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Outdoor PV Performance Evaluation of Three Different Models: Single-diode, SAPM and Loss Factor Model

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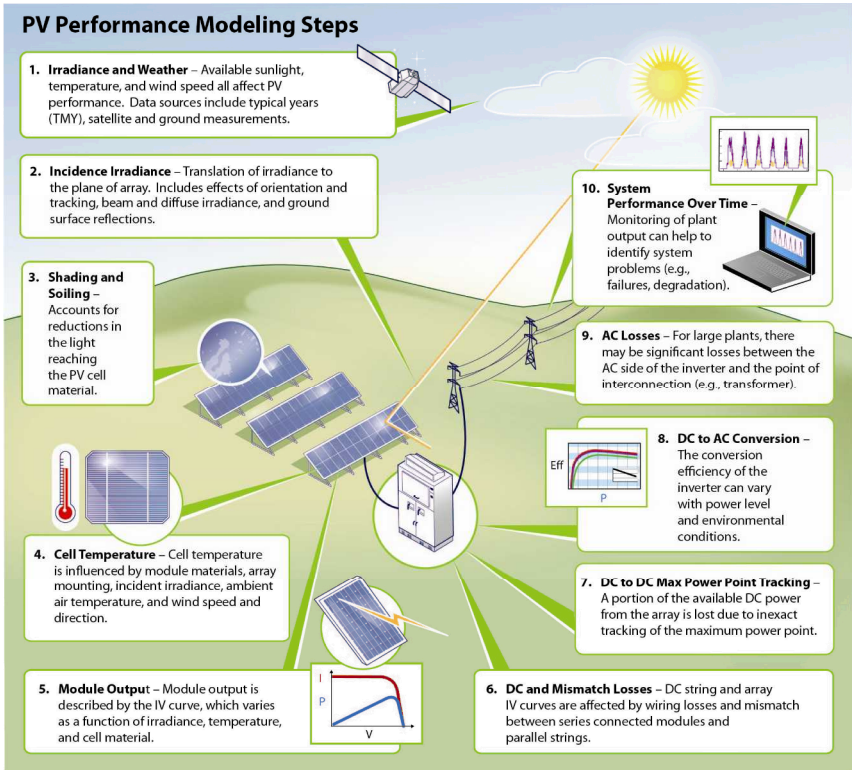
Outline

- Motivation
- Overview of Module Model Formulations
- Methodology for this Study
- Model Comparison Results
- Lessons Learned and Next Steps

Motivation

- The PV module IV model accounts for performance differences between PV technologies
  - $(I, V) = f(G_i, T_c, a_1, a_2, \ldots)$
    - Irradiance effects
      - Spectral effects
      - Low light behavior
    - Temperature effects
    - Transients (e.g., diurnal & seasonal)



- An accurate module model is an essential part of a PV system performance model

Loss Factors Model (TEL/SRCL)

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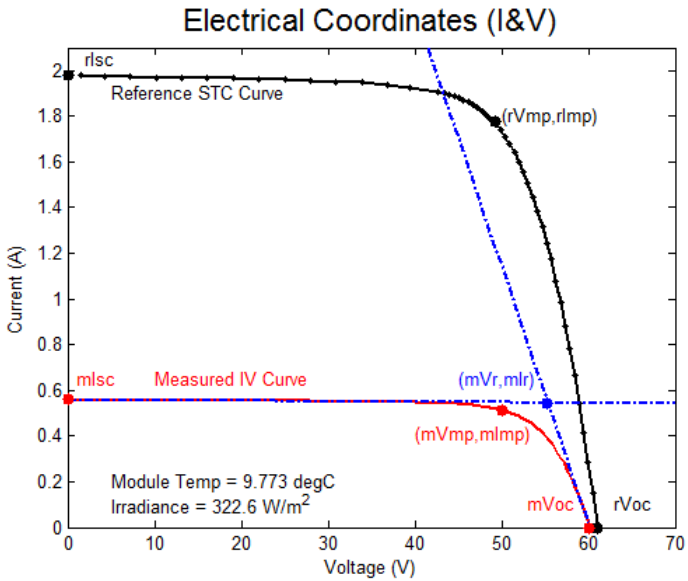
Six Normalized LFM Variables

1. $nIscT = \frac{mIsc}{rIsc} / G_i \times T_{CORR.Isc}$
2. $nRsc = \frac{mIr}{mIsc}$
3. $nImp = \frac{mImp}{mIr} \times \frac{rIsc}{rImp}$
4. $nVmp = \frac{mVmp}{mVr} \times \frac{rVoc}{rVmp}$
5. $nRoc = \frac{mVr}{mVoc}$
6. $nVocT = \frac{mVoc}{rVoc} \times T_{CORR.Voc}$

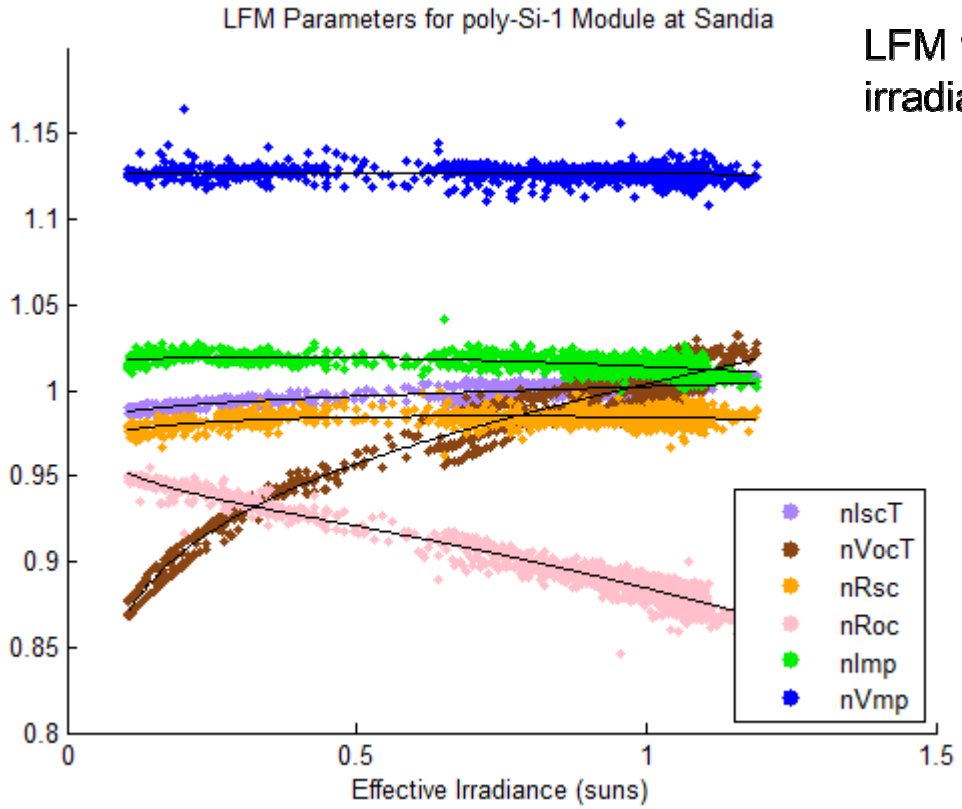
$T_{CORR,Voc} = 1 + \beta_{Voc} \times (25 - T_c)$
$T_{CORR,Isc} = 1 + \alpha_{Isc} \times (25 - T_c)$
MMF = spectral mismatch factor



For this study LFM was run with α_{Imp} and β_{Vmp} instead of α_{Isc} and β_{Voc} because it was found to better fit the measured data.

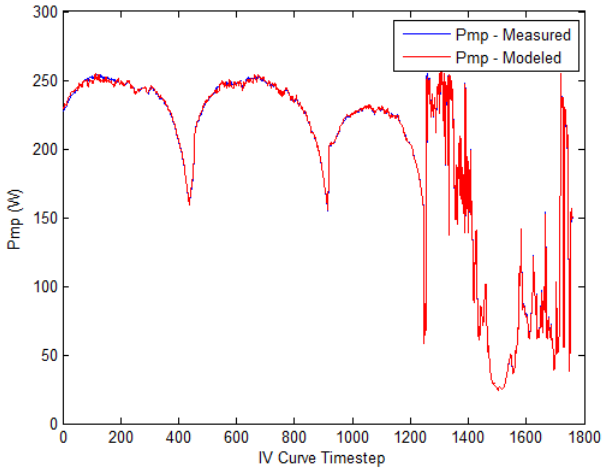
$^*T_{CORR,Voc} = 1 + \beta_{Vmp} \times (25 - T_c)$
$^*T_{CORR,Isc} = 1 + \alpha_{Imp} \times (25 - T_c)$

Loss Factors Model (TEL/SRCL)



LFM fits each of the LFM variables to a function of irradiance for a total of 6×3=18 coefficients

$$nf(G_i) = c_1 + c_2 ln(G_i) - c_3 \times {G_i}^2$$



Prediction of Maximum Power

$$pImp = nIscT \times MMF \times nRsc \times nImp \times rImp \times G_i \div^* T_{CORR.Isc}$$

$$pVmp = nVmp \times nRoc \times nVocT \times rVmp \div^* T_{CORR,Voc}$$

The Sandia Array Performance Model

- Describes module output at SC, OC and MP points
- As a function of beam and diffuse irradiance (E_b and E_{diff}), cell temperature (T_C), air mass (AM_a) and angle of incidence (AOI)
- 14 empirical coefficients, 2 empirical functions (f_1 and f_2)
- With exception of f_2, coefficients determined for individual modules

$$V_{OC} = V_{OC0} + N_S n \delta(T_C) \ln(E_e) + \beta_{OC}(T_C - T_0)$$

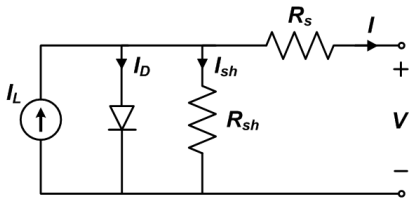
$$V_{MP} = V_{MP0} + C_2 N_S n \delta(T_C) \ln(E_e) + C_3 N_S \left(n \delta(T_C) \ln(E_e)\right)^2 + \beta_{MP}(T_C - T_0)$$

$$I_{SC} = I_{SC0} f_1(AM_a) E_e \left(1 + \alpha_{SC}(T_C - T_0)\right)$$

$$I_{MP} = I_{MP0}\left(C_0 E_e + C_1 E_e^2\right)\left(1 + \alpha_{MP}(T_C - T_0)\right)$$

$$E_e = E_b f_2(AOI) + E_{diff} f_d$$

CEC Single Diode Model



- "Single Diode Models" – PVsyst, CEC, PV*SOL, others (e.g., 4AV.5.52)
  - Each IV curve described by single diode equation ("5 parameters")
  - CEC model includes 4 additional equations that describe how parameters change with irradiance, temperature
  - 7 coefficients
    - I_{L0} = light current at STC
    - I_{o0} = dark current at STC
    - E_{g0} = band gap at T_0
    - R_s = series resistance
    - R_{sh0} = shunt resistance at E_0
    - n = diode ideality factor
    - α_{Isc}= I_{sc} temperature coefficient

$$I = I_L - I_0\left[\exp\left(\frac{V + IR_s}{nV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

$$I_L(E, T_c) = \frac{E}{E_0}\left[I_{L0} + \alpha_{Isc}(T_c - T_0)\right]$$

$$I_o(T_c) = I_{o0}\left[\frac{T_c}{T_0}\right]^3 exp\left[\frac{1}{k}\left(\frac{E_g(T_0)}{T_0} - \frac{E_g(T_c)}{T_c}\right)\right]$$

$$E_g(T_c) = E_{g0}\left(1 - 0.0002677(T_c - T_0)\right)$$

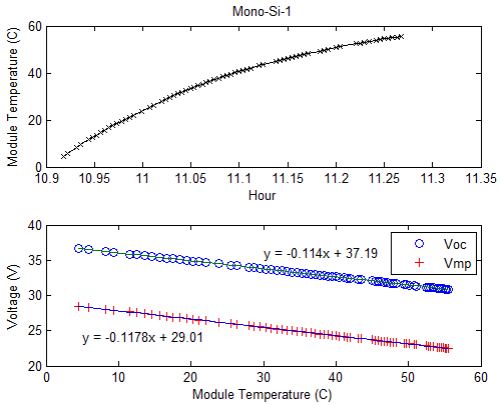
$$R_{sh}(E) = R_{sh0}(E_0/E)$$

- Typical calibration of this model uses a single IV curve and temperature coefficients (Dobos, 2012).
- Sandia is developing methods to use multiple IV curves (e.g., IEC 61853-1) (Hansen and Stein, 2013, 4AV.5.27)

Methodology

- 12 PV modules were characterized outdoors in Albuquerque, NM
  - 5 c-Si, 1 CdTe, and 6 CIGS (preproduction)
  - Preconditioning was performed to manufacturer specifications
- Weather measurements include: DNI, GHI, TNI, DHI, temperature, wind speed, etc.
- Thermal test performed near solar noon during clear sky period
  - Back of module is insulated, module mounted on tracker
  - Opaque cover applied until module temperature is near ambient
  - Cover removed and IV curves and back of module temperature is measured.
  - Coefficients calculated by regression
  - Voltage corrected for irradiance

$$Voc_{cor} = mVoc - \frac{N_s\, kn}{q}\ln(G_i)$$

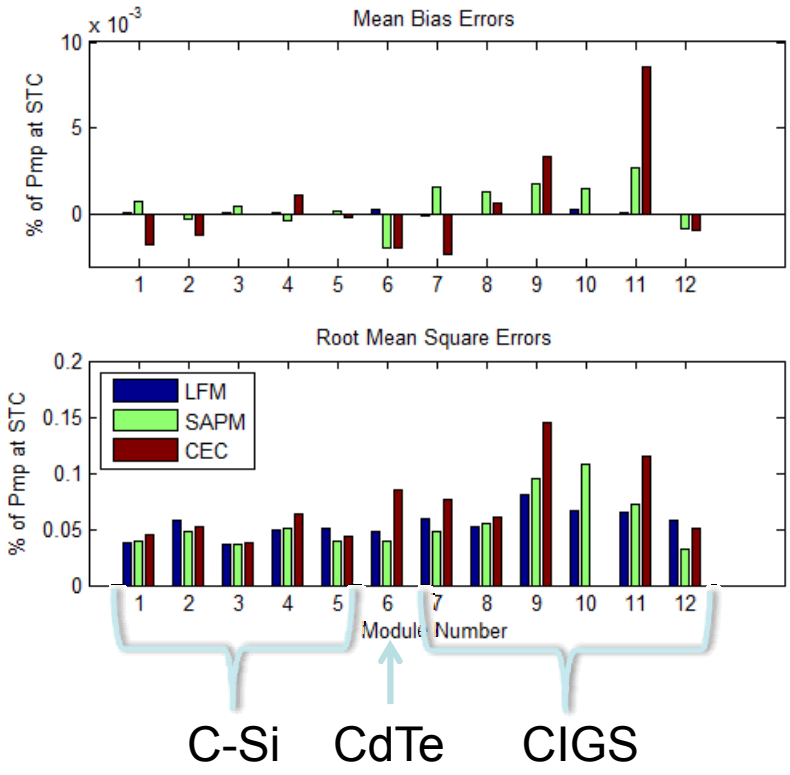


Methodology

- Electrical Performance Test lasted several days
  - Includes clear and diffuse conditions
  - Modules mounted on tracker and held normal to sun
  - IV curves measured approximately every minute
  - Module held at *Vmp* between IV sweeps
- To fairly compare models we used "Effective Irradiance" (*Ee*) in place of irradiance
  - $Ee = mIsc/[rIsc \times \{1 + \alpha_{Isc}(T_{module} - 25)\}]$
  - Use of *Ee* in place of G_i essentially removes need to correct for spectral mismatch (*MMF* = 1)
- All three models (LFM, SAPM, and CEC) were fit to the same set of IV curves, temperature coefficients, and *Ee*.

Model Comparison Results

- All three models fit *Pmp* for c-Si modules rather well.
  - LFM model has lowest bias errors
- All thin film modules resulted in largest errors for all models.
- CEC model did not converge for one of the CIGS modules.
  - Exhibited bias errors in Imp and Vmp for other modules
  - This model form is more sensitive to all points on the IV curve and is more susceptible to measurement errors and noise (variability)
- SAPM model exhibited bias due to Imp fitting errors (quadratic form does not always fit measurements).



Model Residual Comparisons

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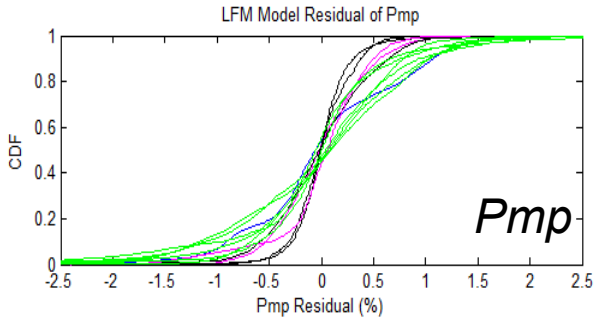
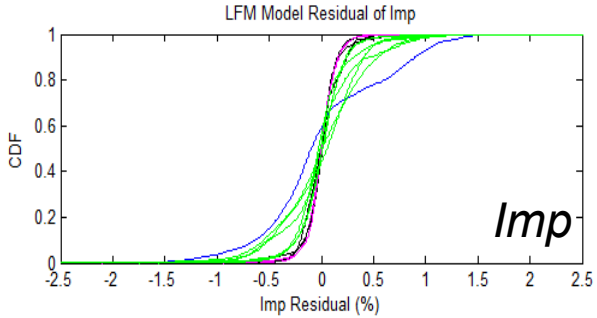
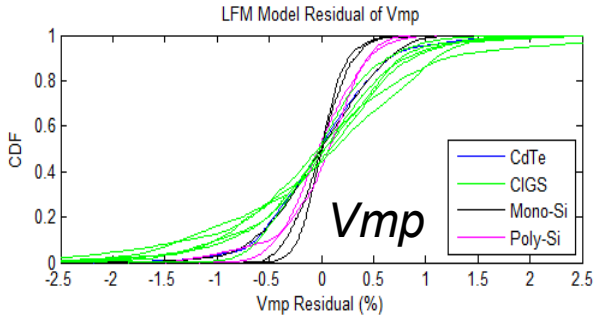
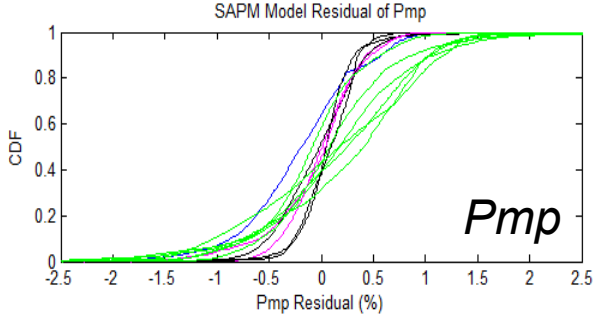
LFM

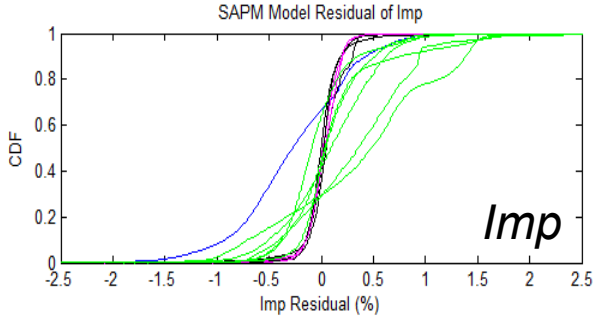


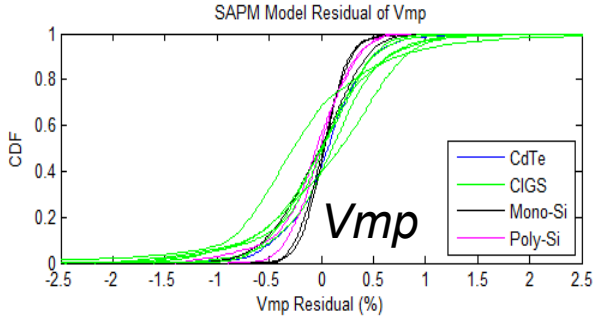




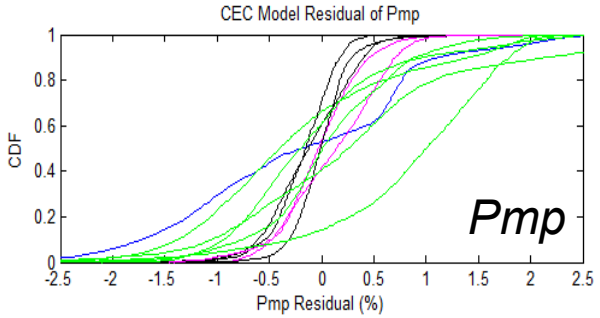
SAPM

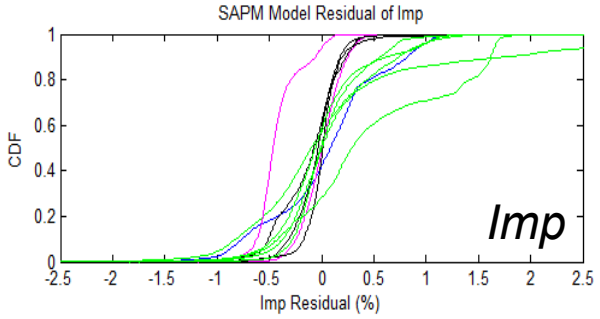


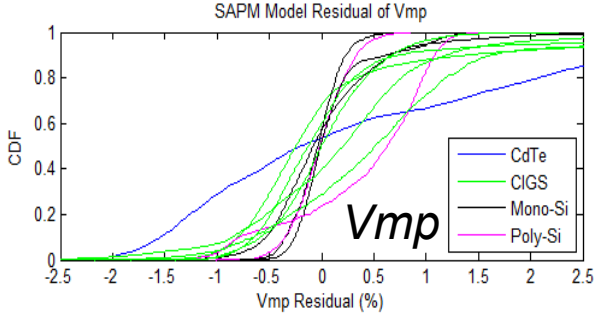




CEC

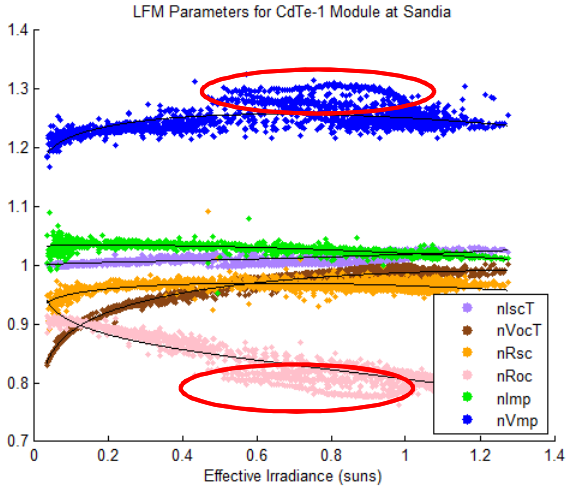


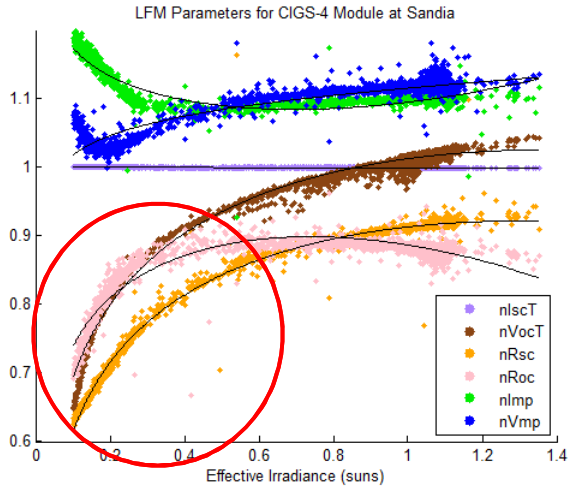




Lessons Learned: LFM Provides Insights into Module Performance

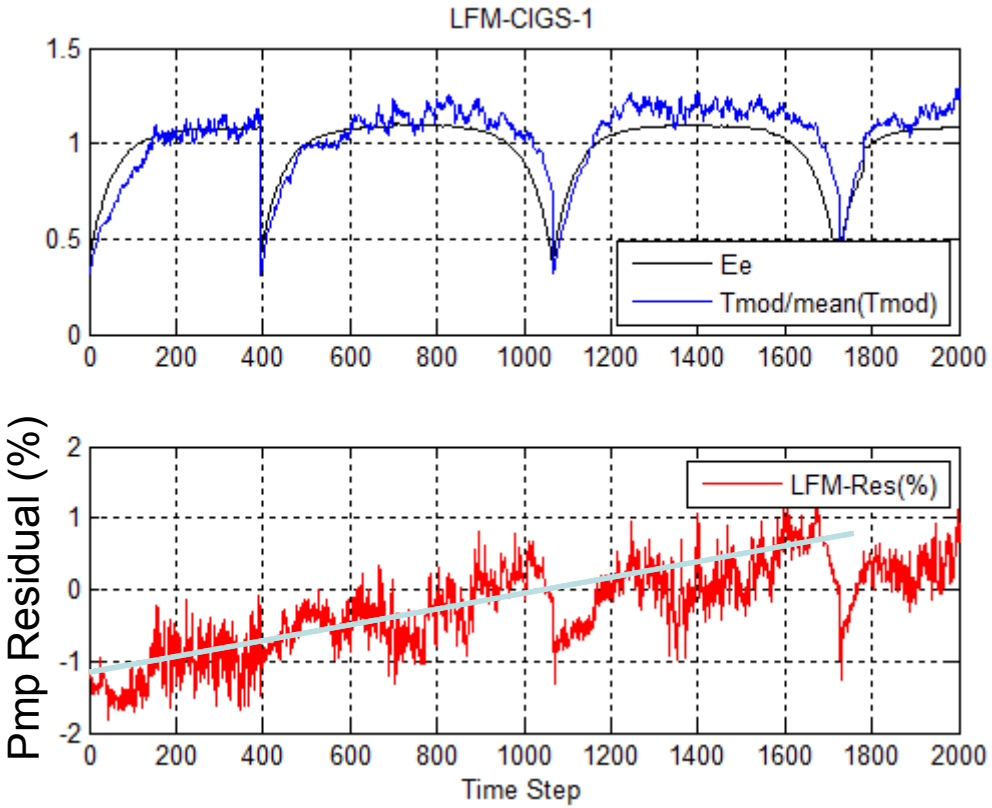
- The normalized LFM variables (and fitting coefficients) provide a powerful way to compare different modules and assess their relative health and performance.
  - CdTe-1 module shows transient deviations in *nVmp* and *nRoc* (cancel out for *Pmp*)
    - Possible Schottky rollover effect with temperature?
  - CIGS-4 module show non-ideal behavior
    - *nRsc* and *nRoc* increasing with irradiance suggests that *Rshunt* is <u>decreasing</u> with irradiance
- SAPM and CEC module coefficients would not provide any evidence of such behavioral anomalies.





Lessons Learned: Accurate Models Help to Identify Performance Changes

- Despite preconditioning, several modules showed metastable features.
  - CIGS-1 shows performance degradation during the test period as an increasing model residual vs. time.
    - FF is decreasing over time



Summary and Conclusions

- All three models were able to fit most of the modules quite well
  - LFM (with some modifications) had smallest bias error
  - LFM and SAPM had lowest random error
  - CEC model performed well for c-Si but not as well for thin film modules
- The fact that LFM is based on normalized variables makes it especially useful as a means to compare and assess relative module performance.
- TEL/SRCR and Sandia plan to further investigate options for LFM temperature corrections to further improve this model's accuracy and flexibility.
  - Sandia plans to include LFM analysis as part of its future module characterization process for customers.

Thank You!

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