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Benchmark Tests for IV Fitting Algorithms

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Abstract — **We propose a set of benchmark tests for current-voltage (IV) curve fitting algorithms. Benchmark tests enable transparent and repeatable comparisons among algorithms, allowing for measuring algorithm improvement over time. An absence of such tests contributes to the proliferation of fitting methods and inhibits achieving consensus on best practices. Benchmarks include simulated curves with known parameter solutions, with and without simulated measurement error. We implement the reference tests on an automated scoring platform and invite algorithm submissions in an open competition for accurate and performant algorithms.**

I. Introduction

The current-voltage curve of a PV device is frequently modeled as an equivalent circuit comprising one or more diodes and resistors. The commonly-used model is that of a single-junction PV device (Figure 1). Applying Kirchoff's circuit laws, the current-voltage combinations at the device's output terminals are described by the single diode equation (Eq. 1) where V and I denote voltage (V) and current (A), respectively. The term N_S is the number of series-connected cells, V_{th} is the thermal voltage (V) given by Eq. 2 where k is the Boltzmann constant (J/K), q is the elementary charge (C) and T_C is the cell temperature in K.

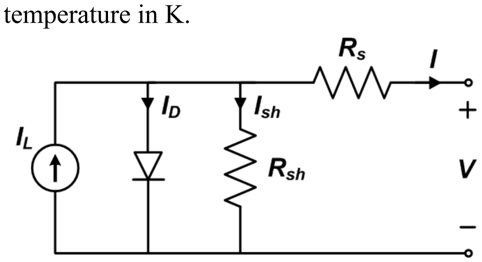


Figure 1. Singe diode equivalent circuit for a PV device.

$$I = I_L - I_O\left(\exp\left(\frac{V + IR_S}{nN_SV_{th}}\right) - 1\right) - \frac{V + IR_S}{R_{SH}} \qquad (1)$$

$$V_{th} = \frac{k}{q}T_C \qquad (2)$$

I-V curves are readily measured by a number of devices. The single-diode equation has five coefficients – photocurrent I_L, saturation current I_O, series resistance R_S, shunt resistance R_{SH} and diode ideality factor n – that can thus be determined by fitting Eq. 1 to measured data.

Fitting of Eq. 1 is a popular topic of interest as evidenced by hundreds of papers proposing new fitting techniques. New articles appear frequently across a large number of journals. To illustrate, 19 papers on this subject have appeared since 2020 in the Journal of Photovoltaics alone. A complete bibliography of published methods is far beyond the scope of this conference paper.

Comparison among proposed methods is practically impossible, due to the absence of common test cases, consistent metrics and validation practices. In our view, the lack of a common validation structure contributes substantially to the proliferation of papers on IV curve fitting, as authors, reviewers and editors cannot reasonably answer a basic question: "does this method improve upon the state of art or practice?"

Often, validation of fitting methods comprises fitting the single diode equation to a few measured I-V curves and computing metrics of the difference between the fitted curves and data. While indicative of a method's ability to yield reasonable results, this procedure overlooks two potential points of failure: misspecified models, and sensitivity to measurement error.

1. The single diode model represents an ideal single junction device with superimposed currents. The measured device's behavior may, or may not, be approximated well by this model. The fitted model may not be appropriate for the device being measured. A misspecified model may be detected by first applying the fitting procedure to synthetic curves calculated from the single diode equation; a successful fitting method should recover the known parameters used to generate the synthetic curves.
2. Measured IV curves always embody some degree of imprecise or inaccurate measurements. A fitting procedure that is overly sensitive to error in some, or all, of the measured values, may return parameters that vary significantly across measurements from the same device under the same conditions. Sensivity to measurement error may be detected by applying the fitting method to synthetic curves with simulated error and comparison of the fitted parameters with the known values used to generate the curves.

We propose a set of benchmark tests for fitting the single-diode equation to data and metrics to measure fitting accuracy. The benchmark tests explicity address the issues of model misspecification and sensitivity to error. We present an automated platform for scoring fitting methods against these benchmarks, with elements of competition including a leaderboard, to encourage progress toward consensus methods for accurate IV curve fitting. The competition platform is

TABLE I
SUMMARY OF BENCHMARK TESTS

Test Set	Description	I_L (A)	I_O (nA)	n (-)	R_S (Ω)	R_{SH} (Ω)	Comments
1	cSi w/o noise	1.0, 8.0	0.5, 30	1.01, 1.3	0.1, 1.0	300, 3000	32 curves (all parameters combinations) 72 cells in series
2	Thin film w/o noise	0.5, 2.5	1, 10	1.3, 1.5	0.1, 1.0	300, 3000	32 curves (all parameter combinations) 140 cells in series
3A	cSi w/ noise	8.0	0.5	1.01	0.1	3000	50 realizations of base curve
3B	cSi w/ noise	1.0	30	1.3	1.0	300	50 realizations of base curve
3C	Thin film w/ noise	2.5	1	1.3	0.1	3000	50 realizations of base curve
3D	Thin film w/ noise	0.5	10	1.5	1.0	300	50 realizations of base curve

designed to accumulate a library of source code in order to enable independent verification and re-use of successful fitting methods.

II. BENCHMARK TESTS

Benchmark tests are used in a number of mathematical settings to provide both a consistent means of comparing algorithms and to ensure algorithms are tested against a wide range of problems. For example, in optimization, libraries are available containing numerous benchmarks (also termed "test functions") for constrained and unconstrained optimization problems for one- and higher-dimensional problems (e.g., [1]).

We propose three sets of benchmark tests, summarized in Table I:

1. Simulated I-V curves without noise (Test Set 1 and 2). These curves are formed by computing precise (abs. error < 10^{-15}) solutions to the single-diode equation for specified parameter sets. Parameters sets are chosen to represent both cSi and thin-film type modules with a wide range of variation in photocurrent, saturation current, resistances and diode ideality factor. These benchmarks measure an algorithm's capability to recover known parameters in the absence of any complicating factors, such as measurement error or model mis-specification, and is a frequently-omitted step in validation of published algorithms.
2. Simulated I-V curves with simulated measurement error. These curves are formed by adding simulated error to four curves selected from the first set of benchmarks; fifty realizations of each base curve are generated. For each set of fifty curves, the parameters for the underlying base curve are fixed and known. This set of benchmarks measures an algorithm's capability to recover known parameters from replicated measurements with reasonable measurement error, but without any complication from model mis-specification.

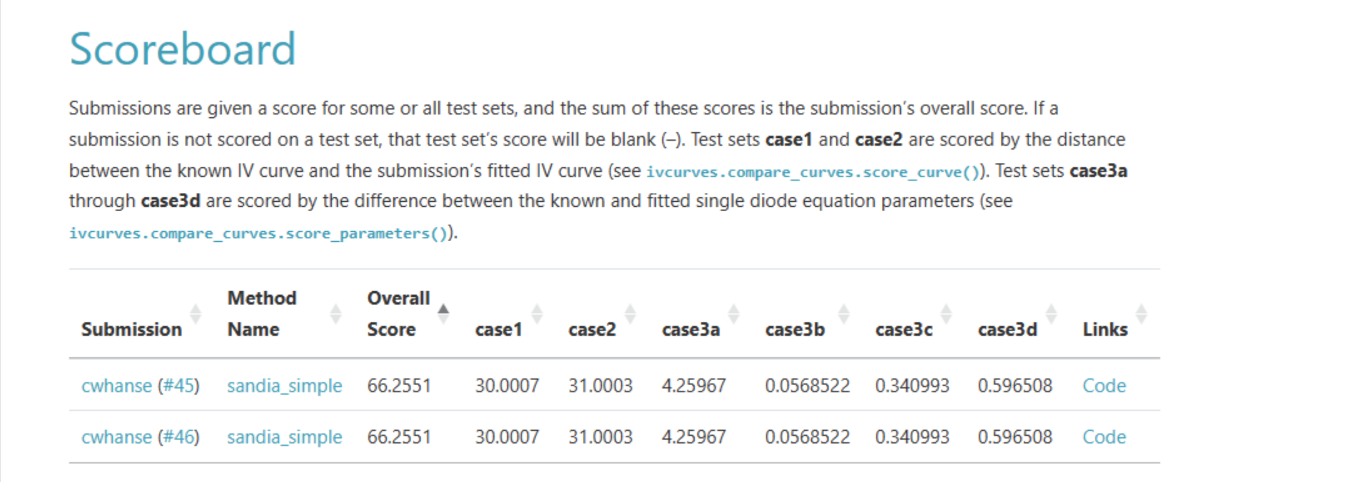
We intentionally do not include measured I-V curves for actual modules in the set of benchmark tests. Measured I-V curves are affected by both measurement error and the possibility of model mis-specification. Model mis-specification occurs when the equation being fit to the data (Eq. 1 in this case) does not accurately describe the physics of the device being measured. Eq. 1 relies on several assumptions (e.g., superposition of currents) and is itself an approximation (see [2]) of more refined descriptions of the relevant physics. For any actual device, it is difficult to know if the assumptions and approximation in Eq. 1 are appropriate. For these reasons, including measured I-V curves as benchmark tests serve only to confirm that the fitting algorithm conforms the equation to the data, in the presence of measurement error, and these aims are already accomplished by the simulated I-V curves.

Curves for Test Sets 1 and 2, and the base curves for Test Set 3, are computed to high precision using functions in pvlib-python [3] and python's mpmath package. The pvlib-python functions provide V, I pairs that solve Eq. 1 with relative error of approximately 10^{-12}; these solutions are then refined using the mpmath library to achieve V, I pairs with less than 10^{-15} absolute error. Code for these calculations is available at https://github.com/cwhanse/ivcurves.

III. IV CURVE FITTING COMPETITION

We have established an automated platform for scoring fitting methods at https://github.com/cwhanse/ivcurves. The platform envisions a competition where algorithms are scored for each category of benchmark tests and ranked on a Leaderboard by the summed scores, lowest (most accurate) score first (Figure 1). Instructions for participation are provided at https://cwhanse.github.io/ivcurves/participating.html.

Submissions must provide python code that reads the test sets, executes the fitting, and returns the fitted parameters as described by the user instructions. The fitting procedure may use code other than python, or may call external services.



Scoreboard

Submissions are given a score for some or all test sets, and the sum of these scores is the submission's overall score. If a submission is not scored on a test set, that test set's score will be blank (–). Test sets **case1** and **case2** are scored by the distance between the known IV curve and the submission's fitted IV curve (see `ivcurves.compare_curves.score_curve()`). Test sets **case3a** through **case3d** are scored by the difference between the known and fitted single diode equation parameters (see `ivcurves.compare_curves.score_parameters()`).

Submission	Method Name	Overall Score	case1	case2	case3a	case3b	case3c	case3d	Links
cwhanse (#45)	sandia_simple	66.2551	30.0007	31.0003	4.25967	0.0568522	0.340993	0.596508	Code
cwhanse (#46)	sandia_simple	66.2551	30.0007	31.0003	4.25967	0.0568522	0.340993	0.596508	Code

Figure 1. Screenshot of scoreboard from IV curve fitting competition website.

However, it is are desireable that all source code be provided so that fitting procedures can be independently verified. Source code must be provided with the BSD 3-clause license. Submitters retain their copyright. Source code is accompanied by documentation that is rendered to html pages. Our vision is to accumulate a library of algorithms, with documentation, so that interested parties may select, download and apply suitable algorithms to their work.

IV. Conclusions

We propose a set of benchmark tests for fitting the single-diode equation to data and metrics to measure fitting accuracy. Benchmark tests provide a consistent, repeatable structure for comparing among fitting methods and for measuring improvement over time. We provide an open evaluation platform with elements of competition to facilitate use of these benchmarks and encourage public sharing of code for fitting algorithms. Our approach could be readily extended for other equivalent circuit models with, e.g., two diodes or infinite shunt resistance, or for evaluating fitting of full single diode models such as [4] or [5].

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