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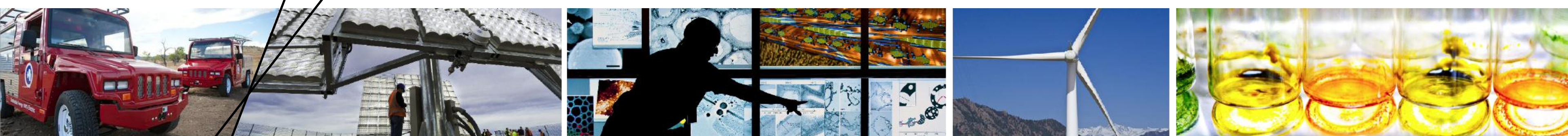
5-parameter PV Module Model



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Outline

1. **Quick review of single diode model**

2. **Automated method for estimating model parameters from STC measurements**

3. **Overview of CEC module database and related processes**

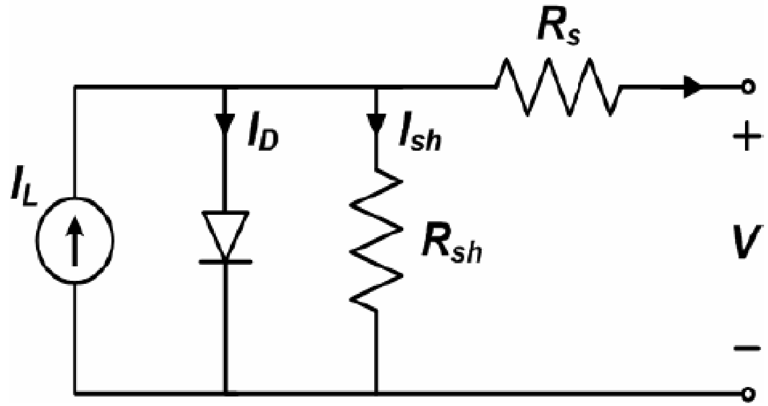
Overview

- **Basic 5 parameter single diode model designed to predict module performance using only data points typically supplied on a manufacturer datasheet**
  - Vmp, Imp, Voc, Isc, α, β, γ, N
- **Many implementations: SAM, PVsyst, PV_LIB, …**
- **Many variations: 6/7 parameters, 2 diodes, …**
- **Evaluations by Boyd, et al (2011) indicate model predicts within 6% RMS for c-Si, mc-Si, less accurate for thin-film CIS and a-Si.**

Model Equations

- **Standard 5 parameter (a, I_L, I_o, R_s, R_{sh}) diode equation:**

$$I = I_L - I_o\left(\exp\left[\frac{V + IR_s}{a}\right] - 1\right) - \frac{V + IR_s}{R_{sh}}$$



- **Translation of parameters to operating conditions:**

$$\frac{a}{a_{STC}} = \frac{T_c}{T_{c,STC}}$$

$$\frac{I_o}{I_{o,STC}} = \left[\frac{T_C}{T_{c,STC}}\right]^3 \exp\left[\frac{1}{k}\left(\left.\frac{E_g}{T}\right|_{T_{C,STC}} - \left.\frac{E_g}{T}\right|_{T_C}\right)\right]$$

$$\frac{E_g}{E_{g,ref}} = 1 - 0.0002677\left(T_C - T_{C,STC}\right) \quad \text{and} \quad E_{g,ref} = 1.121 \text{ eV}$$

$$I_L = \frac{S}{S_{STC}}\frac{M}{M_{STC}}\left[I_{L,STC} + \alpha\left(T_C - T_{C,STC}\right)\right]$$

Variations

- **Observed that modeled max power temp coeff did not always match measured**
  - *"Adjust"* parameter added to tweak α_{Isc}, β_{Voc} temp coeffs until $\gamma_{modeled} = \gamma_{measured}$

- **δ parameter to add temperature dependence to R_s**

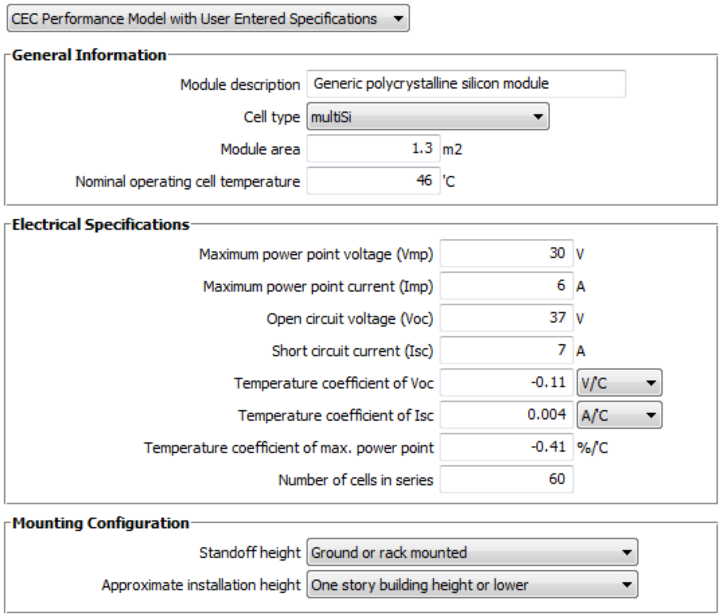
$$R_S = R_{S,STC} \exp\left(\delta\left(T - T_{ref}\right)\right)$$

- ***m* parameter to account for nonlinearity in saturation current**
  - Need data at different irradiance levels, i.e. P_{max} at 200 W/m²
  - $\frac{I_o}{I_{o,STC}} = \left[\frac{S}{S_{STC}}\right]^m \left[\frac{T_C}{T_{C,STC}}\right]^3 \exp\left[\frac{1}{k}\left(\frac{E_g}{T}\bigg|_{T_{C,STC}} - \frac{E_g}{T}\bigg|_{T_C}\right)\right]$

- **PVsyst model adds a recombination current for amorphous modules**

Generating Parameters (SAM impl.)

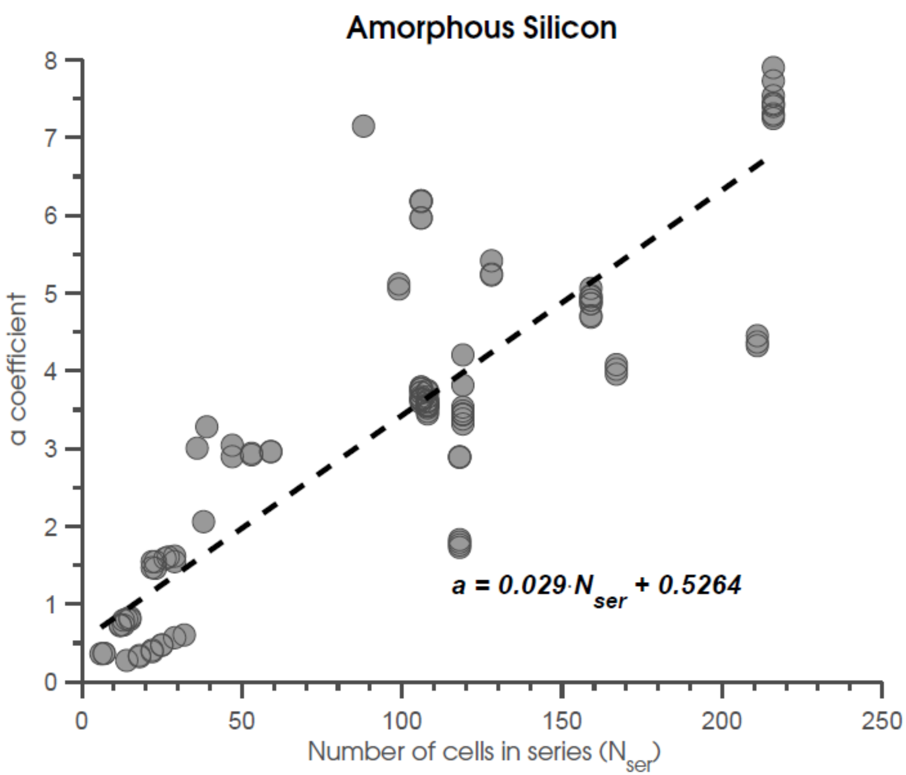
- **Details of method in ref. Dobos, 2012.**
- **6 eq., 6 unk.: a, I_L, I_o, R_s, R_{sh}, Adj**
  1. Short circuit
  2. Open circuit
  3. Maximum power point
  4. Derivative of MPP
  5. Temp coeff of Voc
  6. Gamma measured = Gamma predicted

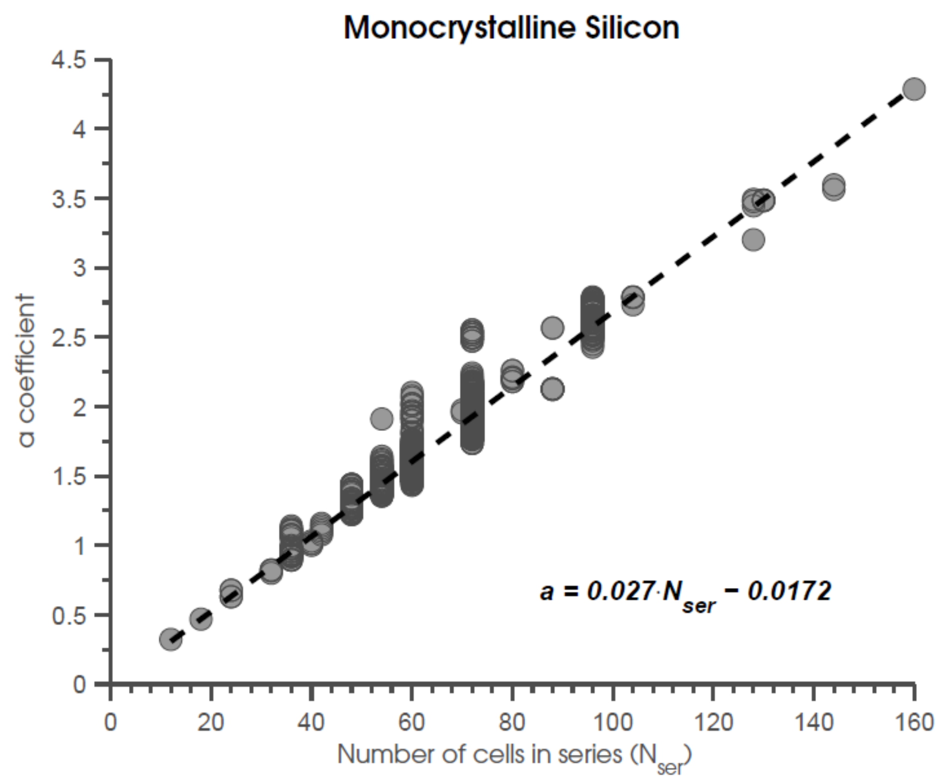


- **Multidimensional Newton-Raphson solver implemented in C++ to solve 6 equations 6 unknowns for the model parameters given STC conditions**
- **6th equation for Adjust requires estimation of model-predicted gamma**
  - This is a 2 equation 2 unknown subproblem that is solved with a nested Newton-Raphson implementation

Guess Values

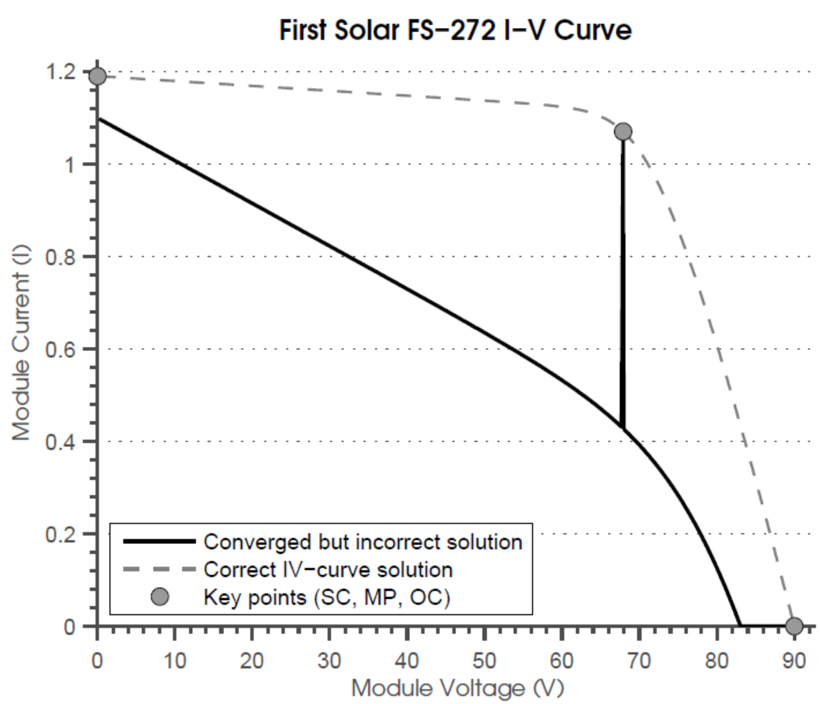
- **Method very sensitive to guess values – frequently fails**
- **Improved convergence with “better” guess values**
  - Linear regressions predict resistances and diode factor from module STC parameters, number of cells, technology type. Plots below for modified nonideality factor **a**
  - Solver run across all modules in database, and regressions calculated from those that converged.

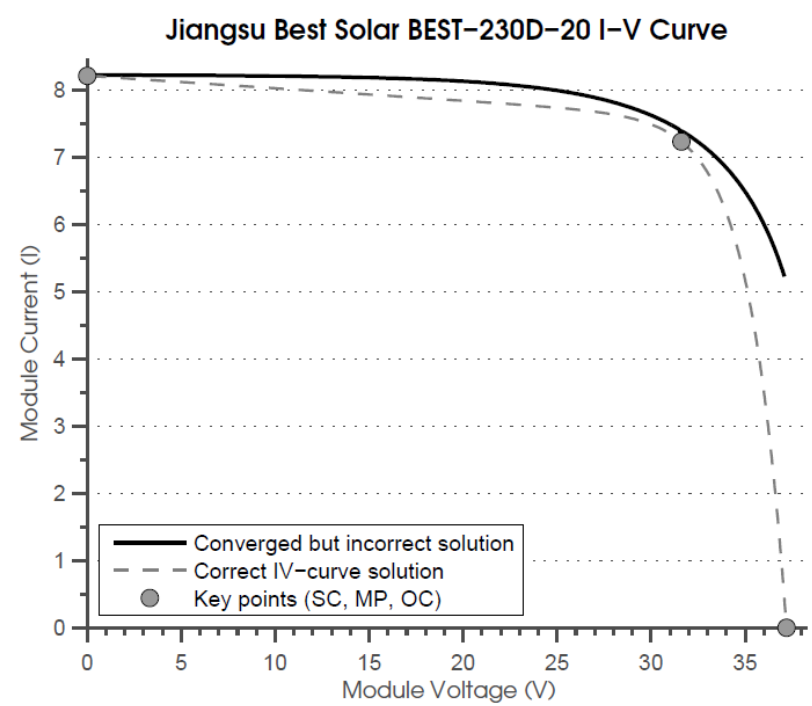




Checking Parameters

- **Method may converge and yield clearly invalid parameters: sanity checks required**
  - Curve-predicted Pmp must be within tolerance of specifed Pmp
  - Curve-predicted current at Voc must be within tolerance of zero
  - Derivative of IV curve must always be negative
- **If invalid solution found, try again with adjusted guesses.**

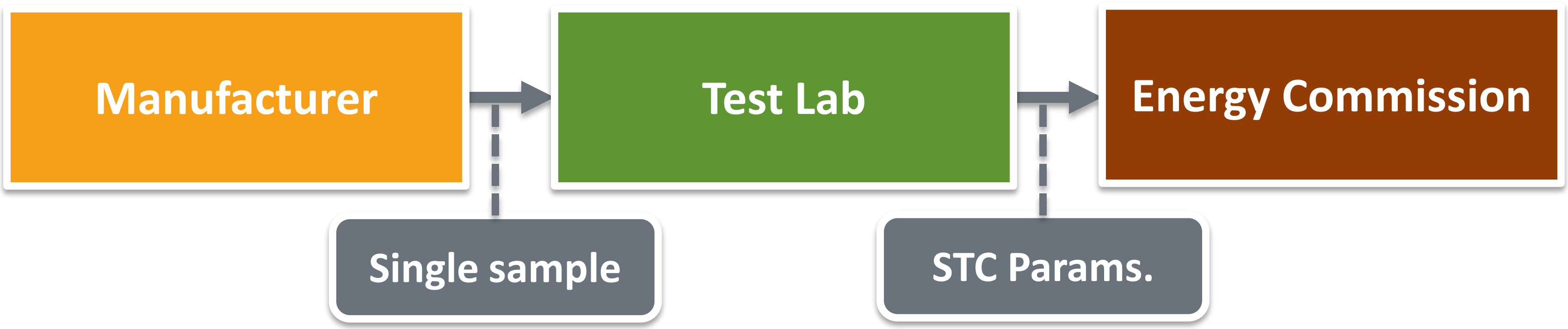




CEC Database

- **Developed in support of California's residential NSHP program**
- **Used to estimate incentive amounts based on projected system performance**
- **Currently over 10000 modules in database, updated several times each year**
- **Since it is a residential program, database not heavily used or originally "intended" for thin-film or amorphous modules – however manufacturers would like to be listed in the database for a variety of reasons**

CEC General Process



- **Manufacturer sends single sample of a module to a test lab holding ILAC accreditation, implementing procedures IEC 61215 and 61646 particularly**
  - Weakness: nobody double checks that accreditations are valid and up to date
- **UL, Intertech, TUV, account for approximately 85% of data in database**
- **Test lab then reports results to CEC per manufacturer's request**
- **CEC receives:**
  - Vmp, Imp, Voc, Isc, Pmp @ STC
  - NOCT @ 800 W/m2
  - 5 measured temperature coefficients: bVoc, bVmp, aIsc, aImp, Gamma
  - Pmp @ 200 W/m2 – data quality issues here, not included in public database

CEC Processes (cont)

- **Data may have "scaled" parameters for modules within 5-10 W of each other.(i.e. one test for a 200 W module, and the 195 W variant does not have independent test data)**
  - Many of the 10000+ modules in DB don't have actual measurements
  - Somewhat "squishy" as to which modules require separate testing
- **NOCT and temp coeffs: these values could be from one set of measurements on a module "family"**
- **Currently KEMA processes incoming data, performs basic screening/cleanup, sends monthly report to the CEC, CEC generates model parameters, updates database**
- **CEC does not receive actual IV curve data**
- **Single sample of manufacturer's choice**
  - Can pick "best" module, can resubmit retested modules to CEC later – no fixed rules on this process

Conclusions

- **Limitations**
  - Prediction errors for thin-film and amorphous modules higher than c-Si
  - Single test sample to characterize a module
- **Successes**
  - Exceptionally large database coverage of up-to-date modules
  - Minimum set of input data can reduce modeling errors due to user errors and improves access: can be used from datasheet parameters
  - Analytical IV curve representation suitable for module and string mismatch modeling
- **Future**
  - Better treatment of nonlinearities with respect to irradiance typically require additional test data to estimate model parameters
  - Other extensions/improvements not described here? Suggestions welcome.

References

- **Boyd, M.T.; Klein, S.A.; Reindl, D.T.; Dougherty, B.P.; Evaluation and Validation of Equivalent Circuit Photovoltaic Solar Cell Performance Models. J. Solar Energy Engineering, 133(2), 2011.**
- **DeSoto, W.; Klein, S.A.; Beckman, W.A.; Improvement and Validation of a Model for Photovoltaic Array Performance. Solar Energy, 80(1), 2006.**
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