Determining series resistance for equivalent circuit models of a PV module

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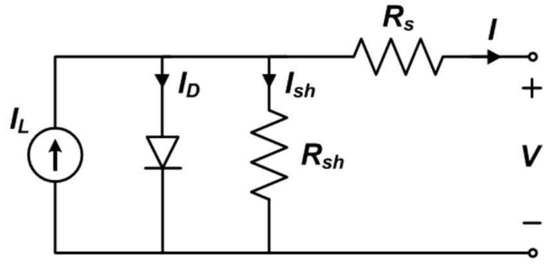
Outline

- Background on single diode PV models
- Describe methods to 'measure' series resistance for a PV device
- Show that measured series resistance differs from the Rs parameter for the single diode model
- Outline a method to determine the Rs parameter, and
- Compare with the methods to measure series resistance

Equivalent circuit models

- Most popular PV performance models use a ***single diode equivalent circuit*** model (Pvsyst, CEC model, PlantPredict, Helioscope, PV*SOL, etc.)



$$I = I_L - \frac{V + IR_S}{R_{SH}} - I_O\left(\exp\left(\frac{V + IR_S}{nN_S V_{th}}\right) - 1\right)$$

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

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

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

Single diode equation

Describes a single IV curve using 5 parameters

Auxiliary equations

Describe how 5 parameters change with irradiance and temperature (e.g., De Soto model)

Single diode equation + Auxiliary equations = PV performance model

Parameters for single diode models

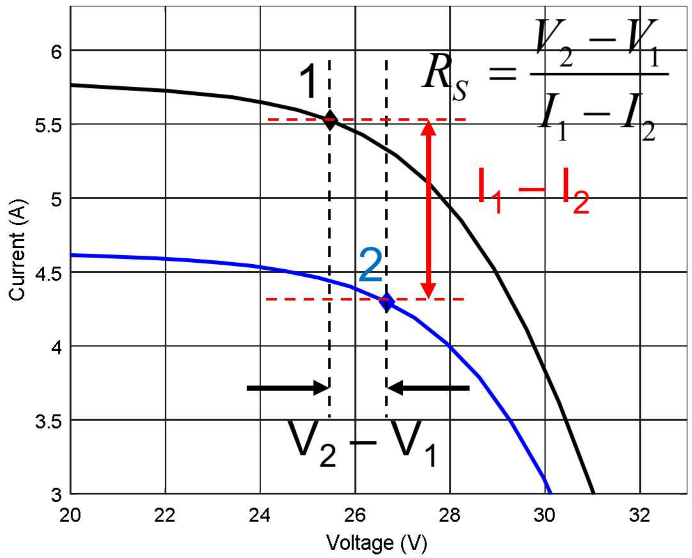
- Most often parameters are determined by optimization
  - E.g., CEC model (in SAM) [Dobos] simultaneously determines parameters by fitting STC IV curve at Isc, Pmp and Voc, and matching temperature coefficients
  - Pvsyst provides a user-driven utility to determine parameters by visually matching inputs (e.g., measured IV curve, datasheet values)
- Parameters determined by optimization are implicitly linked with other parameter values
  - Different optimization objectives will return different parameter sets
  - A parameter set may replicate the IV curve but individual values may lack physical meaning

Methods to find individual parameters would be of significant value for model verification and module analysis

Techniques to “measure” Rs

- We examine six methods from literature [Pysch] to find Rs from a small number of IV curves: *Swanson, Bowden, suns-Voc, Pysch, IEC60891-1, IEC60891-2*

- E.g., *Swanson* uses two IV curves at different irradiances and same temperature



- *Bowden* similar to *Swanson*
- *Pysch* = *Swanson* with more IV curves
- *suns-Voc* compares an IV curve to the suns-Voc curve
- IEC 60891 method translate an IV curve to a target irradiance and temperature
- Translation involves an Rs quantity

We tested the Rs methods

- *__Simulate__* IV curves using the CEC model for representative cSi, CdTe modules
  - Irradiance from 400 to 1100 W/m2
  - Temperature 25, 35, 45
  - With and without noise on current (N(0, 0.15%))
- *__Recover__* Rs value by applying each method to simulated IV curves

TABLE I. CEC MODEL PARAMETERS FOR THE SIMULATED MODULES

Parameter	cSi 240W	CdTe 72W
I_{L0}	8.0 A	1.15 A
α_{Isc}	0.8 mA/K	0.35 mA/K
Adjust	0.0	0.0
I_{O0}	0.5 nA	0.3 nA
E_{g0}	1.121 eV	1.475 eV
R_{S0}	0.2 Ω	0.5 Ω
R_{SH0}	1000 Ω	800 Ω
n_0	1.05	1.40
N_S (cells in series)	60	114

TABLE II. ESTIMATED RS VALUES FOR SIMULATED MODULES AT STC

	cSi: true Rs value 0.2000 Ω			
Rs method	No noise	With noise (100 replicates)		
		5th	Mean	95th
Bowden	0.2051	0.2031	0.2054	0.2085
Swanson	0.2694	−0.2054	0.2244	0.5187
Pysch	0.2584	0.0881	0.2352	0.4076
suns-Voc	0.2144	0.2031	0.2129	0.2230
IEC60891-1	0.2129	0.1992	0.2147	0.2273
IEC60891-2	0.1989	0.1798	0.1985	0.2159

Error < 3%, but biased

Error < 10%, but biased

Why the failure to recover Rs?

Rs estimators (e.g., Swanson) are approximations of the single diode equation

- Omitted terms involve other parameters: R_{SH}, n, Io

1. Solve the single diode equation for V = V(I)

$$V = \left(I_L + I_O - I\right) R_{SH} - IR_S - nN_S V_{th} W\left(\psi\left(I\right)\right), \quad \psi\left(I\right) = \frac{I_O R_{SH}}{nN_S V_{th}} \exp\left(\frac{\left(I_L + I_O - I\right) R_{SH}}{nN_S V_{th}}\right)$$

2. Substitute into V2 – V1 and solve for Rs

$$R_S \approx \frac{V_2 - V_1}{I_1 - I_2} - \frac{nN_S V_{th}}{I_1 - I_2}\left(\ln \frac{R_{SH1}}{R_{SH2}} + \ln \frac{\ln \xi_2}{\ln \xi_1} + \text{other terms}\right), \quad \xi_1 = \frac{I_{O1} R_{SH1}}{nN_S V_{th}} \exp\left(\frac{\left(I_{SC1} - I_1\right) R_{SH1}}{nN_S V_{th}}\right)$$

Approximation of Rs

Difference between approximate and true value

Explains bias

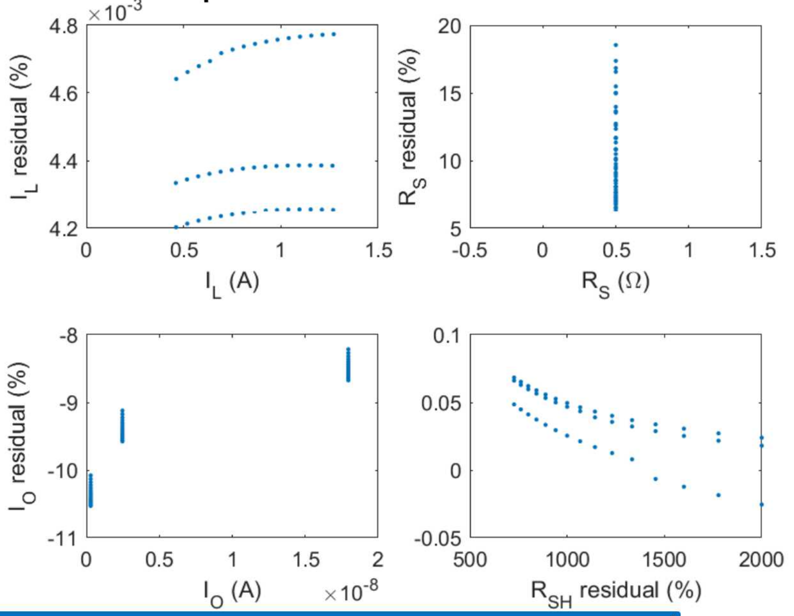
Approximation error increases with larger n, Ns (CdTe module), smaller $I_1 - I_2$ (Swanson method)

Joint estimation of all 5 parameters

- Simplification of Sandia method [Hansen]
- Simulate a set of 45 IV curves (G = 400-1100 W/m2; Tc = {25 35 45})
- Recover 5 parameters for each IV curve

1. Determine n by regressing Voc onto G (W/m2)
   a. Uses a set of IV curves
2. For each IV curve, find R_{SH} from slope near Isc
3. For each IV curve, start with $I_L \approx Isc$
   a. Calculate Io, Rs (see paper)
   b. Update I_L (see paper)
   c. Iterate a few times

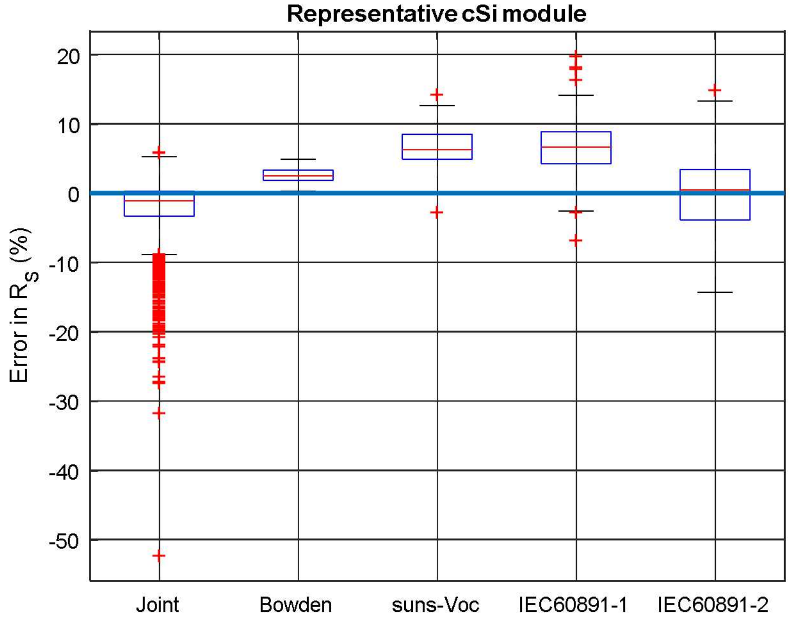
Representative CdTe module

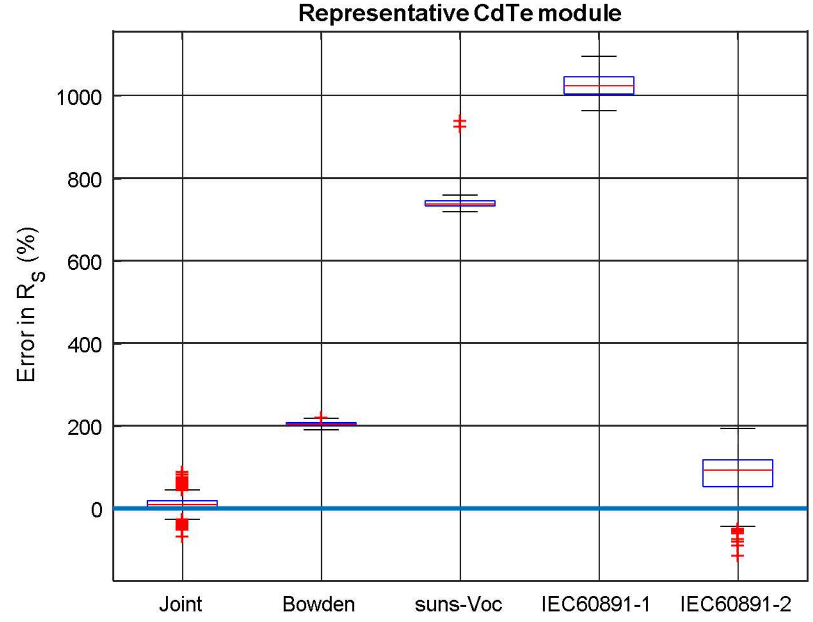


Parameters are recovered with error <10% but
Errors are sensitive to small changes in estimated n

Joint estimation vs Rs methods

- For cSi, joint estimation method is comparable to Rs methods
  - Error less biased, sensitivity to error similar
- For CdTe, joint estimation method provides reasonable results; other methods fail





Conclusions

- Methods to 'measure' series resistance (e.g., Swanson's technique) do not reliably recover the Rs parameter for the single diode model
- The 'measured' series resistance values are affected by diode and shunt currents
- We conclude that the Rs parameter should be determined jointly with other diode model parameters
  - Caution must be taken to verify accuracy of optimization methods
  - Recommend testing methods by recovering known values from simulated IV curves