Overview of Photovoltaic Module Performance Modeling Approaches

PVPerformance MODELING COLLABORATIVE

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Sandia National Laboratories

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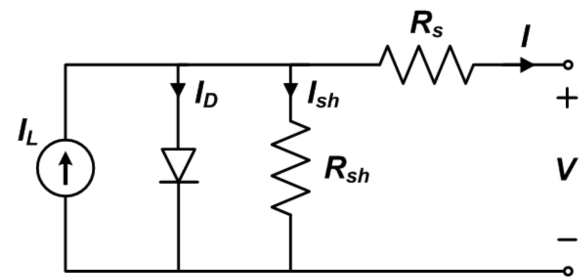
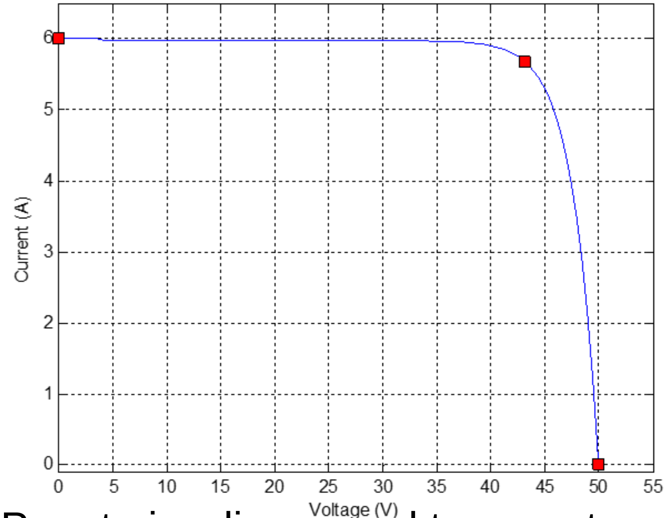
PV Module Modeling Approaches



- Equivalent Circuit Models
  - Describe full I-V curve at desired irradiance and temperature conditions
  - Single diode equation ('5 parameter') is most common
  - Auxiliary equations relate the 5 parameters to irradiance and temperature
    - Different among PVsyst, De Soto, CEC, PV*SOL



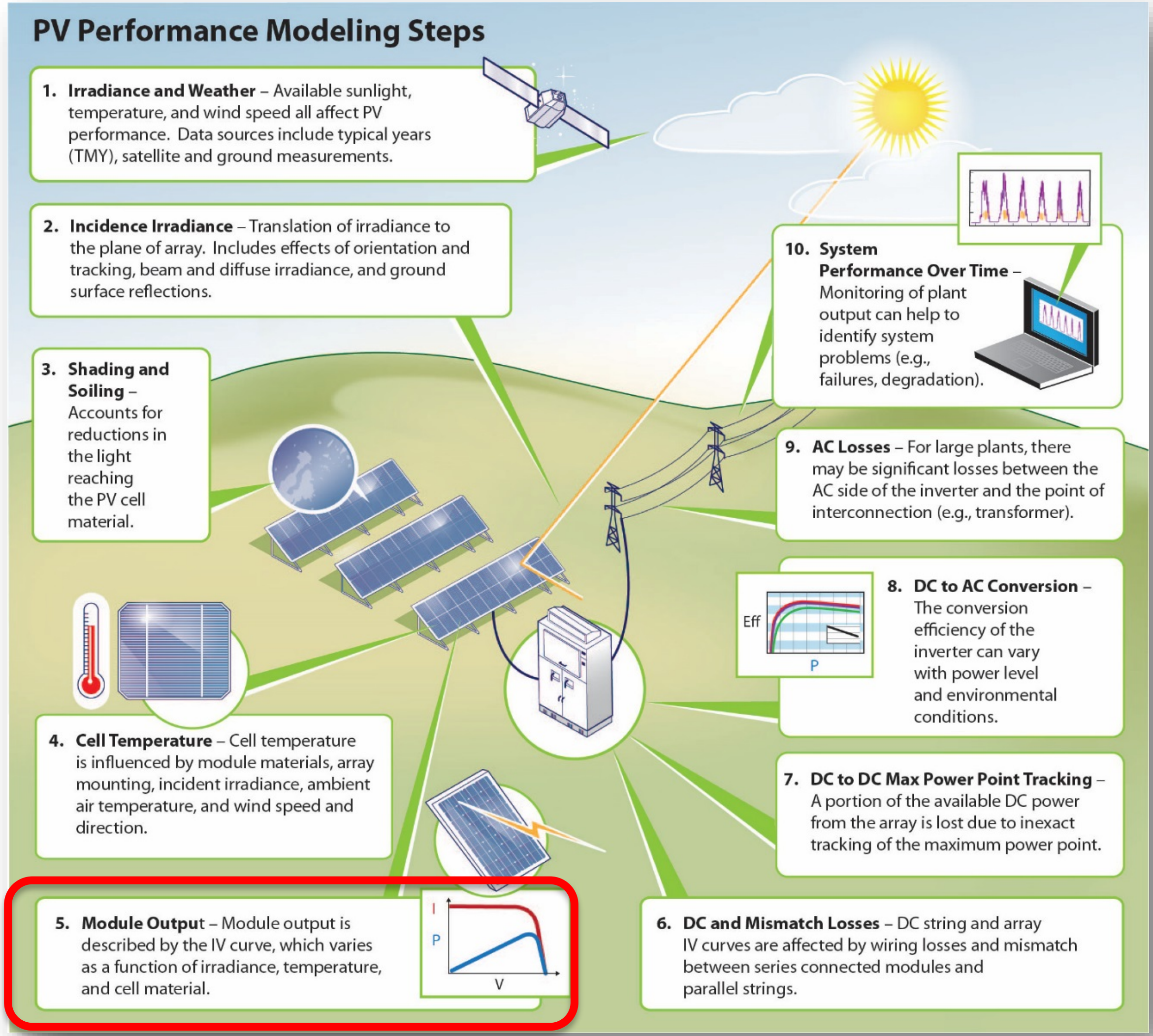
- Point Models
  - Describe cardinal points on the IV curve: Pmp, Imp, Vmp, Isc, Voc
  - PVWatts
  - Huld model

  } Algebraic equations relating Pmp to irradiance and temperature

  - Sandia PV Array Performance Model (SAPM)
  - Loss Factors Model

  } Set of equations describing Imp, Vmp, Isc and Voc
- 'Data' Models

Module model is only one part of a modeling process



Stein, J. S. and B. H. King (2013). Modeling for PV plant optimization. *Photovoltaics International, Solar Media Ltd.* ***19th: 101-109.***

"Single Diode" Models

- CEC, PVsyst, CEC, PV*SOL, others
  - IV curve described by single diode equation
  - "5 parameters" – *for each IV curve*
- Auxiliary equations describe how '5 parameters' change with irradiance, temperature
  - Different equations for each PV model
  - Auxiliary equations contain the model parameters
  - E.g., De Soto model has 7 parameters, PVsyst v6 has 9 parameters

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

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

$$I_O = I_{O0}\left(\frac{T_C}{T_0} \right)^3 \exp\left(\frac{1}{k}\left(\frac{E_{g0}}{T_0} - \frac{E_g(T_C)}{T_C} \right) \right)$$

$$R_{sh} = R_{sh0}\frac{E_0}{E} \qquad R_s, n \text{ constant}$$

De Soto et al, 2006

Ancillary Equations

Diode equation term (unit) symbol	PVsyst v6	CEC '6 parameter' model
light current (A) I_L	$I_L(E,T_C)=\frac{E}{E_0}\left[I_{L0}+\alpha_{Isc}(T_C-T_0)\right]$	$I_L(E,T_C)=\frac{E}{E_0}\left[I_{L0}+\alpha'_{Isc}(T_C-T_0)\right]$ $\alpha'_{Isc}=\alpha_{Isc}(1-Adjust/100)$
dark current (A) I_O	$I_O(T_C)=I_{O0}\left[\frac{T_C}{T_0}\right]^3\exp\left[\frac{q\varepsilon_G}{k\gamma}\left(\frac{1}{T_0}-\frac{1}{T_C}\right)\right]$	$I_O(T_C)=I_{O0}\left[\frac{T_C}{T_0}\right]^3\exp\left[\frac{1}{k}\left(\frac{E_g(T_0)}{T_0}-\frac{E_g(T_C)}{T_C}\right)\right]$ $E_g(T_C)=E_{g0}(1-0.0002677(T_C-T_0))$
series resistance (Ω) R_S	$R_S=R_{S0}$	$R_S=R_{S0}$
shunt resistance (Ω) R_{SH}	$R_{SH}=R_{SH,base}+(R_{SH,0}-R_{SH,base})\exp\left(-R_{SH\exp}\frac{E}{E_0}\right)$ $R_{SH,base}=\max\left[\frac{R_{SH,ref}-R_{SH,0}\exp(-R_{sh\exp})}{1-\exp(-R_{sh\exp})},0\right]$	$R_{SH}(E)=R_{SH0}\frac{E_0}{E}$
ideality factor (unitless) γ or n	$\gamma=\gamma_0+\mu_\gamma(T_C-T_0)$	$n=n_0$

Open issues with diode models

- Simulated IV curves often don't match measurements at low irradiance
- Methods to estimate model parameters are often not carefully scrutinized
  - Many methods return non-physical values, e.g., $n < 1$
  - As a consequence, the same data lead to different parameter sets
  - Could have reference cases to test estimation methods (a common practice in other disciplines)
- Can we validate the auxiliary equations?
  - Light, dark current forms derive from device physics
  - Others are eyeballed from data (e.g., R_{SH} in CEC model)
  - May involve corrections to match IV curves (e.g., γ in PVsyst v6)
  - Equations for R_S, n or γ are most promising targets

Single Point Models

- PVWatts : $$P_{dc} = \frac{I_{tr}}{1000} P_{dc0}(1 + \gamma(T_{cell} - T_{ref}))$$
- Huld Model : $$P(G',T') = G'(P_{STC,m} + k_1 \ln(G') + k_2 \ln(G')^2 + k_3 T' + k_4 T' \ln(G') + k_5 T' \ln(G')^2 + k_6 T'^2)$$
- PVUSA : $$P = I \cdot \left(A + B \cdot I + C \cdot T_a + D \cdot WS\right)$$
  - Because P is P_{AC}, PVUSA combines cell temperature and inverter efficiency model with module performance model

- PVWatts is (almost) module-agnostic: the only term which derives from measurement is the temperature coefficient γ
- PVUSA is not a module model per se; it's a whole system model
- Huld model is intended to be fit to common measurements: back-of-module temperature and broadband plane-of-array

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 must be determined for individual modules

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

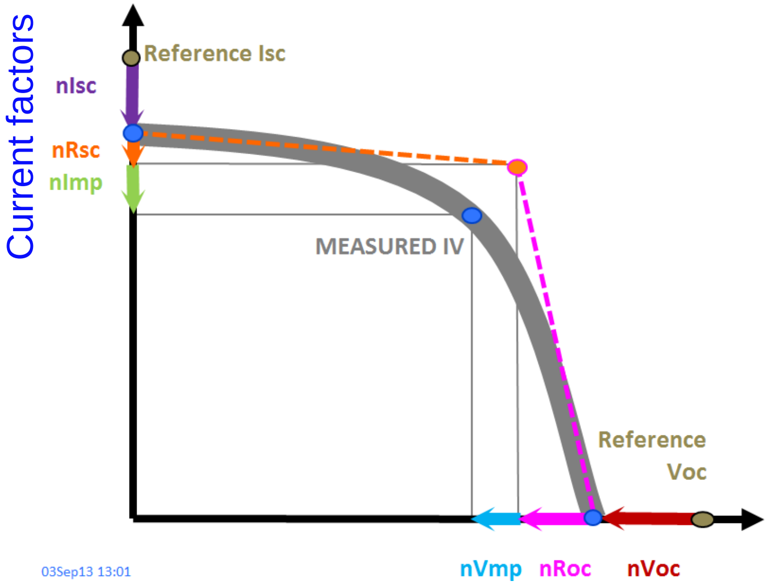
$$V_{MP} = V_{MP0} + C_2 N_S n\delta(T_C)\ln(E_e) + C_3 N_S (n\delta(T_C)\ln(E_e))^2 + \beta_{MP}(T_C - T_0)$$

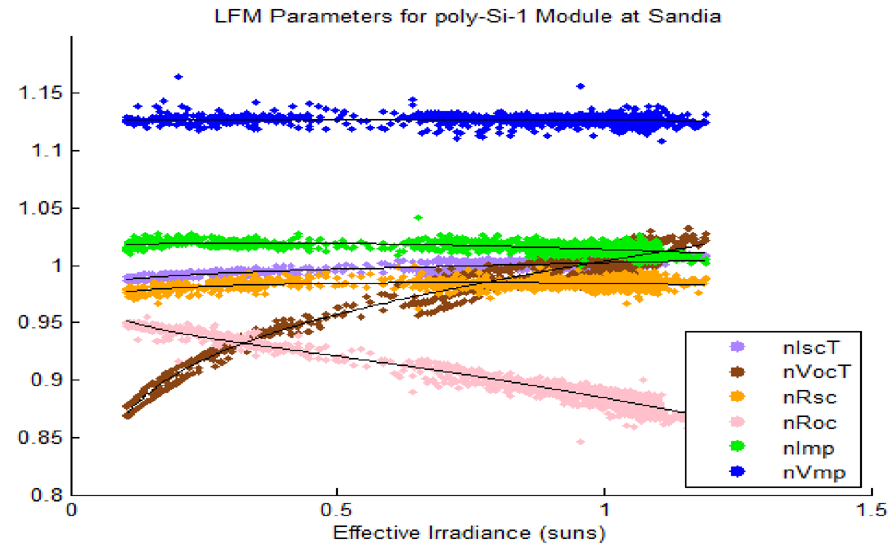
$$I_{SC} = I_{SC0} f_1(AM_a) E_e (1 + \alpha_{SC}(T_C - T_0))$$

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

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

Loss Factors Model





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

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

Six Normalized LFM Variables

1. $nIscT =$
2. $nRsc =$
3. $nImp =$

Current factors

4. $nVmp =$
5. $nRoc =$
6. $nVocT =$

Voltage factors

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

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

$$T_{CORR,Voc} = 1 + \beta_{Vmp} \times (25 - T_c)$$

$$T_{CORR,Isc} = 1 + \alpha_{Imp} \times (25 - T_c)$$

MMF = spectral mismatch, G_i = irradiance

‘Data’ models

- These models are based directly on measure data (e.g., 61853-1) or outdoor IV curves collected over time or trained on these data.
- Models describe how to interpolate and extrapolate from a measured reference data set.
  - *Janine Freeman* will describe one such model developed at NREL.
  - These models do not have parameters but rather are descriptions of a procedure that results in a result.
- Another type of “Data” model is Machine Learning
  - *Birk Jones* from Sandia has used a Gaussian Process Regression algorithm to simulate IV curves
    - Jones, C. B., M. Martınez-Ramonz, R. Smith, C. K. Carmignani, O. Lavrova and J. S. Stein (2016). Automatic Fault Classification of Photovoltaic Strings Based on an In-Situ IV Characterization System and a Gaussian Process Algorithm. 43rd IEEE Photovoltaic Specialist Conference. Portland, OR.

Issues common to all performance models

- Parameter estimation is generally not transparent nor reproducible
- Data requirements are not well understood:
  - Thought to be either:
  - Minimal, e.g., fit a diode model using single IV curve and a temperature coefficient, or
  - Extensive, e.g., requiring days of measurements outdoors on a two-axis tracker
  - Both are wrong
  - 61853-1 is enough for diode or point models, with the exception of the spectral mismatch function
- Multiple models in use but underlying data is not shared
  - Some resort to creating "models of models", e.g., fitting the SAPM to a PVsyst simulation
  - A modeled model inherits the problems of the source model

Useful Module Model Characteristics

- Parameters are easy/straightforward to obtain
  - Standards exist for the collection of the characterization data
  - Calculations yield consistent parameter values (solutions are unique)
  - Estimation is transparent and reproducible from a common data set
  - Parameter values are easily shared and published
  - Values of parameters with physical meaning do not violate physics

- Model predicts performance well across the entire range of environmental conditions
  - High and low irradiance
  - High and low temperatures
  - Spectral effects

Questions?

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