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CALIBRATION OF PHOTOVOLTAIC MODULE PERFORMANCE MODELS USING MONITORED SYSTEM DATA

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Purpose

Calibration of a performance model for PV modules typically relies on data collected outdoors on a two-axis tracker, or indoors using a solar simulator. We present and validate methods to calibrate the Sandia Photovoltaic Array Performance Model [1] and the California Energy Commission model [2] using data collected outdoors for systems at fixed tilt orientation. This work could expand the ability to rapidly characterize as-built PV system performance.

Two axis trackers are used to minimize AOI throughout the day. POA irradiance can be used directly in performance models.

Fixed tilt modules face south at inclination equal to the sites latitude to minimize AOI at solar noon. POA irradiance must be adjusted for AOI and reflection loss.

Sandia Photovoltaic Array Performance Model (SAPM)

SAPM [1] comprises empirical expressions for short-circuit current, open circuit voltage, and the maximum power point.

10 parameters to estimate:

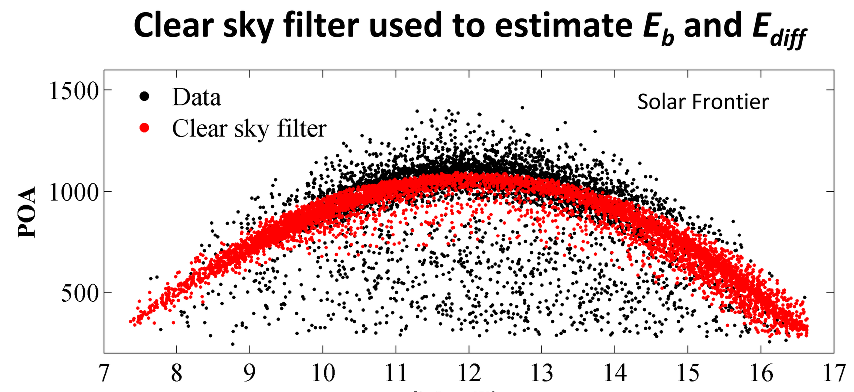
n, I_{SC0}, I_{MP0}, V_{OC0}, V_{MP0}
$f_1(AM_a)$, C_0, C_1, C_2, C_3

$$E_e = f_1(AM_a)\left(E_b f_2(AOI) + E_{diff} f_d\right)/E_0$$
$$I_{SC} = I_{SC0}E_e\left(1+\alpha_{ISC}(T_C - T_0)\right)$$
$$V_{OC} = V_{OC0} + nN_S\delta(T_C)\ln(E_e) + \beta_{VOC}(T_C - T_0)$$
$$I_{MP} = I_{MP0}\left(C_0E_e + C_1E_e^2\right)\left(1+\alpha_{IMP}(T_C - T_0)\right)$$
$$V_{MP} = V_{MP0} + C_2nN_S\delta(T_C)\ln(E_e) + C_3N_S\left(n\delta(T_C)\ln(E_e)\right)^2 + \beta_{VMP}(T_C - T_0)$$

Calibration Method

1. Assume typical values: f_d=1 and $f_2(AOI)$ from [3], datasheet values for temperature coefficients
2. During clear sky conditions:
   - Estimate E_b and E_{diff} from *POA* irradiance
   - Estimate $I_{SC0}f_1(AM_a)$ by regression and estimate I_{SC0} by setting $f_1(1.5) = 1$
3. Estimate n, I_{MP0}, V_{OC0}, V_{MP0}, C_{0-3} by regression techniques using *POA* and T_C data

Clear sky filter used to estimate E_b and E_{diff}



California Energy Commission (CEC) Model

The California Energy Commission (CEC) Model [2] assumes that each module is a single diode equivalent circuit.

7 parameters to estimate:

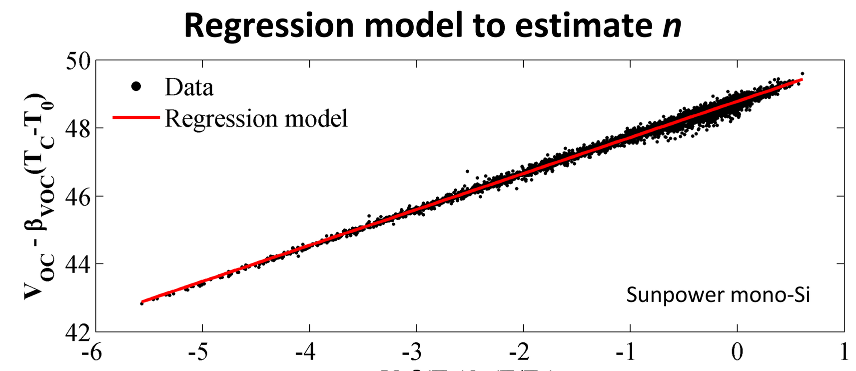
I_{L0}, I_{O0}, R_{SH0}, R_{S0}
n, M/M_0, E_{g0}

$$I = I_L - I_O\left[\exp\left(\frac{V+IR_S}{nN_S\delta(T_C)}\right)-1\right] - \frac{V+IR_S}{R_{SH}}$$
$$I_L = I_L(E,T_C) = \frac{E}{E_0}\frac{M}{M_0}\left[I_{L0} + \alpha_{ISC}(T_C - T_0)\right]$$
$$I_O = I_{O0}\left[\frac{T_C}{T_0}\right]^3 \exp\left[\frac{1}{k}\left(\frac{E_g(T_0)}{T_0} - \frac{E_g(T_C)}{T_C}\right)\right]$$
$$E_g(T_C) = E_{g0}\left(1 - 0.0002677(T_C - T_0)\right)$$
$$R_{SH} = R_{SH0}(E_0/E),\ R_S = R_{S0}$$

Calibration Method

1. Assume datasheet values for temperature coefficients
2. Set $M/M_0 = f_1(AM_a)$
3. Estimate n from V_{OC} vs. irradiance using all IV curves
4. Estimate I_L, I_O, R_{SH}, R_S for each IV curve by an iterative technique [4]
5. Estimate I_{L0}, I_{O0}, R_{SH0}, R_{S0}, *and* E_{g0} by regression using *POA* and T_C data

Regression model to estimate *n*



Monitored System Data

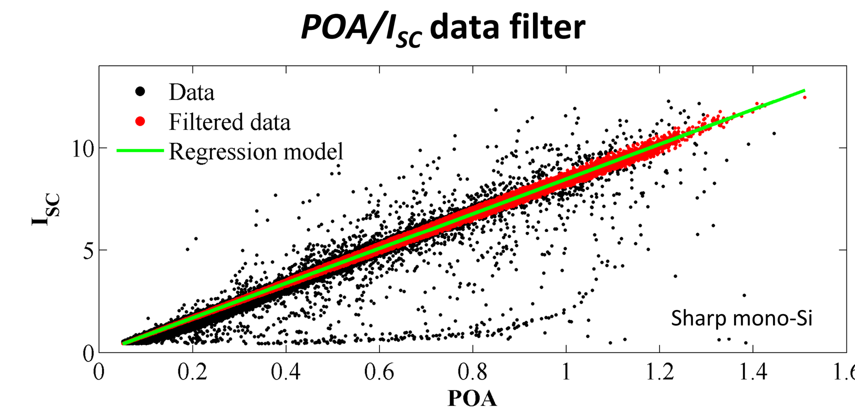
PV modules are located at Los Alamos, NM, USA. Data includes IV curves, POA irradiance, and module temperature sampled every 5 minutes over the course of 9 months.

Module	Cells	Rated Power
Sharp mono-Si	60	240 W
Sunpower mono-Si	72	240 W
Kyocera poly-Si	60	235 W
Keneka tandem a-Si	106	110W
Solar Frontier CIS	109	85 W

Preprocessing data filters include:

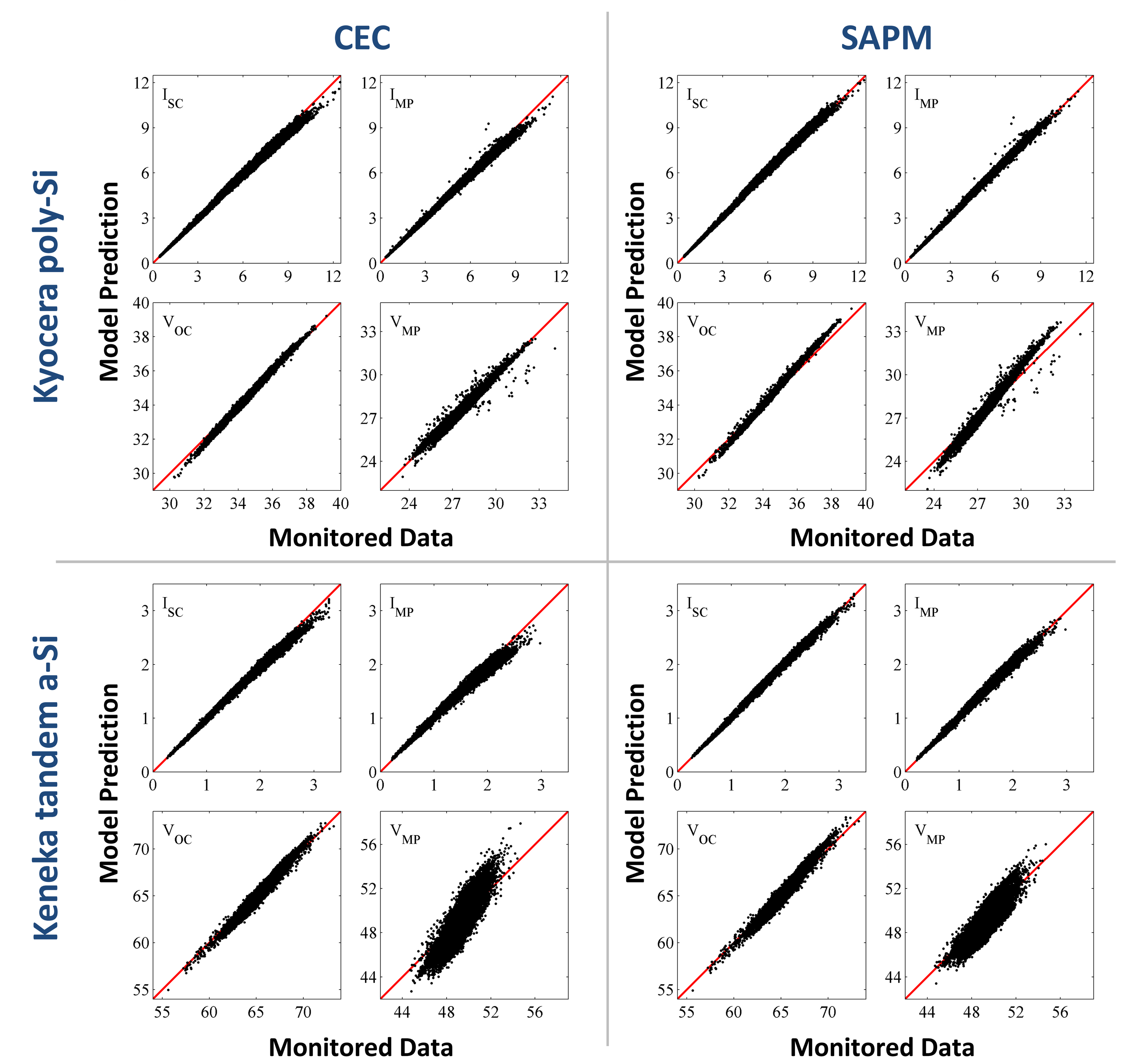
- IV curve extrapolation for I_{SC} and V_{OC}
- Remove data with high AM_a (> 6.5)
- Remove data with high *AOI* (> 70°)
- Remove data if *POA* irradiance and I_{SC} are not linearly correlated

***POA/I_{SC}* data filter**

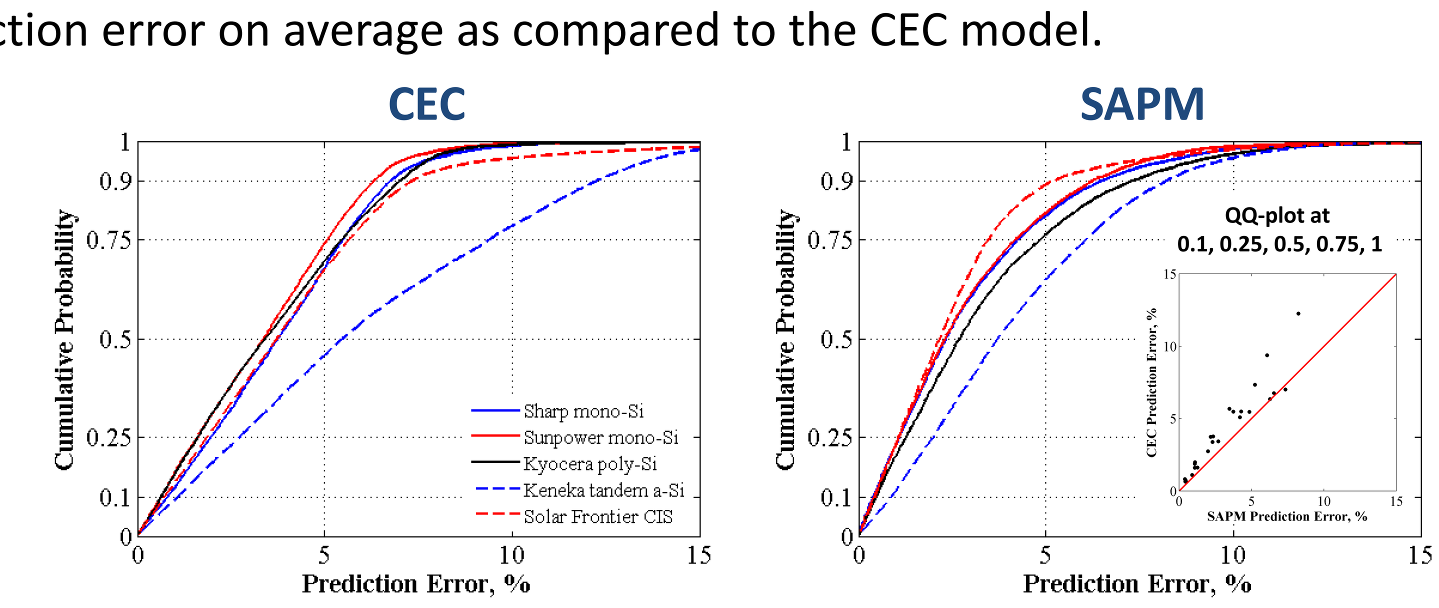


Model Verification

Monitored data compared to model predictions for 2 modules shows similar results using CEC and SAPM.



P_{MP} prediction error CDF for each module. The SAPM results in slightly lower prediction error on average as compared to the CEC model.



Conclusions

- P_{MP} prediction error is below 10% for 90% of the data for most modules.
- Errors are roughly twice that observed for models calibrated using data collected on a two-axis tracker.
- Calibrated temperature coefficients and improvement in $f_1(AM_a)$ could reduce error in the calibrated models.

References

[1] King, D. L., et al. (2004). *Photovoltaic Array Performance Model*, Albuquerque, NM, Sandia National Laboratories.
[2] De Soto, W., et al. (2006), *Improvement and validation of a model for photovoltaic array performance*, Solar Energy 80(1): 78-88.
[3] Martin, N., Ruiz, J. M. (2005) *Annual Angular Reflection Losses in PV Modules*. Progress in Photovoltaics: Research and Applications 13:75-84
[4] Hansen, C., (2013) *Estimation of Parameters for Single Diode Models Using Measured IV Curves*, Proc. of 39th IEEE PVSC, Tampa, FL, USA.

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