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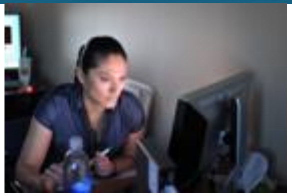
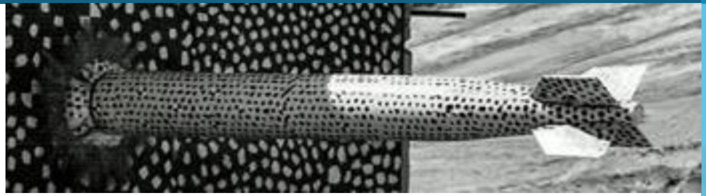
Getting More from PV Field Data:

Data mining and analysis for module diagnostics





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SAND2020-8123 PE

U.S. DEPARTMENT OF ENERGY NNSA

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Motivation: Mechanistic PV Performance and Degradation Modeling

Mechanistic understanding of photovoltaic array performance can decrease the Levelized Cost of Photovoltaic Energy via:

- Decreased Operation/Maintenance Costs
- Increased Energy Production
- Reduced Degradation

in the industrial and R&D sectors.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{(I_t + \boxed{O_t + M_t} + F_t)}{(1+r)^t}}{\sum_{t=0}^{n} \frac{\boxed{S_t}\boxed{(1-d)^t}}{(1+r)^t}}$$

I **- initial cost**
O **- operational cost**
M **- maintenance cost**
F **- interest expenditure**
S **- energy production**
r **- inflation and uncertainty**
(1-d) **- degradation term**

Analytic I_{SC}-V_{OC} and Power Loss Modes

Field I-V Data

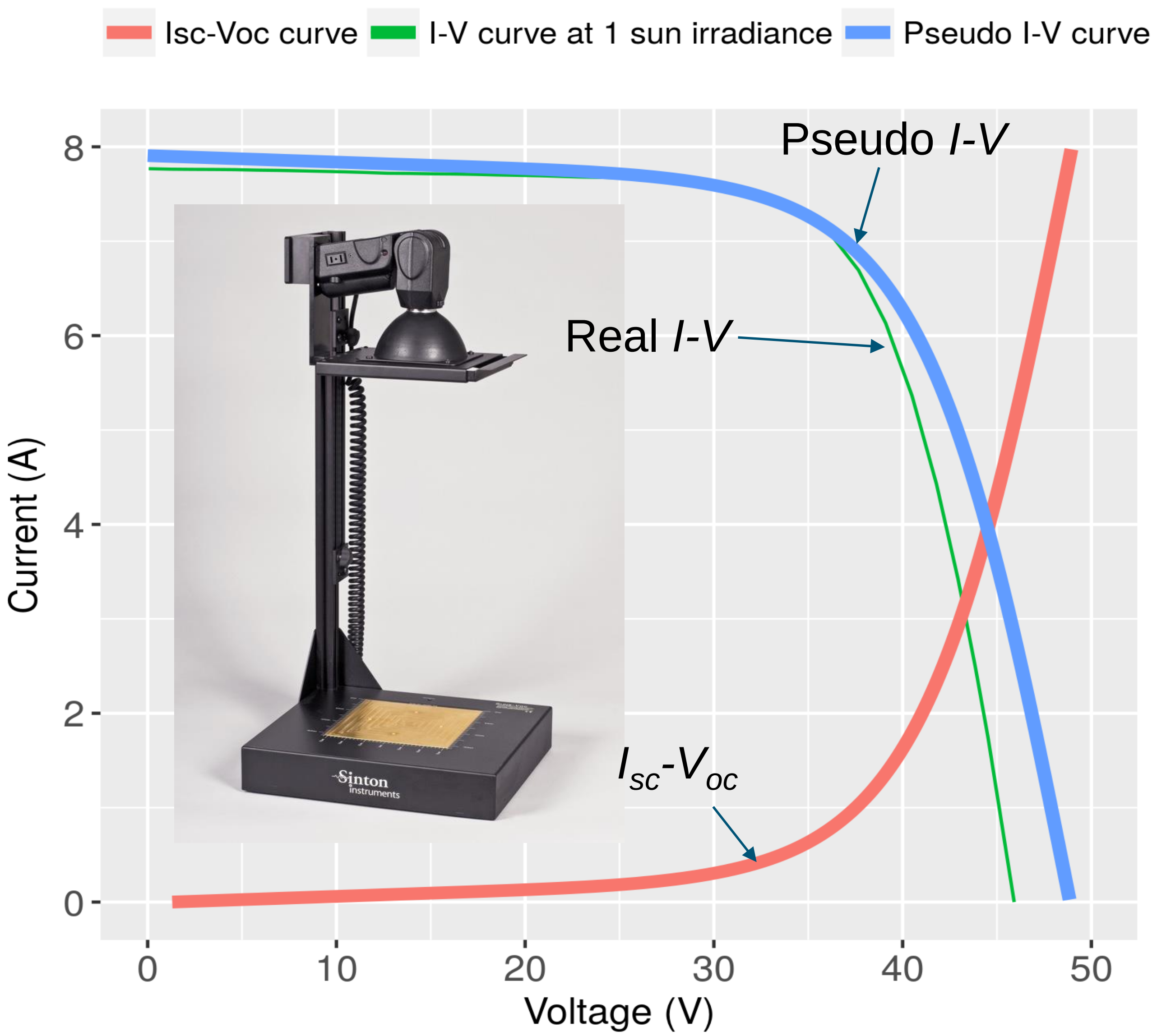
PV systems at all scales produce large amounts of time-series data.

"Smart" inverters or microinverters measure I-V curves on the string or module level.

Parameterizing I-V curves and looking at long-term trends improves understanding of system performance, but:

- values are not directly comparable
- changes in these quantities are not necessarily proportional to power loss

Laboratory-Based Suns-V_{OC}



Suns-V_{OC} / I_{SC}-V_{OC}

- from I-V at varying light intensities
- used to calculate pseudo I-V curve

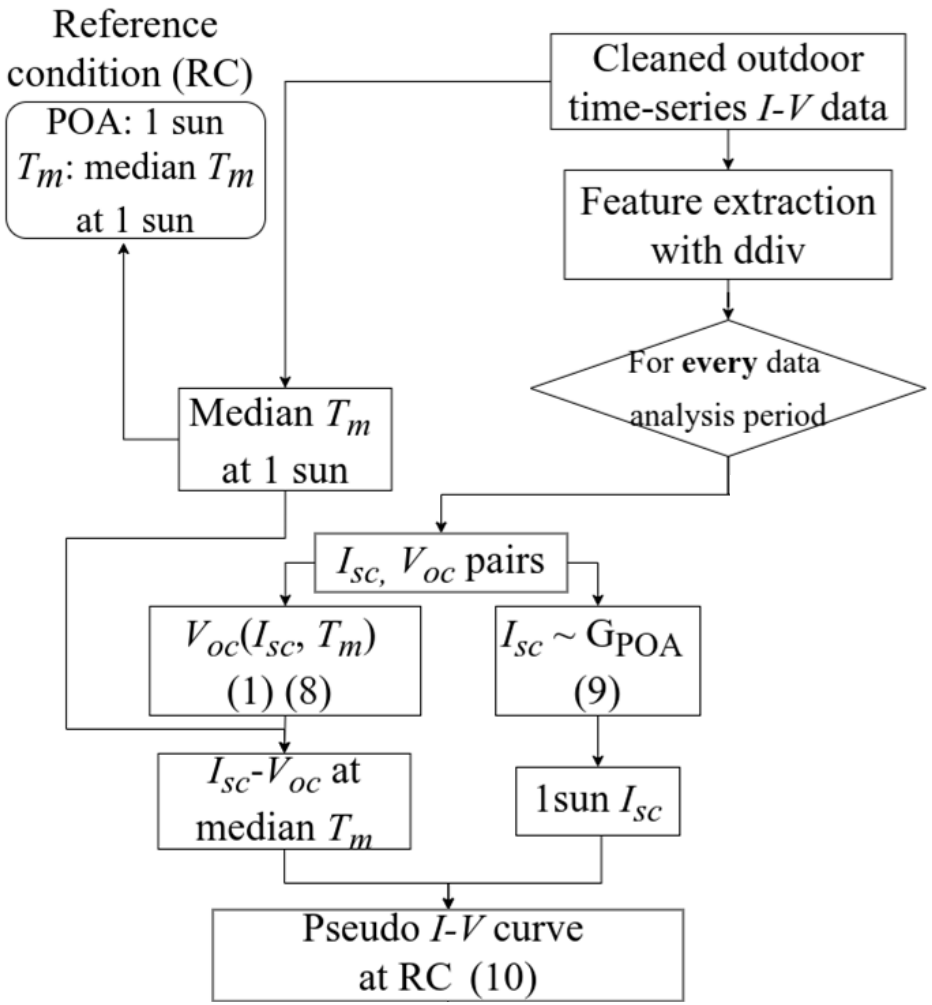
Pseudo I-V curve

- "ideal" I-V
- without series resistance or current mismatch
- gain insight about degradation

Mining I_{SC}-V_{OC} from Field Data

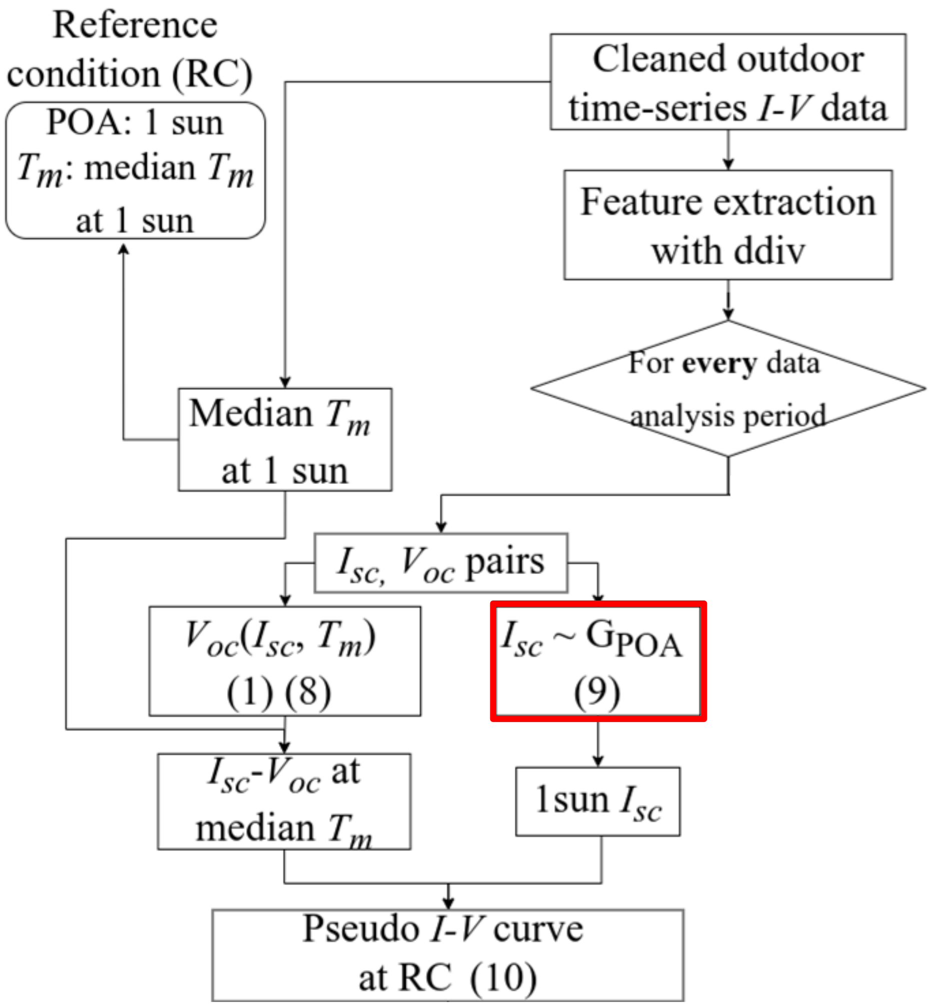
Time-series data is divided into analysis periods

- Sufficiently long to collect enough low irradiance data to build I_{SC}-V_{OC}
- But short enough to ensure pseudo-stability of the module
- To evaluate trends in power loss modes



Outdoor I_{SC}-V_{OC} Curve Construction

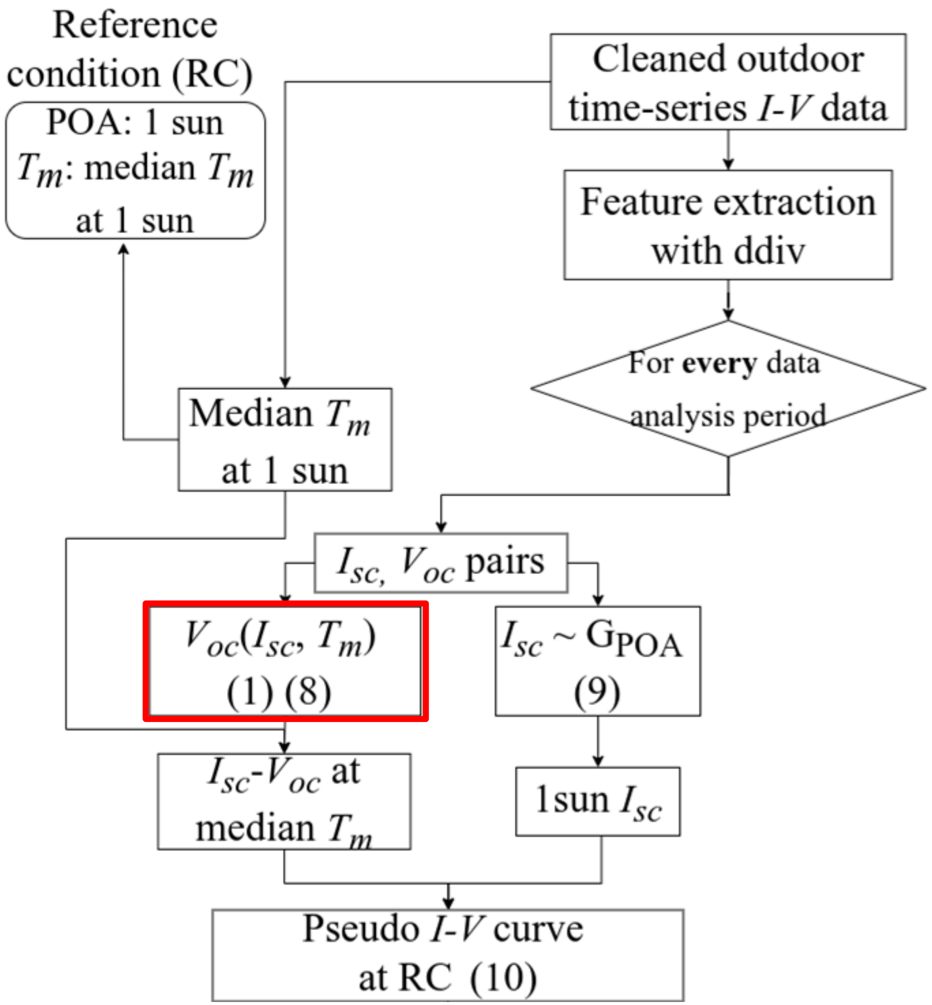
$$I_{sc}(G_{POA}) = k \cdot G_{POA} + \epsilon \qquad (9)$$



Outdoor I_{SC}-V_{OC} Curve Construction

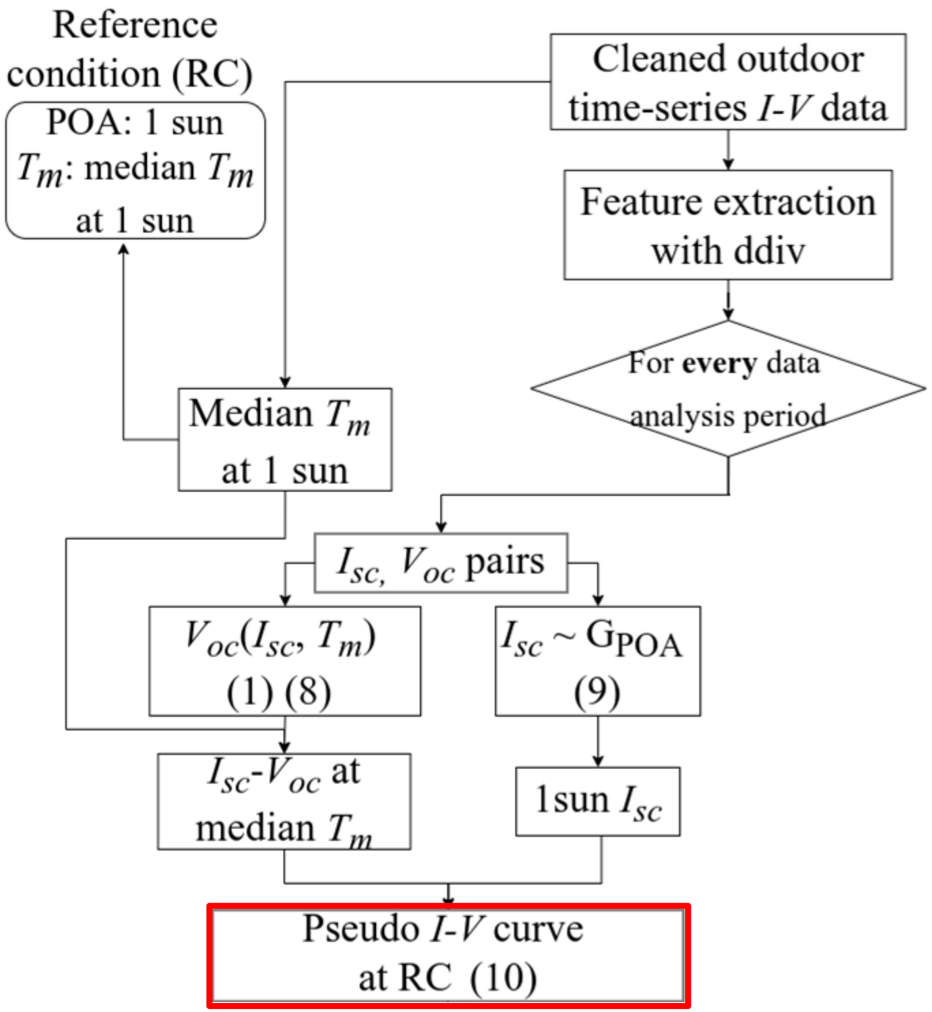
$$V_{oc} = V_{oc0} + N_C \cdot \delta(T_c) ln(E_e) + \beta_{V_{oc}}(T_c - T_0) \quad (1)$$

$$V_{oc}(I_{sc}, T_m) = \alpha_0 + \alpha_1 \cdot (T_m + 273.15) \cdot ln(I_{sc}) + \alpha_2 \cdot (T_m + 273.15) + \epsilon \quad (8)$$



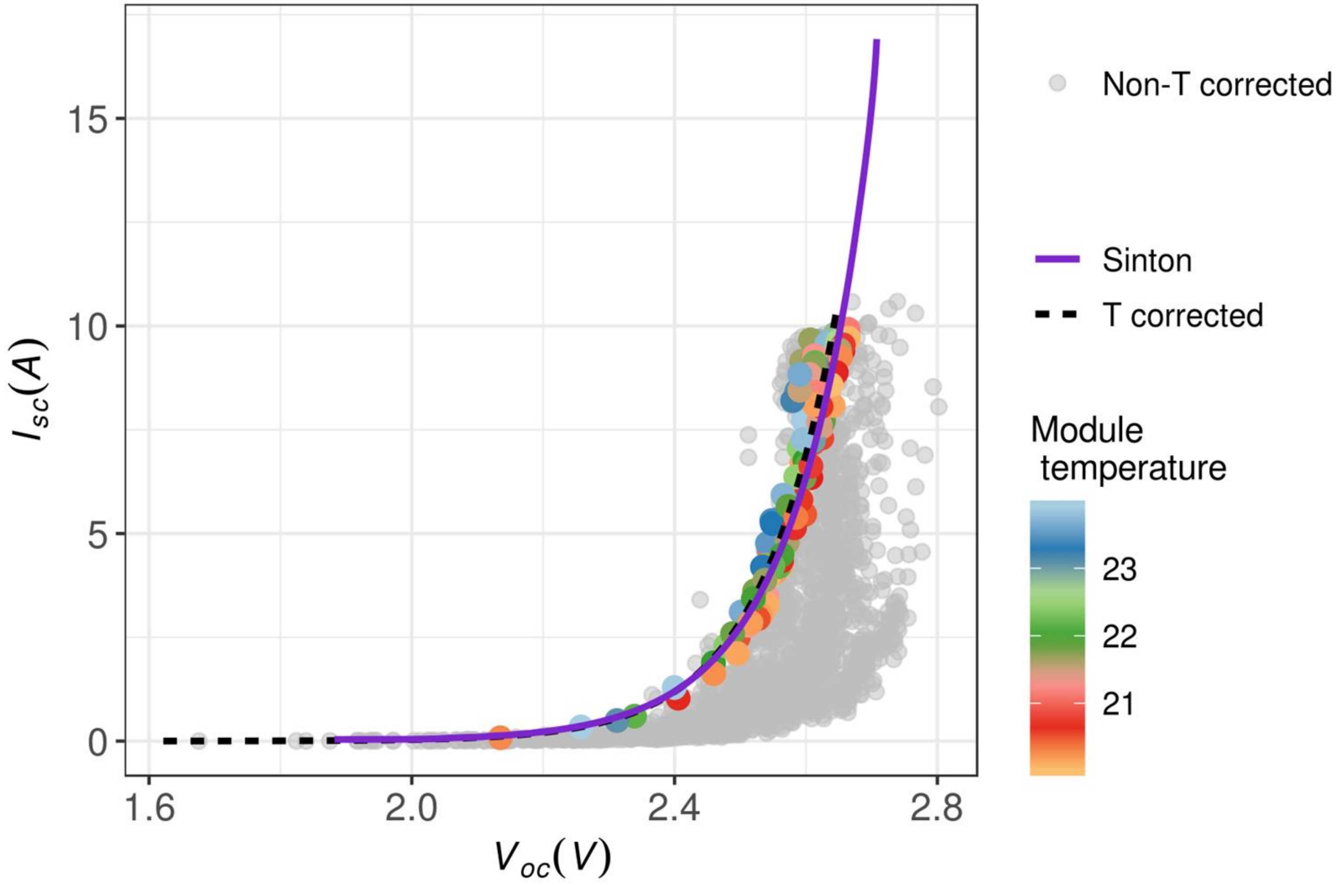
King, David L., Jay A. Kratochvil, and Boyson, William E. *Photovoltaic array performance model*. Sandia National Laboratories, 2004.

Outdoor I_{SC}-V_{OC} Curve Construction

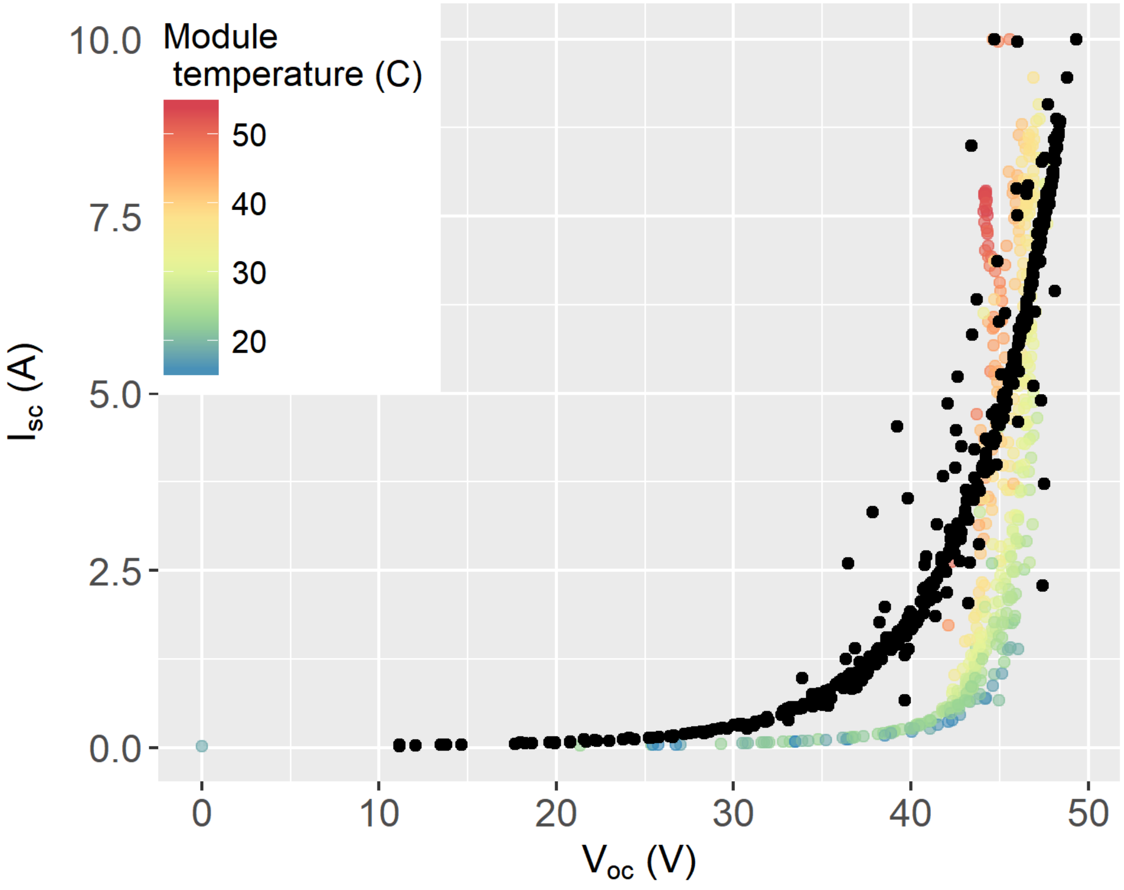


$$I_{psd} = I_{sc}^{RC} - I_{sc} \tag{10}$$

V_{OC} temperature correction results



Mini-module method validation



Full-size module temp correction

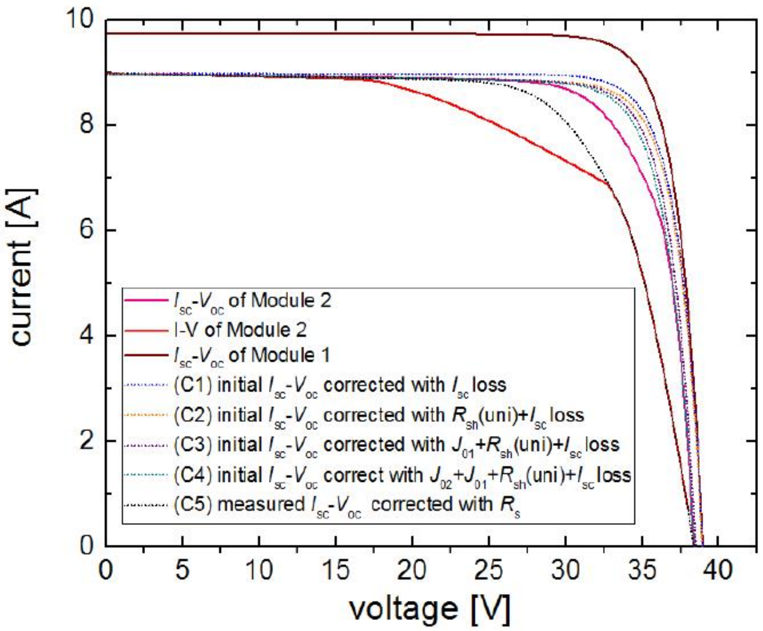
Quantifying power loss mechanisms from I_{SC}-V_{OC}

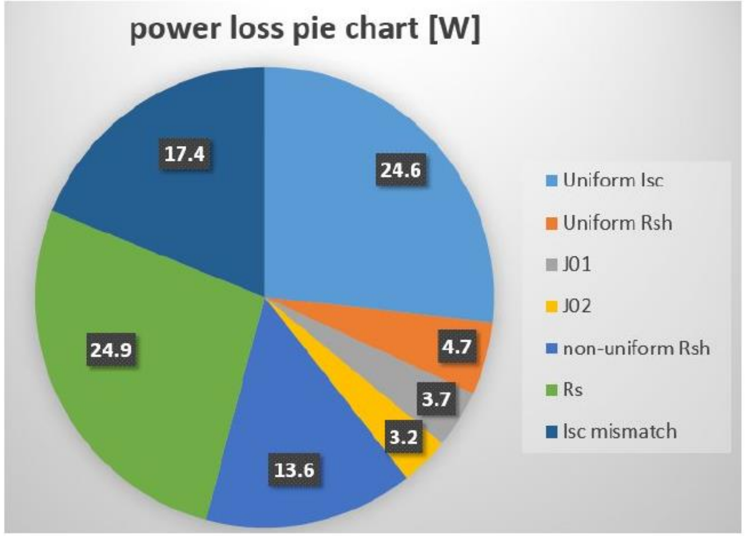
Detecting loss mechanisms of c-Si PV modules by I_{sc}-V_{oc} and I-V measurement

Siyu Guo[a,b], Eric Schneller[a,b], Joe Walters[a,b], Kristopher O. Davis[a,b], Winston V. Schoenfeld[a,b]
[a] Florida Solar Energy Center, University of Central Florida,1679 Clearlake Road, Cocoa, FL 32922,
[b] c-Si Division, U.S. Photovoltaic Manufacturing Consortium, 12354 Research Parkway, Orlando, FL 32826

Reliability of Photovoltaic Cells, Modules, Components, and Systems IX, edited by Neelkanth G. Dhere, John H. Wohlgemuth, Keiichiro Sakurai, Proc. of SPIE Vol. 9938, 99380N · © 2016 SPIE
CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2236939

Proc. of SPIE Vol. 9938 99380N-1



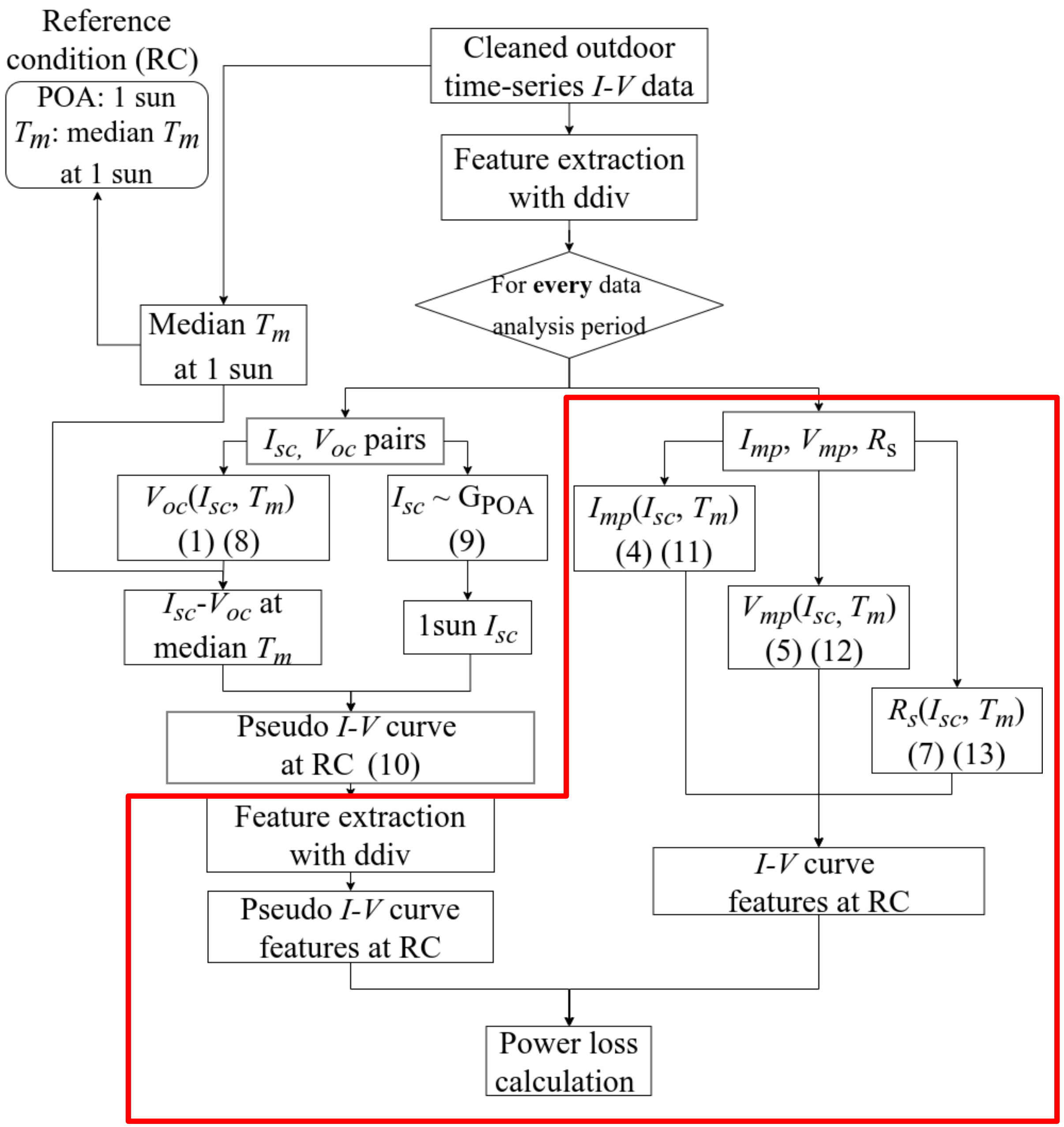


I_{SC}-V_{OC} Mechanistic Power Loss Calculation

In each analysis period:

- I-V features are modeled
- I_{SC}-V_{OC} is constructed
- and parameterized

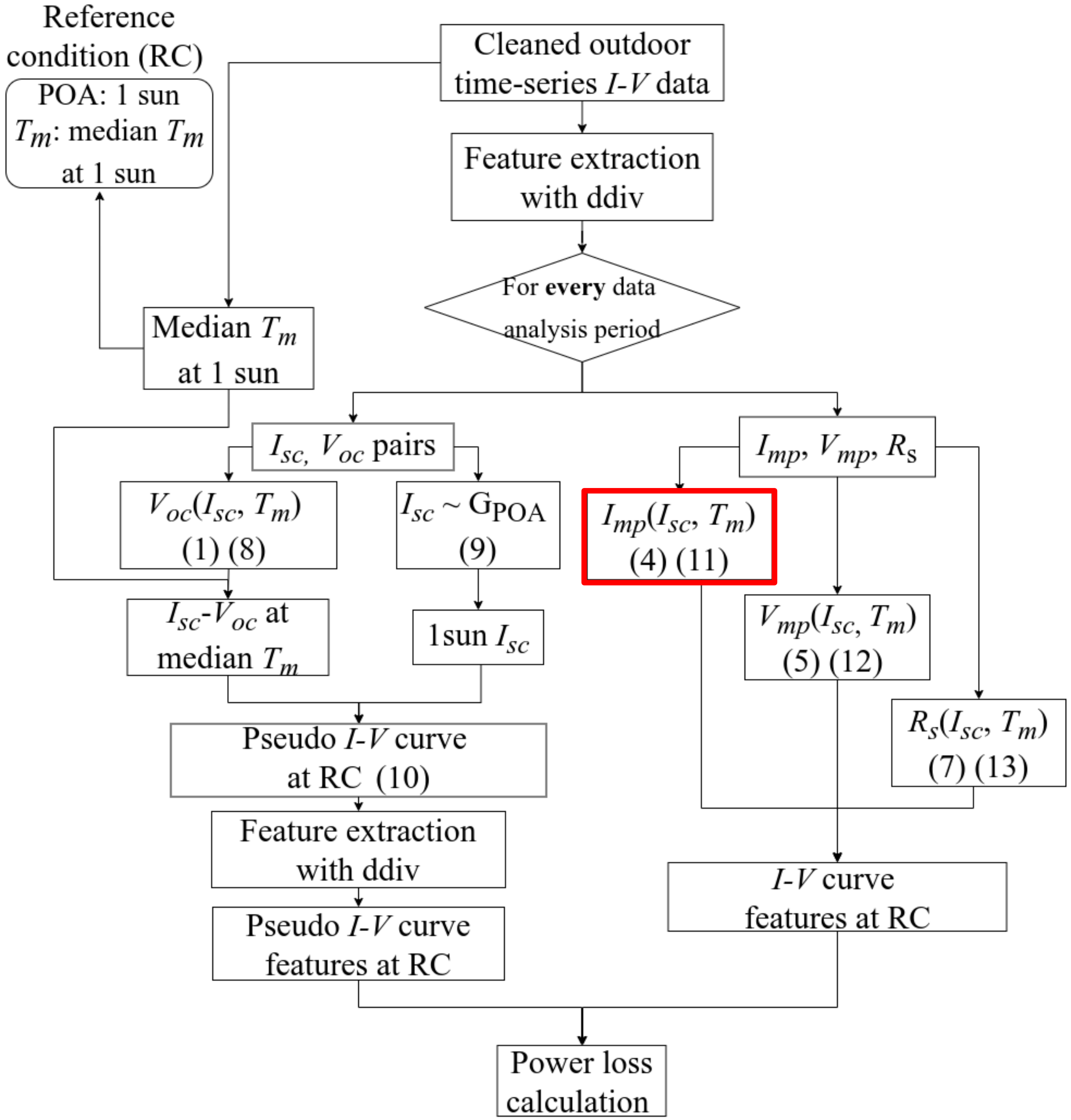
to create the sub-I-V curves for mechanistic power loss calculation



I_{SC}-V_{OC} Mechanistic Power Loss Calculation

$$I_{mp} = I_{mp0} \cdot \{C_0 \cdot E_e + C_1 \cdot E_e^2\} \cdot \{1 + \alpha_{I_{mp}}(T_c - T_0)\} \tag{4}$$

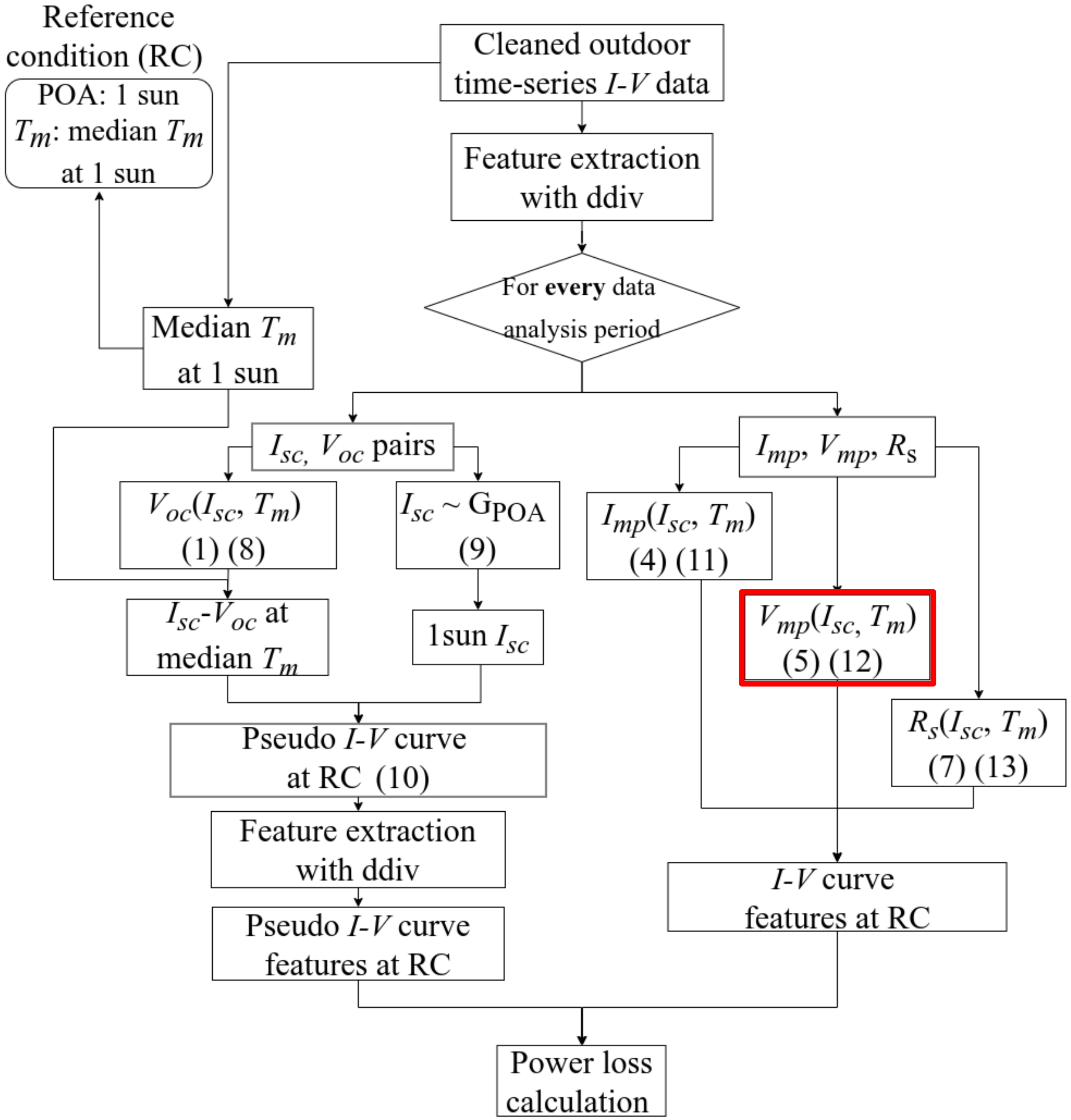
$$\begin{aligned} I_{mp}(I_{sc}, T_m) = \; & \beta_0 + \beta_1 \cdot (T_m + 273.15) \cdot I_{sc} \\ & \beta_2 \cdot (T_m + 273.15) \cdot I_{sc}^2 + \epsilon \end{aligned} \tag{11}$$



I_{SC}-V_{OC} Mechanistic Power Loss Calculation

$$V_{mp} = V_{mp0} + C_2 N_C \cdot \delta(T_c) ln(E_e) + C_3 N_c \{\delta(T_c) ln(E_e)\}^2 + \beta_{V_{mp}}(E_e)(T_c - T_0) \quad (5)$$

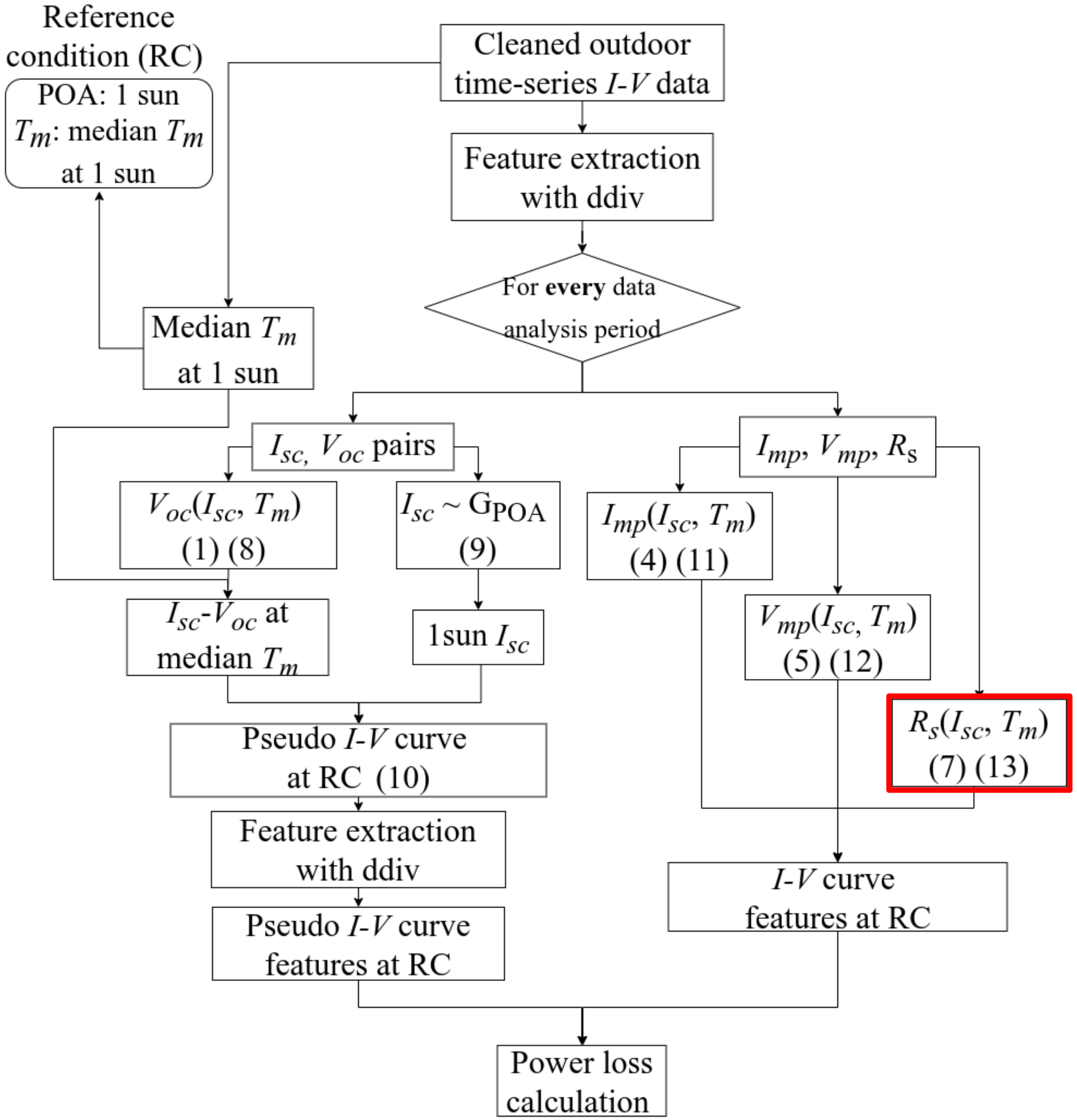
$$V_{mp}(I_{sc}, T_m) = \gamma_0 + \gamma_1 \cdot (T_m + 273.15) \cdot ln(I_{sc}) + \gamma_2 \cdot \{(T_m + 273.15) ln(I_{sc})\}^2 + \gamma_3 \cdot (T_m + 273.15) + \epsilon \quad (12)$$



I_{SC}-V_{OC} Mechanistic Power Loss Calculation

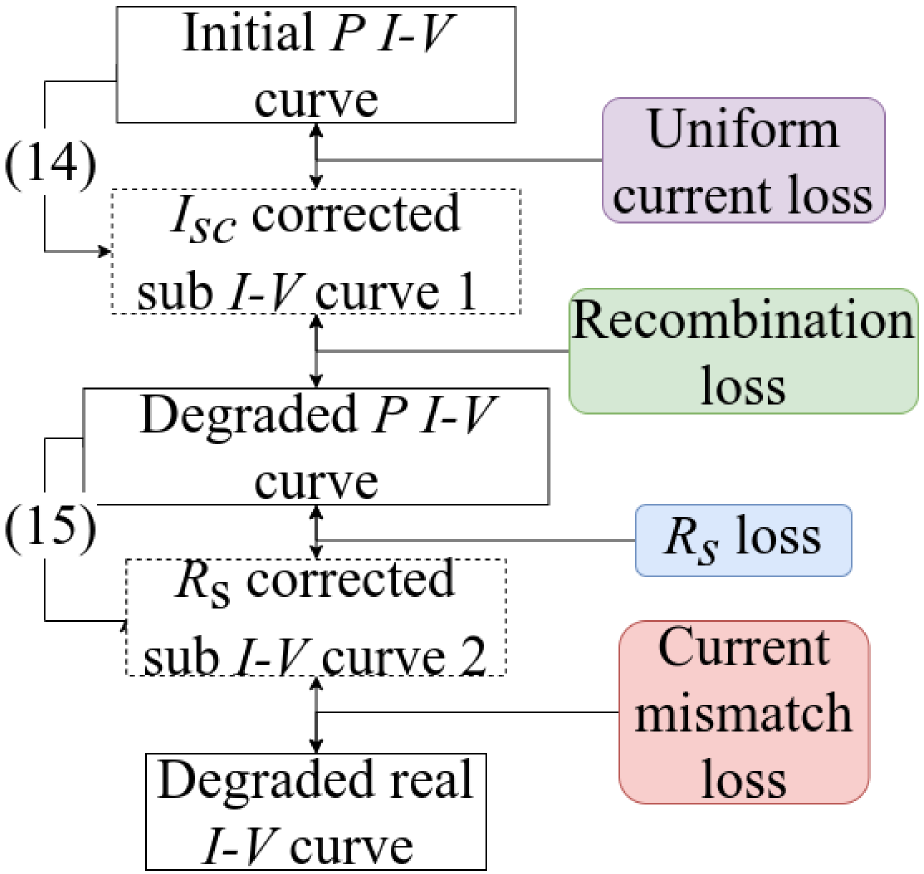
$$R_s = R_{s0} - \frac{N_c}{I_{sc}} \frac{n k_B (T_c + 273.15)}{q} \qquad (7)$$

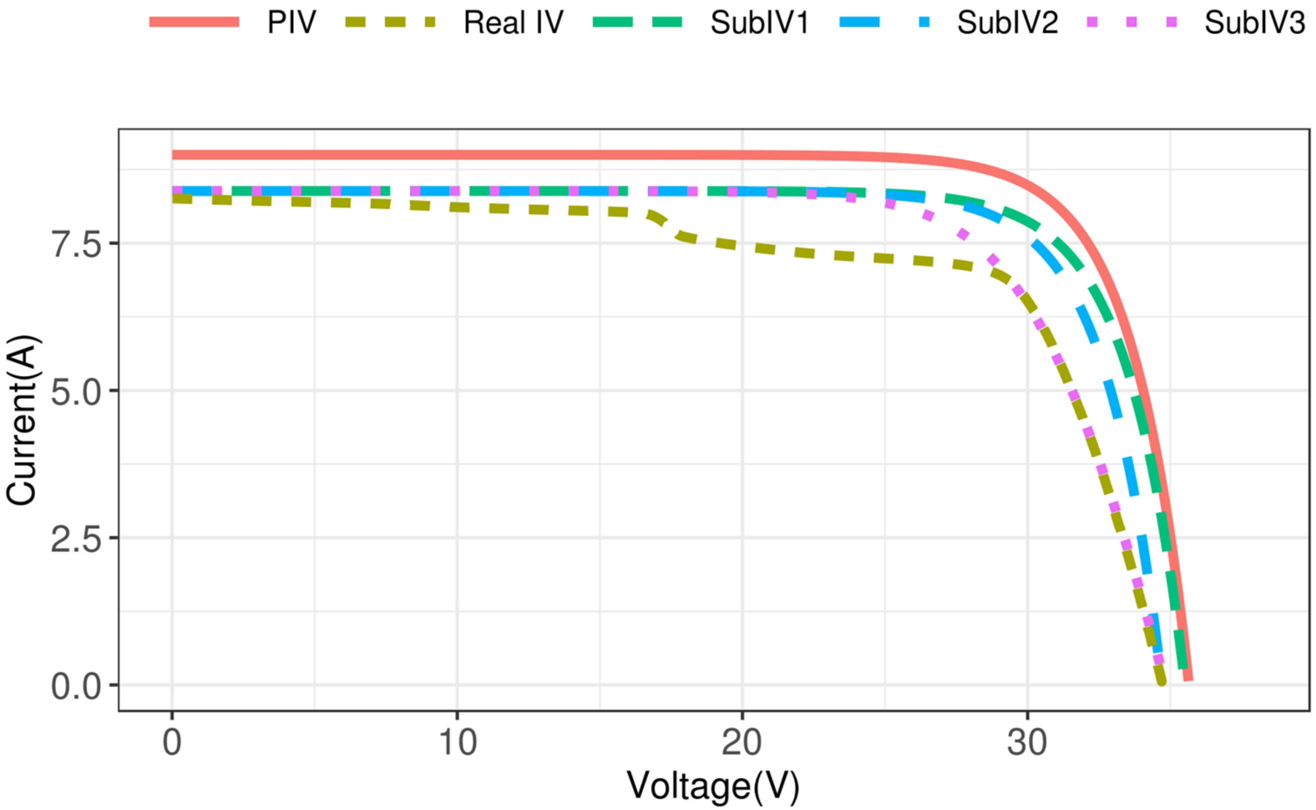
$$R_s(I_{sc}, T_m) = \zeta_0 + \zeta_1 \frac{T_m + 273.15}{I_{sc}} + \epsilon \qquad (13)$$



Wang, Jen-Cheng et al. "A novel method for the determination of dynamic resistance for photovoltaic modules." *Energy* 36, no. 10 (2011): 5968-5974.

I_{SC}-V_{OC} Power Loss Calculation





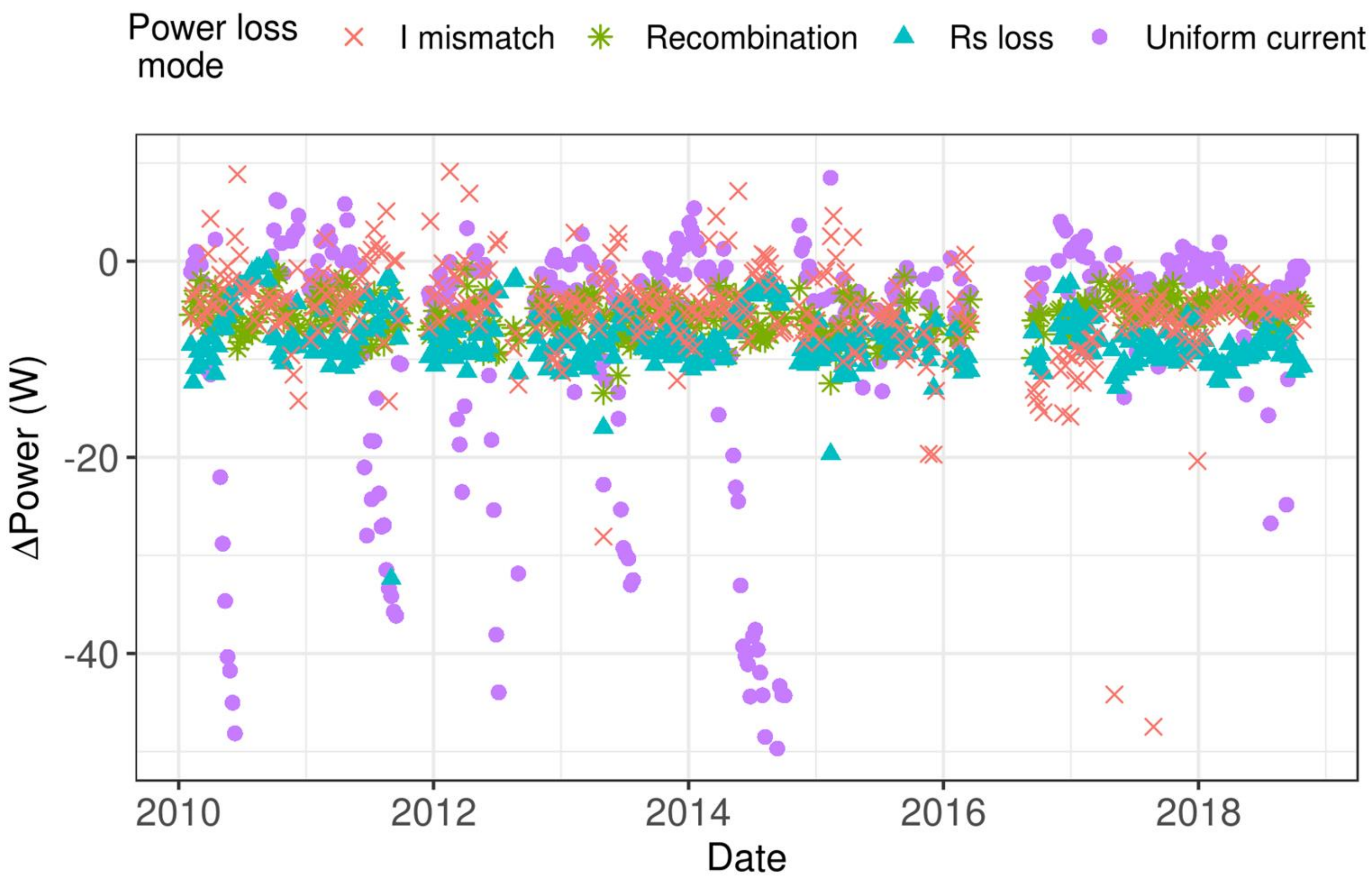
$$I_{C1} = I_{init} - \Delta I_{sc} \tag{14}$$

$$V_{C2} = V_{degrPIV} + I \cdot R_{s-degrPIV} - I \cdot R_{s-IV} \tag{15}$$

Analytic I_{SC}-V_{OC} Obtained Loss Mechanism Time-series

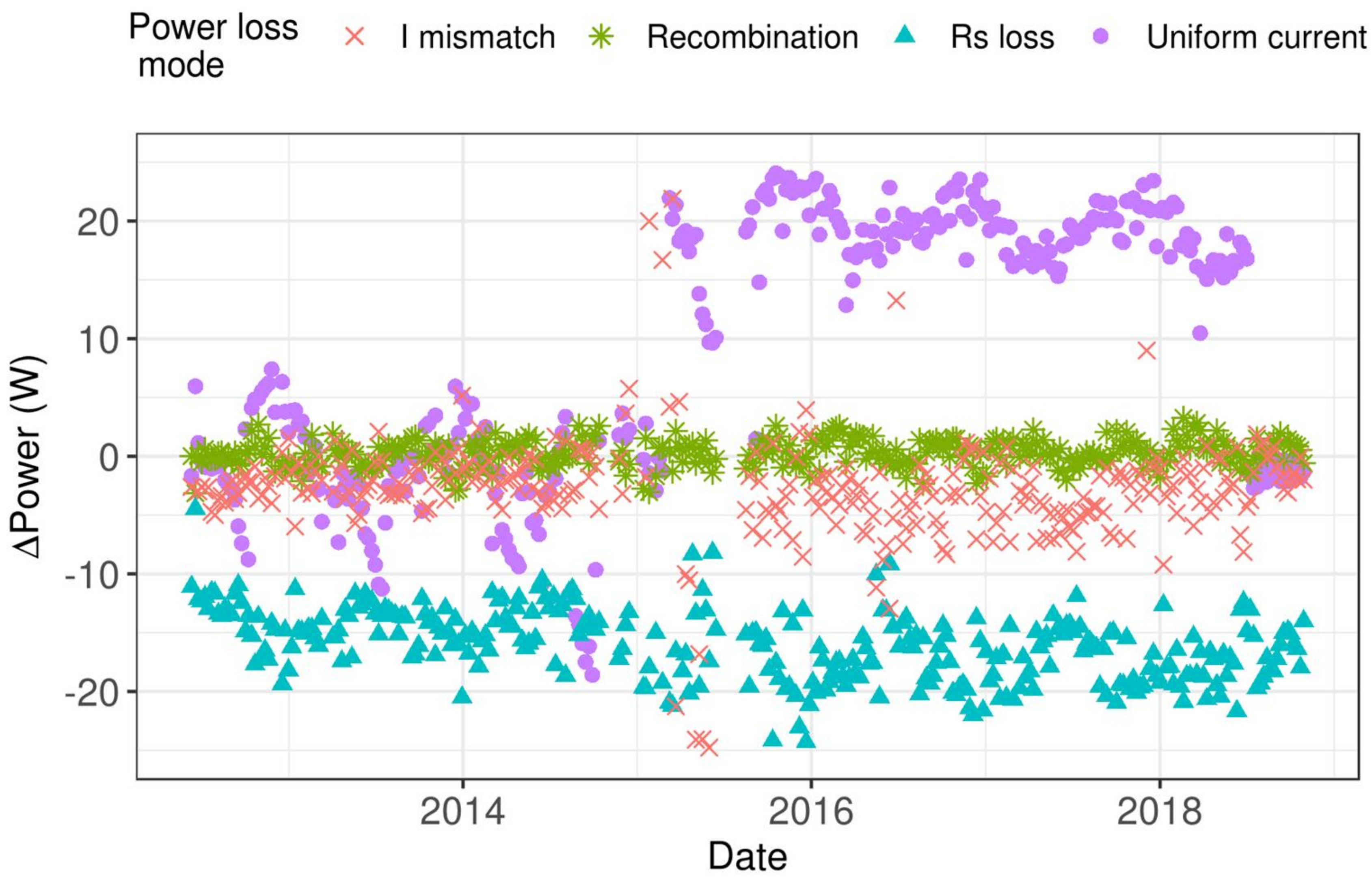
For outdoor I-V data:

- loss mechanisms as time-series variables



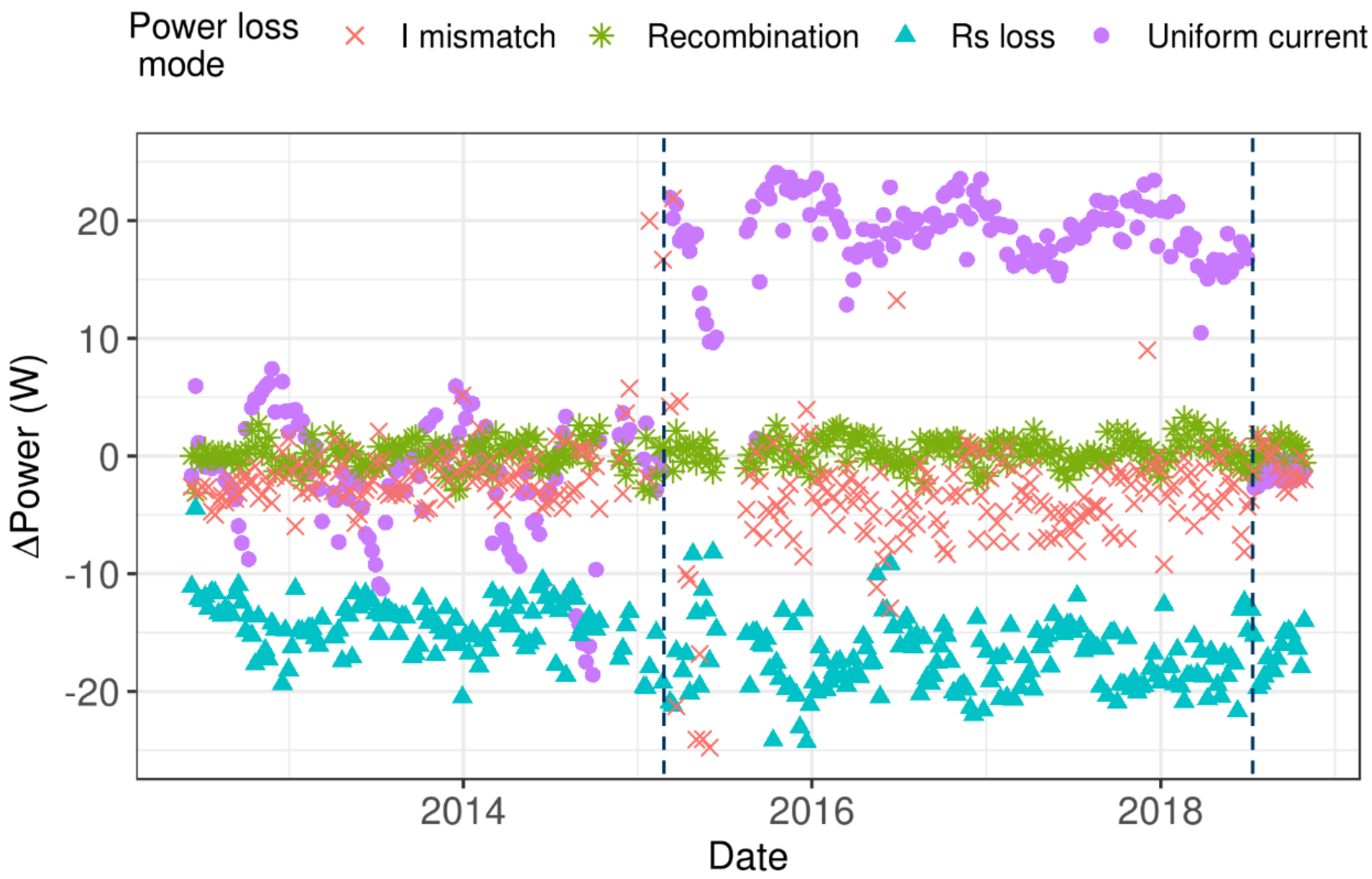
Results for c-Si module in Gran Canaria

Analytic I_{SC}-V_{OC} Obtained Loss Mechanism Time-series



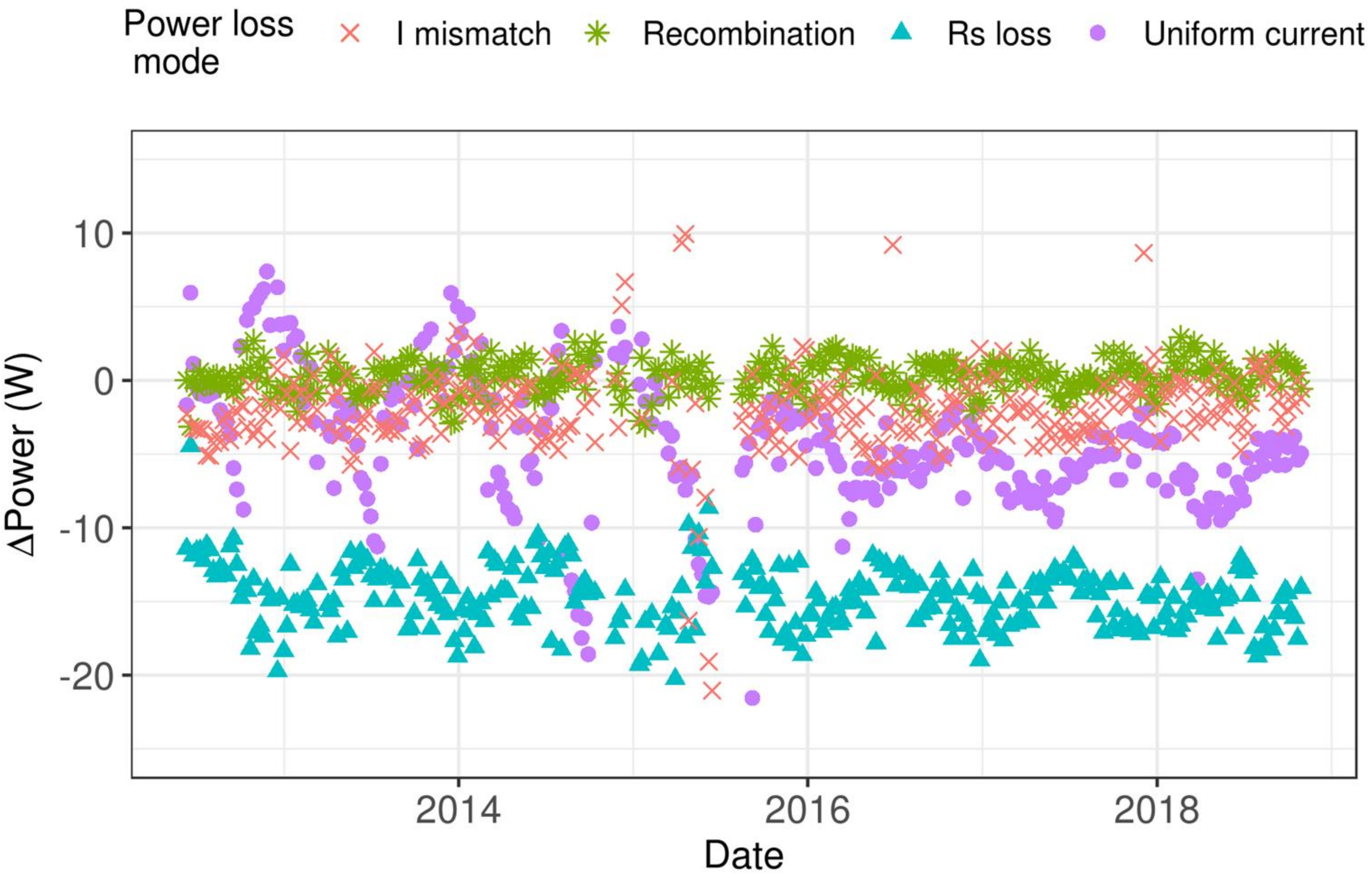
Results for c-Si module in the Negev

Analytic I_{SC}-V_{OC} Obtained Loss Mechanism Time-series



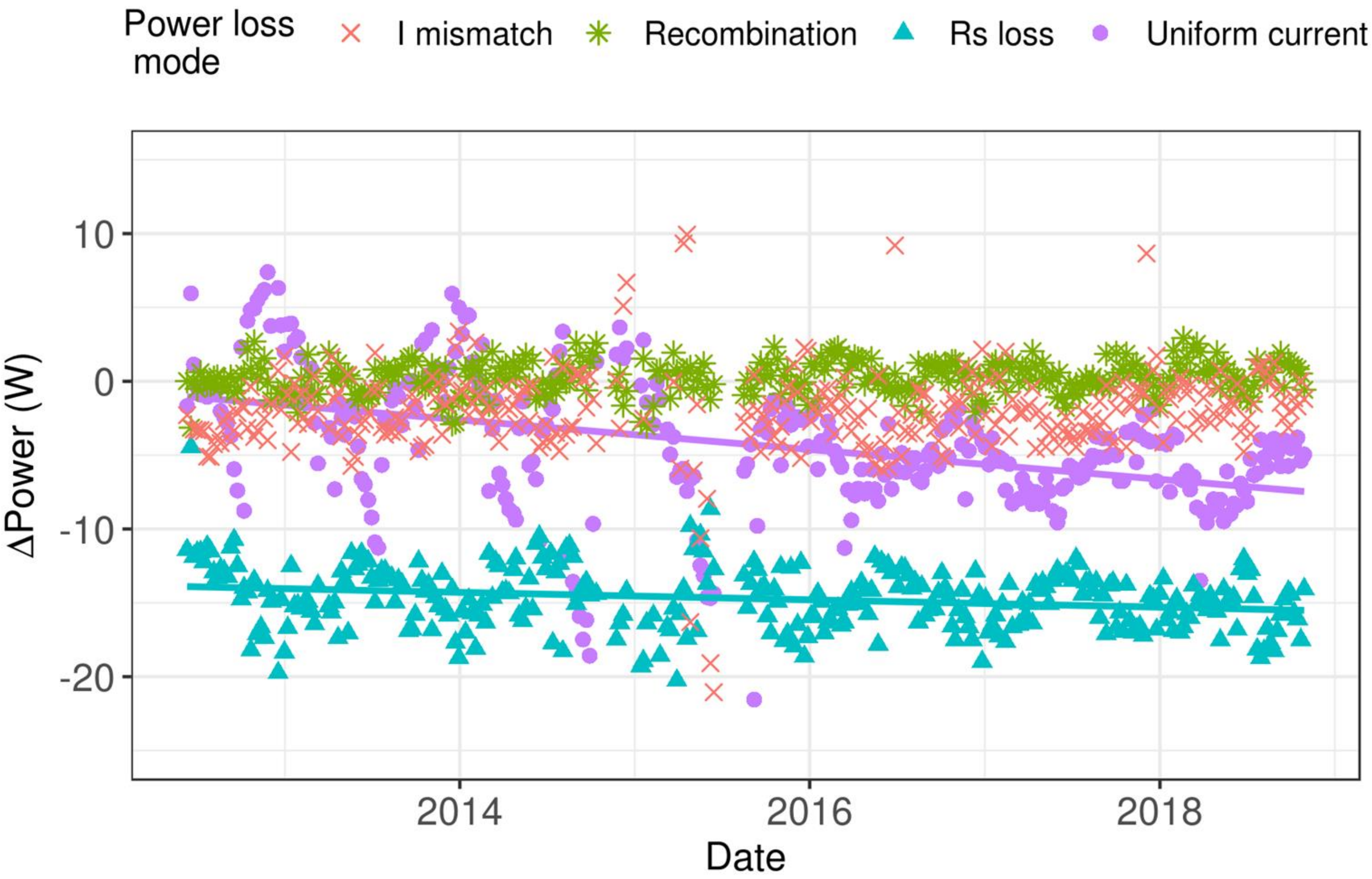
Results for c-Si module in the Negev

Analytic I_{SC}-V_{OC} Obtained Loss Mechanism Time-series



Results for c-Si module in the Negev

Analytic I_{SC}-V_{OC} Obtained Loss Mechanism Time-series



Results for c-Si module in the Negev

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

IEEE JOURNAL OF PHOTOVOLTAICS 1

Analytic I_{sc}–V_{oc} Method and Power Loss Modes From Outdoor Time-Series I–V Curves

Menghong Wang, Jiqi Liu, Tyler J. Burleyson, Eric J. Schneller, Kristopher O. Davis, Roger H. French, *Member, IEEE*, and Jennifer L. Braid, *Member, IEEE*

CRAN - Package SunsVoc

https://cran.r-project.org/web/packages/SunsVoc/index.html

SunsVoc: Constructing Suns-Voc from Outdoor Time-Series I-V Curves

Suns-Voc (or Isc-Voc) curves can provide the current-voltage (I-V) characteristics of the diode of photovoltaic cells without the effect of series resistance. Here, Suns-Voc curves can be constructed with outdoor time-series I-V curves [1,2,3] of full-size photovoltaic (PV) modules instead of having to be measured in the lab. Time series of four different power loss modes can be calculated based on obtained Suns-Voc curves. This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number DE-EE0008172. Jennifer L. Braid is supported by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-SC0014664. [1] Wang, M. et al, 2018. <doi:10.1109/PVSC.2018.8547772>. [2] Walters et al, 2018 <doi:10.1109/PVSC.2018.8548187>. [3] Guo, S. et al, 2016. <doi:10.1117/12.2236939>.

Version:	0.1.0
Depends:	R (≥ 3.5.0)
Imports:	ddiv, magrittr, stringr, dplyr, purrr, data.table, rlang
Suggests:	testthat (≥ 2.1.0), knitr, rmarkdown, ggplot2
Published:	2020-06-29
Author:	Menghong Wang [aut], Tyler J. Burleyson [aut, cre], Jiqi Liu [aut], Alan J. Curran [aut], Eric J. Schneller [aut], Kristopher O. Davis [aut], Jennifer L. Braid [aut], Roger H. French [aut, cph]
Maintainer:	Tyler J. Burleyson <tjb152 at case.edu>
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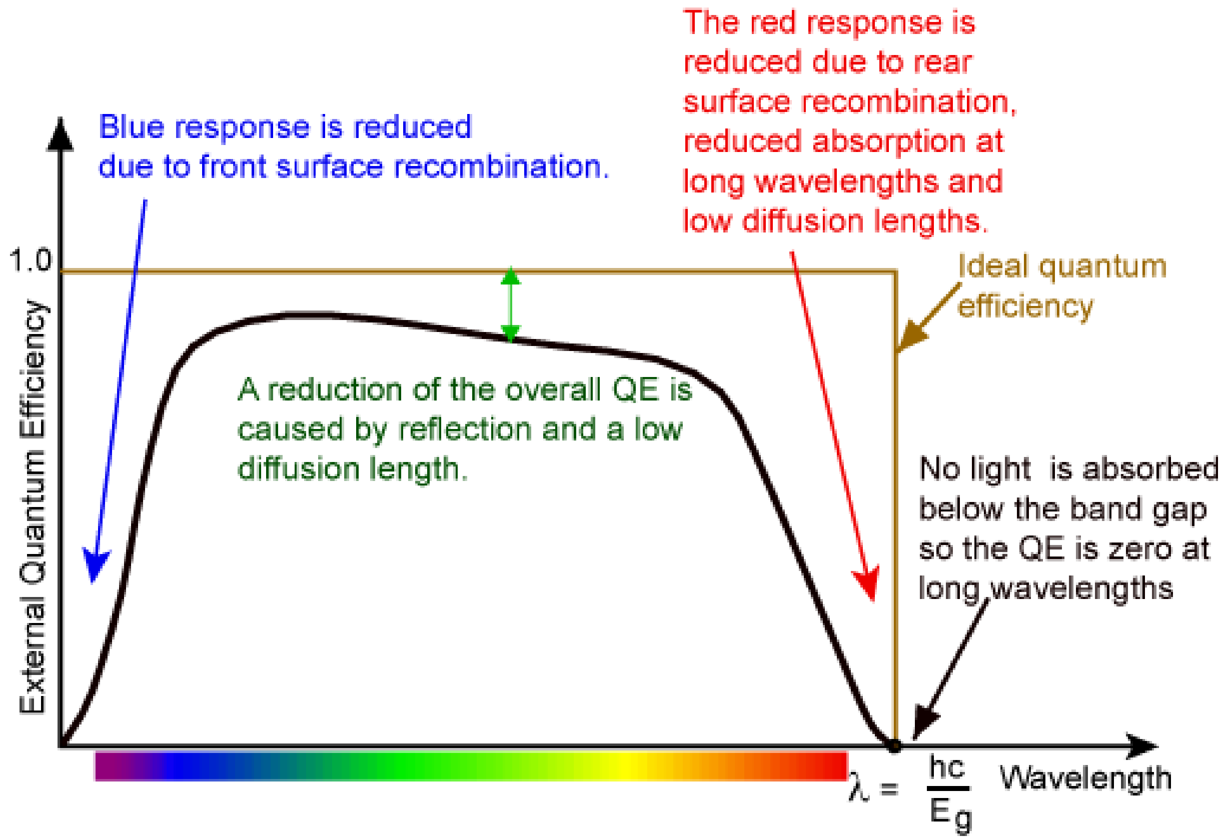
Analytic External Quantum Efficiency

Laboratory External Quantum Efficiency

$$EQE = \frac{J_{SC} / q}{\phi_{in}}$$

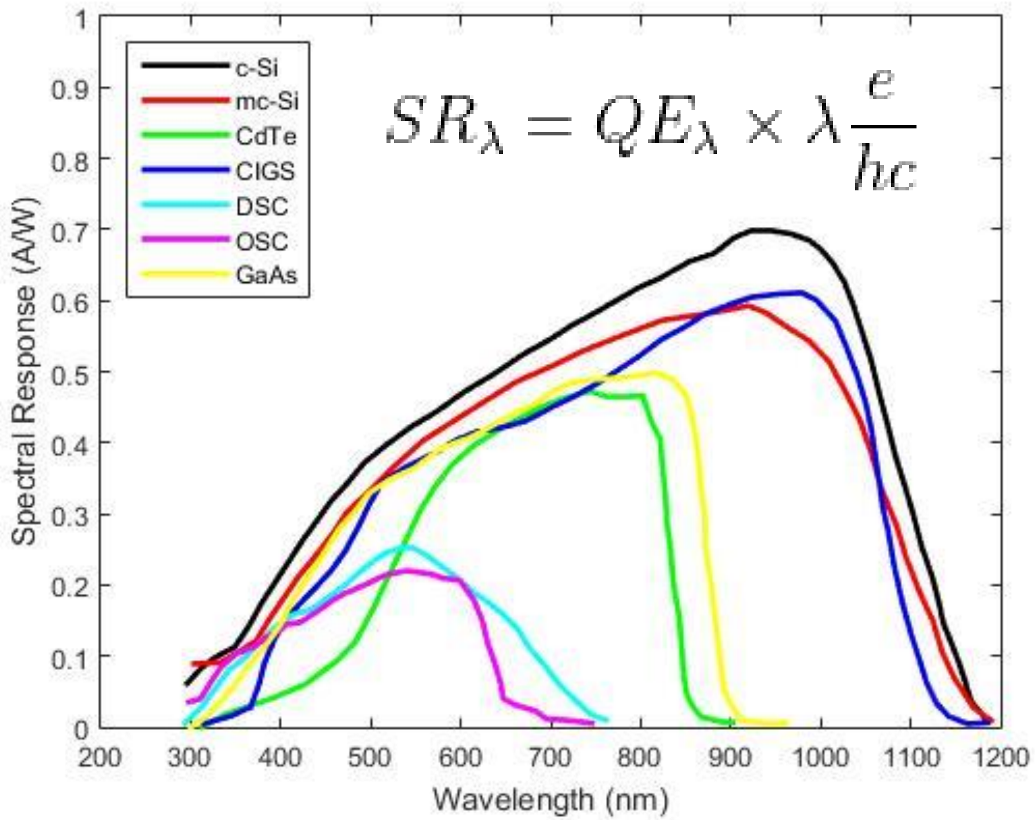
External Quantum Efficiency (EQE)

- Ratio of collected electrons to incident photons on device
- Depends on absorption of light and collection of charge carriers
- Usually measured on cells using monochromator

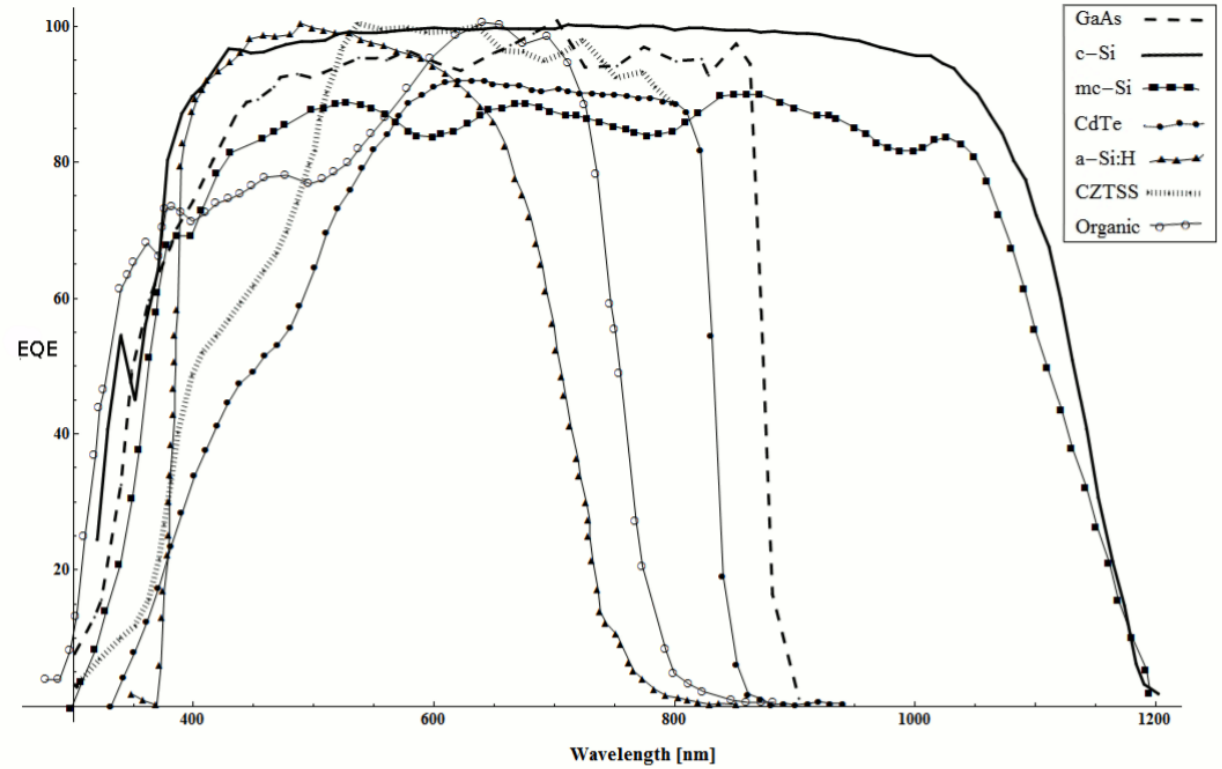


pveducation.org/pvcdrom/solar-cell-operation/quantum-efficiency

Spectral Response vs EQE



https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/effective-irradiance/spectral-response/



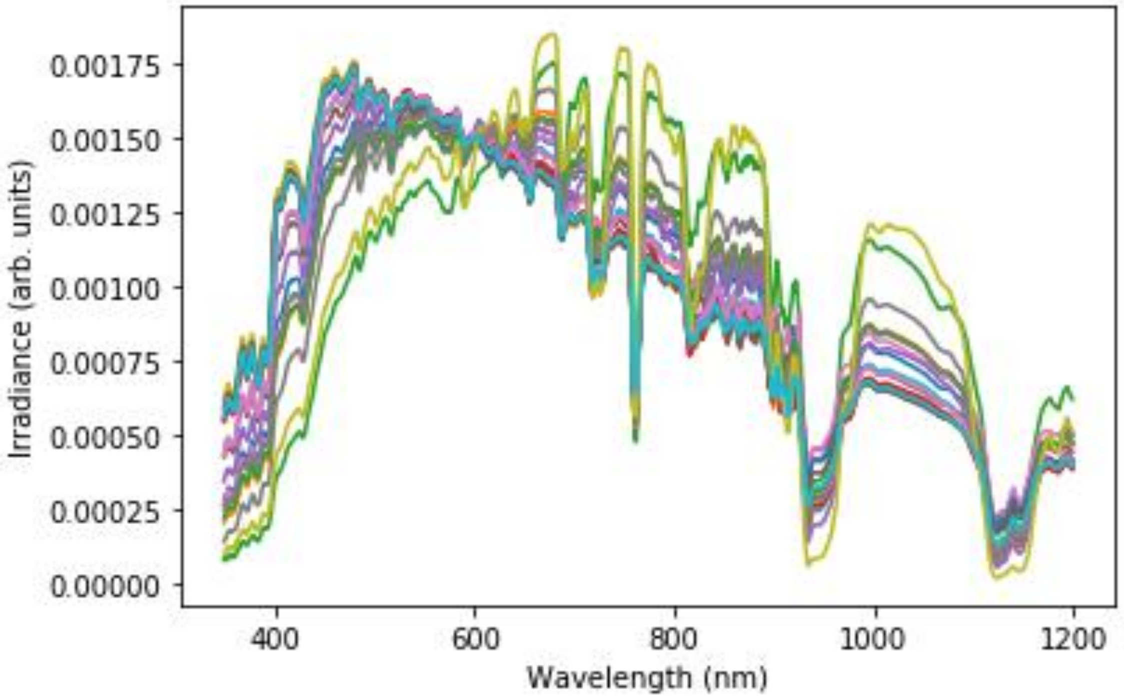
Brennan, M.P.; Abrahamse, A.; Andrews, R.; Pearce, J. (2014). Effects of Spectral Albedo on Solar Photovoltaic Devices. Solar Energy Materials and Solar Cells. 124. 111–116. 10.1016/j.solmat.2014.01.046.

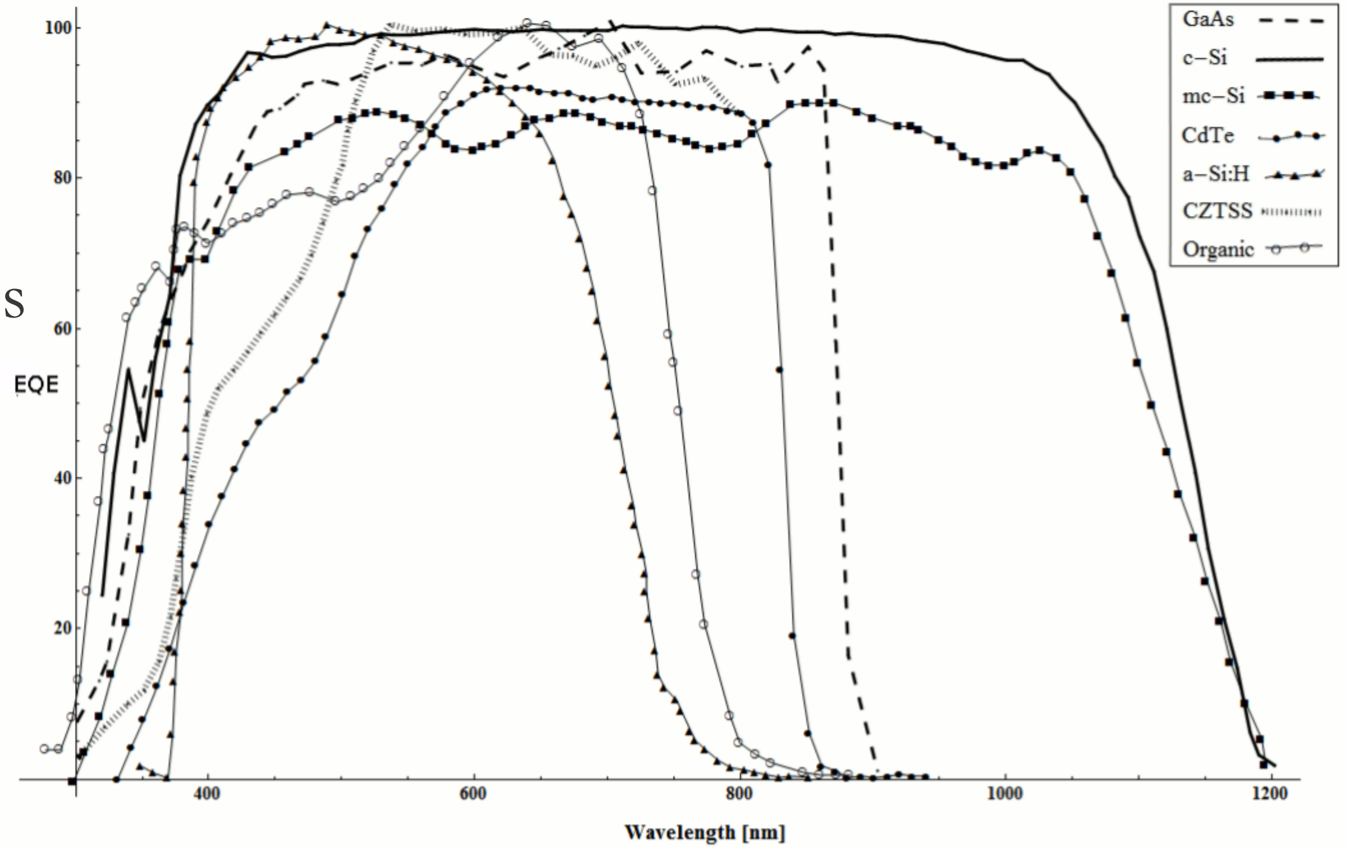
Mining EQE from Field Data

Relies on natural variations in the incident solar spectrum

Similar to Analytic Suns-V_{OC}, need sufficiently long and varying time series

Unique challenges for modules





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Time Series Matrix Representation

$$J_{SC} = q\int EQE(\lambda)\phi(\lambda)d\lambda$$

$$J_{SC} = q\sum_{\lambda} EQE(\lambda)\phi(\lambda)\Delta\lambda$$

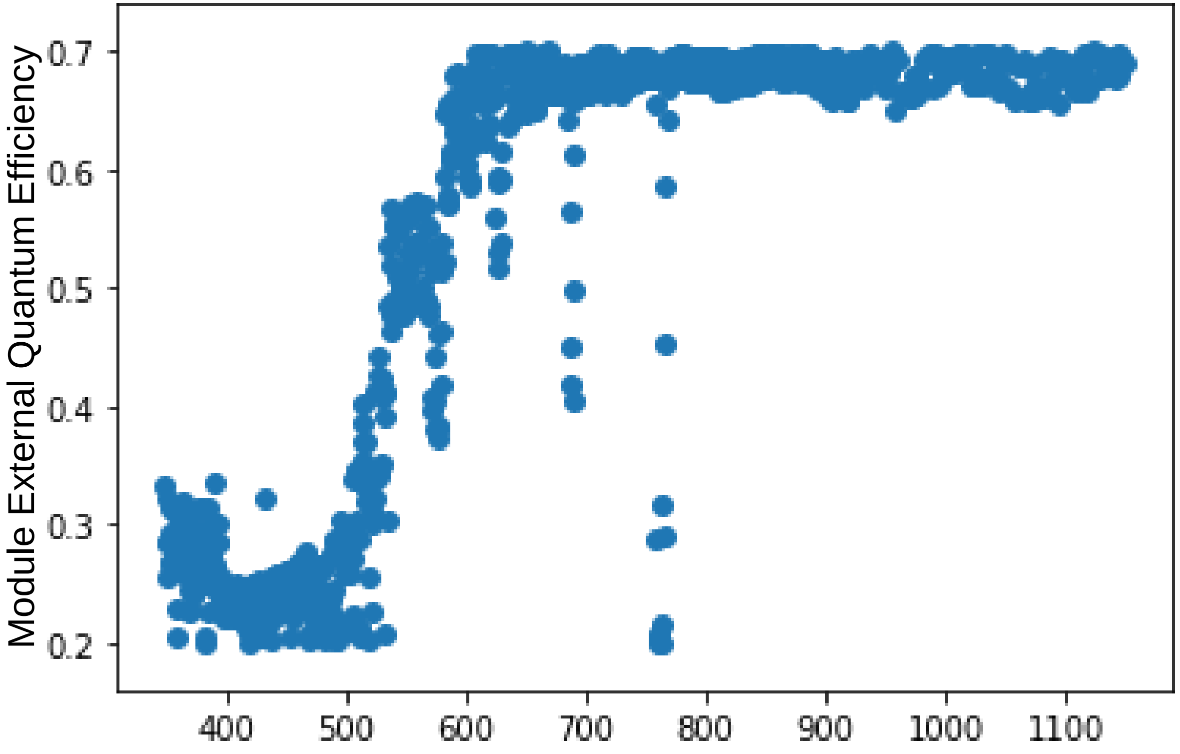
$$\begin{bmatrix} J_{SC1} \\ J_{SC2} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ J_{SCt} \end{bmatrix} = q \begin{bmatrix} \phi_1(\lambda_1)\ \phi_1(\lambda_2)\ \ldots\ \ldots\ \ldots\ \ldots\ \phi_1(\lambda_n) \\ \phi_2(\lambda_1)\ \phi_2(\lambda_2)\ \ldots\ \ldots\ \ldots\ \ldots\ \phi_2(\lambda_n) \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \phi_t(\lambda_1)\ \phi_t(\lambda_2)\ \ldots\ \ldots\ \ldots\ \ldots\ \phi_t(\lambda_n) \end{bmatrix} \begin{bmatrix} EQE(\lambda_1) \\ EQE(\lambda_2) \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ EQE(\lambda_n) \end{bmatrix} \Delta\lambda$$

Initial Analytic EQE result

Reasonable shape of QE curve in UV region based on bound least-squares matrix inversion

EQE is overestimated in IR region due to temperature effect on the band gap

Also shows decreases in EQE corresponding to O_2 and H_2O absorbance in AM1.5G spectrum



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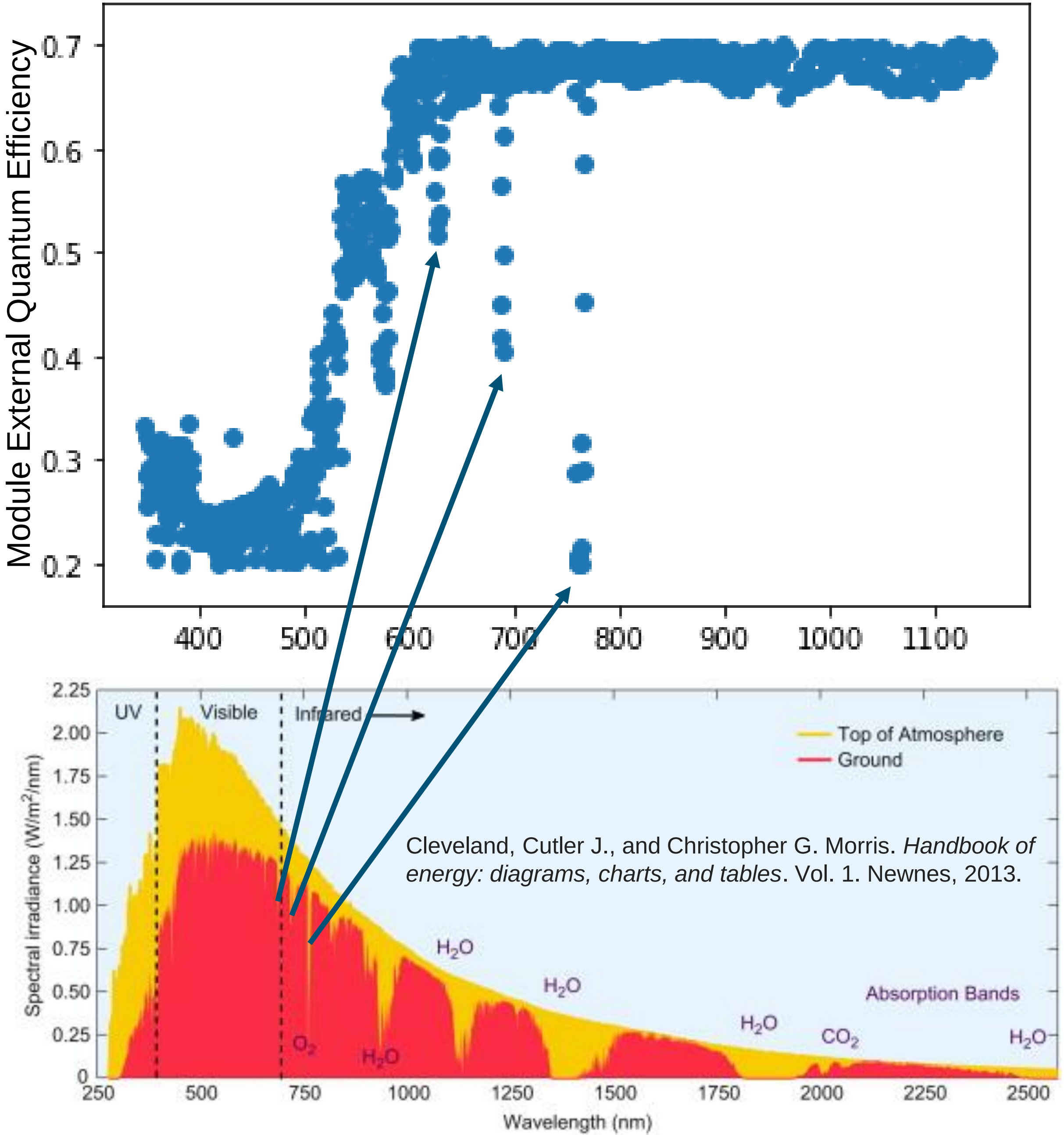


Cleveland, Cutler J., and Christopher G. Morris. *Handbook of energy: diagrams, charts, and tables*. Vol. 1. Newnes, 2013.

Temperature-based band gap shift applied to spectral data

Varshni, Y. P. 1967 | Physica 34 149–154

TEMPERATURE DEPENDENCE OF THE ENERGY GAP IN SEMICONDUCTORS

by Y. P. VARSHNI

Department of Physics, University of Ottawa, Ottawa, Canada

Synopsis

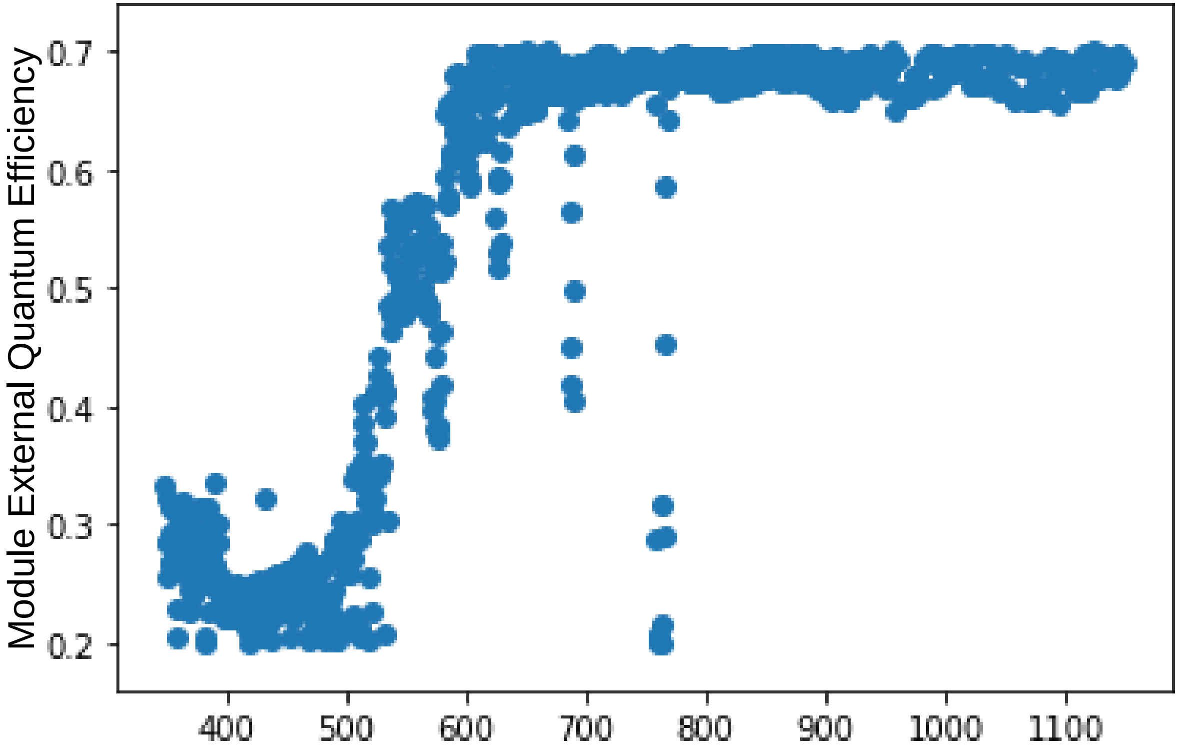
A relation for the variation of the energy gap (E_g) with temperature (T) in semiconductors is proposed:

$$E_g = E_0 - \alpha T^2/(T + \beta)$$

where α and β are constants. The equation satisfactorily represents the experimental data for diamond, Si, Ge, 6H–SiC, GaAs, InP and InAs.

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

$$\lambda_i' = \lambda_i \times \frac{E_g(T)}{E_g(300)}$$



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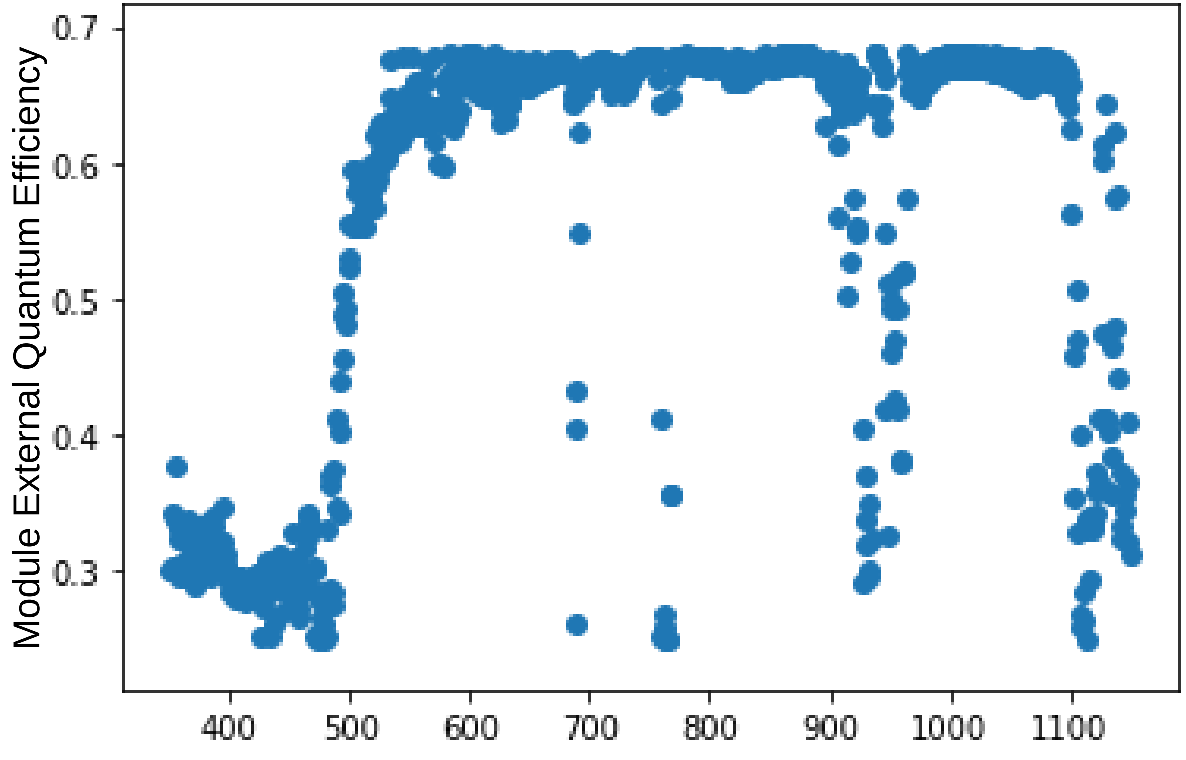

Conclusions

Mechanistic performance data mined from time-series can be used to:

- Evaluate long-term trends in performance
- Identify dominant or changing degradation mechanisms

Or can be used as a monitoring tool to:

- Alert operators to "abnormal" conditions or data issues
- Indicate need for service e.g., cleaning

Future work:

- Adapt Field Analytic Isc-Voc and EQE measurements for inverter data
- Validation of mined datatypes and analysis with laboratory measurements

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Roger French

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Joshua Stein
Cliff Hansen

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

CASE WESTERN RESERVE UNIVERSITY EST. 1826

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