PVT Performance Prediction

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Abstract

Photovoltaic Thermal (PVT) hybrid modules producing electricity and heat in parallel are becoming more relevant in the Solar Thermal market. Especially PVT modules in combination with heat sinks operating in low temperature ranges like heat pumps are showing perfect conditions for that kind of combination. One important topic for a broader market implementation and distribution will be a clear and overall performance characterization with respect to electrical and thermal power measurements and their interaction.

The presented project has validated a method for a junction (module) temperature forecast based on the thermal behavior of PVT's under consideration of mean fluid temperature, ambient temperature and wind speed. This approach will give the required link between thermal collector testing and electrical PV module characterization and provide a clear distinction of responsibilities for the thermal and PV experts and laboratories.

Keywords: PVT, Performance prediction, junction temperature, module temperature

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1. Motivation

As for most PVT applications it is not possible to use temperature probes for direct measurement of the cell temperature, a new approach without additional sensors inside the PVT construction was developed.

Based on the method of the equivalent cell temperature ECT [IEC 60904-5:2011] it is possible to receive all required information for a detailed description of the overall thermal behavior including the cell/ junction temperature.

$$ECT = 25°C + \frac{1}{\beta}\left[\frac{U_{OC2}}{U_{OC,STC}} - 1 - \alpha\, ln\left(\frac{G_2}{1000}\right)\right] \qquad \text{(eq. 1)}$$

A general equation to estimate the module temperature by field measurements is described in IEC 61853-2:2016:

$$T_m - T_{amb} = G/\,(u_0\text{-}u_1{*}v) \qquad \text{(eq. 2)}$$

As this approach is not covering the main influence of PVT's, the fluid temperature dependency, it is not applicable for modules combined with a thermal heat absorber. Therefore, a new model or equation was developed to cover also this influence.

This new approach which will be presented in the next clause was already introduced before in the project report "Harmonization and Standardization of multi-functional PVT Solar Collectors (PVT-Norm)" Fritzsche et al. (2016). The current work should validate the indoor steady state results with dynamic outdoor field results. A detailed field test of two similar PVT modules with (PVT 1) and without thermal back-side insulation (PVT 2) was performed over several months to provide a large set of data with a wide range of environmental conditions.

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2. Procedure

Based on the long experience of performance testing of PVT's and the results of absorber temperature estimation right from the beginning of our testing it was obvious, that the behavior of the module resp. cell temperature could be described similar to that of the thermal performance, but with an opposite sign as the temperature is rising and not decreasing with higher fluid temperatures. Figure 1 is showing an excellent example, how the measurement points from the steady state indoor test are distributed and how the resulting curves will look like.

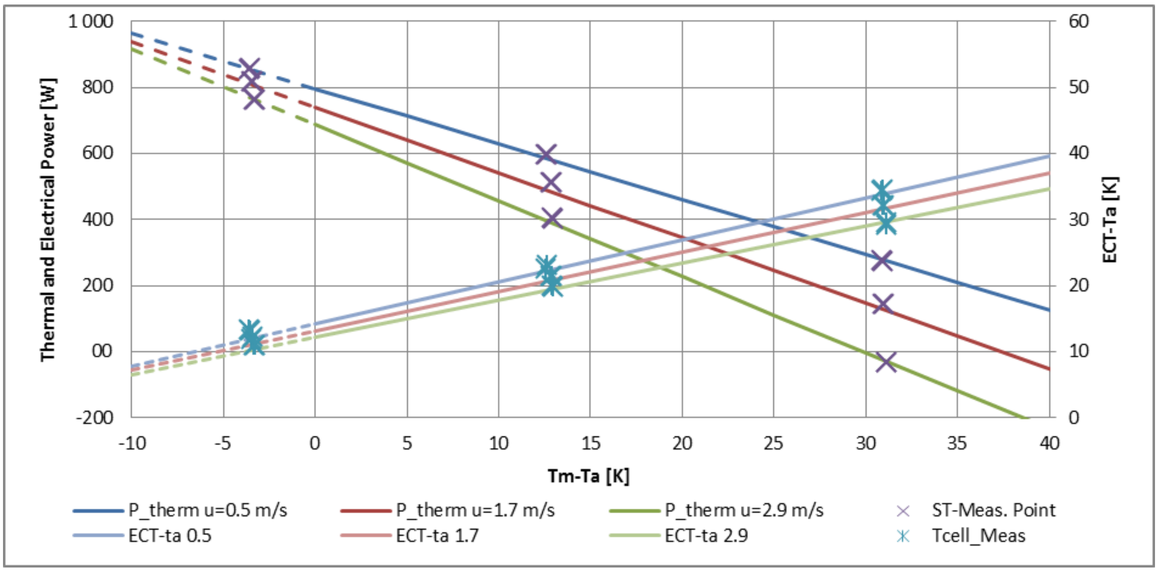

Fig. 1: Example of thermal performance and cell over temperature measurement points and resulting curves

EN ISO 9806:2013 is giving the following equation 3 for the steady state testing of "uncovered" collectors.

$$\dot{Q} = \dot{A}_G \cdot G'' \left(\eta_{0,hem}(1 - b_u u) - (b_1 + b_2 u)\frac{\vartheta_m - \vartheta_a}{G''}\right) \qquad \text{(eq. 3)}$$

The new equation describing the cell over temperature is based on the regular equation for thermal performance of unglazed collectors. By changing the sign, the gradient of the cell (absorber) over temperature could be described as seen in equation 4. It was evaluated, if the global irradiance has to be taken into account, but the influence of wind and fluid temperature was dominating, that the global irradiance was finally neglected.

$$\vartheta_{cell} - \vartheta_a = \vartheta_{cell,0}(1 - d_u u) + (d_1 + d_2 u)\,(\vartheta_m - \vartheta_a) \qquad \text{(eq. 4)}$$

With:

ϑ_{cell} = cell (absorber) temperature

$\vartheta_{cell,0}$ = cell (absorber) temperature conversion point

d_u = wind dependence of the conversion point

d_1 = heat „gain" coefficient

d_2 = wind dependence of heat gain coefficient

The units are currently following the EN ISO systematic. The nomenclature itself is open for discussion, but describes the different coefficient in the best way.

3. Test sequences

As mentioned before, two similar PVT modules with and without a thermal insulation were used for the validation of the procedure. After an initial indoor test of electrical and thermal properties, the modules had performed an outdoor field test over several months.

3.1. Initial steady state testing

Beside a characterization of the electrical performance according to standard test conditions STC, a detailed indoor performance test was. The collectors were tested according to EN ISO 9806:2013 with the steady state test method for uncovered collectors. This method requires a constant high irradiance level and three different inlet temperatures with three different wind speed ranges.

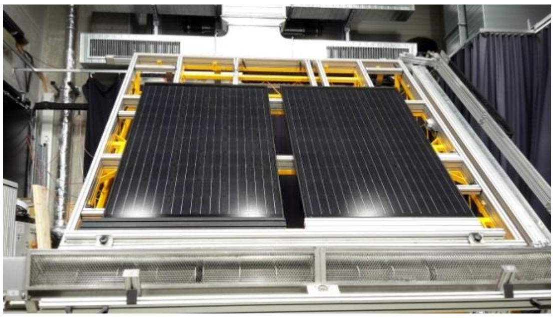

Fig. 2: Indoor steady state test set up

It is obvious, that those requirements are really hard to fulfill, if this procedure should be applied outdoors. As the boundary conditions within a sun simulator are stable and highly reproducible, it was always the preferred method at TÜV to test this wind dependent collector types.

During thermal performance testing, the electrical part of the PVT was operating in the so called MPP Maximum Power Point controlled by an electronic load. In addition to that, the load was measuring the PV module IV curve every five minutes. Even, if not the full IV curve is necessary for the ECT method; at least the open circuit voltage signal has to be detected regularly.

The parameter sets describing the thermal performance according to equation (3) as well as the cell temperature above ambient (4) were determined for the two used test samples are described in table 1 and 2.

Tab. 1: Data set for prediction of the thermal performance of the two test samples

	PVT 1 with back side insulation		**PVT 2 without back side insulation**	
	Value	**Standard deviation [%]**	**Value**	**Standard deviation [%]**
$\eta_{0,hem}$ [ ]	0.490	0.9	0.538	1.6
b_u [s/m]	0.055	8.3	0.048	14.6
b_1 [W/(m²K)]	9.336	2.5	13.805	3.4
b_2 [J/(m³K)]	1.574	7.5	1.905	10.4

Tab. 2: Data set for prediction of the module (cell) temperature above ambient

	PVT 1		**PVT 2**	
	Value	**Standard deviation [%]**	**Value**	**Standard deviation [%]**
$\vartheta_{cell,0}$ [°C]	19.82	1.12	14.65	1.11
d_u [s/m]	-0.047	10.3	-0.058	9.79
d_1 [ ]	0.651	1.80	0.653	1.29
d_2 [s/m]	-0.030	16.6	-0.032	13.3

3.2. Field Test

As described before, the two samples had been sent to our outdoor test field in Italy after initial indoor testing. There we've extended the already existing infra structure to monitor not only the electrical the PV long term performance, but also the thermal behavior of PVT modules.

Beside additional sensors as Pyrgeometer for long wave irradiation detection or wind speed sensors to measure the wind speed in the aperture area, a thermal testing loop for two samples had been realized.

Fig. 3: Field test set up

Delayed tests for certification of the products are the reason, that only about four month from October to January had been available for the final validation of this procedure. The initial plan was at least half a year including the summer and autumn.

3.3. Final steady state testing

After that outdoor field test, the samples had been sent back to Cologne to undergo a final test under the sun simulator. As this test was showing performance degradation, these values had not been used for the final validation. As the field measurement didn't show any degradation over time, the vertical transport of the samples might be the reason for that minor degradation.

Nevertheless, the final tests had been used to perform the tests not only according to the "old" method described in EN ISO 9806:2013, but also according to the new method described in the 2017 release of the standard. The comparison of both methods didn't show significant deviations, that the applicability of this new equation for so called WISC collectors under the sun simulator was confirmed.

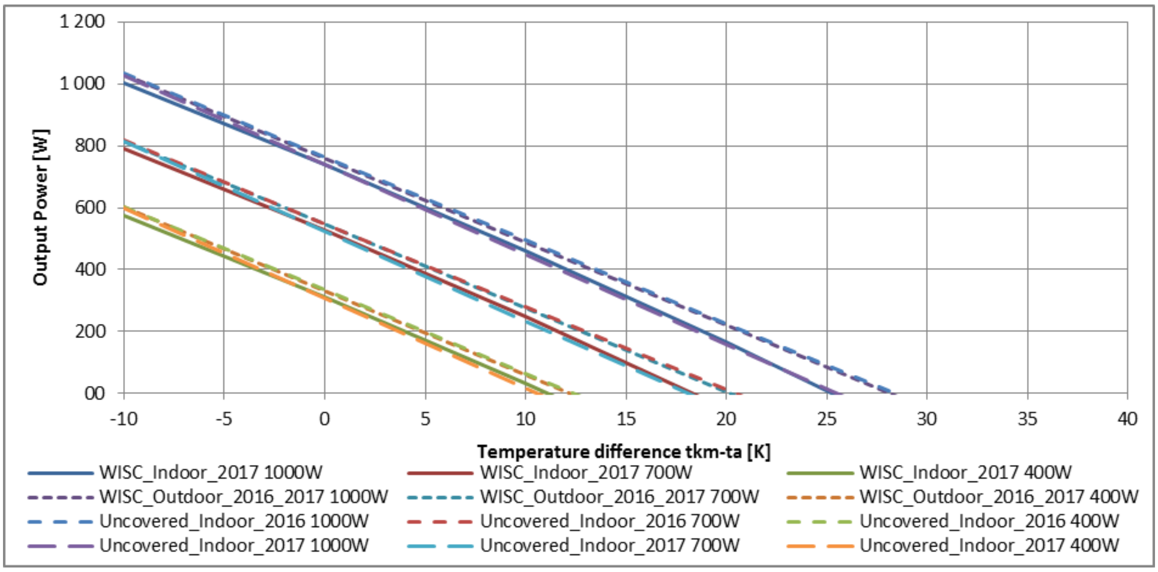

Fig. 4: Comparison of initial and final test performance tests for the PVT 2 collector without thermal insulation

4. Validation

The validation of the new model was made on the basis of the resulting electrical performance. Even, if the model itself gives only the module temperature above ambient, the final aim is a precise prediction of the electrical output. This approach was also necessary, as the electrical output was measured with a much higher resolution than the open circuit voltage signal during the IV-Curve measurement.

The limit for the minimum irradiance level was set to 200 W/m² not only because of spectral response of the cells, but also because of higher uncertainties during this low irradiance performance.

4.1 PVT 2 without thermal insulation

In figure 5, you will find the comparison results between measured and calculated electrical output for the PVT without thermal insulation.

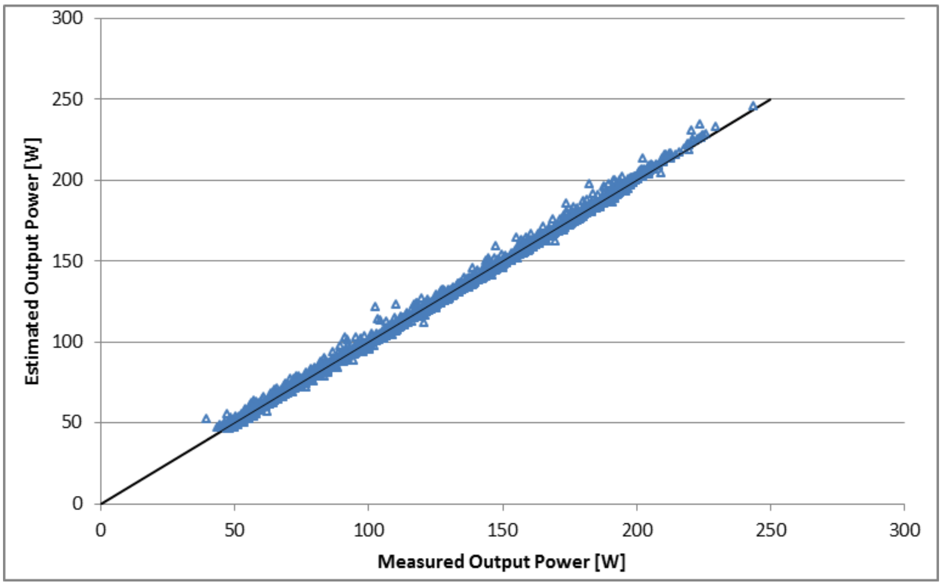

Fig. 5: Precision of measured and calculated electrical performance

In general, the comparison of simulated and measured output power fits quite well as shown in figure 5. The energy difference during irradiance levels above 200 W/m² over the complete test period is about 0.14%. The used quality figure described as the integral of the absolute deviation (energy of deviation) divided by the measured energy is only 1.3 %.

The following figures 6 & 7 are showing representative days and the resulting deviation of measured and estimated electrical output. For a long term prediction, these short time depending deviations up to a few percentages are not relevant and could be neglected.

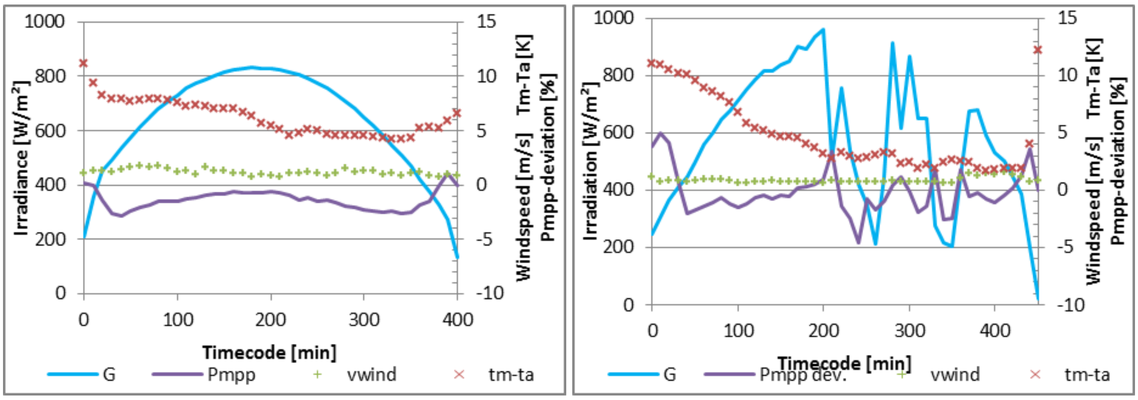

Fig. 6 & 7: Representative days for clear sky and partly cloudy days

4.2 PVT 1 with thermal Insulation

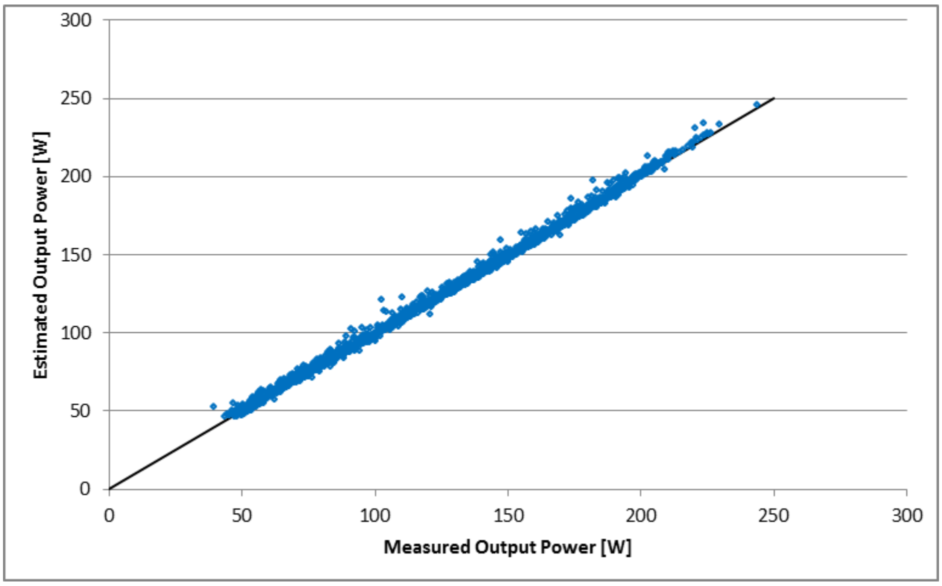

Fig. 8: Precision of measured and calculated electrical performance

In general, the comparison of simulated and measured output power fits quite well as shown in Fig. 8. The energy difference during irradiance levels above 200 W/m² over the complete test period is about 0.24 %. The used quality figure described as the integral of the absolute deviation (energy of deviation) divided by the measured energy is only 1.8 %.

The following figures 9 & 10 are again showing representative days and the resulting deviation of measured and estimated electrical output for the sample with thermal insulation.

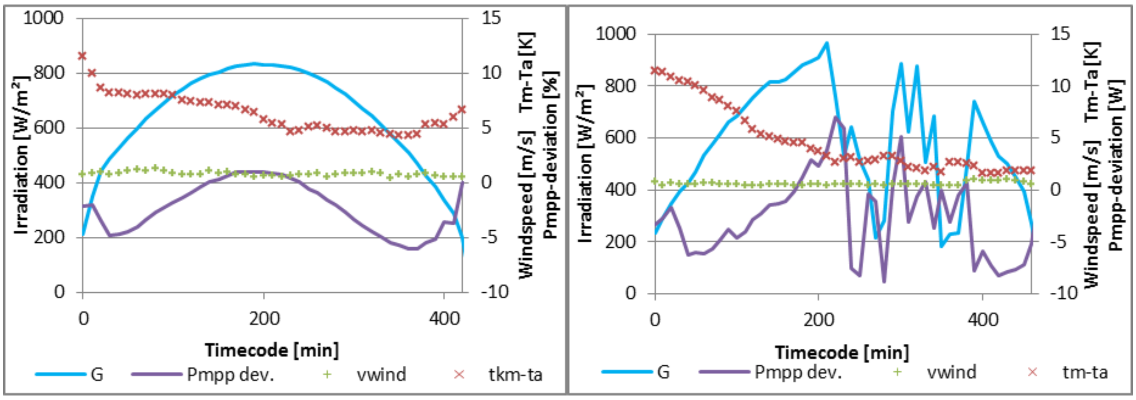

Fig. 9 & 10: Representative days for clear sky and partly cloudy days

The resulting deviation between measured and calculated output power and energy is slightly higher than for PVT 2. But even this higher deviation is still more than appropriate for a long term energy yield.

5. Conclusion

5.1 Model for estimation of cell temperature of PVT's

This model is showing promising results with an appropriate accuracy. As you can see below in Fig. 6, 7, 9, 10, there is still a daytime depending deviation as well as deviations based on quick irradiance changes, but this is not relevant for long time or annual performance prediction. From current perspective, this might be solved by using a 2-node model, where the cell is the first and the fluid the second note. As this model is not referred in the collector standard or necessary for the described purposes, this might be a solution for R&D, but not for certification and general performance indication.

Beside the accuracy, a clear distinction of the different responsibilities is given. Beside a regular determination of the open voltage signal and the already required performance under MPP, no additional electrical measurements are necessary.

An accurate measurement of the wind speed over aperture will be the main challenge for outdoor measurements.

5.2 Performance Indicator for PVT collectors based on NMOT conditions

A harmonized and realistic presentation of the electrical as well as thermal performance of PVT's is a main requirement for a broader distribution and acceptance of this technology. Currently, there's no harmonized way to present these results and a direct comparison of the performance of different PVT's is nearly impossible. Furthermore, the partly used unrealistic presentation based on reference conditions, which will never occur at the same time will result in unrealistic expectation and disappointed owner or user.

The performance indication based on standard test conditions, which will usually be used for PV modules are not applicable for PVT. These conditions are fixed to a cell temperature of 25°C and could never consider the thermal behavior in an appropriate way. One opportunity for PVT's is a performance indication based on Nominal Module Operation Temperature conditions, as these are considering a realistic module temperature in the field as basis. Not only for PVT, but also for standard PV modules, the performance at NMOT as described in IEC 61215-2:2016 is a much more realistic performance indicator than the performance at a fixed cell temperature of 25°C and 1000 W/m² irradiance.

Beside the conditions at NMOT, additional reference conditions for the collector inlet temperature or the mean collector fluid temperature has to be defined. To distinguish between different applications of PVT's as combined with heat pipes, pools or as pre-heater, there should be a set of different inlet temperatures available.

To cover the main fields of application the inlet temperature levels 10 K below ambient, ambient and 10 K above ambient might be a reasonable range. Considering the ambient temperature of 20°C for NMOT, this would result in mean fluid temperatures of 10, 20 and 30°C. A possible nomenclature would be $NMOT_{PVT10}$.

Table 3 is showing exemplary results for the PVT 1 with thermal insulation.

Table 3: Performance indication based on NMOT conditions with a global irradiance of 800W/m², 20°C ambient temperature and a wind speed of 1 m/s

	Mean Fluid Temperature [°C]	**Equivalent Cell Temperature @ NMOT [°C]**	**Electrical Power @ NMOT [W]**	**Electrical power gain [%]**	**Thermal Power @ NMOT [W]**
$NMOT_{PVT10}$	10	29.5	197.7	8.2	747
$NMOT_{PVT20}$	20	35.8	192.3	5.2	567
$NMOT_{PVT30}$	30	42.0	187.0	2.3	476
NMOT	PV module	46.9	182.8	-	-

If the mean fluid or the inlet temperature should be used need to be discussed. The use of the mean fluid temperature would be much easier, but if we think about an overall indication as used in the Solar Keymark data sheets and calculated also of the electrical energy yield in the future, it might be worse to start directly with fixed defined inlet temperatures. This would be applicable, if the resulting means fluid temperature for these fixed inlet temperatures will be calculated in advance.

6. Outlook

In the framework of this small project PVT Field evaluation, a new approach to estimate the cell temperature of PVT collectors under consideration of the thermal working point was developed. This model is independent from the chosen collector model and could be used for indoor and outdoor measurements.

To reach more confident, further validations with additional PVT collectors should be performed. Therefore, existing monitoring results might be used or new field measurements need to be performed.

As a final step, a technical specification out of an IEC or ISO work item may be published. In the meantime, certification schemes like Solar Kemyark or SRCC might consider this model for an appropriate performance indication in the frame of their individual data sheets.

7. Reference

EN ISO 9806:2013, Solar Energy – Solar thermal collectors – Test methods

IEC 60904-5:2011, Photovoltaic devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method

IEC 61853-2:2016, Photovoltaic (PV) module performance testing and energy rating – Part 2: Spectral responsivity, incidence angle and module operation temperature measurement

IEC 61215-2:2016, Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures

“Harmonization and Standardization of multi-functional PVT Solar Collectors (PVT-Norm)” Fritzsche et. al. (2016).

Symbols

IEC 60904-5:2011

α	Temperature coefficient of the short circuit current	%/°C
β	Temperature coefficient of the open circuit voltage	%/°C
U_{OC}	Open circuit voltage	V
$U_{OC,STC}$	Open circuit voltage at standard test conditions	V
G	Global irradiance	W/m²

IEC 61853-2:2016

T_m	Module temperature	°C
T_{amb}	Ambient temperature	°C
u_0	Irradiance depending correction factor	
u_1	Wind depending correction factor	
v	Wind speed	m/s

EN ISO 9806:2013

Q	Useful power extracted from collector	W
A_G	Gross area of collector as defined in the ISO 9488	m²
G''	Net irradiance	W/m²
G_{hem}	Hemispherical solar irradiance	W/m²
$\eta_{0,hem}$	Collector efficiency based on hemispherical irradiance G_{hem}	-
b_u	Collector efficiency coefficient (wind dependence)	s/m
b_1	Heat loss coefficient at $(\vartheta_m - \vartheta_a) = 0$	W/(m2·K)
b_2	Wind dependence of the heat loss coefficient	Ws/ (m3·K)
ϑ_m	Mean temperature of heat transfer fluid	°C
ϑ_a	Ambient air temperature	°C
u	Surrounding air speed	m/s