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D8-6: PVT performance measurement guidelines

Guidelines for performance measurements of liquid-cooled non-concentrating PVT collectors using c-Si cells

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This report presents a guideline for performance testing issues that are specific for PVT and that are not covered by the IEC 61215 and the EN 12975. The report limits itself to liquid-cooled non-concentrating PVT collectors using c-Si cells. The aim of this guideline is to provide a basis for the future development of dedicated PVT testing, which is considered to be an important factor in the further market penetration of the PVT products. It is part of the reporting of the project PV Catapult, supported by the European Union. More information on the project can be found at: www.pvtforum.org

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1 Introduction

This is a guideline for performance measurements of liquid-cooled non-concentrating PVT collectors using c-Si cells. PVT stands for PV-thermal, and is related to PV modules that produce both electricity and heat. Side-by-side systems are therefore not included in this document.

This document is a deliverable of work package 8 of the EU-project PV-CAtapult. The aim of work package 8 of the PV-CAtapult project is the development of guidelines for the performance measurement of PV modules and of PVT-modules. This document addresses the PVT-part only (deliverable 8-6: PVT Performance guidelines).

Up till now, no dedicated guideline existed for the performance testing of PV-Thermal. Basically, performance measurements of PVT collectors need to be in agreement with IEC 61215 for the electrical part and with EN 12975-2 for the thermal part. Yet, due to the close energetic interactions between the PV cells and the thermal part of PVT collectors, many additional aspects need to be taken into account, especially concerning the procedures and conditions of measurements.
This guideline focuses on these additional aspects, so it is recommended to consider IEC 61215 and EN 12975-2 for the details of testing, and to regard this guideline as supplementary to the two mentioned standards.

2 Objective

The objective of this guideline for the performance of PVT-modules is

1. to characterise the module in such a way that the characteristics can be used to predict the annual energy production, both thermal and electrical, for any given site with standard meteorological data (chapter 3 and 4),
2. to present a method with which the annual yield can be calculated (chapter 5)

The present guideline is limited to PVT collectors using liquid heat transfer media, and crystalline silicon (c-Si) to produce electrical energy. It applies both to collectors that are covered by a glazing ("glazed collectors") and to uncovered ("unglazed") collectors (see figures 1 and 2).

The following collector types are not covered by the text:

- PVT air collectors
- Ventilated PV facades and roofs
- PVT concentrators

The main reason for this limitation is that this makes it possible to take EN 12975 as the starting point for the present guideline.

In addition, only c-Si is covered. The main reason for this choice is that this makes it possible to skip issues such as the following

- the instability of the PV material
- the effect of spectral variations
- the non-linearity of the power coefficient as a function of temperature

Occasionally, the guideline gives additional background information on PV issues or solar thermal issues, because the guideline is meant for both PV experts and solar thermal experts, and it is expected that experts in one field may benefit from some additional background information to understand fully the issues of the other field.

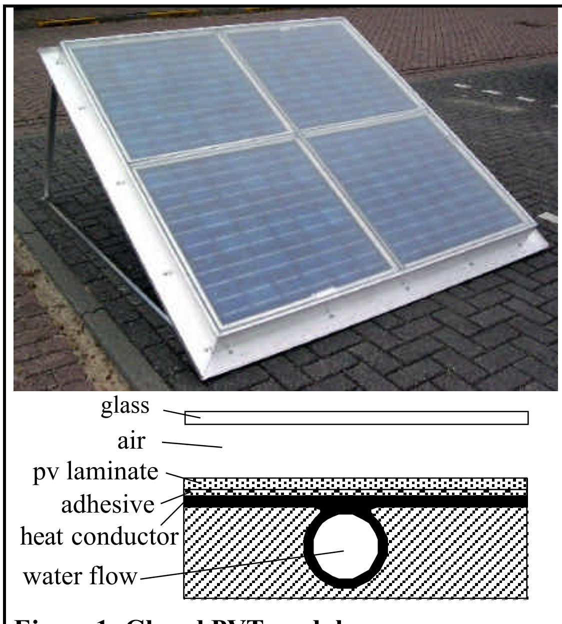

Figure 1: Glazed PVT module

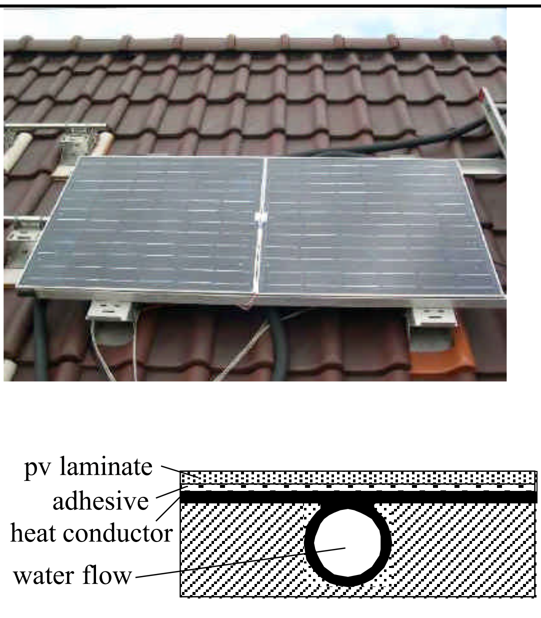

Figure 2: Unglazed PVT module

3 Efficiency measurements

3.1 Characterisation issues

PVT performance testing combines the electrical and thermal testing of the module. This raises a number of issues that does not appear in the separate testing of solar thermal and PV. Below, an overview is presented of the different issues. Also the approach taken in this guideline is indicated.

General aspects:

1. The thermal yield is influenced by the electrical yield; a high PV performance lowers the amount of energy available for conversion to thermal energy, as shown in Figure 3. In this performance guideline, it is argued that thermal measurements should be taken under simultaneous electrical performance, where the PV is functioning at its mpp in order to obtain a representative thermal efficiency curve. For simultaneous measurements taking IV sweeps, the module must be operated at the maximum power point in the waiting time between the electric measurements. In principle, also the choice could have been made in which the thermal efficiency curve was measured without electrical performance, and a correction for the electrical performance could have been made afterwards in the calculation of the annual thermal performance. However, it was felt that such a procedure would lead to errors, first of all due to the fact that the correction itself is not self-evident (depending on the heat removal factor) and secondly because of the fact that the application of electrical corrections in the thermal annual performance calculation is rather deviant from standard practice which will lead to confusion for those who in practice will have to do these calculations.

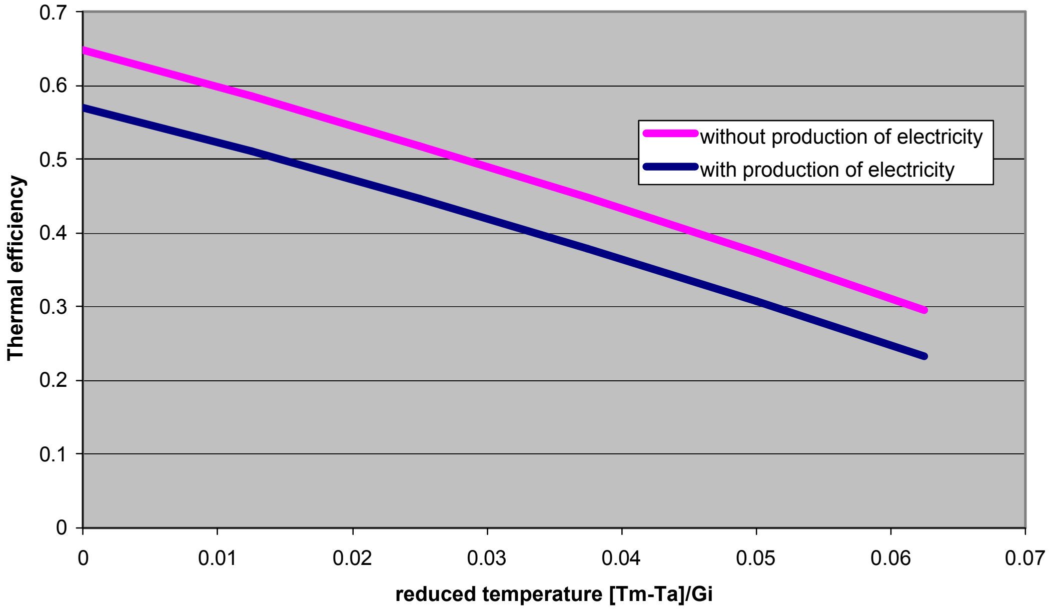

Figure 3: Effect of simultaneous production of electricity on the thermal efficiency of a glazed PVT module.

2. The electrical efficiency depends on the absolute temperature, whereas the thermal efficiency depends on the reduced temperature. In theory, this presents a

complication due to the fact that the electrical efficiency influences the thermal efficiency, that can therefore not be fully represented by means of the reduced temperature. However, in practice also for conventional collectors the absolute temperature has significant effects (e.g radiation effects), which results in a higher order coefficient in the efficiency curve. Here, the position is taken that the temperature effect of the PV efficiency only has a small effect on the thermal collector performance, that can be expressed sufficiently by means of its effect on the collector performance coefficients.

3. In a PVT collector, the PV performance may be affected by additional issues such as edge shading and the thermal resistance between collector fluid and PV cells. For these two issues, dedicated measurement methods are indicated.
4. In principle, the in-plane irradiance can be measured with a pyranometer or with a reference cell that matches the PV-cells of the PVT-module. The advantages and disadvantages for each method are indicated in Table 1. For collector testing, the EN-12975-2 clauses 6.1.2 and 6.2.2 prescribe a pyranometer for the measurement of the solar irradiance. For PV testing, the IEC 61215 clause 10.2.2 prescribes a PV reference device. The main aspects in which a reference cell differs from a pyranometer are the spectral sensitivity and the somewhat reduced angle of view. However, it is considered here that these two effects will only have a small impact for c-Si cells, since for such cells the performance is largely independent of spectral effects. In addition, it is considered here that an additional source of error is introduced if the solar radiation is measured with two different devices for the assessment of the PV performance and the solar thermal performance, especially since the thermal and the electrical performance affect each other. Therefore, it is recommended that a pyranometer should be applied for the irradiance measurements on the PVT collector, both for the thermal and the electrical measurements.

Pyranometer	Reference cell
• A pyranometer has a uniform spectral response, which represents the spectral response of a solar thermal collector • The use of a pyranometer facilitates the direct use of results for predicting the annual energy production at or near the test site since also the meteorological data from weather stations are measured with pyranometers	• The main objective of the use of a reference cell is to correct for spectral variations (if the actual spectrum does not equal the AM 1.5 spectrum). This is mainly important for high bandgap techniques such as amorphous silicon and CdTe, but not so much for crystalline silicon cells or CIS, due to their lower bandgap. • The reflection coefficient (as a function of the angle of incidence) of a reference cell resembles that of a PV(T) module much more than that of a pyranometer • A reference cell has a similar frequency response as the corresponding electrical output of the PV(T)-module. • Cheaper than a pyranometer

Table 1: Pyranometer versus reference cell

For outdoor performance measurements

5. For the outdoor measuring of the electrical performance, a power matrix approach is taken. In this approach normally the PV performance is measured as a function of ambient temperature and irradiance. For PVT, however, no direct relation exists between ambient conditions and PV temperature, due to the fact that the PV temperature is also strongly affected by the temperature of the collector fluid (see also appendix B). It is therefore more sensible to take in the power matrix approach a temperature that is representative of the PV temperature. In principle, one could take the temperature at the rear of the module or the collector fluid temperature. However, a problem is that neither of these temperatures has a one-to-one relation to the PV cell temperature; there will always be a thermal resistance between the fluid (or the PV rear) and the cells, that may lead to a significant temperature difference in the case of high heat flows (which is a function of irradiance and thermal efficiency). For a non-optimised adhesive contact between the PV and the metal absorber, the temperature difference between rear side and PV cells may be as high as 15 K, significantly affecting the PV performance. In the present guideline, the following approach is proposed:
    a. For a sheet-and-tube absorber, the approach is taken to use the mean temperature of the absorber rear side (see appendix B) in the power matrix.
    b. For a fully wetted absorber, the approach is taken to use the mean fluid temperature in the power matrix.

    However, if a characteristic temperature can be established that resembles more accurately the average PV temperature, and if it is possible to calculate this characteristic temperature with sufficient accuracy for the annual yield predictions, this method is to be preferred. More R&D is needed here.

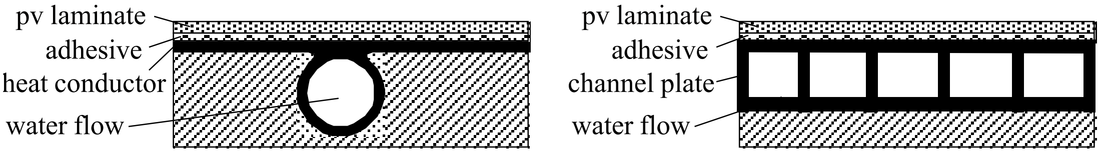

Figure 4: LEFT sheet-and-tube absorber, RIGHT: fully wetted absorber

6. Thermal collector measurements are normally carried out under quasi-stationary conditions in order to avoid thermal capacity effects. In practice this means that the collector performance is monitored continuously, but that most of the collected data is simply 'thrown away' because it does not qualify as quasi-stationary. For PV however, such a criterion does not apply and almost all data can be used for the determination of the electrical performance. This means that collecting PV performance data is much faster than collector performance data, resulting in the situation that for PV characterisation often hundreds of data points are available, whereas for thermal characterisation 16 (for glazed) or 9 (for unglazed) independent data points are required, which nevertheless take a very substantial time to collect. In order to limit the test period to an acceptable level, it is necessary to limit the requested amount of thermal data much more than for electrical data. This will be reflected in the procedures to be followed for the establishment of the electrical and thermal efficiency.

For indoor performance measurements:

7. For electrical performance measurements, the approach is followed to carry out flash tests on the entire PVT collector, in order to assess properly the effects of reflection at the top cover and possible shading by the collector casing and the side insulation.
8. For thermal performance measurements, it is argued that indoor tests are problematic due to the strong spectral sensitivity of the PVT absorber. This problem is further enhanced by the fact that the PV should be functional, which strongly increases the demands on spatial uniformity and spectral distribution compared to conventional solar thermal indoor testers. At the other hand, most PV testers will also not qualify, because the irradiance should be steady state and have a sufficiently accurate longwave spectrum, while wind speed and sky temperature should be sufficiently controlled.

The thermal and electrical efficiencies of a PVT-module can be measured simultaneously in one test or separately. Furthermore, the measurements can be performed indoors or outdoors. The various measurement possibilities are elaborated in the following paragraphs.

	Thermal and Electrical simultaneously	Electrical separately	Thermal separately
Indoor	par. 3.3.1	par. 3.3.2	par. 3.3.3
Outdoor	par. 3.4.1 & 3.4.2	par. 3.4.3	par. 3.4.4

3.2 Definitions

Both the electrical and the thermal performance of solar energy converters are commonly expressed in terms of efficiencies, i.e. the performance is related to the incoming solar irradiance. The efficiencies for quasi-stationary conditions are defined below.

Electrical efficiency for glazed and unglazed collectors:

$$\eta_{el} \equiv \frac{I_{mpp} * V_{mpp}}{G_i * A}$$

The thermal efficiency is determined and expressed as a function of the reduced temperature. For glazed collectors the following equations apply:

$$\eta_{th} \equiv \frac{\Phi * \rho * C_p \left(T_{out} - T_{in}\right)}{G_i * A} \text{ and } T_{red} \equiv \frac{T_m - T_a}{G_i}$$

Thermal efficiency and reduced temperature for unglazed collectors are as follows (the irradiance is corrected for the infrared radiation exchange):

$$\eta_{th} \equiv \frac{\Phi * \rho * C_p \left(T_{out} - T_{in}\right)}{\{G_i + \frac{\varepsilon}{\alpha}(E_L - \sigma T_a^4)\} * A} \text{ and } T_{red} \equiv \frac{T_m - T_a}{\{G_i + \frac{\varepsilon}{\alpha}(E_L - \sigma T_a^4)\}}$$

The symbols used in these equations are explained in Appendix D.

3.3 *Indoor measurements*

3.3.1 Simultaneous PVT indoor measurement

In principle, indoor measurements are preferred because of the independence of weather conditions. However, the indoor measurements must be performed under realistic outdoor conditions. If not, the results cannot be used for the annual energy prediction.
In principle, the required PVT-characteristics can be measured with an indoor facility provided that a number of conditions are simulated realistically. The most important conditions to address are listed below.

- Spectrum of the irradiance

The spectral sensitivity of the PV-cells is much more irregular than for conventional solar thermal absorbers, as illustrated in Figure 5. For crystalline silicon, the cells are only sensitive for wavelengths between about 0.3 and 1.1 µm, and even within this range the sensitivity is far from uniform. For this reason the irradiance spectrum must resemble the specified spectrum (AM1.5) within narrow limits (PV solar simulator Class A (IEC 60904-9)). However, additional constrains apply for the spectrum over 1.1 µm, for which the electrical performance of the PV is not sensitive but which affect the thermal performance. For the combined PVT measurements, the requirements for the solar simulator are therefore very strict: PV class A, with the additional constraint that the spectral match for the wavelength interval 1.1 µm to 3 µm should be in conformance with the solar thermal requirements for the spectral distribution as specified in EN 12975-2 clause 6.1.5.

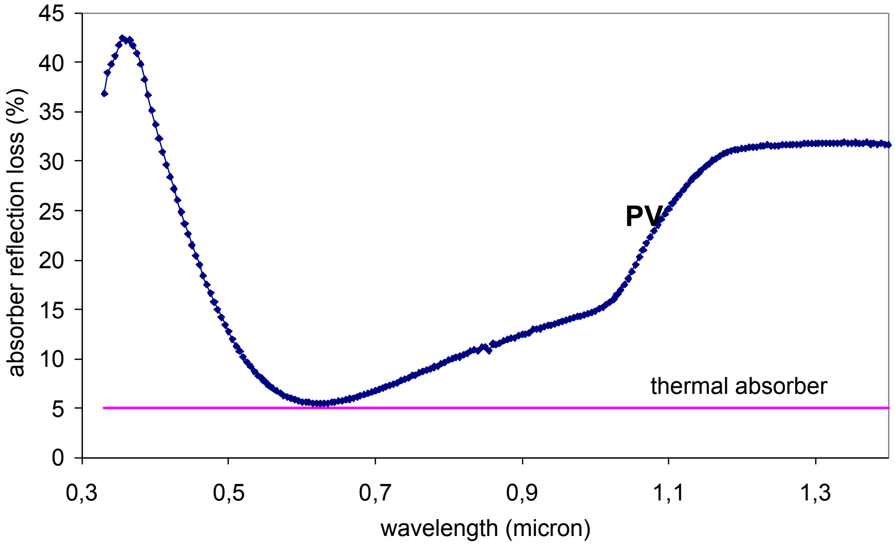

Figure 5: Example of the spectral behaviour of a solar thermal absorber and a c-Si PV cell.

- Spatial uniformity of the irradiance

The PV-cells in the module are connected in series meaning that their currents are forced to be equal. Non-uniform irradiance over the various cells will cause over-proportional power loss due to the mismatch effect. This requires a non-uniformity of the irradiance of maximum +/-2% (IEC60904-9). This is much more stringent than would be required for thermal measurements; Elswijk et al. (2002) show that non-uniformity of the irradiance of maximum +/-10% is adequate for the thermal measurements. For the combined PVT measurements the required class is the most stringent one: class A.

- Time stability of the irradiance

The electric characteristics of a PVT-module can be measured within a very short period of time with a flash tester (order: less than 1 s). The measurement of the thermal characteristics however requires a continuous source of light, long enough to obtain a quasi-stationary situation (order: 10 minutes to 1hour, dependent on the thermal time constant of the PVT-module).

- Sky radiation

The radiation loss from the PVT module towards the sky influences the thermal efficiency. The sky can be regarded as a black body with an effective sky temperature T_S. The value of T_S is very dependent on the meteorological conditions. Conventionally, typical values in the range of 5 to 15 K below the ambient temperature are assumed, depending on cloud cover (see Figure 6)[1]. Realistic simulation of the sky temperature is required.

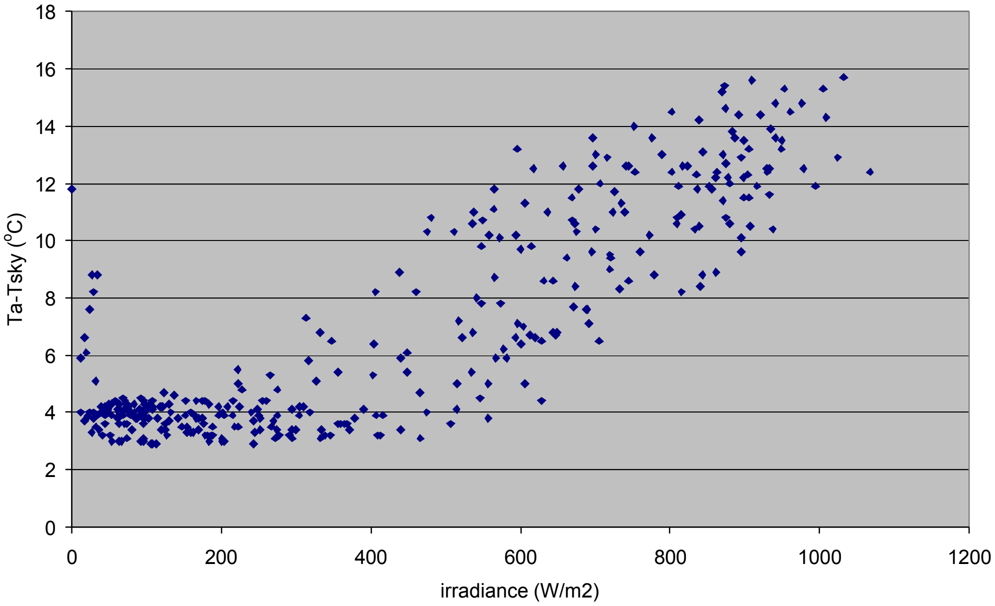

Figure 6: Sky temperature versus irradiance at midday (13:00) as calculated by TRNSYS from the Dutch test reference year. Only data at midday are taken in order to reduce effects of the angle of irradiance on the irradiance intensity.

- Wind speed

Obviously the wind speed influences the thermal efficiency and therefore a flow of air must be created in the test chamber with a range that corresponds to the real, outdoor, wind speeds.

No or only few test institutes will be able or willing to invest the resources to make an indoor test facility that fulfils these requirements. As a consequence in this document the combined indoor measurement of a PVT-module is not elaborated further.
For separate tests, a number of the issues above are relieved.

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[1] However, also more extreme values are reported; one and a half year of measurements at Cadarache (Guerin de Montgareuil, 2005) revealed values for the sky temperature ranging from 3 °C to 23 °C below ambient temperature.

3.3.2 Separate PV indoor measurement

The separate indoor measurement of the electrical PVT performance gives much less problems than the combined electrical and thermal measurement, since the issues of sky temperature, wind speed and time stability are not important anymore. The electric efficiency of the PVT-module can be measured indoor, in accordance with IEC 61215 clause 10.2 (maximum power determination) and clause 10.4 (measurement of temperature coefficient). The test should be carried out on the full module, and not just the absorber, in order to take into account the reflection losses caused by the glass cover and possible shading of the PV.
IEC 61215 clause 10.4 prescribes a variation in the PV module temperature over a range of at least 30 °C in steps of 5 °C. Although for glazed PVT modules the temperature range may be much larger, these data are considered sufficiently representative for extrapolation to higher temperatures, due to the linearity of the temperature power coefficient for crystalline silicon.

3.3.3 Separate thermal indoor measurement

For the separate thermal indoor measurement the situation is much more difficult than for the separate electrical indoor measurement. The requirements for the test facility are basically the same as for the combined measurement described above. It should be realised that PVT collectors have a much higher spectral sensitivity than conventional solar collectors (see figure 3), which will cause problems for conventional indoor thermal test facilities. This problem is strongly enhanced if the PV should be functional during the thermal measurements, which is the approach in this testing guideline. It can be concluded that also separate thermal indoor testing may be very problematic. Therefore, this is not recommended.

3.4 Outdoor measurements

3.4.1 Simultaneous PVT outdoor measurement - electrical measurements

A practical representation of the results is the power matrix. The relation between this scheme and the IEC 61215 is discussed in appendix C. In the power matrix method, the power (P_{mpp}) is presented in bins of irradiance and temperature, as shown in general form in Table 2. The proper choice for the irradiance and temperature will be discussed later in this paragraph.

T G	0 - 5 ºC	5 - 10 ºC	10 - 15 ºC	etc
0 - 100 W/m^2	P_{mpp}			
100 - 200 W/m^2				
200 - 300 W/m^2				
300 - 400 W/m^2				
etc				

Table 2: Power matrix for electrical PV performance

For solar thermal professionals, such a scheme may seem excessive, but they should be aware that for electrical performance measurements, quasi-stationarity as defined in EN-

12975 is not required. Therefore, in practice the required data can be collected in a reasonable time frame.
It is not required to fill all cells in the power matrix. As a minimum, at an irradiance larger than 700 W/m^2, a sufficient range of module temperatures should be measured to determine the thermal power loss coefficients, for which temperatures have to be recorded over a range spanning 30 K. However, under normal circumstances, the prescribed temperature levels for the simultaneous thermal measurements will guarantee that a sufficient range is covered. In addition, data have to be collected at all irradiance intervals, with a maximum bin size of 100 W/m^2.
For the thermal bins, a temperature should be used that has a one-to-one relation to the average PV cell temperature, as this determines the electrical cell efficiency. In addition, for the annual electrical yield calculations, it should be possible to calculate this temperature from the ambient conditions, the inflow temperature and the collector characteristics on an hourly basis with sufficient accuracy (see also chapter 5).

Now a number of issues has to be covered regarding irradiance, temperature and valid electrical power measurements.

Irradiance

First of all, it is recommended to measure the irradiance with a pyranometer, as explained previously in paragraph 3.1. Care should be taken that in the first irradiance bin the accuracy of the pyranometer is sufficient.
The in-plane irradiance should be used in the power matrix, because in this way the measurements are independent of the specific orientation of the module.
Finally, shading issues are important for PVT. Valid measurements can only be carried out for irradiance conditions in which no part of the active PV material is shaded from direct irradiance by the collector casing. This may limit the angle of incidence under which valid measurements can be done. This could be achieved by positioning the PVT on a tracking device. However, also a stationary positioning of the collector is possible, for which the angular conditions can be met by setting a time frame for measurements without shading, as can be calculated by means of programs such as PVSYST. An example of such a time frame is presented in Figure 7.

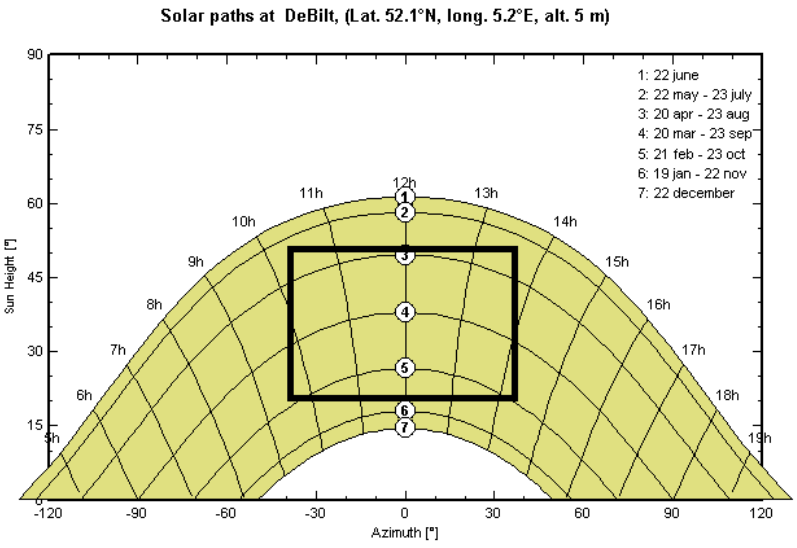

Figure 7: Example of time frame for non-shading conditions (angular graph calculated by PVSYST)

Temperature

In principle a temperature should be used in the power matrix that has a one-to-one correlation to the PV temperature, that can be measured without ambiguity and that can be calculated for use in the determination of the annual performance. For PVT, no such temperature exists.

The ambient temperature, which is often used in power matrix measurements, is not useful for PVT since the PVT module temperature is largely determined by the temperature of the collector fluid flowing through the PVT.

However, also the collector fluid temperature and even the absorber rear temperature are suffering from the fact that a substantial temperature gradient may exist between the fluid, the rear and the actual PV cell temperature. This temperature gradient is not constant but depends on the thermal resistance between PV cells, the collector rear and the collector fluid, and on the heat flow through the absorber, which is a function of thermal efficiency and irradiance.

In this guideline the following choice is made:

1. For sheet-and-tube absorbers, the choice is made to use the PVT absorber rear temperature (for measurement method see appendix B). This temperature is chosen because it is the temperature that most closely resembles the PV cell temperature (more closely than e.g. the average collector fluid) and therefore allows for a more accurate characterisation. This choice implies that for the annual yield predictions, a method is required to calculate the PVT absorber temperature from a combination of ambient conditions and collector characteristics. Such a method will be presented in paragraph 4.4 and chapter 5.
2. For fully wetted absorbers it is not possible to measure 'between the tubes' and the choice is made to use the mean collector fluid temperature as the characteristic temperature in the power matrix. The choice is based on the fact that, of the temperatures that can be measured, this temperature will be closest to the cell temperature. However, in this case, the temperature difference between PV cell temperature and characteristic temperature will be larger than in the case of the sheet-and-tube absorbers, due to the fact that in addition to the thermal resistance of the encapsulant and adhesive layers, now also the thermal resistance of the channel wall and the channel-to-fluid resistance will play a role, which will increase the scatter in the power matrix. One should be aware that the temperature gradient between fluid temperature and PV cell temperature depends now also on the flow rate of the collector fluid (especially on the fact whether the flow is in the laminar or turbulent regime), but since the flow rate also influences the thermal efficiency, the results of the thermal part of the performance testing depend on the flow rate anyway, so this does not give additional problems. On the positive side, one should be aware that the mean collector fluid temperature is determined routinely and unambiguously in the thermal efficiency measurements and is also input for the thermal annual yield predictions.

From the arguments presented here, it will be clear that if a method could be found to determine the actual PV cell temperature with more accuracy, and if in addition there would be a sufficiently accurate method to calculate this characteristic temperature for the annual yield prediction, this determination of the PV cell temperature would be preferred over the present proposal. Further R&D will be needed here.

Power

The values of P_{mpp} can be obtained in two ways.

- By loading the module continuously by an electronic load with maximum power tracking. The P_{mpp} is determined by measuring the input voltage and current of the MPP-tracker. However, it needs to be realised that mpp tracking errors may be large especially with low-cost one-module mpp-trackers.
- By loading the module by an electronic load which sweeps through the IV-curve during short intervals (0.1 - 1 s) every (say) 10 minutes[2]. During the sweep all (say 1000) IV-pairs are measured and the P_{mpp} is determined as the highest product of the various pairs. In between the sweeps, the module should be kept approximately in its mpp point in order not to disturb the thermal measurements.

Because of possible mpp-tracking errors, the procedure with the IV-tracer is the recommended one.

Summary

The considerations presented above lead to a power matrix in the following form.

T^* G_i	0 - 5 ºC	5 - 10 ºC	10 - 15 ºC	etc
0 - 100 W/m^2	P_{mpp}			
100 - 200 W/m^2				
200 - 300 W/m^2				
300 - 400 W/m^2				
400 - 500 W/m^2				
500 - 600 W/m^2				
etc				

Table 3: Measured power matrix for electrical PV performance

- For a sheet-and-tube absorber: T^* equals the mean PVT absorber rear temperature (see also appendix B for the determination of this quantity).
- For a fully wetted absorber, T^* equals the mean collector fluid temperature.

However, the thermal resistance between the location where T^* is measured and the actual PV cell will lead to scatter in the power matrix, due to the fact that the temperature difference between T^* and the cell temperature will depend on the heat flux between the two (which is a function of the irradiance and the thermal efficiency). It is suggested that the accuracy of the PV characterisation may be increased by presenting the results in the form of a derived power matrix, as further explained in appendix E, but experience has not yet been obtained with this technique and more R&D is required to establish its feasibility.

3.4.2 Simultaneous PVT outdoor measurement - thermal measurements

The thermal measurements must result in data that can be recalculated unambiguously to the thermal efficiency as a function of the in-plane irradiance and the difference between

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[2] Also higher measuring frequences are used; e.g. CEA uses 3 minute intervals for PV characterisation (Guerin de Montgareuil, 2005).

the coolant temperature and the ambient temperature. A practical way to do this is to determine the collector efficiency curve, presenting the collector efficiency as a function of reduced temperature, as described in this chapter. In addition, several correction factors should be determined such as the collector capacitance (paragraph 4.1), the angular correction factor for the incident angle of the irradiance (paragraph 4.2) and for unglazed collectors the wind correction (this chapter).

The irradiance will be measured by means of a pyranometer. In principle the thermal measurements will be identical to those prescribed in EN 12975-2 clause 6.1 for glazed collectors and in clause 6.2 for unglazed collectors. This includes the provision with regard to the flow rates to be used (for glazed collectors clause 6.1.4.3 applies (approximately 0,02 kg/s per square metre of collector gross area, unless otherwise specified), while for unglazed collectors clause 6.2.4.3 applies (approximately 0,04 kg/s per square metre of collector gross area, unless otherwise specified)). Also this includes the provisions with respect to the allowed test conditions (irradiance above 700 W/m^2, incidence angle small enough for keeping the deviations of the thermal efficiency from the case of normal incidence below ±2%, surrounding air speed between 2 and 4 m/s for a glazed collector and between 0 and 3.5 m/s for an unglazed collector). Also, the diffuse solar radiation must be less than 30%, as stated in EN 12975-2 clause 6.1.4.8.4.1. In addition, only measurement data obtained at quasi-stationary conditions are to be used in the data assessment. To qualify as quasi-stationary, the maximum variation limits during the measuring interval are for the irradiance +/- 50W/m^2, for the flow rate +/- 1%, for the ambient temperature +/- 1K and for the coolant temperature at the module's inlet +/- 0.1K. In addition, for unglazed collectors also the longwave radiation should not vary more than +/-20 W/m^2.

However, for PVT two special provisions need to be made

1. During the measurements, the PV should be operated at the maximum power point. Valid data can only be obtained when no part of the active PV material is shaded by the collector edges, which may limit the range of irradiance angles over which valid data can be collected (see paragraph 3.4.1 - Irradiance).
2. The large thermal capacitance of the PVT collector relative to a conventional thermal collector should be taken into account, and the correspondingly large time constant of the collector.

For the determination of the time constant see chapter 4.1.

For the determination of the efficiency curve, the procedure should be followed as prescribed in EN 12975-2 clause 6.1.4.4 for glazed collectors and 6.2.4.4 for unglazed collectors. For the glazed collector, measurements have to be taken at four temperature levels spaced evenly over the operating range of the collector, one being equal to the ambient temperature, and at each temperature level four independent values have to be obtained, amounting to 16 data points. For unglazed collectors, measurements have to be taken at three temperature levels and at three levels for the wind speed, amounting to 9 data points. Schematically, this is represented in Table 4 and Table 5.

Glazed PVT collector

	data 1	data 2	data 3	data 4
$T_m = T_a \pm 3$°C	(η_{th}, T_{red})			
$T_m \approx 40$°C				

Tm ≈ 60ºC				
Tm ≈ 80ºC				

Table 4: Thermal matrix glazed collector (temperature levels are indicative). All points should be evaluated under quasi-stationary conditions and at an irradiance > 700 W/m^2.

Unglazed PVT collector

	u < 1 m/s	u = 1.5 ±0.5 m/s	u = 3 ± 0.5 m/s
Tm = Ta ± 3ºC	(η_{th}, T_{red}, u)		
Tm = Ta+0.5 DTmax ± 3ºC			
Tm = Ta+1.0 DTmax ± 3ºC			

Table 5: Thermal matrix unglazed collector as prescribed by EN 12975-2 clause 6.2.4.4. All points should be evaluated under quasi-stationary conditions and at an irradiance > 700 W/m^2.

Table 5 is prescribed in the presented form by EN 12975-2, clause 6.2.4.4. DTmax is the maximum temperature difference between fluid and ambient under normal operation of collector. From the set of data measured for the unglazed PVT, the wind modifiers shall be calculated in accordance with EN 12975-2, clause 6.2.4.8.1.

It is not recommended to do measurements with the inflow temperature below the ambient temperature. An important reason not to go below ambient temperature is that condensation of air humidity might occur inside the collector, with lots of undesired effects (optical transmittance, thermal insulation, thermal capacitance may change; condensate will deliver extra-enthalpy to the collector which may yield wrong results of thermal performance measurement). In addition, the heat transfer processes (especially convection) may change when the collector gets below ambient temperature. This may influence the value of the heat loss coefficient.

3.4.3 Separate PV outdoor measurement

The electric efficiency of the PVT-module can be measured outdoor. The procedure is identical to the one described previously for the determination of the electrical performance under simultaneous outdoor thermal and electrical testing (4.3.1). In addition, water should be run through the collector at the temperatures prescribed in the procedure for the determination of the thermal performance (4.3.2) in order to obtain a representative filling of the power matrix.

3.4.4 Separate thermal outdoor measurement

For separate outdoor thermal testing, the procedure is identical to the one described previously for the determination of the thermal performance under simultaneous outdoor thermal and electrical testing (4.3.2). It is important to have the PV operated at its maximum power point during the measurements since this will strongly affect the thermal performance.
Although separate testing is possible, it appears to be more economic to carry out the measurements for electrical and thermal performance simultaneously as described in 4.3.1 and 4.3.2, due to the fact that the PV has to be functional anyway.

3.5 Presentation of the data

Thermal

For a glazed PVT collector, a representation of the collector performance in the form of a graph of the thermal efficiency as a function of the reduced temperature is recommended (for details, see EN 12975-2, annexes D to G).

For an unglazed collector, the same is recommended, with separate curves for each surrounding air speed.

Electrical

The electrical efficiency should be presented separately in two graphs that can be derived from the power matrix; once as a function of the module temperature (for a fixed irradiance) and once as a function of the irradiance (for a fixed temperature).

3.6 Summary

The paragraphs in chapter 3 are summarised in the following table.

	Thermal and Electrical simultaneously	**Electrical separately**	**Thermal separately**
Indoor	possible but not recommended	possible	possible but not recommended
Outdoor	recommended	possible	possible if PV functionality is active

4 Measurement of additional collector characteristics

4.1 Collector thermal capacity

The collector thermal capacitance can be determined according to the calculation method described in EN 12975-2 clause 6.1.6.2 or the procedure described in appendix J2 of EN 12975-2. The procedure described in appendix J3 of EN 12975-2 is not recommended as it seems to lead to values that are too high (Eisenmann et al, 2004).

4.2 Collector incident angle modifier

Collector incident angle modifier measurements can be performed in a way identical to the description in EN 12975-2.

- For glazed collectors, clause 6.1.7 applies.
- For unglazed collectors, clause 6.2.7 applies.

The determination of the collector incident angle modifier is recommended both for glazed and for unglazed PVT, due to the PV substrate that makes it more reflective than a conventional absorber.

4.3 PV shading effect

In PVT modules, shading of the PV may occur due to the edge of the collector casing. This effect does not occur for conventional PV modules or solar thermal collectors, and is therefore not present in either EN 12975 or IEC 61215. For unglazed PVT modules, this effect will normally not be important and can be ignored. However, for glazed PVT collectors the effect may be substantial. Values shall be given for the angle under which direct shading occurs at the upper edge, as well as at the sides of the PVT modules, as presented in the drawing below, resulting in 3 angular values that need to be specified.

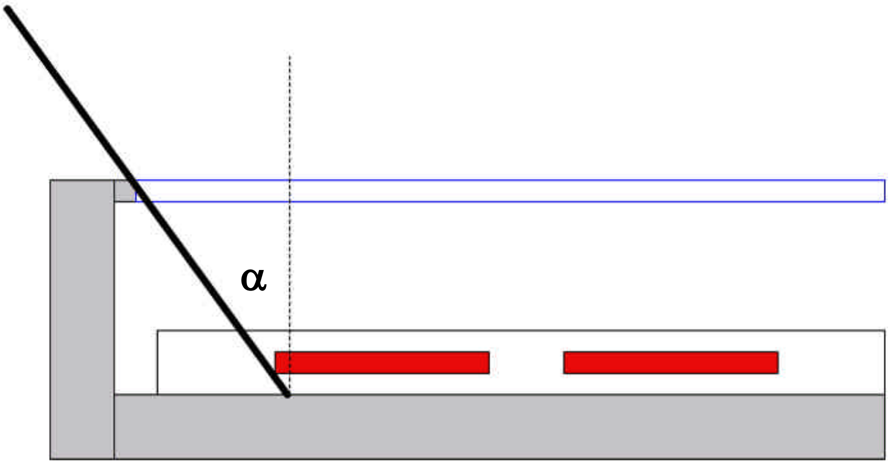

Figure 8: Definition PV shading angle α

In addition, the effect of shading on PV performance needs to be investigated. This can be tested similar to the procedure in which the collector incidence angle modifier is determined (EN 12975, clause 6.1.7), but now the effect on the PV output is measured, instead of on the thermal output. It is recommended to test at the prescribed values for 'unusual optical performance characteristics' under angles of 20°, 40° and 60°, and in addition at an angle very close to the PV shading angle, but a little smaller (e.g. 2.5°) so that the PV is not yet shaded (resulting in 4 measurement values, which for the larger angles may have partial PV shading). Two sets of such measurements need to be carried out in order to assess rotation along both edges of the collector, which is similar to the measurements required for an anisotropic collector (e.g. evacuated tube). This is also necessary if the shading angle is the same for all directions, since in that case a difference will probably still exist due to the orientation of the PV strings. For angles between 60° and 90° no additional measurements are proposed, since the accuracy of the measurements will become too low for such angles. Compared to the collector incidence angle modifier measurements, the measurement of the PV-output as a function of angle is a relatively fast procedure because quasi-stationarity is not required.

This test should be carried out under conditions of high direct irradiance (beam irradiance over 500 W/m^2), because otherwise the diffuse fraction of the irradiance will obscure the angular effect.

For convenience, it is recommended to combine the tests for the determination of the PV shading effect and the thermal incidence modifier in one set of measurements. Note that the thermal angle modifier and the electrical angle modifier will partially overlap, but once the angle is such that the PV is shaded, the two angle modifiers will start to differ from each other.

4.4 PVT thermal resistance measurement

For sheet-and-tube PVT modules, in the power matrix the mean PVT absorber rear temperature is used. In order to be able to predict the annual electrical yield, it is now required to be able to predict this mean PVT absorber rear temperature from the available inputs, being the ambient conditions and the mean collector fluid temperature. Now the mean PVT absorber rear temperature can be calculated if the thermal resistance between the collector fluid and the absorber is known, which therefore needs to be measured. No standard method is available for this measurement in EN 12975. Nevertheless, methods have been suggested in the literature. In particular, Rockendorf et al. (1995) suggest two methods, for which they indicate an error of about 12%.

The local method as recommended by Rockendorf et al. is followed here. During the thermal efficiency measurements, it is suggested to record the temperature difference between mean collector fluid temperature and mean absorber rear temperature, together with the thermal yield per unit absorber area. For their method to determine the average absorber temperature, see appendix B. The measurement should be carried out under quasi-stationary conditions, but since it can be carried out simultaneously with the thermal efficiency measurements, this does not lead to an increase in the time required for the characterisation. It is suggested to plot the temperature difference as a function of the thermal yield per unit absorber area and determine R_{rf} from the slope of this curve.

4.5 Pressure drop

Pressure drop measurements can be performed in a way identical to the description in EN 12975-2.

- For glazed collectors, clause 6.1.8 applies.
- For unglazed collectors, clause 6.2.8 applies.

Since the pressure drop strongly depends on the viscosity and the density of the fluid, the measurement should be carried out with the fluid that will be used in normal application later on.

5 Annual energy prediction

This paragraph depicts the use of the measured efficiency data for the annual energy prediction

5.1 General issues

1. In the power matrix method, the PV performance was shown versus the PVT mean fluid temperature and the irradiance. In this chapter, a method is presented to calculate the PV rear temperature from the mean fluid temperature and the ambient conditions.
2. In practical applications, it can be expected that the solar thermal collector will be switched off during a significant amount of time over the year (stagnation), while the PV will continue to provide electrical energy. The PV temperature should be determined for these cases in order to establish a realistic PV performance. Here, the approach is followed to calculate the stagnation temperature for various ambient conditions from the collector efficiency curves. A consequence of this choice is that for glazed collectors, the effect of wind speed on stagnation temperature is neglected, resulting in an overprediction of the PV temperature for these cases. The effect of wind speed on the stagnation temperature of a typical glazed PVT collector is shown, to show the order of magnitude of the effect. For unglazed collectors, the effect of wind speed is included in the efficiency curves.

5.2 Ambient conditions

The prediction of the annual energy production for a given site is based on the long-term meteorological data of that site. These data are available as hourly values or can be derived from available monthly data (e.g. using Meteonorm) for a complete calendar year. The available hourly data are:

- Irradiance on the horizontal plane (G_o)
- Ambient temperature (T_a)
- Wind speed (V_w)

The extra required hourly ambient data are:

- In-plane irradiance (G_i)
- In-plane wind speed (V_i)
- for an unglazed collector: Sky temperature (T_s) and longwave radiation (E_L)

The hourly values of G_i may need to be derived from G_o. However, in general, it is not obvious to deduce the in-plane radiation from horizontal values. Some sources of meteorological data include the beam and diffuse fractions of the global irradiance in the horizontal plane, which makes the calculation for the tilted collector plane easier and more accurate. However, if such data are not available, it is possible to calculate the beam and diffuse component of G_o, using the values of G_o and information on time and location (e.g. using the model of Orgill and Hollands (Duffie&Beckman, 1991)). From the data for beam and diffuse radiation, the total (beam, diffuse and ground reflected) in-plane irradiance can be calculated, e.g. using the model of Perez (Duffie&Beckman, 1991). The accuracy of various correlations was investigated by Van der Borg and Wiggelinkhuizen (2001).

The in-plane wind speed is problematic. First of all, the wind speed is a function of height. The test reference year will probably contain the wind speed, but on a height that is different from the location of the collector. However, this can be corrected for by means of a standard logarithmic profile that includes the effect of local surface roughness. However, a second problem exists, since in the built environment the local wind speed can be affected strongly by nearby buildings. Also, one should be aware that the building on which the collector is installed will itself affect the local wind speed, as the roof will cause the wind to deflect from its course. As an example, Figure 9 shows a relation between the in-plane wind speed at a test roof and the wind speed measured at a nearby meteomast (measured at a height of 10 meters) for different wind directions[3].

There is not really a good solution available for the calculation of the local in-plane wind speed; a detailed calculation of the flow field around the buildings in a street or block is possible but will be far beyond the scope of a normal annual yield calculation. It is suggested here to calculate the thermal performance simply by ignoring all detailed effects and to use a correction factor of 25% in a wind-protected situation or 75% in a wind-exposed situation. In addition, when the annual yield calculation is used for the sizing of a system, it is advisable to do a sensitivity study on the wind correction parameter.

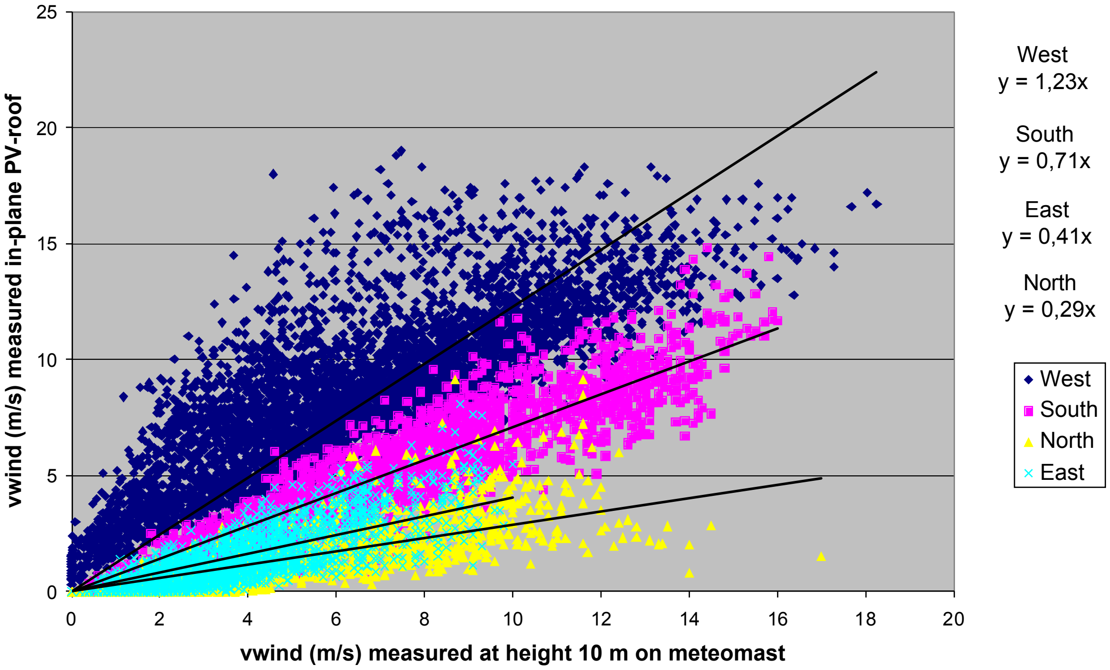

Figure 9: Relation between in-plane wind speed (measured on PV roof) and free field wind speed (measured at nearby meteomast) for different wind directions. The PV roof is oriented South.

Hourly data for the sky temperature should be obtained for the thermal performance of an unglazed PVT collector. The sky temperature can be calculated from the cloudiness factor and the clear sky emittance (see e.g. the TRNSYS type 69 sky temperature calculation). The longwave radiation can be calculated from the sky temperature and the view factor of the module.

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[3] Note that the wind direction has wide bins in the graph, e.g. west is defined as due west ± 45°.

5.3 Annual thermal yield

The thermal efficiency depends on the reduced temperature, which is a function of ambient conditions and mean collector fluid temperature. The mean fluid temperature is determined by the rise of the fluid temperature over the collector and by the inlet temperature of the collector. The rise in fluid temperature is calculated from the collector efficiency, the collector flow rate and the ambient conditions (G_j, T_a, V_w). However, the inlet temperature depends on the system, such as the thermal demand by the user, the solar fraction to be covered, the size of the storage, losses from storage and piping and other system parameters. The calculation of the inlet temperature requires a modelling of the full system, which can be carried out with the help of programs like TRNSYS. However, if the inlet temperature is known, the collector yield can be determined from the following formulas.

For glazed collectors only the angular dependence and the correction for capacitance are included:

$$E_{th} = A * \sum_{hour1}^{8760} \{G * K_{th}(\theta) * \eta_0 - a_1 * (T_m - T_a) - a_2 * (T_m - T_a)^2 - C\frac{dT_m}{dt}\}\,.$$

For unglazed collectors two additional wind terms and a correction for sky radiation apply:

$$E_{th} = A * \sum_{hour1}^{8760} \{G''*K_{th}(\theta) * \eta_0\left(1 - b_u \cdot u\right) - (b_1 - b_2 \cdot u) * (T_m - T_a) - C\frac{dT_m}{dt}\}$$

where

$$G'' = G + \frac{\varepsilon}{\alpha}(E_L - \sigma T_a^4)\,.$$

5.4 Annual electrical yield

For the determination of the electrical yield, the calculation is easier than for the thermal yield, due to the fact that for grid connected PV, the electrical performance is independent of the electrical demand. Given the amount and the angle of the irradiance, together with the PV cell temperature, the electrical efficiency can be calculated from the formula

$$E_{el} = A * \sum_{hour1}^{8760} (G_b * K_{el}\left(\theta\right) + G_d K_{el}) * \eta_{el}(G, T_{cell})$$

In this formula, $K_{el}(\theta)$ and K_{el} represent the direct and diffuse PV shading effect as indicated previously. A more detailed procedure for determining the annual electrical yield is presently developed in PV Catapult work Package 9 (in preparation).

The hourly values of the PV cell temperature can be calculated from the mean fluid temperature. This can be obtained by means of the following.

- If water is flowing through the collector, T^* needs to be calculated to be able to obtain the electrical efficiency from the power matrix.
  For a sheet-and-tube absorber $T^* = T_{rear} = T_m + \Delta T_{rear\_to\_fluid} \approx T_m + R_{rf} \times \eta_{th} G$
  For a fully wetted absorber: $T^* = T_m$
  where T_m is the mean collector fluid temperature and R_{rf} is explained in paragraph 4.4.

- If the collector is stagnating, for low wind conditions, the stagnation temperature can then be calculated from the thermal efficiency curves. In this case the module temperature is equal to the mean fluid temperature, since no heat is transferred; therefore T_m=T_{cell}. Now T_m can be calculated from the efficiency curves:
  $\eta_{th} = 0 \Rightarrow GK_{th}\eta_0 - a_1 * (T_m - T_a) - a_2 * (T_m - T_a)^2 = 0$,
  - for a2=0 this leads to
    $$T_m = \frac{\eta_0 K_{th} G}{a_1} + T_a$$
  - for a2>0 this leads to
    $$T_m = \sqrt{\frac{a_1^2}{4a_2^2} + \frac{\eta_0 K_{th} G}{a_2}} - \frac{a_1}{2a_2} + T_a$$

  In general, the effect of a2 on the calculated stagnation temperature is substantial and should be taken into account. If a2 is ignored, this will lead to a substantial overprediction of the stagnation temperature.
  One should be aware that for glazed PVT modules this procedure gives somewhat too low values for low-wind conditions and too high temperatures for windy conditions. For unglazed modules, the effect of wind is larger, but here it can be calculated directly from the efficiency curve since wind coefficients have been determined (see paragraph 3.4.2). To illustrate the order of magnitude of this effect, Figure 10 shows the stagnation temperature[4] for the extreme condition of 1000 W/m^2 irradiance for various wind speeds. In addition, the figure shows the value calculated from an extrapolation of the efficiency curve as indicated above. For the glazed modules, also the calculated value is shown of the stagnation temperature if the effect of a2 is ignored, to indicate that the second order calculation (a2>0) is more accurate than the much higher value found by the first order calculation.
  The figure shows that wind effects are substantial during stagnation, even for glazed modules. A wind correction for glazed modules could be measured, but it is argued here that since the occurrence of stagnation is in itself already an exception, the effect of this higher order correction on the annual PV yield will be small[5].

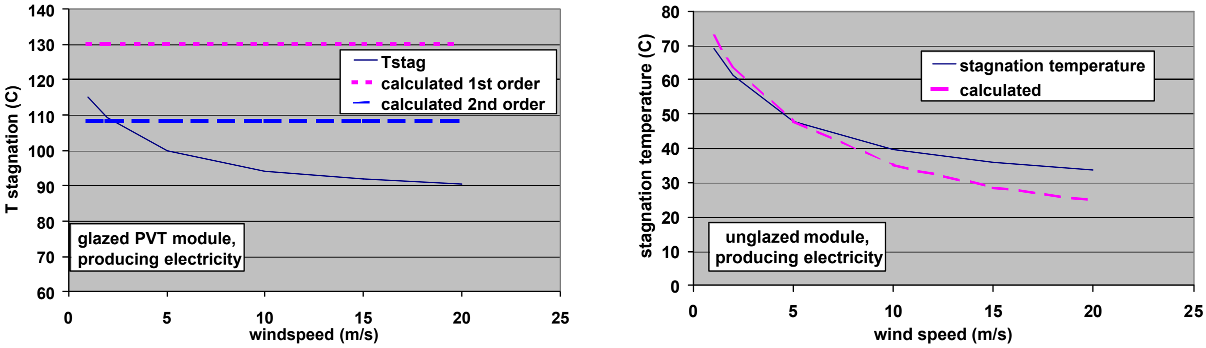

Figure 10: Stagnation temperature for varying wind speed, calculation by solving the energy balance versus calculation from the efficiency curve (G=1000 W/m^2, Ta= 20 C). LEFT: glazed PVT, RIGHT: unglazed PVT

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[4] Calculated by means of solving the energy balance (for model description, see Zondag et al., 2002).

[5] However, if such a correction would be deemed necessary, the basis for such a correction could be Kleins equation (see Duffie and Beckman, 1991). The correction will depend on the module characteristics (coefficient of emissivity of the PVT absorber, number of covers), which should therefore be parameters in the correction.

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Appendix A Proposal for PVT Reliability tests

A.1 General

A very important issue for PVT collectors is the subject of reliability tests. Presently, the experience in long term behaviour of PVT is insufficient to draw firm conclusions on reliability issues. However, some problem areas can be identified that need special attention.

A.2 Outdoor exposure test (outdoor test)

In IEC 61215 clause 10.8, an outdoor exposure test is described for PV to make a preliminary assessment of the ability of the module to withstand exposure to outdoor conditions and to reveal any synergistic degradation effects that may not be detected by laboratory tests. Similarly, EN 12975 clause 5.4 describes an outdoor exposure test for solar thermal collectors. This test describes a period of exposure during which the collector will be under stagnation. During this period, the collector should be exposed to a certain minimum level of irradiance (in W/m^2/day) for at least 30 hours, during which the ambient temperature should be above a temperature level, and should in addition have passed a minimum total amount of irradiation (in MJ/m^2) for at least 30 days, in which the prescribed levels depend on the climate type (the climates "temperate", "sunny" and "very sunny" are distinguished).
A point of attention is the total amount of irradiance that should have been received; for a temperate climate EN 12975 prescribes 14 MJ/m^2/day over 30 days (resulting in a total of 420 MJ/m^2), while IEC 61215 prescribes a total of 60 kWh/m^2 (=216 MJ/m^2). It is suggested here that the more demanding EN 12975 should be followed, in order to assess as accurately as possible the critical effect of long term stagnation on the collector. In addition, it is suggested that the collector is mounted, including any active or passive overheating protection devices that are prescribed by the manufacturer, and that the PV should not be producing electricity (because that would lower the stagnation temperature by a few degrees).

The collector temperature, the irradiance, the ambient temperature and the rainfall should be recorded. Care should be taken that the attachment of the sensors to the module does not compromise the reliability of the module in terms of rain penetration, insulation, etc. Visual checks should be carried out before and after the test.

This procedure seems particularly useful to start the testing procedure with:

- both IEC 61215 and EN 12975 indicate that this test allows the device to 'settle', increasing the reliability of the results found with subsequent testing.
- it provides a means to obtain information on typical collector stagnation conditions, which are relevant for other reliability tests such as thermal cycling, the UV test and the bypass diode thermal test.

It is suggested that from the monitoring data, an estimate for the maximum stagnation temperature is derived. This is the stagnation temperature that is to be expected at an irradiance of 1100 W/m^2, an ambient temperature of 30 °C and the minimum wind speed (corresponding to natural convection). A method for this extrapolation will most likely be included in the upcoming EN 12975:2006. From this maximum stagnation temperature, the critical temperature is determined, that will be defined as the maximum stagnation temperature, increased with another 10 °C, to ensure a sufficient safety margin. This critical temperature will be used in the subsequent reliability tests as described below.

A.3 Thermal cycling tests (indoor test)

In the PV test standard IEC 61215, the thermal cycling test is described, in which a PV module is subjected to a number of thermal cycles ranging from -40 °C to +85 °C. The aim of these tests is to find out if the PV will withstand a prolonged number of thermal expansions, without damaging the electrical contacts or other parts of the PV laminate.
In glazed PVT collectors, much higher temperatures can be found, with the maximum stagnation temperature typically in the range from 120-140 °C[6]. Therefore, a much more severe thermal cycling test is recommended. As a maximum temperature, the critical temperature as determined from the outdoor exposure test should be used.

Based on the prescriptions of the IEC 61215, thermal cycling is only prescribed for the PVT absorber. Although it may be problematic to introduce PVT-absorber tests in addition to PVT module tests, it is suggested here to carry out the thermal cycling tests on PVT absorber level, since it is considered that by prescribing this test on module level, unreasonable complications would be introduced due to the fact that the insulation would strongly decrease the thermal response time of the module, which would strongly increase the required duration of the cycling test (which, even without this effect, is already elongated due to the increased temperature range, taking over 2 months to complete 200 cycles). In addition, it is thought that a thermal cycling test on module level may be unreasonably demanding for the exterior parts of the module, that in practical application would never heat up to the absorber temperature.

A.4 UV test (indoor test)

The encapsulating material may show browning when subjected to long term UV exposure. This effect is strongly increased at high temperatures (as a rule of the thumb, the UV problem doubles with every 10 ºC temperature increase). The test described in IEC 61215 prescribes a temperature of 60±5ºC. It seems important to subject PVT to prolonged UV exposure under typical stagnation conditions.

- For glazed PVT collectors, the prescribed temperature in the UV test in IEC 61215 should be increased to the critical temperature.
- For unglazed PVT collectors, the procedure from IEC 61215 applies.

Whenever possible, this test should be carried out on the PVT module as a whole. It should be kept in mind that the collector cover may increase the UV stability, since UV-filters that may be present in the cover will be absent if absorbers are tested instead of modules.

A.5 Electrical insulation test and wet-leakage current test (indoor test)

Most PVT collectors will have a metal rear. A connection between the PV cell and the metal rear will result in short circuiting of the system. It is important to test the electrical

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[6] As a side remark, it should be noted here that the high stagnation temperature that can occur in glazed PVT modules will be problematic for many PV module manufacturers, since they may be willing to guarantee their products for temperatures above 85 °C. Encapsulation manufacturers may be willing to guarantee somewhat higher temperatures, but temperatures above 120 °C will be critical for many encapsulants.

resistance between the PV matrix and the metal rear. It addition, the PVT absorber may be placed in a metal collector box, with electrical wiring passing through the box.
First of all, a check should be carried out whether the prescribed level of electrical insulation has been applied, according to IEC 61730 (Photovoltaic module safety qualification). Next, an insulation test and a wet leakage current test can be carried out according to the procedure described in IEC 61215 clause 10.3 and clause 10.15, which seems to cover the aspect of electrical insulation sufficiently for PVT collectors as well. The wet leakage current test is of special significance for PVT due to the possible occurrence of condensation and wet thermal insulation in the collector casing. If the collector box is made of metal, also the insulation between the PV and the metal box should be tested. This may be done similar to the procedure described in IEC 61215 clause 10.3 and 10.15. These tests should be carried out both before and after the combined test for outdoor exposure test and internal thermal shock (see section on internal thermal shock); the difference between both test results should be below a threshold value (to be defined). Whenever possible, these tests should be carried out on the PVT module as a whole.

A.6 Bypass diode thermal test (indoor test)

In IEC 61215 a bypass diode thermal test is described. In the description of this test, the module is heated to 75 °C and a short circuit current is applied to the PV laminate. For PVT collectors the insulation increases any temperature problems that may occur.

- For a glazed PVT collector, the critical temperature should be applied.
- For an unglazed PVT device, the procedure from IEC 61215 applies.

Whenever possible, this test should be carried out on the PVT module as a whole, since the insulation will increase the bypass diode temperature.

A.7 Load due to external effects (indoor or outdoor test)

In EN 12975 tests are prescribed for external thermal shock (clause 5.5), impact (e.g. due to hail) (clause 5.10) and mechanical load (clause 5.9). The mechanical load test includes both pressure (e.g. due to snow) and lift, due to wind.
For unglazed PVT devices, it seems of specific importance to carry out these tests, since tension within the laminates may make them more vulnerable for these effects. Also for glazed PVT devices these tests should be carried out, but here no special sensitivities are expected, since these tests will concern the collector frame and glazing, which will be similar to conventional glazed collectors. In both cases, it is expected that the prescribed procedure in EN 12975 can be followed.

A.8 Internal thermal shock (outdoor test)

Cold water may be inserted into a stagnating collector, resulting in strong, sudden and inhomogeneous thermal contraction of the absorber and generation of steam. If PV is connected to the absorber, the effect of the thermal shock on the PV and on the connection of the PV to the absorber is of importance. However, the description of the internal thermal shock test in EN 12975 clause 5.6 seems to be sufficient for PVT also. It is suggested to combine this test with the outdoor exposure test, and to repeat it 2 times at various moments during this test, as described also as optional in EN 12975-2 clause 5.4.

A.9 Hot spot endurance (outdoor test)

PVT collectors are particularly sensitive to hot spots, since the insulation increases any temperature problems that may occur. In addition, if a hot spot occurs in combination with stagnation conditions, the resulting temperatures can be very high; the temperature may get substantially above hot-spot temperatures that may occur in a conventional PV laminate.

- For a glazed PVT collector, shadowing or soiling will not result in the full shading of a single cell. It is recommended to do the shading of a glazed module by blocking a part of the cover at a time when the irradiance is not less than 800 W/m^2 and the collector is under stagnation.
- For an unglazed module, the same procedure applies as in IEC 61215, with the provision that the irradiance is not less than 800 W/m^2 and the collector is under stagnation.

A.10 Conclusion

It will be clear that dedicated PVT reliability tests are required. Especially the stagnation temperature issue should receive attention. For such dedicated tests, a number of suggestions are made in this appendix. However, it should be emphasised that very little experience has been obtained with these test procedures until now and more R&D is required to establish the reliability and feasibility of these schemes.

Appendix B Absorber temperature gradient

B.1 Determination of the average absorber temperature

A PVT module will show a substantial temperature gradient over its absorber surface. In Figure 11, an infrared photograph of an unglazed sheet-and-tube PVT is shown, while cold water is flowing through. This photograph shows both the gradient over the collector (cold entrance to hot exit) and the gradient in between the collector tubes. Of course, the temperature gradient in between the collector tubes will not be present if the collector is stagnating or if a fully wetted absorber is used.

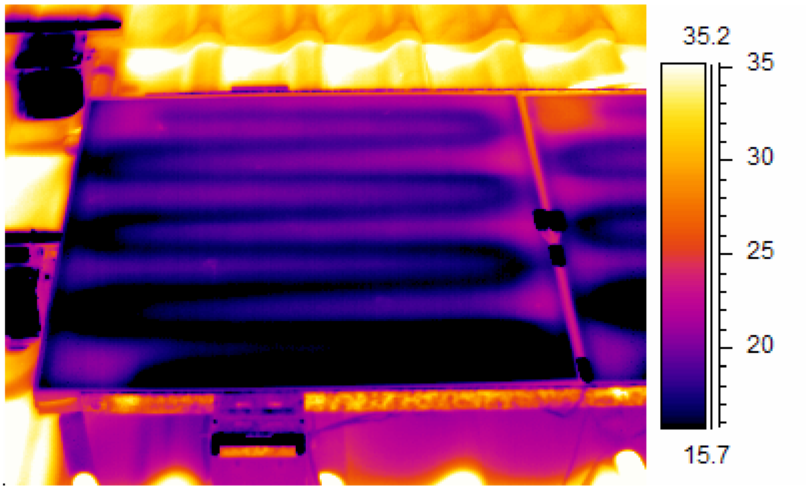

Figure 11: IR photograph of an unglazed PVT collector (top view). The temperature gradients in the top glass clearly resemble the cooling of the module by the collector tubes.

A typical temperature gradient over a glazed nonselective solar thermal absorber under high irradiance and low collector fluid temperatures (a worst case) is shown in Figure 12.

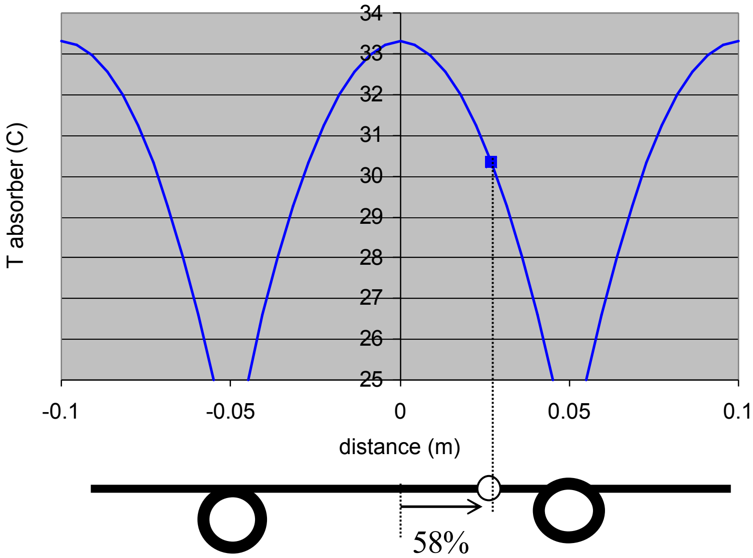

Figure 12: Temperature gradient between the tubes of a solar thermal collector (location of tubes as shown)

The temperature gradients over the PVT absorber complicate the determination of the average absorber temperature. However, Rockendorf et al. (1995) indicate that for typical absorbers, for which m(W-D)/2 lies between 0.1 and 0.8, the temperature at the location x=0.58(W-D)/2 as measured from the edge of the fin, is equal to the average temperature over the absorber. This distance is also indicated in Figure 12. In these formulas, D is the tube diameter, W is the distance between the centrelines of the tubes and m is given by the formula $m = \sqrt{U / kd}$, where d is the absorber plate thickness, k the coefficient of conductivity and U is the loss coefficient (see Duffie and Beckman, 1991, chapter 6). By putting a thermosensor at this location, the average absorber temperature can be measured directly. This method is cheap and easy to perform. This measurement of the absorber temperature requires that a hole is made in the backside insulation, the thermosensors are located onto the absorber and the insulation is re-inserted, but this is often necessary anyhow for the determination of the stagnation temperature (Rockendorf et al., 1995). Nevertheless, care should be taken that the thermal insulation is not degraded by this procedure.

In the present guideline, this method is followed and it is suggested to measure the PVT absorber rear temperature at this location between the tubes and at half the way that the fluid takes through the collector. As a point of attention, Rockendorf gives the warning that the outcome of this method depends on the local value of the thermal resistance between the absorber and the fluid; the method could be improved by the use of a second sensor location. However, more experience is required before more detailed recommendations are given on this aspect.

Of course, one will then have the average absorber temperature, which will still differ from the average PV cell temperature due to the temperature gradient between cells and rear (see appendix E2).

B.2 Effect of temperature gradient on electrical efficiency

Now the temperature gradient may affect the PV efficiency. For the case that the cells are all connected in series, the average cell temperature of the module determines the cell efficiency, even if a temperature gradient exists over the module (Smith et al, 1978). However, if (strings of) cells are connected in parallel, voltage mismatch will occur and the PV yield will be lower than in the case of series connection (Lambarski, 1984). In such cases, the temperature coefficient will be larger than expected due to the additional temperature induced mismatch. A point of attention is the temperature gradient on the level of a single cell. A cell can be regarded as a parallel connection of two half cells, and also here the voltage mismatch may lead to increased mismatch losses. This effect is expected to be small and is not taken into account in the present performance guideline.

Appendix C Power matrix method and IEC 61215

The power matrix procedure is not opposing the IEC 61215 standard but it goes a little bit further. The ultimate purpose of the performance characterization is to determine a set of module data that allows for the prediction of the annual electric energy output for a given site (accommodated with hourly data on irradiance and ambient temperature). As a consequence the module output at maximum power point must be known at all relevant in-plane irradiances and module temperatures. The IEC standard describes how to measure the temperature coefficient of the P_{mpp} through indoor tests. It does not provide guidance for outdoor measurements to arrive at the temperature coefficients. Furthermore the IEC standard describes the measurement of performance at 1000 W/m^2 and 200 W/m^2 only. In the power matrix procedure for outdoor measurements we propose to measure the module output as a function of the module temperature (in bins of 5 K) and as a function of the in-plane irradiance (in bins of 100 W/m^2). The difference with IEC is that the temperature coefficient is obtained by outdoor measurements and that the irradiance dependency of the module output is determined in more detail. The matrix procedure allows furthermore to combine measurement data within each element of the matrix to averaged values of $P_{mpp}(G_i , T_{mod})$.

The disadvantage of the power matrix representation of the measurement results is that empty matrix elements, which are unavoidable, suggest that the dataset is incomplete and that therefore the IEC standard would be preferable. This is a misconception since the dataset will be more complete than the data resulting from the IEC standard.

Appendix D Symbols

Greek symbols	
α	coefficient of absorption [-]
ε	coefficient of emission [-]
η_{el}	electrical efficiency [-]
η_{th}	thermal efficiency [-]
ρ	density [kg/m3]
Φ	volume flow rate [m3/s]

Latin symbols	
A	aperture area [m^2]
a1, a2	collector loss coefficients glazed collector
bu, b1, b2	collector loss coefficients unglazed collector
C	effective collector thermal capacity [J/K]
C_p	specific heat capacity [J/kgK]
D	tube diameter [m]
DT_{max}	maximum temperature difference between fluid and ambient under normal operation of collector [K]
E_L	longwave radiation measured in collector plane [W/m^2]
G	irradiance [W/m^2]
Gi	irradiance on tilted plane [W/m^2]
Go	irradiance on horizontal plane [W/m^2]
I_{mpp}	Current in maximum power point [A]
P_{mpp}	Electric power at maximum power point [W]
q	Heat flux [W/m^2]
R_{cf}	Specific thermal resistance [m^{2}K/W] between fluid and PV cells
R_{cr}	Specific thermal resistance [m^{2}K/W] between PV cells and absorber rear
R_{rf}	Specific thermal resistance [m^{2}K/W] between fluid and absorber rear
T	temperature [ºC]
T_a	ambient temperature [ºC]
T_{cell}	average temperature of PV cell [ºC]
T_{front}	average temperature of front glass of PV module [ºC]
T_m	mean fluid temperature (equals $(T_i+T_e)/2$) [ºC]
T_{red}	reduced temperature (equals (Tm-Ta)/Gi) [m^{2}K/W]
T_s	sky temperature [°C]
u	surrounding air speed [m/s]
V_{mpp}	Voltage in maximum power point [V]
v_w	wind speed [m/s]
W	distance between centrelines of the collector tubes [m]

Appendix E Proposal for a derived power matrix method

E.1 Derived power matrix method

The power matrix may be measured in the form as shown in paragraph 3.4.1. However, as indicated before, the relation between T^* and the PV cell temperature is not unique. A temperature difference exists between T^* and the PV cell temperature that depends on the thermal resistance and the local heat flow, which is a function of both the thermal efficiency and the irradiance.

Therefore, one may present in addition to the measured power matrix as shown in paragraph 3.4.1 also a corrected table in which not the fluid temperature is used for the temperature bins, but a corrected temperature that is an approximation of the actual cell temperature:

For a sheet-and-tube absorber: $T_{cell} = T_{rear} + R_{cr} \times \eta_{th} G_i A$

For a fully wetted absorber: $T_{cell} = T_m + R_{cf} \times \eta_{th} G_i A$

where T_{cell} is the average cell temperature, T_{rear} the mean PVT absorber rear temperature, T_m the mean collector fluid temperature, η_{th} the thermal efficiency (can be calculated from the thermal collector efficiency curve, the inflow temperature and the ambient conditions (irradiance, ambient temperature and for unglazed collectors also the wind speed)), and R_{cr} and R_{cf} are the thermal resistances between rear and PV or fluid and PV respectively, for which a measurement procedure is described below. In order to be able to calculate these "derived temperatures", one needs to measure not only the electrical power itself, but also the coefficients required for the calculation of the thermal efficiency (which for unglazed includes wind speed). If this correction is applied, it is expected that the scatter in the power matrix will reduce, leading to a more accurate prediction of the performance.

$T_{cell, calculated}$ G_i	0 - 5 ºC	5 - 10 ºC	10 - 15 ºC	etc
0 - 100 W/m^2	P_{mpp}			
100 - 200 W/m^2				
200 - 300 W/m^2				
300 - 400 W/m^2				
etc				

Table 6: Derived power matrix for electrical PV performance

For the calculation of the annual yield from the derived power matrices, one should of course find a way to calculate T_{cell} instead of T*. This can be done as follows:

For a sheet-and-tube absorber $T_{cell} = T_m + \Delta T_{cell-to-fluid} \approx T_m + (R_{cr} + R_{rf}) \times \eta_{th} G$

For a fully wetted absorber: $T_{cell} = T_m + \Delta T_{cell-to-fluid} \approx T_m + R_{cf} \times \eta_{th} G$

where T_m is the mean collector fluid temperature.

E.2 Proposal for an approximate method to determine the thermal resistances used in the derived power matrix method for well-insulated PVT modules.

A problem of the derived power matrix approach is that the thermal resistances R_{cr} for a sheet-and-tube absorber and of R_{cf} for a fully wetted absorber are required, for which no standard measurement method exists. In addition, only very little experience has been gained on the determination of these quantities. As a first tentative proposal on how such a quantity could be determined, the following procedure is presented for well-insulated PVT modules.

For a sheet-and-tube absorber, R_{cr} can be determined from the formula:

$$R_{cr} = \frac{T_{cell} - T_{rear}}{q}$$

These quantities may be measured as follows:

T_{rear}: As indicated in appendix B, a substantial temperature gradient may exist over the PVT absorber. In appendix B a method is presented to determine the mean absorber rear temperature.

T_{cell}: Since it is not possible to measure the cell temperature itself, the temperature has to be measured at the front of the PVT absorber. If the thermal loss from the PV cells to the PVT absorber front is small, the temperature difference between cells and front is also small. This will be the case for reduced temperatures of about zero, especially if the collector is glazed. Now the PV front temperature is not easy to define, because of the temperature gradients over the PVT absorber (see appendix B). It is suggested here to measure the PV front temperature by putting a thermosensor at the PV front exactly above the thermosensor that is used for the determination of the average rear temperature.
A temperature sensor at the front may cause PV shading, strongly affecting the PV performance and disturbing the measurement. These measurements should therefore be carried out while the PVT is not electrically active. Furthermore, the thermosensor should not be affected by the irradiance it receives and care should be taken that the shading by the thermosensor (including fixing tape and radiation shield) does not affect the local module absorber temperature too much. It is recommended to shield this sensor by means of reflecting tape, but to keep the area of reflecting tape as small as possible.

q: The heat flux between PV cells and collector fluid can be approximated by the thermal yield of the PVT collector. It should be stressed here, that this assumption implies that the rear losses from the collector are very small. This will not always be the case (e.g. when little or no thermal rear insulation is applied). For this measurement, quasi-stationarity is required.

It may be concluded that R_{cr} has to be measured under non-standard conditions (no electrical yield). Therefore it is suggested to measure R_{cr} in a short dedicated test. For the presentation of the results, it is suggested to plot the temperature difference as a function of q and to determine R_{cr} from the slope of this plot.

For the case of a fully wetted absorber, the thermal resistance between PV cells and the collector fluid is required which can be determined from

$$R_{cf} = \frac{T_{cell} - T_{fluid}}{q}$$

For the PV cell temperature and the heat flux the same holds as above, while the mean fluid temperature is defined as the average of inflow and exit temperatures.

However, it will be clear that the presented method for the calculation of R_{rc} and R_{cf} is far from a general procedure, and more R&D is required to establish better and more general methods for the determination of these thermal resistances, as well as the to establish to what extent the "derived power matrix method" itself is able to increase the accuracy of the PVT characterisation.