



Getting Started with PVfit

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Tutorial Overview

- 1 Setup & Preliminaries
- 2 Single-Diode Model Calibration
- 3 DC Performance Prediction
- 4 Flex Your Model!

Setup & Preliminaries

Python Environment and Package Installation

Set up a Python 3.10-12 virtual environment—

```
$ python -V
Python 3.11.7
$ python -m venv pvfit_pvpmmc2024
$ . pvfit_pvpmmc2024/bin/activate
$ python -m pip install --upgrade pip setuptools
```

Install `pvfit v0.0.1` from PyPI with demo dependencies—

```
$ python -m pip install pvfit[demo]==0.0.1
$ python -c "from pvfit import __version__; \
print(__version__)"
0.0.1
```

Tutorial Notebook Setup

Install jupyterlab for interactive tutorials—

```
$ python -m pip install jupyterlab
```

Run jupyterlab within a web browser (or VSCode, etc.)—

```
$ jupyter lab
```

This presentation follows these Jupyter notebooks from
<https://github.com/markcampanelli/pvpmc2024/tutorial>—

- 1_single_diode_model_calibration.ipynb
- 2_dc_performance_prediction.ipynb
- 3_flex_your_model!.ipynb

Design Patterns and Usage Notes

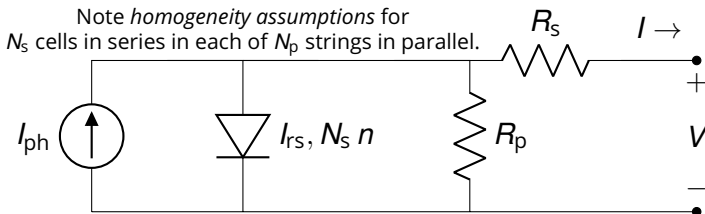
- `pvfit` has not yet reached stable v1.0. For latest, visit <https://github.com/markcampanelli/pvfit>.
- Objects encapsulate immutable data (validation in initializer).
- Functions transform data from input object to output object.
- Functions/methods/initializers take named arguments—
`result = fit(iv_performance_matrix=my_matrix)`
- Functions return multiple values in dictionaries.
- Variable names typically include units, e.g., `I_sc_A`.
- The minimal library requires only `numpy` and `scipy`.
- Vectorization used wherever practicable.

Single-Diode Model Calibration

Single-Diode Equation (SDE)

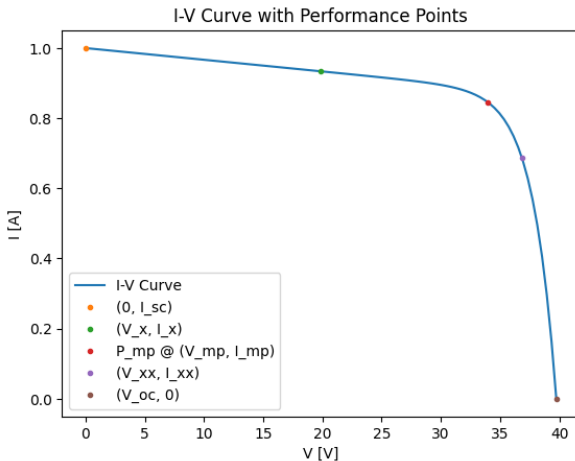
The current-voltage (I - V) relationship of a photovoltaic (PV) device at fixed irradiance and temperature can be modeled by—

$$I = I_{\text{ph}} - I_{\text{rs}} \left(e^{q \frac{V + I R_s}{N_s n k_B T}} - 1 \right) - \underbrace{G_p}_{=1/R_p} (V + I R_s) \quad (\text{SDE})$$



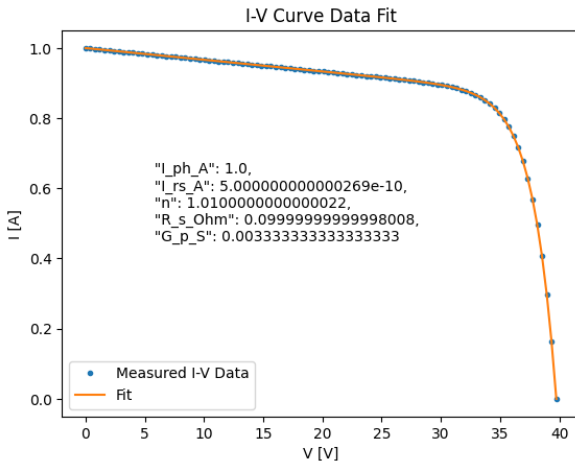
Solving the SDE: Forward Problem

Given SDE parameters I_{ph} , I_{rs} , n , R_s , and G_p , compute I - V curve.



Solving the SDE: Inverse Problem

Given measured I - V curve data, estimate the SDE parameters.



Single-Diode Model (SDM) from Auxiliary Equations

Which SDE parameters depend on irradiance and/or temperature?

$$\begin{aligned} I_{rs} &= I_{rs0} \left(\frac{T}{T_0} \right)^3 e^{\frac{E_{g0}}{n_0 k_B T} \left(\frac{1}{T_0} - \frac{1}{T} \right)}, \\ I_{ph} &= I_{rs} \left(e^{q \frac{I_{sc} R_s}{N_s n k_B T}} - 1 \right) + (G_p R_s + 1) I_{sc}, \\ I_{sc} &= F I_{sc0}, \quad n = n_0, \quad R_s = R_{s0}, \quad G_p = G_{p0}, \end{aligned} \quad (\text{SDM})$$

with six *unobservable* model parameters at STC—

I_{sc0} : short-circuit current [A],

R_{s0} : series resistance [Ω],

I_{rs0} : reverse-saturation current [A],

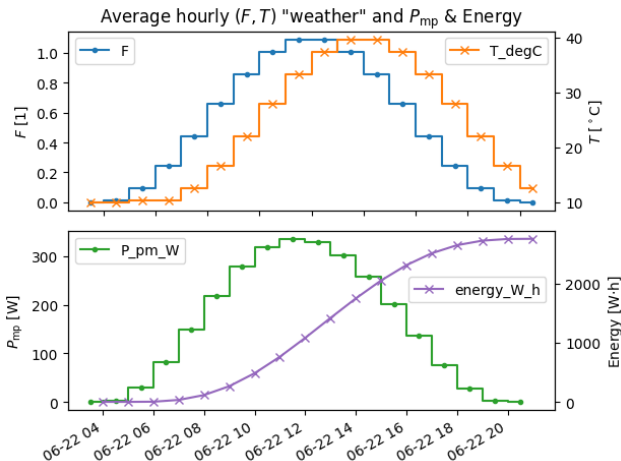
G_{p0} : parallel conductance [S],

n_0 : diode ideality factor [\cdot],

E_{g0} : material bandgap [eV].

Solving the SDM: Forward Problem

Given calibrated SDM and (F, T) time series, compute P_{mp} .



Solving the SDM: Inverse Problem I

I_{sc} , P_{mp} , V_{mp} , and V_{oc} reported according to IEC 61853-1¹ at the following operating conditions—

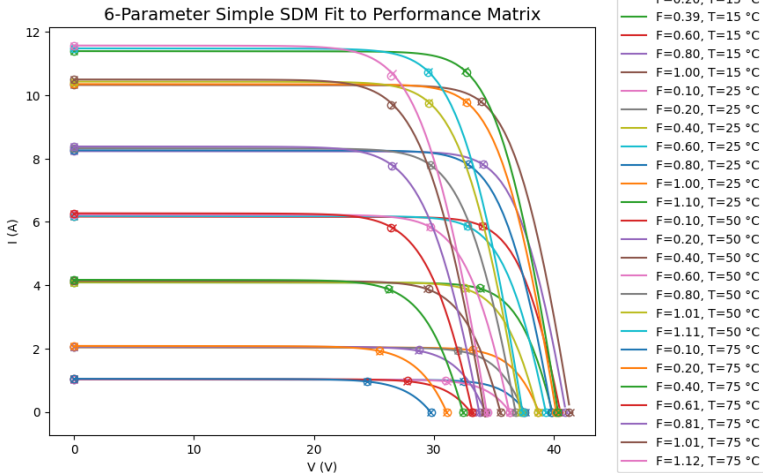
		G [W/m ²]						
		100	200	400	600	800	1000	1100
T [°C]	75	○	○	○	●	●	●	●
	50	○	○	●	●	●	●	●
	25	●	●	●	●	●	●	●
	15	●	●	●	●	●	●	○

Given such performance-matrix data, estimate SDM parameters—

I_{sc0} , I_{rs0} , n_0 , R_{s0} , G_{p0} , and E_{g0} .

¹ ● indicates required, ○ indicates optional; STC spectrum w/ normal irradiance

Solving the SDM: Inverse Problem II



Solving the SDM: Inverse Problem — Limited Data I

PVfit can fit the SDM to limited data from a specification datasheet.

Three performance points from I-V curve at STC—

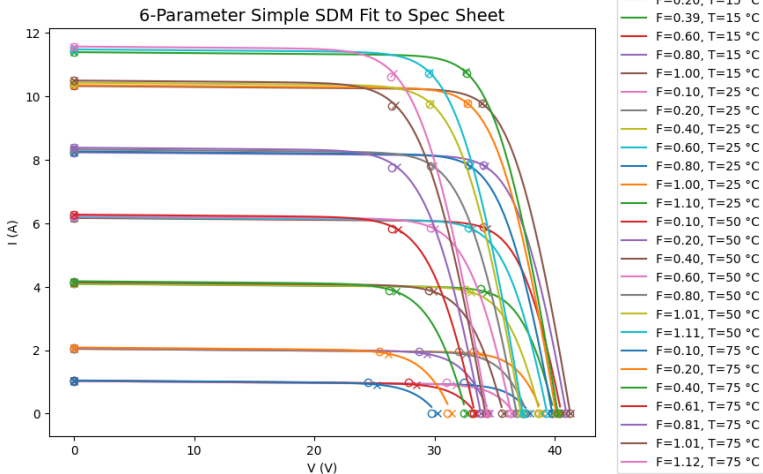
$$(0, I_{sc0}), (I_{mp0}, V_{mp0}), \text{ and } (V_{oc0}, 0),$$

with three temperature coefficients at STC—

$$\alpha_{I_{sc0}}, \gamma_{P_{mp0}}, \text{ and } \beta_{V_{oc0}}.$$

- Fit quality is typically reduced.
- Be careful fitting a SDM that is not well informed by data, e.g., a photoconductive shunt $G_p = F G_{p0}$ when spec sheet lacks data about performance w.r.t. effective irradiance ratio F .

Solving the SDM: Inverse Problem — Limited Data II



DC Performance Prediction

Determining Cell Temperature T

PVfit's SDM presumes model calibration w.r.t. *cell* temperature T .

Several model options to choose from (thanks `pvlib-python`!).

E_{POA} computed using Perez model. Parameters U_0 and U_1 may be installation specific, while ΔT is not typically measured—

- Ambient to back-of-module temperature—

$$T_m = T_a + \frac{E_{\text{POA}}}{U_0 + U_1 \times WS} \quad (\text{Faiman})$$

- Back-of-module to cell temperature—

$$T = T_m + \frac{E_{\text{POA}}}{E_0} \Delta T \quad (\text{SAPM})$$

Recall homogeneity, and also here steady-state, assumptions.

Determining Effective Irradiance Ratio F

- Reference PV device (matched temp's & angular responses)—

$$F = \frac{I_{sc}}{I_{sc0}} = \overbrace{M(T, T_0)}^{\substack{=1 \text{ when} \\ \text{matched}}} \frac{I_{sc,ref}}{I_{sc,ref0}} = \frac{\int_{\lambda=0}^{\infty} S(\lambda, T) E_{\lambda}(\lambda) d\lambda \int_{\lambda=0}^{\infty} S_{ref}(\lambda, T_0) E_{\lambda,0}(\lambda) d\lambda}{\int_{\lambda=0}^{\infty} S(\lambda, T_0) E_{\lambda,0}(\lambda) d\lambda \int_{\lambda=0}^{\infty} S_{ref}(\lambda, T) E_{\lambda}(\lambda) d\lambda}$$

- Sandia Array Performance Model (SAPM)—

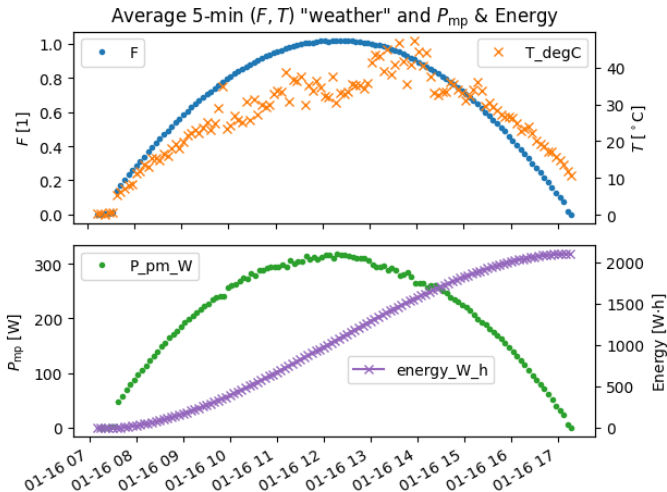
$$F = \frac{I_{sc}}{I_{sc0}} = \overbrace{f_1 \frac{f_2 E_b + f_d E_d}{E_0}}^{\text{Effective irradiance } E_e} (1 + \alpha_{sc0} (T - T_0))$$

- PVfit's Spectral+Angular-Diffuse Correction—

$$F = \frac{I_{sc}}{I_{sc0}} = \frac{\int_{\lambda=0}^{\infty} S(\lambda, T_0) E_{\lambda,eff}(\lambda) d\lambda}{\int_{\lambda=0}^{\infty} S(\lambda, T_0) E_{\lambda,0}(\lambda) d\lambda} (1 + \alpha_{sc0} (T - T_0))$$

with $\int_{\lambda=0}^{\infty} E_{\lambda,eff}(\lambda) d\lambda = E_{eff}$ (sum of IAM-corrected POA-irradiance components)

A Realistic DC Performance Prediction



Flex Your Model!

New Opportunities from a Well-Calibrated SDM

We've paid good money for the IEC 61853-1 measurements to fit our SDM, so let's make good use of it.

The F formulation bridges a gap between the calibration laboratory and traditional MET-station methodologies—

- Soiling measurements often provide a reference PV device, which could infer F and T , perhaps more accurately and less expensively, esp. if matched. (So, about that unknown ΔT ...)
- Tune satellite-based models directly to ground-based, PV-derived (F , T) time series—Look Mom, No MET Station!.
- Incorporate degradation into a minimally sufficient SDM?
- Other ideas welcome! Send to mark.campanelli@gmail.com.

(F, T) from a PV-Based MET Station I

Recall the simple SDM—

$$I = I_{\text{ph}} - I_{\text{rs}} \left(e^{q \frac{V + I R_s}{N_s n k_{\text{B}} T}} - 1 \right) - G_p (V + I R_s)$$

$$I_{\text{rs}} = I_{\text{rs}0} \left(\frac{T}{T_0} \right)^3 e^{\frac{E_{\text{g}0}}{n_0 k_{\text{B}} T} \left(\frac{1}{T_0} - \frac{1}{T} \right)},$$

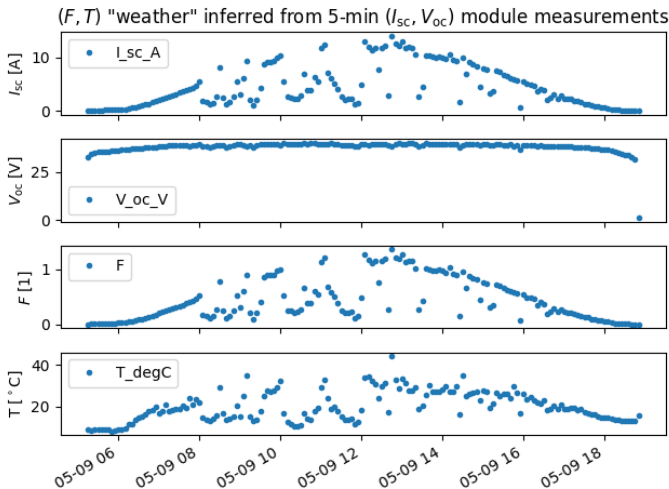
$$I_{\text{ph}} = I_{\text{rs}} \left(e^{q \frac{I_{\text{sc}} R_s}{N_s n k_{\text{B}} T}} - 1 \right) + (G_p R_s + 1) I_{\text{sc}},$$

$$I_{\text{sc}} = F I_{\text{sc}0}, \quad n = n_0, \quad R_s = R_{s0}, \quad G_p = G_{p0},$$

Suppose we calibrate this for a reference PV module, then measure two sufficiently separated I-V points.

This is typically enough to infer F & T , i.e., a PV-based MET station.

(F, T) from a PV-Based MET Station II



The End...or the Beginning?

Thanks for trying PVfit!

- Could you integrate PVfit into your modeling workflow?
- Could you integrate PVfit into your measurement systems?
- How could you better flex your model?

Open-source software isn't free.

Perhaps you have funding to support the effort?

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