TRNSYS Type 835

PV model for the coupling with solar thermal absorber and collector models as PVT model

Documentation

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Contents

This model is based on work of Manuel Lämmle, Axel Oliva, Michael Hermann, Korbinian Kramer and Wolfgang Kramer, published in Lämmle et al. 2017.

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Disclaimer

Nomenclature

A_{PV}	gross area of PV modules or PVT collector [m²]
a	model parameter a for irradiance dependence of PV efficiency calculation [m²/W]
b_0	constant for incident angle modifier IAM [-]
b	model parameter b for irradiance dependence of PV efficiency calculation [-]
c	model parameter c for irradiance dependence of PV efficiency calculation [-]
G	solar irradiance in PV or PVT plane [W/m²]
$P_{\mathrm{el,PV}}$	electrical power output of the PV modules or PVT collector [W]
$p_{\mathrm{el,PV}}$	specific electrical power output of the PV modules or PVT collector [W/m²]
PR_{G}	performance ratio due to loss effects of irradiance [-]
PR_{IAM}	performance ratio due to loss effects of incidence angle [-]
PR_{T}	performance ratio due to PV cell temperature dependence [-]
PR_{tot}	overall performance ratio [-]
$\dot{q}_{\mathrm{th}}$	specific thermal power output of the PVT collector [W/m²]
T_{amb}	ambient air temperature [°C]
T_{cell}	temperature of PV $T_{\mathrm{cell,PV}}$ or PVT $T_{\mathrm{cell,PVT}}$ cells [°C]
$T_{\mathrm{cell,ref}}$	PV cell temperature at reference conditions (usually STC conditions) [°C]
T_{m}	mean fluid temperature of the PVT collector [°C]
U_0	coefficient for radiation dependence of PV module temperature [W/m²K]
U_1	coefficient for wind dependence of PV module temperature [Ws/m³K]
U_{L}	heat loss coefficient of the PV module [W/m²K]
u	wind speed in the PV plane [m/s]
U_{AbsFl}	internal heat transfer coefficient [W/m²K]
β	power temperature coefficient of the PV cells [%/K]
$\eta_{\mathrm{el,PV}}$	overall electrical efficiency of the PV modules or PVT collector, gross area [-]
$\eta_{\mathrm{el,ref}}$	electrical efficiency at reference conditions (usually STC) of the PV modules or PVT collector, gross area [-]
θ	incidence angle of beam radiation [°]
$\tau\alpha$	effective transmittance-absorptance product [-]

1 Overview

The main idea behind this model is to develop a PV performance model in TRNSYS, which can be coupled to existing models of solar thermal collectors or absorbers for the calculation of the electrical power output of uncovered and covered PVT collectors (see Fig. 1). It is especially developed for the connection with thermal models which are based on the quasi-dynamic model of ISO 9806:2013 (ISO 9806, 2013), e.g. TRNSYS Type 832 (Haller et al., 2013). As the electrical mode of operation has a significant impact on the thermal efficiency, the thermal performance coefficients for the thermal power output calculation of the PVT collector should be determined in MPP mode (Lämmle et al., 2017).

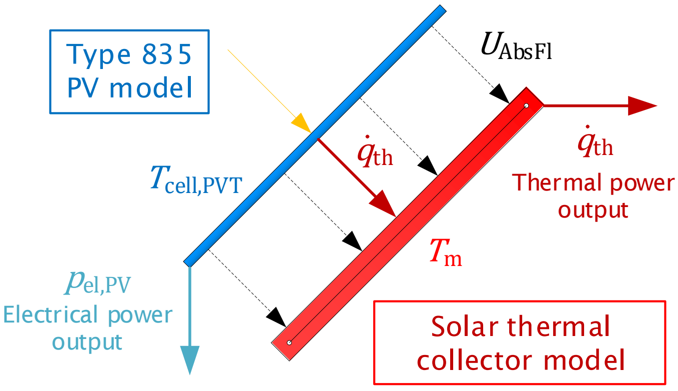

Fig. 1. Coupled PVT-model

As addition, the model includes a PV mode to simulate PV modules based on the same performance model, e.g. for a comparison of electrical yield of a PV module and PVT collectors with use of identical PV cells. The major difference between the calculation of PV modules and PVT collectors in this approach results from the cell temperatures, which are determined by the fluid temperature in PVT collectors and by a steady-state module temperature in PV modules.

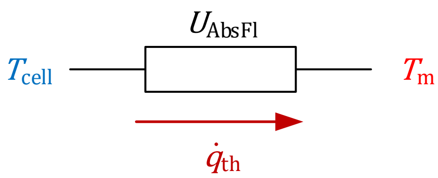

Fig. 2. Thermal network

In case of PVT collectors, the PVT cell temperature $T_{cell,PVT}$ is calculated via an equivalent thermal network with an internal heat transfer coefficient U_{AbsFl}, which connects the PVT cell temperature with the mean fluid temperature T_m of the PVT collector (see Fig. 2), according to the electrical performance model of Lämmle et al. (2017). In case of PV modules, the PV cell temperature $T_{cell,PV}$ is calculated by the Faiman model (Faiman, 2008) or from NOCT conditions. For details see mathematical description.

2 Parameter, Inputs and Outputs

Parameter

Nr.	Short	Description	Unit
1	PVTmode	mode for PVT or PV calculation 1: PVT - connection to solar thermal fluid temperature 2: PV - stand-alone calculation 3: PVT - cell temperature as input value	-
2	PVmode	mode for the irradiance dependence calculation of the PV efficiency 1: Calculation in MPP according to Heydenreich et al. 2: not defined	-
3	PVcellmode	mode for PV cell temperature calculation of stand-alone PV (only for PVT mode 2) 1: Faiman model 2: NOCT model (constant heat loss coefficient) 3: NOCT model (wind speed dependent heat loss coefficient)	-
4	Area	Area of the PVT collectors or PV modules (gross area)	m²
5	Eta_ref	electrical efficiency at reference conditions (gross area)	-
6	b0	constant for IAM	-
7	beta	temperature coefficient of solar cell efficiency	%/K
8	Tcell_ref	PV Cell temperature at reference conditions	C
9	a	model parameter a for PV efficiency (PV mode: 1)	m²/W
10	b	model parameter b for PV efficiency (PV mode: 1)	-
11	c	model parameter c for PV efficiency (PV mode: 1)	-
7	Uabsfl	internal heat transfer coefficient connecting cell and fluid temperature (PVT mode: 1)	W/m²K
12	U0	coefficient for module temperature (radiation) (PVT mode: 2, PV cell mode 1)	W/m²K
13	U1	coefficient for module temperature (wind) (PVT mode: 2, PV cell mode 1)	Ws/m³K
14	Tcell_NOCT	PV Cell temperature at NOCT conditions (PVT mode: 2, PV cell mode 2 and 3)	C
15	Tamb_NOCT	ambient temperature at NOCT conditions (PVT mode: 2, PV cell mode 2 and 3)	C
16	It_NOCT	Global radiation on PV plane at NOCT conditions (PVT mode: 2, PV cell mode 2 and 3)	W/m²
17	Taualpha	effective transmittance-absorptance product (PVT mode: 2, PV cell mode 2 and 3)	[-]

Inputs

Nr.	Short	Description	Unit
1	It	Global radiation on PV plane	kJ/hm²
2	Theta	Incidence angle of beam radiation	degrees
3	Tm	mean fluid temperature of the PVT collector	C
4	qth	specific thermal power output of the PVT collector	kJ/hm²
5	u	wind speed in the PV plane	m/s
6	Tamb	ambient air temperature	C
t	Tcell_in	temperature of the PV cell (only for PVT mode 3)	C

Outputs

Nr.	Short	Description	Unit
1	Pel	Electric power output	kJ/h
2	Tcell	temperature of the PV cell	C
3	EtaPV	total efficiency of PV modules (gross area)	-

3 Mathematical description

The PV model Type 835 can be used for the simulation of:

1) the electrical part of PVT collectors by coupling the PV model with models of solar thermal absorbers or collectors (PVT collector simulation, PVT mode 1), or
2) stand-alone PV systems (PVT mode 2).

Overall electrical efficiency and electrical power output

The overall (or total) electrical efficiency $\eta_{\mathrm{el,PV}}$ is calculated with:

$$\eta_{\mathrm{el,PV}} = \eta_{\mathrm{el,ref}} \cdot PR_{\mathrm{tot}} \qquad \text{(Eq. 1)}$$

The electrical power output of the PV modules or PVT collector $P_{\mathrm{el,PV}}$ is given by:

$$P_{\mathrm{el,PV}} = \eta_{\mathrm{el,ref}} \cdot PR_{\mathrm{tot}} \cdot G \cdot A_{\mathrm{PV}} \qquad \text{(Eq. 2)}$$

and as specific electrical power output by (Lämmle et al., 2017):

$$p_{\mathrm{el,PV}} = \eta_{\mathrm{el,ref}} \cdot PR_{\mathrm{tot}} \cdot G \qquad \text{(Eq. 3)}$$

where $\eta_{\mathrm{el,ref}}$ is the electrical efficiency at reference conditions (usually STC conditions), PR_{tot} is the overall instantaneous performance ratio, G (or I_T) the global radiation on PV or PVT plane and A_{PV} the PV or PVT area.

The overall instantaneous performance ratio is calculated with (Lämmle et al., 2017):

$$PR_{\mathrm{tot}} = PR_{\mathrm{IAM}} \cdot PR_{\mathrm{T}} \cdot PR_{\mathrm{G}} \qquad \text{(Eq. 4)}$$

The electrical performance model for PV takes into account the following loss effects (performance ratios PR):

- loss effects of incidence angle PR_{IAM}
- loss effects of irradiance PR_{G} and
- PV cell temperature dependence of electrical efficiency PR_{T}.

The major difference between the calculation of PV modules as stand-alone PV system and PVT collector is given by the cell temperatures, which are determined by the fluid temperature in PVT collectors (PVT mode 1) and by the steady-state module temperature in PV modules (PVT mode 2) or set as input value from external calculation (PVT mode 3).

Loss effects of incidence angle

The instantaneous performance ratio due to incidence angle losses PR_{IAM} is calculated with (Duffie and Beckman, 2013):

$$PR_{\mathrm{IAM}} = 1 - b_0 \cdot (1/\cos(\theta) - 1) \qquad \text{(Eq. 5)}$$

where b_0 is the constant for IAM and θ the incidence angle of beam radiation.

Tab. 1. Typical values for b_0 of PV modules

Parameter	Type	Value	Reference
b_0	PV	0.07	Lämmle et al., 2017

Loss effects of irradiance

The instantaneous performance ratio due to irradiance losses PR_{G} is calculated with (Heydenreich et al., 2008):

$$PR_{\mathrm{G}} = a \cdot G + b \cdot \ln(G+1) + c \cdot \left[\left(\ln(G+\mathrm{e})\right)^2/(G+1) - 1\right] \quad \text{(Eq. 6)}$$

with the model parameters a in m²/W, b and c dimensionless, the global irradiance G in W/m² and the Euler's number e.

Tab. 2. Typical values for the parameters a, b and c of PV modules

Parameter	Type	Value	Reference
a	Crystalline (c-Si)	-0.0000109 m²/W	Lämmle et al., 2017
b	Crystalline (c-Si)	-0.047	Lämmle et al., 2017
c	Crystalline (c-Si)	-1.40	Lämmle et al., 2017

PV cell temperature dependence of the electrical efficiency

The PV cell temperature dependence of the electrical efficiency is calculated with (Skoplaki and Palyvos, 2009):

$$PR_{\mathrm{T}} = 1 - \beta \cdot \left(T_{\mathrm{cell}} - T_{\mathrm{cell,ref}}\right) \quad \text{(Eq. 7)}$$

where β is the power temperature coefficient of the PV cells, T_{cell} the temperature of the PV cells and $T_{\mathrm{cell,ref}}$ the PV cell temperature at reference conditions (usually STC conditions).

Tab. 3. Typical values for the power temperature coefficient β of PV modules

Parameter	Type	Value	Reference
β	PV modules	0.43 %/K	Lämmle et al., 2017
β	Average from literature	0.45 %/K	Skoplaki and Palyvos, 2009
β	Average of Sandia and commercial cells	0.38 %/K (0.32-0.46 %/K)	Skoplaki and Palyvos, 2009
β	Monocrystalline (Mono-Si)	0.30-0.50 %/K	Skoplaki and Palyvos, 2009
β	Polycrystalline (Poly-Si)	0.40 %/K	Skoplaki and Palyvos, 2009
β	Amorphous (a-Si)	0.11-0.26 %/K	Skoplaki and Palyvos, 2009

PV cell temperature

As described before, the main difference between the calculation of PV modules as stand-alone PV system and PVT collectors is given by the calculation of the PV cell temperatures.

In case of PVT collectors (PVT mode 1), the PVT cell temperature is calculated with a simple equivalent thermal network with an internal heat transfer coefficient U_{AbsFl}, which connects the PVT cell temperature $T_{\mathrm{cell,PVT}}$ with the mean fluid temperature T_{m} of the PVT collector. In this case, the PVT cell temperature is given by (Lämmle et al., 2016, 2017):

$$T_{\mathrm{cell,PVT}} = T_{\mathrm{m}} + \dot{q}_{\mathrm{th}}/U_{\mathrm{AbsFl}} \quad \text{(Eq. 8)}$$

where $\dot{q}_{\mathrm{th}}$ is the specific thermal power output of the PVT collector.

In case of PV modules as stand-alone PV system, the PV cell/module temperature with different models. In PV cell mode 1, the PV cell/module temperature is calculated with (Faiman, 2008):

$$T_{\mathrm{cell,PV}} = T_{\mathrm{amb}} + G/(U_0 + U_1 \cdot u) \qquad \text{(Eq. 9)}$$

where T_{amb} is the ambient air temperature, U_0 the coefficient for radiation dependence of PV module temperature, U_1 the coefficient for wind dependence of PV module temperature and u the wind speed in the PV plane. At this, the PV cell temperature is assumed to be equal to the module temperature.

Tab. 4. Typical values for U_0 and U_1 of PV modules

Parameter	Type	Value	Reference
U_0	Crystalline (c-Si)	30.02 W/m²K	Koehl et al., 2011
U_1	Crystalline (c-Si)	6.28 Ws/m³K	Koehl et al., 2011
U_0	Crystalline (c-Si), combined fit	25.00 W/m²K (23.5-26.4 W/m²K)	Faiman, 2008
U_1	Crystalline (c-Si), combined fit	6.84 Ws/m³K (6.25-7.68 Ws/m³K)	Faiman, 2008
U_0	Amorphous (a-Si)	25.26-26.16 W/m²K	Koehl et al., 2011
U_1	Amorphous (a-Si)	4.25-10.67 Ws/m³K	Koehl et al., 2011

In PV cell mode 2 and 3, the PV cell temperature is calculated from NOCT conditions. The energy balance of a PV module per unit area can be written as (Duffie and Beckman, 2013):

$$(\tau\alpha) \cdot G = \eta_{\mathrm{el,PV}} \cdot G + U_{\mathrm{L}} \cdot (T_{\mathrm{cell,PV}} - T_{\mathrm{amb}}) \qquad \text{(Eq. 10)}$$

where $\tau\alpha$ is the effective transmittance-absorptance product (usually estimate with 0.9 or 0.95) and U_{L} the heat loss coefficient of the PV module.

With Eq. 10 the PV temperature difference to the ambient is given by:

$$T_{\mathrm{cell,PV}} - T_{\mathrm{amb}} = G \cdot (\tau\alpha) \,/\, U_{\mathrm{L}} - G \cdot \eta_{\mathrm{el,PV}} \,/\, U_{\mathrm{L}} \qquad \text{(Eq. 11)}$$

or

$$T_{\mathrm{cell,PV}} - T_{\mathrm{amb}} = G \cdot (\tau\alpha) \,/\, U_{\mathrm{L}} \,(1 - \eta_{\mathrm{el,PV}} \,/\, (\tau\alpha)) \qquad \text{(Eq. 12)}$$

For NOCT conditions (G_{NOCT} = 800 W/m², $T_{\mathrm{amb,NOCT}}$ = 20°C, u_{NOCT} = 1 m/s) with no-load operation ($\eta_{\mathrm{el,PV}} = 0$), the energy balance of Eq. 12 is given by:

$$T_{\mathrm{cell,PV,NOCT}} - T_{\mathrm{amb,NOCT}} = G_{\mathrm{NOCT}} \cdot (\tau\alpha) \,/\, U_{\mathrm{L,NOCT}} \qquad \text{(Eq. 13)}$$

The PV cell temperature at any ambient temperature and global radiation is than found from:

$$(T_{\mathrm{cell,PV}} - T_{\mathrm{amb}}) / (T_{\mathrm{cell,PV,NOCT}} - T_{\mathrm{amb,NOCT}}) = (G/G_{\mathrm{NOCT}})\,(U_{\mathrm{L,NOCT}}/U_{\mathrm{L}})\,[1 - (\eta_{\mathrm{el,PV}}/\tau\alpha)] \qquad \text{(Eq. 14)}$$

or:

$$T_{\mathrm{cell,PV}} = T_{\mathrm{amb}} + (G/G_{\mathrm{NOCT}})\,(U_{\mathrm{L,NOCT}}/U_{\mathrm{L}})\,(T_{\mathrm{cell,PV,NOCT}} - T_{\mathrm{amb,NOCT}})[1 - (\eta_{\mathrm{el,PV}}/\tau\alpha)] \qquad \text{(Eq. 15)}$$

With the assumption that the heat loss coefficient (PV cell mode 2) is constant, the PV cell temperature can be calculated from Eq. 15 with:

$$T_{\mathrm{cell,PV}} = T_{\mathrm{amb}} + (G/G_{\mathrm{NOCT}})\,(T_{\mathrm{cell,PV,NOCT}} - T_{\mathrm{amb,NOCT}})[1 - (\eta_{\mathrm{el,PV}}/\tau\alpha)] \qquad \text{(Eq. 16)}$$

An approximation of U_L for variable wind speeds is (Duffie and Beckman, 2013):

$$U_\mathrm{L} = 5.7\ \mathrm{W/m^2K} + 3.8\ \mathrm{Ws/m^3K} \cdot u \qquad \text{(Eq. 17)}$$

With the approximation in Eq. 17, the wind speed at NOCT u_NOCT = 1 m/s and Eq. 15, the PV cell temperature for variable wind speeds (PV cell mode 3) can be calculated with:

$$T_\mathrm{cell,PV} = T_\mathrm{amb} + \frac{G}{G_\mathrm{NOCT}} \cdot \frac{9.5\ \mathrm{W/m^2K}}{5.7\ \mathrm{W/m^2K} + 3.8\ \mathrm{Ws/m^3K} \cdot u} \left(T_\mathrm{cell,PV,NOCT} - T_\mathrm{amb,NOCT}\right) \left[1 - \frac{\eta_\mathrm{el,PV}}{\tau\alpha}\right] \qquad \text{(Eq. 18)}$$

In addition, in PVT mode 3, the PVT cell temperature can set as input value from external calculation.

Detailed calculation of PV cell temperature in PV cell mode 2 and 3

In PV cell mode 2 and 3, the calculation of the PV cell temperature depends on the actual overall (or total) electrical efficiency $\eta_\mathrm{el,PV}$ of the PV modules. As $\eta_\mathrm{el,PV}$ depends on the actual PV cell temperature, Eq. 1 has to be used in Eq. 16 / Eq. 18 and the equations has to solve for the PV cell temperature $T_\mathrm{cell,PV}$.

With Eq. 4 and Eq. 7, Eq. 1 can be written for PV modules as:

$$\eta_\mathrm{el,PV} = \eta_\mathrm{el,ref} \cdot PR_\mathrm{IAM} \cdot PR_\mathrm{G} \cdot \left[1 - \beta \cdot \left(T_\mathrm{cell,PV} - T_\mathrm{cell,PV,ref}\right)\right] \qquad \text{(Eq. 19)}$$

For simplification of the following calculations, the variable k_1 is introduced as:

$$k_1 = \eta_\mathrm{el,ref} \cdot PR_\mathrm{IAM} \cdot PR_\mathrm{G} \qquad \text{(Eq. 20)}$$

In addition, the variable k_2, which depends on the PV cell mode (PV cell mode 2 or 3), is defined as:

$$k_2 = (G/G_\mathrm{NOCT})\left(T_\mathrm{cell,PV,NOCT} - T_\mathrm{amb,NOCT}\right) \qquad \text{(Eq. 21)}$$

for PV cell mode 2 and

$$k_2 = \frac{G}{G_\mathrm{NOCT}} \cdot \frac{9.5\ \mathrm{W/m^2K}}{5.7\ \mathrm{W/m^2K} + 3.8\ \mathrm{Ws/m^3K} \cdot u} \left(T_\mathrm{cell,PV,NOCT} - T_\mathrm{amb,NOCT}\right) \qquad \text{(Eq. 22)}$$

for PV cell mode 3.

With Eq. 19 – 22, Eq. 16/18 can be written as:

$$T_\mathrm{cell,PV} = T_\mathrm{amb} + k_2\left[1 - \left(k_1/\tau\alpha \cdot \left[1 - \beta \cdot \left(T_\mathrm{cell,PV} - T_\mathrm{cell,PV,ref}\right)\right]\right)\right] \qquad \text{(Eq. 23)}$$

Solving Eq. 23 for $T_\mathrm{cell,PV}$:

$$T_\mathrm{cell,PV} = T_\mathrm{amb} + k_2\left[1 - \frac{k_1}{\tau\alpha} + \frac{k_1}{\tau\alpha} \cdot \beta \cdot \left(T_\mathrm{cell,PV} - T_\mathrm{cell,PV,ref}\right)\right] \qquad \text{(Eq. 24)}$$

$$T_\mathrm{cell,PV} = T_\mathrm{amb} + k_2 - \frac{k_1 k_2}{\tau\alpha} + \frac{k_1 k_2}{\tau\alpha} \cdot \beta \cdot \left(T_\mathrm{cell,PV} - T_\mathrm{cell,PV,ref}\right) \qquad \text{(Eq. 25)}$$

$$T_\mathrm{cell,PV} = T_\mathrm{amb} + k_2 - \frac{k_1 k_2}{\tau\alpha} + \frac{k_1 k_2}{\tau\alpha} \cdot \beta \cdot T_\mathrm{cell,PV} - \frac{k_1 k_2}{\tau\alpha} \cdot \beta \cdot T_\mathrm{cell,PV,ref} \qquad \text{(Eq. 26)}$$

$$T_\mathrm{cell,PV} - \frac{k_1 k_2}{\tau\alpha} \cdot \beta \cdot T_\mathrm{cell,PV} = T_\mathrm{amb} + k_2\left[1 - \frac{k_1}{\tau\alpha} - \frac{k_1}{\tau\alpha} \cdot \beta \cdot T_\mathrm{cell,PV,ref}\right] \qquad \text{(Eq. 27)}$$

$$T_\mathrm{cell,PV} \cdot \left(1 - \frac{k_1 k_2}{\tau\alpha} \cdot \beta\right) = T_\mathrm{amb} + k_2\left[1 - \frac{k_1}{\tau\alpha}\left(1 + \beta \cdot T_\mathrm{cell,PV,ref}\right)\right] \qquad \text{(Eq. 28)}$$

the PV cell temperature can be calculated with:

$$T_\mathrm{cell,PV} = \frac{T_\mathrm{amb} + k_2\left[1 - k_1/\tau\alpha \cdot \left(1 + \beta \cdot T_\mathrm{cell,PV,ref}\right)\right]}{1 - k_1 \cdot k_2 \cdot \beta/\tau\alpha} \qquad \text{(Eq. 29)}$$

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Appendix: Changelog

Version 2.0: NOCT calculation for the PV cell temperature was added (with fixed electrical efficiency)

Version 3.0: NOCT calculation for the PV cell temperature was added with detailed calculation and use of actual electrical efficiency

Version 3.1: Correct Calculation for Theta (Calculation in radians (*PI/180) from input degree values and maximum as well as zero value of PRiam for negative PRiam's)