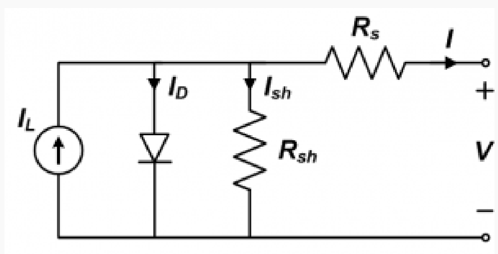
« Spectral Mismatch   De Soto “Five-Parameter” Module Model »

Single Diode Equivalent Circuit Models

Equivalent circuit models define the entire I-V curve of a cell, module, or array as a continuous function for a given set of operating conditions. One basic equivalent circuit model in common use is the single diode model, which is derived from physical principles (e.g., Gray, 2011) and represented by the following circuit for a single solar cell:



The governing equation for this equivalent circuit is formulated using Kirchoff's current law for current I:

$$I = I_L - I_D - I_{sh}$$

Here, I_L represents the light-generated current in the cell, I_D represents the voltage-dependent current lost to recombination, and I_{sh} represents the current lost due to shunt resistances. In this single diode model, I_D is modeled using the Shockley equation for an ideal diode:

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

where n is the diode ideality factor (unitless, usually between 1 and 2 for a single junction cell), I_0 is the saturation current, and V_T is the thermal voltage given by:

$$V_T = \frac{kT_c}{q}$$

where k is Boltzmann's constant $(1.381\ \times 10^{-23}\ \mathrm{J/K})$ and q is the elementary charge $(1.602\ \times 10^{-19}\ \mathrm{C})$.

Writing the shunt current as $I_{sh} = (V + IR_S)\,/R_{sh}$ and combining this and the above equations results in the complete governing equation for the single diode model:

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

The five parameters in this equation are primary to all single diode equivalent circuit models:

- I_L : light current (A)
- I_0 : diode reverse saturation current (A)

- R_s : series resistance (Ω)
- R_{sh} : shunt resistance (Ω)
- n : diode ideality factor (unitless)

For a photovoltaic module or array comprising N_s cells in series, and assuming all cells are identical and under uniform and equal irradiance and temperature (i.e., generate equal current and voltage), $I_{module} = I_{cell}$ and $V_{module} = N_s \times V_{cell}$
The single diode equation for a module or array becomes (Tian, 2012):

$$I_M = I_L - I_0 \left[\exp\left(\frac{V_M + I_M N_s R_s}{n N_s V_T} \right) - 1 \right] - \frac{V_M + I_M N_s R_s}{N_s R_{sh}}$$

where I_M and V_M are the current and voltage, respectively, of the module or array. Care should be taken when implementing model parameters, as they are either applicable to a cell, module, or array. Parameters for modules or arrays are strictly used with the single diode equation for I , which is the more commonly implemented form.

In some implementations (e.g., De Soto et al., 2006) the thermal voltage V_T, diode ideality factor n, and number of cells in series N_s are combined into a single variable a termed the modified ideality factor:

$$a \equiv \frac{N_s n k T_c}{q}.$$

Content for this page was contributed by Matthew Boyd (NIST) and Clifford Hansen (Sandia)

The following equivalent circuit module models are described. These models have been proposed with different sets of auxiliary equations that describe how the primary parameters of the single diode equation change with cell temperature and irradiance. Module models, or those with parameters applicable to a module using I_M, are examined here instead of those for cells or arrays because module models are the basic performance models used for modeling arrays in PV modeling software packages.

- De Soto "Five-Parameter" Module Model
- PVsyst Module Model

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« Single Diode Equivalent Circuit Models   PVsyst Module Model »

De Soto “Five-Parameter” Module Model

The De Soto model (De Soto et al., 2006), also known as the five-parameter model, uses the following equations to express each of the five primary parameters as a function of cell temperature T_c and total absorbed irradiance S:

- $I_L = \frac{S}{S_{ref}} \frac{M}{M_{ref}} \left[I_{L,ref} + \alpha_{Isc} \left(T_c - T_{c,ref} \right) \right]$
- $I_0 = I_{0,ref} \left(\frac{T_c}{T_{c,ref}} \right)^3 \exp \left[\frac{1}{k} \left(\frac{E_g \left(T_{ref} \right)}{T_{ref}} - \frac{E_g \left(T_c \right)}{T_c} \right) \right]$
- $E_g \left(T_c \right) = E_g \left(T_{ref} \right) \left[1 - 0.0002677 \left(T_c - T_{ref} \right) \right]$
- $R_s = \text{constant}$
- $R_{sh} = R_{sh,ref} \frac{S_{ref}}{S}$
- $n = \text{constant}$

Absorbed irradiance, S, is equal to POA irradiance reaching the PV cells (including incident angle reflection losses but not spectral mismatch). In each equation, the subscript “ref” refers to a value at reference conditions. In De Soto et al., 2006, the modified ideality factor a is used, and expressed as a linear function of cell temperature T_c, which is equivalent to a constant diode ideality factor n.

M, termed the “air mass modifier”, represents the spectral effect, from changing atmospheric air mass and corresponding absorption, on the light current. M is the polynomial in air mass from the Sandia PV Array Performance Model (SAPM). The term α_{Isc} is the temperature coefficient (A/K) of short-circuit current, set equal to the temperature coefficient of the light current.

The term $E_g \left(T_c \right)$ is the temperature-dependent bandgap (eV); given as the simplified first order Taylor series of the experimental bandgap temperature. The empirical constant 0.0002677 is representative of silicon cells at typical operating temperatures, and it is used for all cell technologies.

The primary advantage of the De Soto model is that its parameters can be calculated from data given on module manufacturer datasheets.

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« De Soto "Five-Parameter" Module Model

Point-value models »

PVsyst Module Model

PVsyst is a software package for modeling complete photovoltaic systems including PV modules, inverters, energy storage, and electrical connection components. PVsyst employs a single diode module model with the following ancillary equations:

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

Note: in the PVsyst User's Guide, I_{PH}, G, and μ_{Isc} are used to denote the light current, absorbed irradiance and temperature coefficient of I_{sc}, where we use I_L, S and α_{Isc} respectively for these quantities.

$$I_0 = I_{0,ref} \left(\frac{T_c}{T_{c,ref}} \right)^3 \exp \left[\frac{qE_g}{nk} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$$

Note: in the PVsyst User's Guide, γ is used to denote the diode quality (ideality) factor where we use n.

The term E_g is regarded as constant and values are provided for various technologies (e.g., 1.12 eV for cSi) in the PVsyst User's Guide.

$R_s = \text{constant}$ and

$$R_{sh} = R_{sh,ref} + \left(R_{sh,0} - R_{sh,ref} \right) \exp \left(-R_{sh,exp} \frac{S}{S_{ref}} \right).$$

Note: in the PVsyst User's Guide, $R_{sh,ref}$ is written as $R_{sh}\left(S_{ref}\right)$ and $R_{sh,0}$ is written as $R_{sh}(0)$; R_{sh} is a function of irradiance S, and $R_{sh,ref}$ is the value of the shunt resistance at the reference irradiance S_{ref}.

The term $R_{sh,exp}$ is a constant, with values given in Mermoud and Lejeune, 2010 for CdTe (2.0), micro-crystalline silicon (3.0), and all other module technologies (5.5).

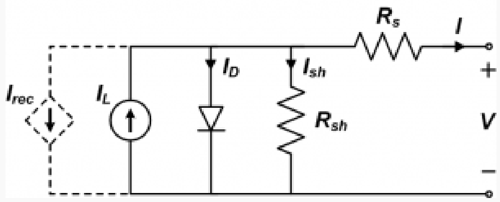
The PVsyst User's Guide provides an option to use a temperature-dependent diode factor expressed as:

$$n = n_0 + \mu_n \left(T_c - T_{ref} \right)$$

For amorphous modules, PVsyst modifies the single diode equation to account for recombination losses I_{rec}:

$$I = I_L - I_D - I_{sh} - I_{rec}$$

by modeling them as a controlled current drain as represented in the following equivalent circuit:



The recombination current I_{rec} is governed by:

$$I_{rec} = I_L \frac{d_i^2}{m_{eff}\left[V_{bi} - (V + IR_s)\right]}$$

Inclusion of this current sink changes the standard single diode equation to:

$$I = I_L\left[1 - \frac{d_i^2}{m_{eff}\left[V_{bi} - (V + IR_s)\right]}\right] - I_0\left[\exp\left(\frac{V + IR_s}{nV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

where d_i is the thickness of the intrinsic layer that separates the p and n junctions, V_{bi} is the voltage potential across the intrinsic layer, and m_{eff} ($\mu\tau eff$ in the PVsyst User's Guide, and $\mu\tau_{eff}$ in Mermoud and Lejeune, 2010) is the effective diffusion length of the charge carrier. In implementation, $V_{bi} = 0.9$ V per junction and the combined quantity $d_i^2/m_{eff} = 1.4$ V are regarded as constant in the PVsyst User's Guide.

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