The CEC/UW n-parameter model

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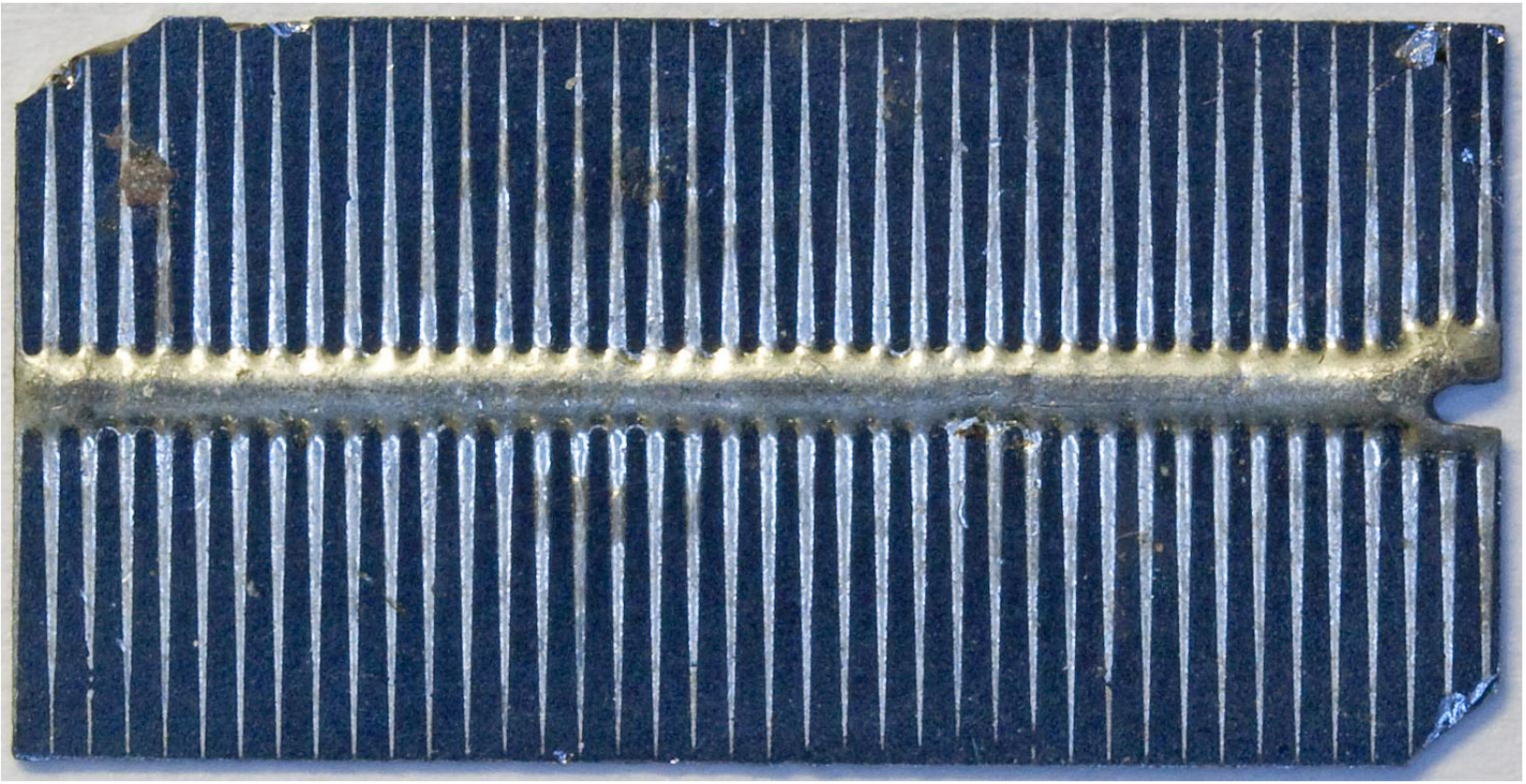
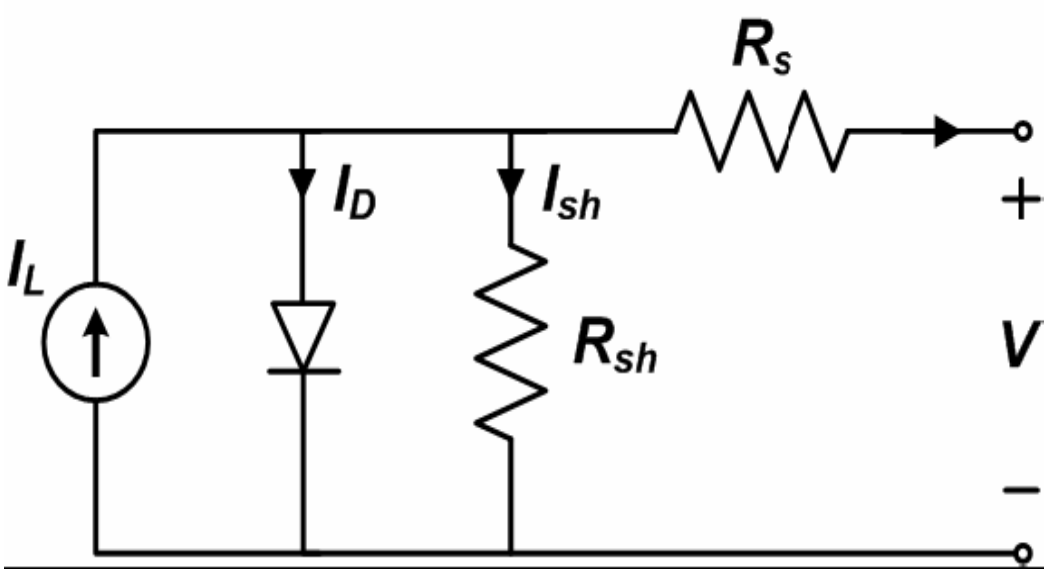
History of the CEC/UW n-parameter model

- High flux (400 suns) in 1964-1967
- UW study to model I-V curve for small systems (e.g. water pumping) without inverters using only manufacturer's PV data
- Extended to include inverter for CEC performance based incentive
- Max power temperature coefficient available
- Low radiation operation data available

A 1X2 cm cell designed for 400 suns 36 cm^2 produced 50W (~1965)



The original model



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

Five conditions for finding the reference parameters

Short circuit current: $I = I_{sc,ref}$, $V = 0$

Open circuit voltage: $I = 0$, $V = V_{oc,ref}$

Maximum power point: $I = I_{mp,ref}$, $V = V_{mp,ref}$

and, $$\left.\frac{d(IV)}{dV}\right|_{mp} = I_{mp} - V_{mp}\left.\frac{dI}{dV}\right|_{mp} = 0$$

Temperature coefficient of open circuit voltage:

$$\beta_{Voc} = \left.\frac{\partial V}{\partial T}\right|_{I=0} \approx \frac{V_{oc,ref} - V_{oc,T_c}}{T_{ref} - T_c}$$

Parameters at operating conditions

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

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

$$\frac{E_g}{E_{g,T_{ref}}} = 1 - 0.0002677 \;\; T - T_{ref}$$

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{S_{ref}}{S}$$

$$R_s = \text{constant}$$

$$I_L = \frac{S}{S_{ref}} \frac{M}{M_{ref}} [I_{L,ref} + \alpha_{Isc}(T_c - T_{c,ref})]$$

Incident and effective radiation

Liu and Jordan shown but Hay-Davies-Klutcher-Reindl used

$$G_T = G_b R_{beam} + G_d \frac{(1+Cos\beta)}{2} + G\rho \frac{(1-Cos\beta)}{2}$$

$$S = (\tau\alpha)_n \left[G_b R_{beam} K_{\tau\alpha,b} + G_d K_{\tau\alpha,d} \frac{(1+Cos\beta)}{2} + G\rho K_{\tau\alpha,g} \frac{(1-Cos\beta)}{2} \right]$$

Direction and air mass corrections

$$\tau\alpha\ \ \theta\ \ = e^{-\ KL/\cos\theta_r}\left[1-\frac{1}{2}\left(\frac{\sin^2\ \ \theta_r-\theta}{\sin^2\ \ \theta_r+\theta}+\frac{\tan^2\ \ \theta_r-\theta}{\tan^2\ \ \theta_r+\theta}\right)\right]$$

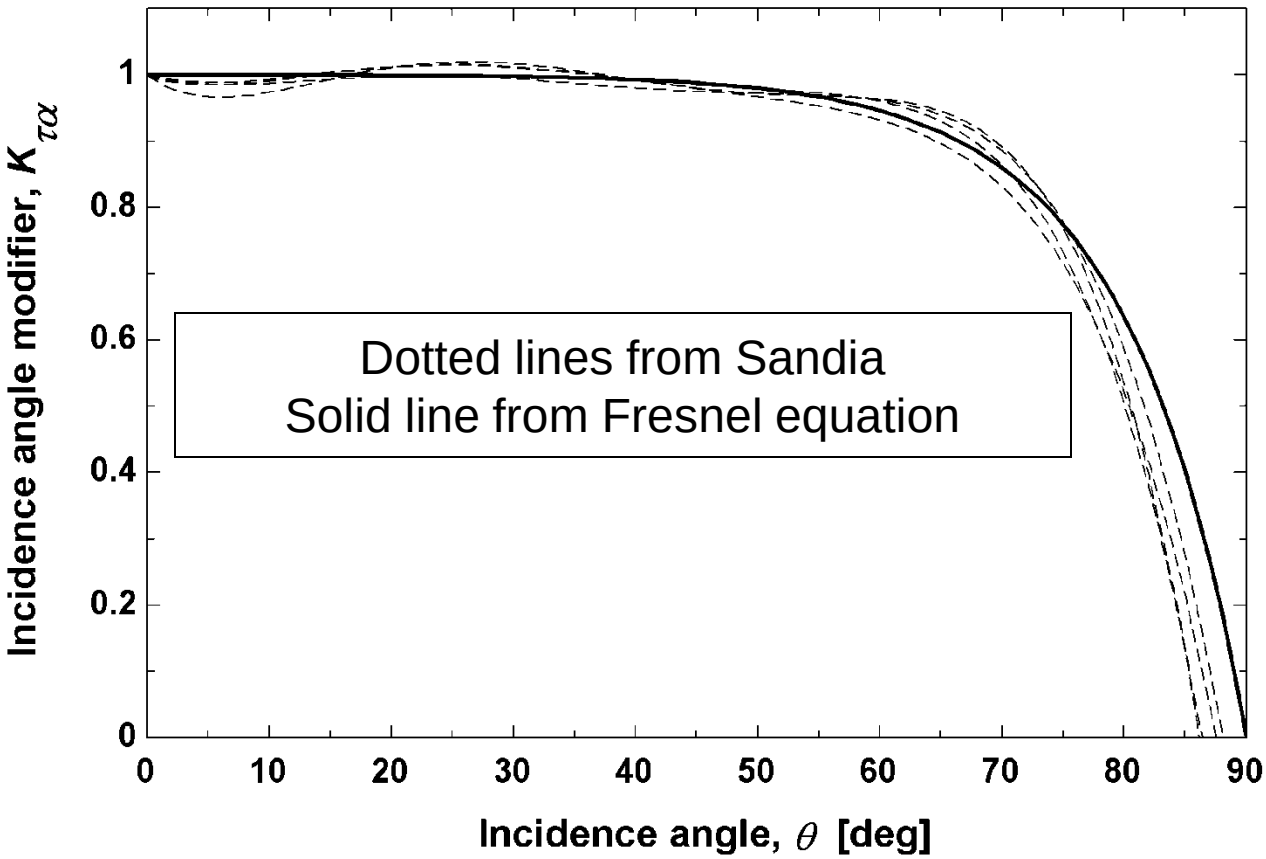
$$K_{\tau\alpha}\ \ \theta\ \ = \frac{\tau\alpha\ \ \theta}{\tau\alpha\ \ 0}$$

$$\frac{M}{M_{ref}} = \sum_{0}^{4} a_i\ \ AM^{\ i}$$

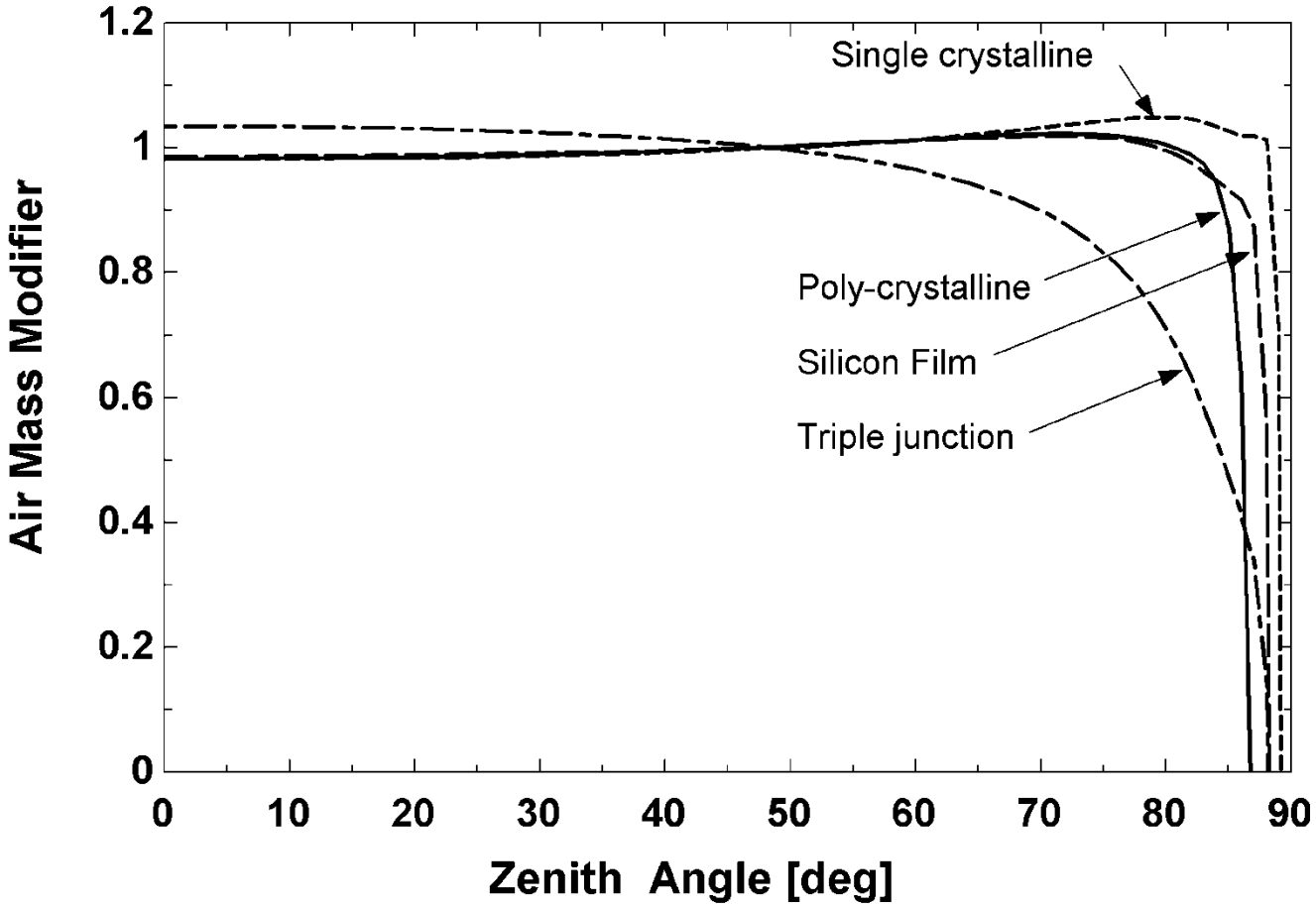
$$AM = \frac{1}{\cos\ \theta_z\ \ + 0.5057\ \ 96.080-\theta_z^{\ -1.634}}$$

AM and AM correction from Sandia

Incidence angle modifier



Poly-crystalline used for all cell types



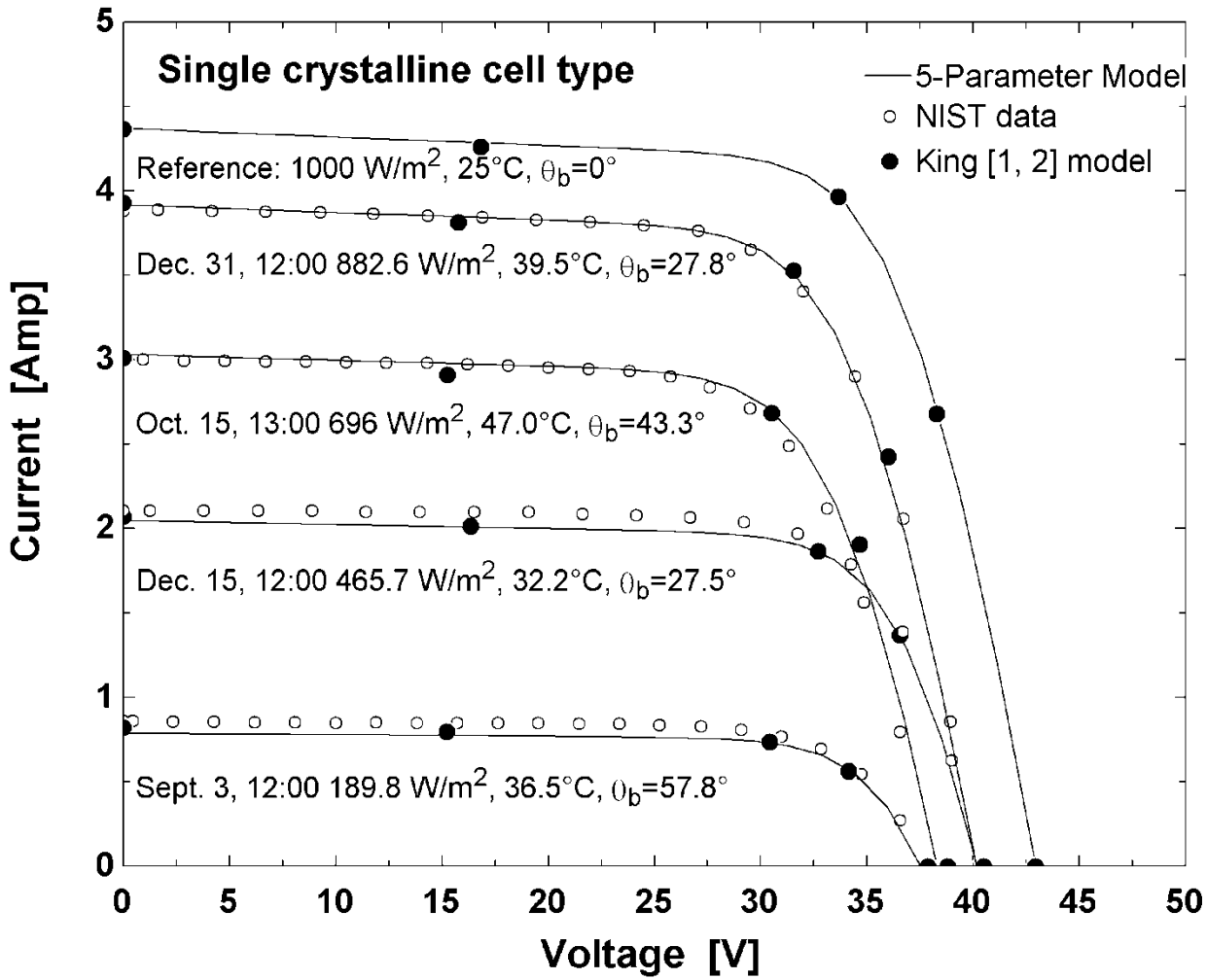
Curve fits from Sandia model

Cell temperature model

$$\tau\alpha \quad G_T = \eta_c G_T + U_L \quad T_c - T_a$$

$$\tau\alpha \quad G_{T,NOCT} = \eta_c G_{T,NOTC} + U_L \quad T_{NOCT} - T_{a,NOCT}$$

$$\frac{T_c - T_a}{T_{NOCT} - T_{a,NOCT}} = \frac{G_T}{G_{T,NOTC}} \frac{9.5}{5.7 + 3.8V} \left[1 - \frac{\eta_c}{\tau\alpha} \right]$$


Single crystalline cell type
5-Parameter Model
NIST data
King [1, 2] model
Reference: 1000 W/m2, 25°C, θb=0°
Dec. 31, 12:00 882.6 W/m2, 39.5°C, θb=27.8°
Oct. 15, 13:00 696 W/m2, 47.0°C, θb=43.3°
Dec. 15, 12:00 465.7 W/m2, 32.2°C, θb=27.5°
Sept. 3, 12:00 189.8 W/m2, 36.5°C, θb=57.8°
Current [Amp]
Voltage [V]
0
1
2
3
4
5
0
5
10
15
20
25
30
35
40
45
50

Temperature coefficient of power did not always agree with experiments

$$\alpha_{sc} = \alpha_{sc,reported}(1 - inc)$$

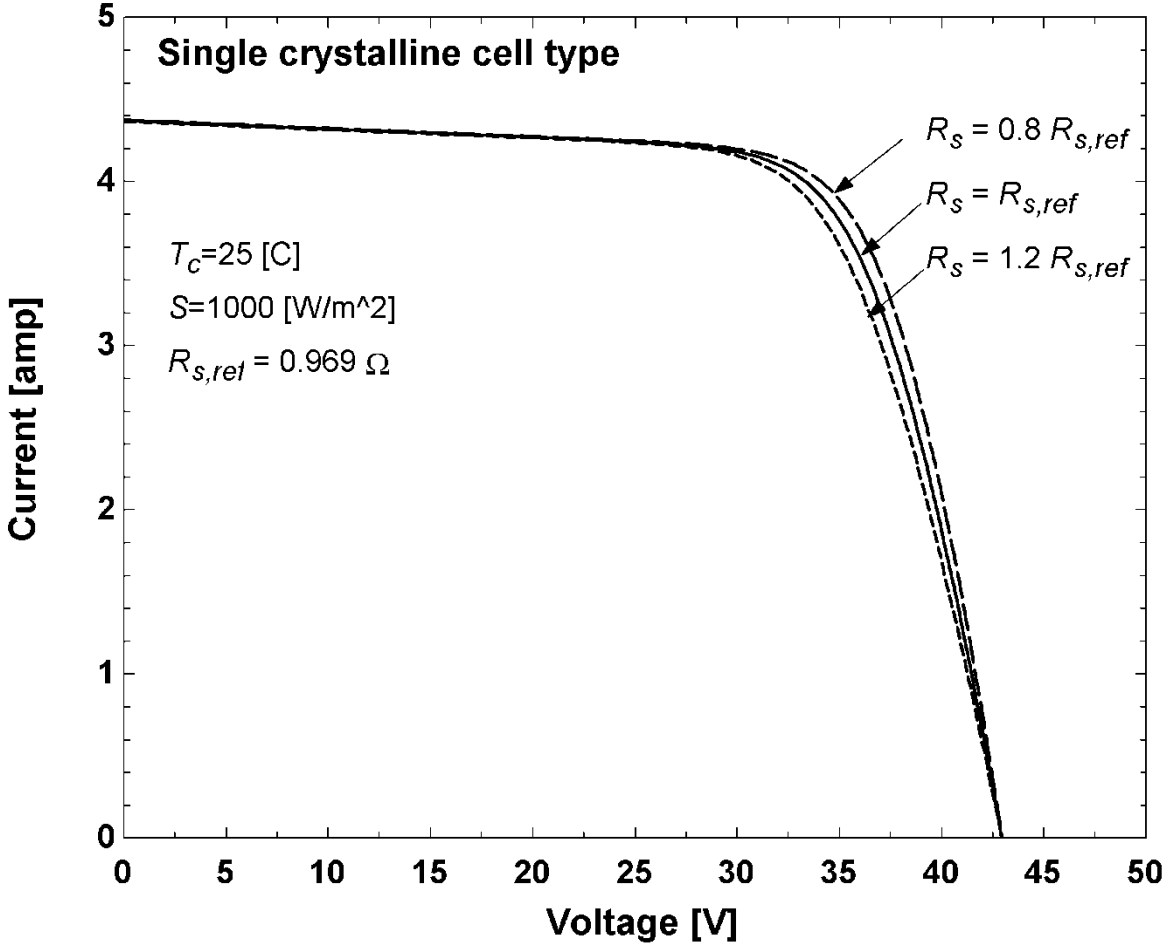
$$\beta_{oc} = \beta_{oc,reported}(1 + inc)$$

find inc such that

$$\gamma_{mp} = \gamma_{mp,reported}$$

CEC data for ~2000 modules
(lots of repeats)
$0.2<\gamma<0.6$
$-0.4<\ln c<+0.4$

A better approach

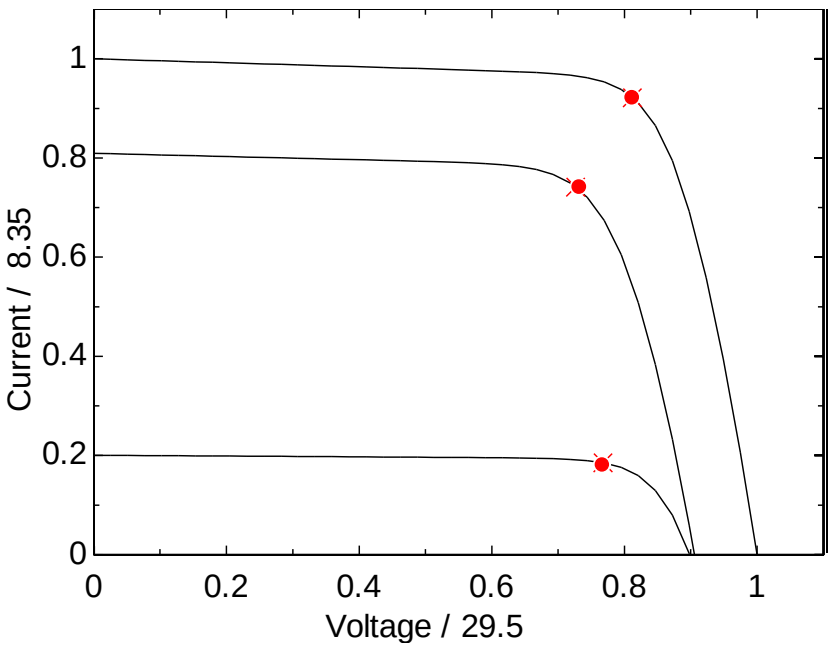


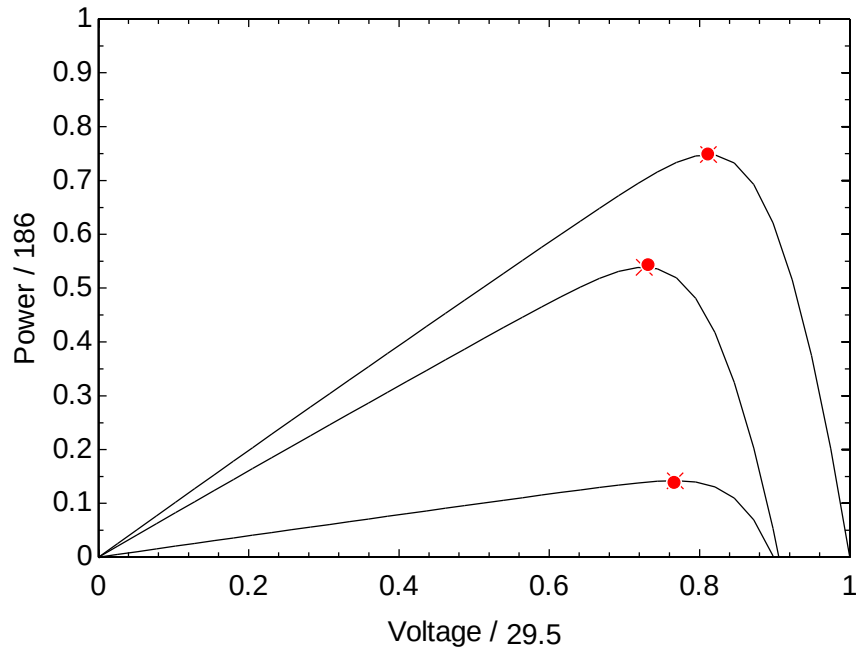
$$R_s = R_{s,ref}[1+\delta(T_c - T_{c,ref})]$$

Choose δ so that $\gamma_{model}=\gamma_{measured}$

Find 7th parameter, *m*, by fitting P_{max} at 200W/m^2 & 25C

$$\frac{I_o}{I_{o,ref}} = \left[\frac{G}{G_{ref}}\right]^m \left[\frac{T_c}{T_{c,ref}}\right]^3 \exp\left[\frac{1}{k}\left(\left.\frac{E_g}{T}\right|_{T_{ref}} - \left.\frac{E_g}{T}\right|_{T_c}\right)\right]$$





How to solve for the parameters

- Make good guesses from experience
- Set value of I_o (6 orders of magnitude)
- Define an error
- Find range of I_o where error changes sign
- Minimize error^2 within small range of I_o
- Solution when $\text{error}^2 \approx 0$
- I-V equations are then easy to solve

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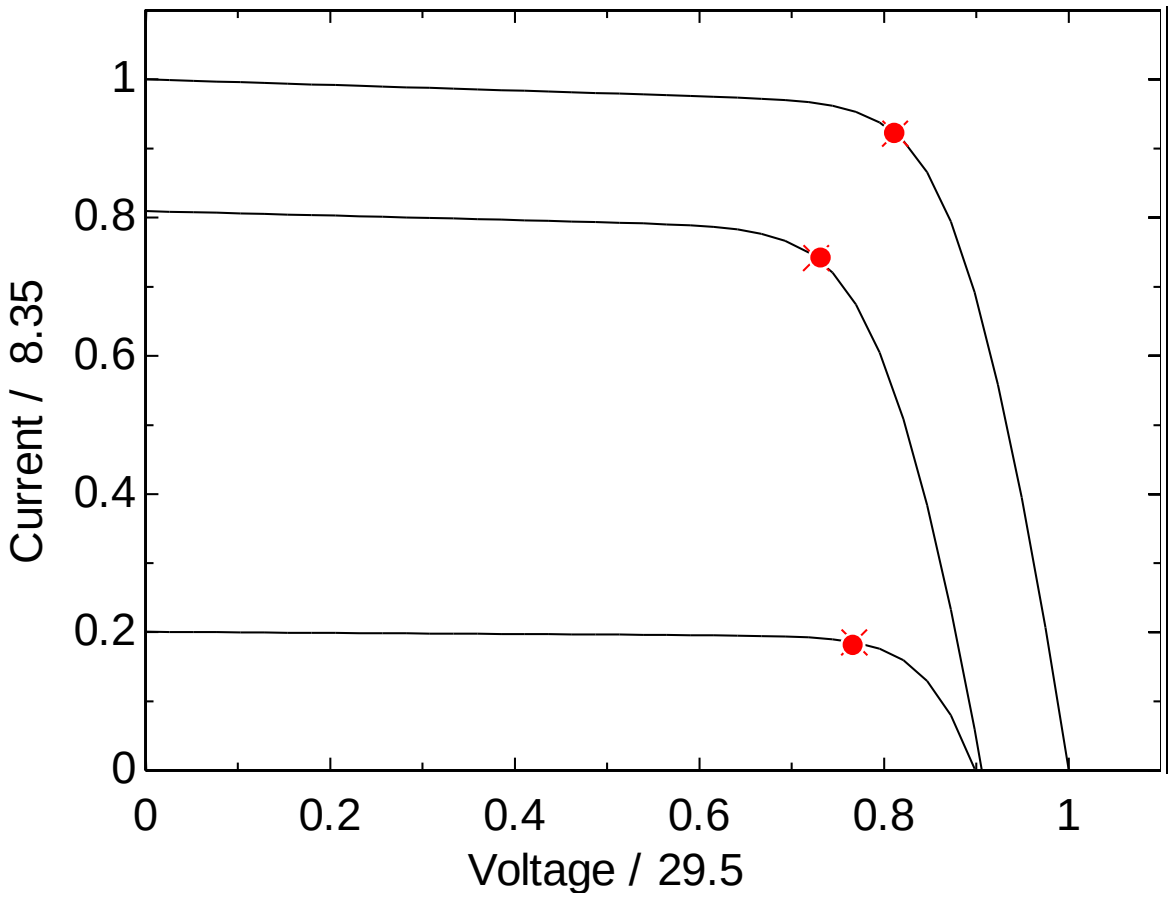
1
0.8
0.6
0.4
0.2
0
Current / 8.35
0
0.2
0.4
0.6
0.8
1
Voltage / 29.5