature-coefficients.

PV-Based Sensing of Irradiance and Cell Temperature



Rethinking Irradiance and Temperature (1 of 2)



Combine F and T with T_{m} measurements to infer ΔT!

Rethinking Irradiance and Temperature (2 of 2)

Soiling-measurement systems have matched reference devices—

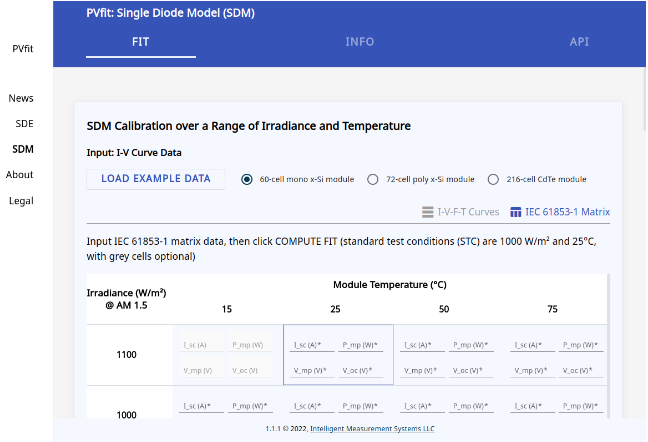
- Simply (?) add V_{oc} measurement with I_{sc} to infer T
- Combine with T_m measurement (and F) to infer ΔT

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

–Photo credit: NRGSystems

PVfit: Because Measurements Cost Money

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



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

References

1. *PV Performance Modeling Collaborative*, https://pvpmc.sandia.gov
2. *pvlib-python*, https://github.com/pvlib/pvlib-python
3. *Effective Irradiance Ratios to Improve I–V Curve Measurements and Diode Modeling Over a Range of Temperature and Spectral and Total Irradiance*, Campanelli and Osterwald, JPV, 2016.
4. *Calibration of a Single-Diode Performance Model without a Short-Circuit Temperature Coefficient*, Campanelli and Hamadani, Energy Science and Engineering, 2018.
5. *Look Mom, No MET Station!* Campanelli, 12th PV Performance Modeling and Monitoring Workshop, 2019. https://pvpmc.sandia.gov/download/7302