Hukseflux
Thermal Sensors

USER MANUAL PVMT01

PV module temperature sensor, Pt1000 Class A, for back-of-module temperature measurement

compliant with IEC 61724-1 Class A

Cautionary statements

Cautionary statements are subdivided into four categories: danger, warning, caution and notice according to the severity of the risk.

DANGER
Failure to comply with a danger statement will lead to death or serious physical injuries.

WARNING
Failure to comply with a warning statement may lead to risk of death or serious physical injuries.

CAUTION
Failure to comply with a caution statement may lead to risk of minor or moderate physical injuries.

NOTICE
Failure to comply with a notice may lead to damage to equipment or may compromise reliable operation of the instrument.

Contents

List of symbols

Quantities	Symbol	Unit
Voltage output	U	V
Temperature	T	°C
Electrical resistance	R_e	Ω
Time in hours	h	h
Plane of Array	POA	W/m^2
Thermal resistance	R_{th}	$°C/(W/m^2)$

Subscripts

back of PV module	BOM
PV cell	CELL
sensor	SEN

Acronyms

ASTM	American Society for Testing and Materials
AWM	Appliance Wiring Material
AWG	American Wire Gauge
EN AW	European Aluminium Wrought
FEP	Fluorinated ethylene propylene
IEC	International Electrotechnical Commission
IPA	Isopropyl alcohol
ISO	International Organization for Standards
TCR	temperature coefficient of resistance
PV	Photovoltaic
PRT	platinum resistance thermometer
PR	performance ratio
WMO	World Meteorological Organization

Introduction

PVMT01 measures the temperature of a PV module. Assessing PV system performance, this back-of-module temperature measurement allows users to estimate and correct the performance index for the temperature dependence of module efficiency. PVMT01 meets or exceeds the specifications required by IEC 61724-1.

PVMT01 consists of a Class A Pt1000, connected in a 4-wire configuration for increased accuracy. The sensor is enclosed in a small aluminium disk. The small size minimises the impact on bifacial modules (IEC requires obscuring less than 10 % of the surface area of any cell). The adhesive on the sensor disk is well-suited for long-term outdoor use. The adhesive has excellent thermal properties, including a total heat transfer coefficient larger than 500 W/(m^2·K) as required by IEC.

The flexible and weather-proof cable has a small diameter. For bifacial modules this cable should be routed between the cells, as recommended by IEC. The small cable diameter not only helps to improve measurement accuracy, but also helps minimising the mechanical stress on the sensor disk and on the adhesive connecting the sensor to the module. PVMT01 comes with a standard cable length of 1 m. The cable can be easily extended using an extension cable.

PVMT01 is designed for compatibility with the most commonly used data logger models. For many models, there are example programs and wiring diagrams available.

Figure 0.1 *PVMT01 installed on the rear side of a PV module. The sensors are preferably installed at the centre of a cell close to the centre of the module. IEC requires 3 sensors per monitoring station.*

Suggested use for PVMT01:

- long-term PV system performance monitoring
- module temperature measurement in PV prospecting

PVMT01 unique features and benefits:

- high measurement accuracy
- compliant with requirements of IEC 61724-1:2021 for Class A systems
- disk adhesive rated for prolonged outdoor use
- small surface area to minimise impact on bifacial modules
- thin cable for routing between cells of bifacial modules
- thin cable minimises the mechanical force on the adhesive connecting the sensor to the module
- easily extendable cable
- ingress protection class: IP67

1 Ordering and checking at delivery

1.1 Ordering PVMT01

PVMT01 is supplied in packs of ten sensors, each sensor is provided with a cleaning alcohol wipe, two solar edge clips to attach the cable to the edge of the PV module and two polyester tapes to secure the sensor cable on the module. PVMT01 comes with a 1 meter cable with connector and a sensor disk with adhesive for easy installation.

1.2 Included items

Arriving at the customer, the delivery should include:

- 10 x PVMT01 sensor with serial number
- installation instructions

For each PVMT01 sensor:
- 1 x pre-saturated IPA (isopropyl alcohol) wipe per sensor
- 2 x solar clip per sensor
- 2 x polyester tape per sensor

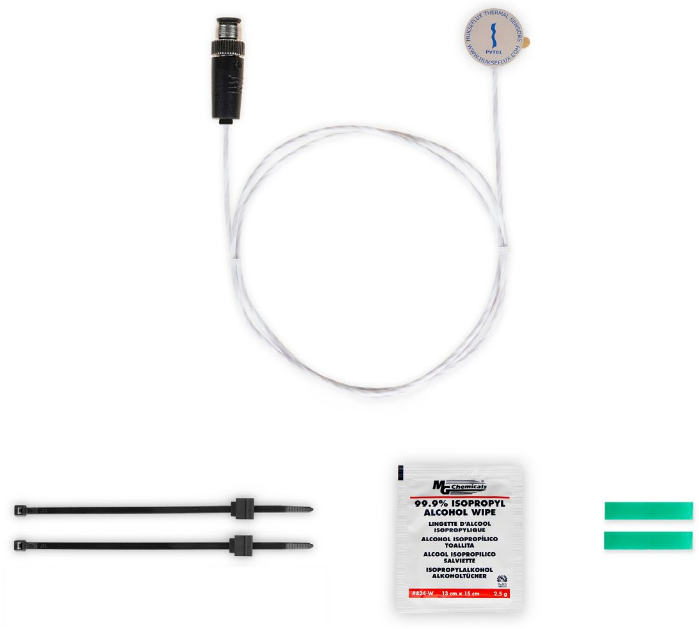

Figure 1.2.1 *PVMT01 comes with 2 x solar clips, 2 x polyester tapes and a pre-saturated IPA wipe.*

1.3 Quick instrument check

Inspect the packing and contents for any damage. Check the sensor serial number on the cable label against the product certificate provided with the sensor.

2 Instrument principle and theory

PVMT01 measures back-of-module temperature for solar energy applications. The disk houses a high accuracy Class A Pt1000. The measurement made with PVMT01 is used to correct the performance index for the temperature dependence of the efficiency of PV modules in PV system performance monitoring.

2.1 Stable and accurate

The Pt1000 is stable over a broad temperature range. It can measure back-of-module temperature accurately, also when a cable is extended to longer cable lengths than the standard 1 m cable. The 4-wire configuration eliminates the electrical resistance of the cable from the measurement and is the recommended way to connect this sensor.

The sensor is enclosed in a small aluminium disk. The compact design minimises impact on bifacial modules (IEC 61724-1 requires obscuring less than 10 % of the surface area of any cell). The adhesive on the sensor disk is well-suited for prolonged outdoor use. The adhesive has excellent thermal properties, including a thermal conductance larger than 500 W/(m^2·K) as required by IEC 61724-1:2021.

Figure 2.1.1 *Adhesive on the back of the aluminium disk with excellent thermal properties. The paper release liner should be removed before mounting the sensor to the surface.*

The flexible and weather-proof cable has a small diameter. For bifacial modules, the cable is routed between the cells to minimise module shading. The small cable diameter helps improve measurement accuracy and helps minimising the mechanical stress on the sensor disk and the connector. The thin adhesive tab on the disk ensures easy installation and promotes heat transfer from the surface.

Secure the sensor cable to the module's back sheet using polyester tape at 2 points to reduce strain on the sensor element and to keep cable temperature as close as possible to module temperature.

2.2 Attaining a high measurement accuracy

The PVMT01 measures the "back-of-module temperature", T_{BOM}. IEC 61724-1 recommends the use of back-of-module temperature sensors, and thereby accepts T_{BOM} as a good approximation of cell temperature, T_{CELL}. At the same time, IEC 61724-1 explains that T_{BOM} is not equal to T_{CELL} and also that the measured temperature T_{SEN} may not be equal to T_{BOM}; certain measurement errors are accepted.

Users should carefully select and install PV module temperature sensors.

It is important to realise that sensors such as PVMT01, unless they are thermally insulated (which is not recommended), will measure a temperature T_{SEN} between ambient air temperature and T_{BOM}.

This means that, in the presence of solar radiation, T_{SEN} will be lower than T_{BOM} , which is again lower than T_{CELL}. You may also say that measurements with poorly designed and badly installed sensors will have a higher uncertainty of "the quantity to be measured (measurand)" T_{BOM}.

The PVMT01 is designed to optimise the measurement accuracy.
- PVMT01 employs a Class A Pt1000, which keeps sensor-related uncertainties as low as possible
- PVMT01's adhesive has a very low thermal resistance

Measures that users may take to attain a high measurement accuracy:

- working with PVMT01 users should connect as much of the sensor and cable to the PV panel as possible. Use tape, supplied with the sensor, to connect cable to panel. Using tape, the cable temperature will be close to the panel temperature.
- regular inspection of the connection between sensor and PV module.

NOTICE
Do not apply thermal insulation material to the sensor.

IEC 61724-1 Annex B states "*Temperature sensor readings may be affected by wind causing temperature readings lower than cell temperature. Application of thermal insulating tape over the sensor can be used to suppress the wind cooling effect. For this purpose using foam resin tape with an aluminium cover layer over the temperature sensor glued to the surface of the PV module backsheet is introduced in IEC 60904-5*" Hukseflux does not agree. Sensors must not be insulated, because then the PV panel has a locally insulated backside. The local PV module temperature will then be much higher than that of the rest of the panel; so the temperature that is measured with thermally insulated sensors will no longer be representative of the module or array temperature, and be much too high.

2.3 PV system performance ratio

Performance ratio (PR) of a PV system is the ratio of measured energy to expected energy (based on measured irradiance). It offers an indication of the overall effect of losses on the system. There are many factors that impact the energy production of a solar installation. A detailed performance model may be used to predict electrical output of PV system as function of meteorological conditions.

Temperature is one of the main "influence quantities" on the performance ratio.

A typical temperature dependence of a PV panel electrical output power is in the order of -0.3 %/°C to -0.4 %/ °C. IEC 61724-3 gives an example in Table 1 of a module power temperature coefficient of -0.35 %/°C.

IEC 61724-3 introduction states that module temperature is primarily a function of

- irradiance,
- ambient temperature and
- wind speed

This gives seasonal variation, with higher performance ratio values in winter and lower in summer (for systems in the northern hemisphere). See Figure 2.3.1.
Also, the performance ratio generally decreases with increasing irradiance. Usually, higher irradiance leads to increasing PV module temperature and results in a lower panel efficiency.

IEC 61724-1 chapter 14 distinguishes between different temperature-corrected performance ratio parameters. For more information, refer to the standard.
By calculating the temperature-corrected performance ratio, the seasonal variation in PR can be significantly reduced.

IEC 61724-2 (via Annex A) allows two methods to determine PV cell temperature:

- estimated, using a model, from measurements of POA irradiance, ambient temperature and wind speed
- from direct measurements of back-of-module temperature, using a PV module temperature sensor like PVMT01

The first method is not often used, because uncertainty of this model-based approach is relatively high. Temperature data from PVMT01 sensors can be used to perform a direct measurement.

Optionally, additional corrections may be used to calculate PV cell temperature: IEC 61724-2 appendix A suggests to correct for error [T_{CELL}-T_{BOM}] . The formula [T_{CELL} = T_{BOM} + POA·R_{th}] may be used for correction, with R_{th} a thermal resistance which depends on the module design and in the range of (1 to 3) x 10^{-3} °C /(W/m^2), in °C per W/m^2 POA irradiance.

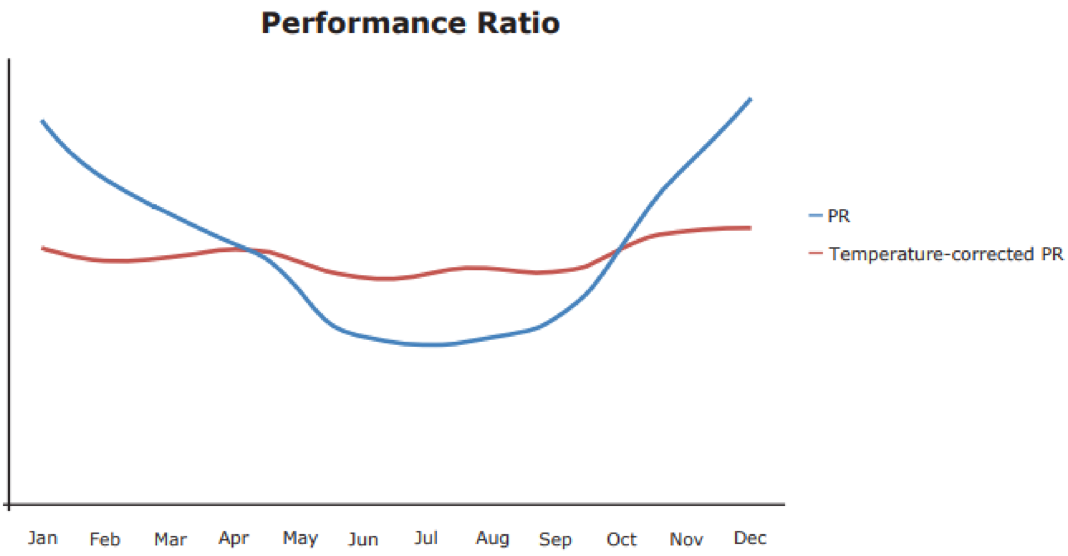

Figure 2.3.1. *Performance ratio (PR) with and without temperature correction. This schematic graph is for a PV system located in the northern hemisphere. Temperature measurements with PVMT01 can be used for temperature correction.*

PV modules have temperature coefficients in the order of – 0.35 %/K; at lower temperature we expect PV panels to perform better. Using badly designed sensors, the measured back of module temperature will always be underestimated, leading to an underestimation of the cell temperature. At the lower temperature, we expect the panel to perform better than it actually does. The result is a lower estimate of the performance index.

We assume that the absolute error in °C is proportional POA irradiance, so that the error is not a constant percentage; the performance index is reduced by a higher percentage at higher irradiance levels.

In compliance testing or system commissioning, this systematic underestimation of the performance is a disadvantage for the seller of a PV system.

2.4 Converting resistance into temperature

The linear correlation between the electrical resistance of the Pt1000 and the temperature is used to measure the temperature. A rise in temperature is proportional to the rise in electrical resistance.

See equation 2.3.1 for the conversion formula.

$$T = \frac{-A+\sqrt{A^2-4B\left(1-\frac{R_{Pt1000}}{1000}\right)}}{2B} \qquad \text{(Formula 2.3.1)}$$

With R_{Pt1000} the resistance in Ω, T the temperature in °C, and A and B the Pt1000 coefficients.

$A = 3.908 \times 10^{-3}$
$B = -5.775 \times 10^{-7}$

3 Specifications of PVMT01

3.1 Specifications of PVMT01

PVMT01 measures the temperature of the rear side surface of PV modules. It can only be used in combination with a suitable measurement system. The instrument should be used in accordance with IEC 61724-1:2021, section 9.1.

Table 3.1.1 *Specifications of PVMT01 (continued on next pages).*

TEMPERATURE SENSOR	
Sensor type	Pt1000 Platinum resistance thermometer (PRT)
Sensor class (IEC 60751)	A
Product description	precision 1000 Ω platinum temperature sensor
Sensor connection	4-wire, 4P male M12-A connector
Sensor housing	aluminium disk
Measurand in SI units	back-of-module surface temperature in °C
Rated operating temperature range Sensor and cable Connector	 -40 to +150 °C -40 to +80 °C
Long-term stability	resistance drift < 0.15 ºC at 0 °C (after 1000 h at 300 °C) as per ISO 60751:2022
Insulation resistance	> 2 GΩ at 1 kV as per IEC 60060-1
Measurand	
Uncertainty related to sensor classification	± (0.15 + 0.002|T|) ºC
Measurement resolution	≤ 0.1 °C
Achievable measurement uncertainty	± 2 °C from back-of-module surface temperature (at steady state POA 1000 W/m²) See chapter 6
Measuring current	< 1.0 mA
PVMT01 COMPLIANCE	
Standard governing use	IEC 61724-1:2021 photovoltaic system performance – part 1: monitoring, section 9.1 and appendix B
PRT standard	IEC 60751:2022
Ingress protection class	IP67 as per IEC 60529
Hazardous substances	EU RoHS2 (2011/65/EU) and EU 2015/863 amendment known as RoHS3
IEC 61724-1:2021 COMPLIANCE	
IEC 61724-1:2021 compliance	meets Class A and Class B performance specifications
Number of sensors required for IEC compliance	suggested: 3 per monitoring station required: minimum 6 per PV system, depending on the size of the system
Sensor surface area for bifacial modules	sensors and wiring should obscure < 10 % of the area of any cell. A common cell size is 6 by 6 inch. The PVMT01 sensor obscures 2.1 % of such cell. A 2.5 mm diameter PVMT01 wire obscures 1.6 %. The sum of 3.1 % is well within the IEC requirements.

Table 3.1.1 *Specifications of PVMT01 (continued on next pages).*

PVMT01 ADDITIONAL SPECIFICATIONS	
Marking	Hukseflux logo indicating front side; 1 x label at end of the cable showing the sensor serial number
Response time (95%)	< 30 s
Recommended readout	4-wire configuration
Nominal sensor resistance	1000 Ω
MECHANICAL	
Aluminium disk	
Disk material	anodized aluminium, EN AW 6082
Disk diameter	25×10^{-3} m
Disk thickness	5.5×10^{-3} m
Net weight including 1 m cable	approx. 0.5 kg
Adhesive	
Adhesive	3M VHB F9469PC
Adhesive material	acrylic sticker material
Adhesive thickness	0.13×10^{-3} m
Adhesive thermal conductivity	0.16 W/(m/K)
Adhesive heat transfer coefficient	> 500 W/(m²·K) as required in IEC 61724-1
ENVIRONMENT	
Ingress protection rating (IEC 60529)	IP67
Maximum pressure	6 bar
UV resistance	no UV degradation
electrical insulation sensor to PV module	> 1 kV
INSTALLATION AND USE	
Typical conditions of use	outdoors, at the rear side of PV modules
Product lifetime	10 years (expected)
CALIBRATION	
Calibration traceability	to SI units
Validity of calibration	if stored properly, product retains its performance and properties for 24 months from date of manufacture.
Requirements for recalibration	depends on the application and its requirements for measurement uncertainty. The decision is left to the user.
CABLE REQUIREMENTS	
Cable length	1 m
Cable extension	may be extended by the user to preferred length see section 4.2 for more information

Table 3.1.1 *Specifications of PVMT01.*

CABLE SPECIFICATIONS	
Jacket material	white TPU (thermoplastic polyurethane)
Jacket rating	-40 °C to 90 ºC, 3000 hours: 150 ºC
Wiring	4 x copper stranded wire
Conductor cross-section	0.14×10^{-6} m^2 (26 AWG)
Maximum conductor resistance	134.5 mΩ/m
Cable diameter	2.5×10^{-3} m
Marking	1 x label with serial number at connector-end cable
Rated bending radius	static > 12.5 mm dynamic > 50 mm
CONNECTOR SPECIFICATIONS	
Connector type	4P male M12-A connector (thread external, on outside of connector housing)
Requirements for connector of extension cable	4P or 5P female M12-A connector (thread internal, on inside of locking nut)
Connector weight	31×10^{-3} kg
Strain relief connector (IEC 61215-2)	> 40 N
Connector rated operating temperature	-40 °C to + 80 ºC
SUPPLY AND PACKAGING	
Supply	10 x PVMT01 in one bag
Packaging size for 10 x PVMT01	1 zip bag of (0.42 x 0.40 x 0.05) m
Gross weight for 10 x PVMT01	0.75 kg
Net weight for 10 x PVMT01	0.5 kg
Packaging size for 1 x PVMT01	1 zip bag of (0.3 x 0.2 x 0.02) m
weight for 1 x PVMT01	0.045 kg

3.2 Dimensions of PVMT01

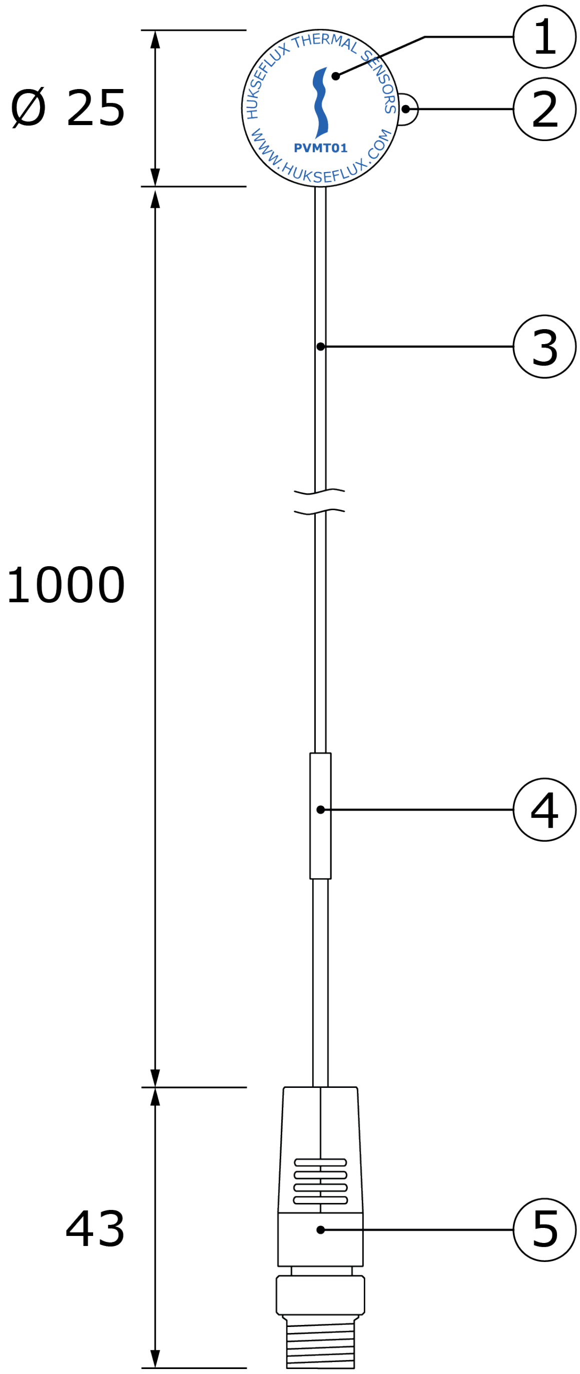

Figure 3.2.1 *Dimensions of PVMT01 in x 10^{-3} m. Total sensor thickness including adhesive is 5.8 x 10^{-3} m.*

(1) *sensor housing*
(2) *adhesive with paper release liner*
(3) *cable; standard length 1 m*
(4) *product label*
(5) *connector*

4 Installation of PVMT01

4.1 Site selection and mechanical installation

Table 4.1.1 *Recommendations for installation of PVMT01.*

Location	mount the sensor on the rear side of the module. IEC 61724-1 recommends selecting a location at the centre of a cell close to the centre of the module, avoiding boundaries between cells. do not place the cable and/or connector in direct sunlight.
Location – bifacial modules	wiring/cable should be routed in between cells when possible.
Site selection	before mounting, clean the back of the PV module with the provided IPA wipe. Allow all cleaned surfaces to dry completely before proceeding.
Adhesive mounting	an adhesive layer covers the back of the aluminium disk. To mount the sensor, remove the paper release liner and place the disk on the back of the PV module. Press the disk firmly for a few seconds to ensure good bonding of the sensor to the surface.
Mechanical mounting / thermal insulation	there should be no dust, dirt or other debris between the sensor and the PV module.
Attachment of the cable / strain relief	for mechanical stability, in order to avoid exerting too much force on the sensor and to keep cable temperature as close as possible to module temperature, attach sensor cable with strain relief with the provided solar clips and polyester tape. Two clips and two tapes are provided with every sensor.
Performing a representative measurement	IEC 61724-1:2021 requires a minimum of 6 PVMT01 sensors per PV system, depending on the size of the system as per IEC 61724-1. Suggested by IEC: 3 per monitoring station.
Long cable lengths	Cable extension is possible by using a connector matching the PVMT01 connector and an extension cable. Placement of extension cable inside a rugged conduit is advisable for longer cable lengths, especially in locations subject to digging, mowing, traffic, animals, etc.

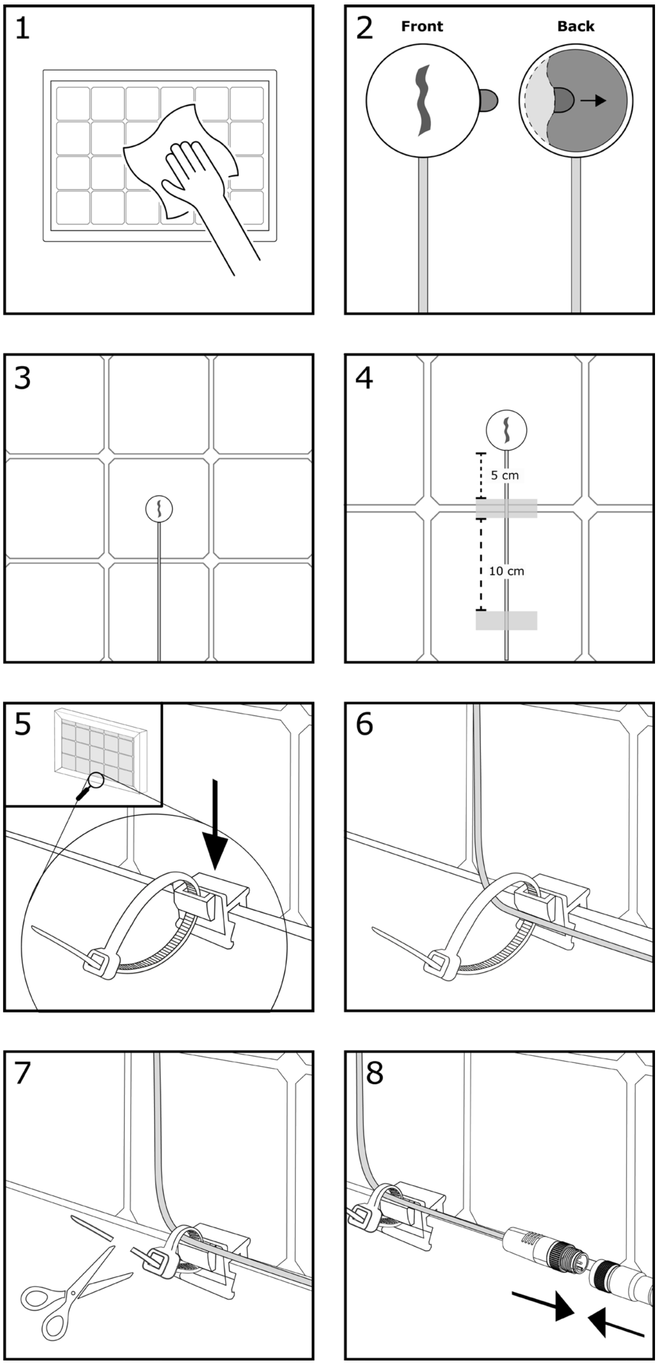

Figure 4.1.1 *PVMT01 installation instructions.*

1. Clean the rear side of the PV module with the provided pre-saturated IPA wipe.
2. Remove the protective release liner on the back from PVMT01.
3. Stick the PVMT01 on the rear side of the PV module, according to IEC 61724-1. Press the disk firmly for a few seconds to ensure good bonding of the sensor to the surface.
4. Place 2 x polyester tape strain relief to hold the cable in place.
5. Attach 2 x solar edge clips on the PV module frame.
6. Guide the PVMT01 cable through the tie-wrap.
7. Tighten the tie-wrap and cut off the excess.
8. Connect the M12 connector to extend the cable.

4.2 Cable extension

PVMT01 is equipped with one cable containing four wires and a 4P male M12-A connector. Standard cable length is 1 m. The cable can be extended to a preferred length by the user, using a cable with a matching 4P female M12-A connector. A 5P (5 pin) will also fit. Keep the distance between data logger and sensor as short as possible. Cables may act as source of distortion by pick up capacitive noise. In an electrically "quiet" environment the PVMT01 cable may be extended up to 20 meters, if needed even longer to 100 m.

Please consider the following when extending the cable:

- use high quality shielded connectors to ensure high measurement accuracy
- connect the cable shield to the data logger cabinet ground to reduce electrical noise
- match the wire cross-section of the extension cable with the sensor cable or use a larger cross-section to avoid a large voltage drop in a 2-wire configuration
- extension cable must be suited for outdoor use.

Cable and connection specifications are summarised below.

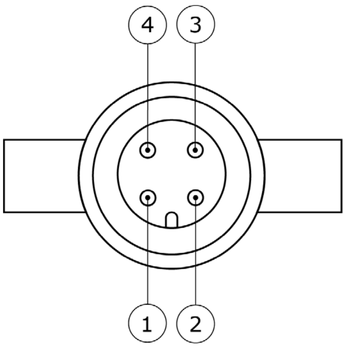

Figure 4.2.1 *Schematic PVMT01 4P M12 connector diagram, indicating the pin numbers.*

In many cases, the extension cable will be the readily available standard 5 pin M12-A.

In that case, the connection will be as in the table below.

Table 4.2.1 *Extension cable and connector connections*

PIN	WIRE	FUNCTION
1	Brown	Pt1000 [+]
4	Black	Pt1000 [-]
3	Blue	Pt1000 [-]
2	White	Pt1000 [+]
5	Grey	not connected
-	Yellow	cable shield

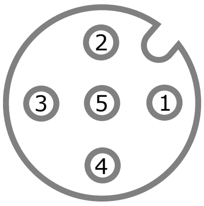

Figure 4.2.2 *Schematic of the extension cable M12-A connector layout, indicating the pin numbers.*

Connecting the cable shield is optional. There is no through connection to PVMT01 housing.

NOTICE
Always use a shielded extension cable and connect the cable shield to ground.

Table 4.2.1 *Preferred specifications for cable extensions of PVMT01.*

Connector	4P (or 5P) M12-A, with an outside thread on the connector body, use a female connector (4P or 5P) with an internal thread on the locking nut for connecting to the sensor connector
Wire	4 x or 5 x copper, 24 AWG, stranded wire
Extension sealing	make sure connectors are well connected and sealed against humidity ingress
Wire configuration	cable resistance can cause significant error. To counter such errors, a 4-wire configuration readout is the best configuration, especially for long cable lengths. Using 4-wire connection will eliminate errors due to cable resistance. The PT1000 is equipped with 4 wires; 1 and 2 at one end , 3 and 4 at the other end. The principle relies on the fact that a known current [I] is fed in through wire 1, through the Pt1000, and out through wire 3 at the opposite end. Two additional wires, 2 and 4 are used to measure the voltage drop [V] across the Pt1000. These wires do not carry any current because the voltage measurement circuit has a very high electrical resistance. Therefore there is no voltage drop across these measurement wires 2 and 3. The wires 1 and 3 may show a voltage drop but the current remains constant. So Pt1000 resistance simply is [V/I].
Conductor resistance	< 0.09 Ω/m (24 AWG)
Extension cable	always use a shielded extension cable.
Length	cable length should be as short as possible, we recommend the total cable length should be less than 100 m
Cable cladding/ outer mantle	with specifications for outdoor use (for good stability in outdoor applications)

4.3 Strain relief & cable to panel connection

PVMT01's cable must be properly strain-relieved, and the cable temperature must be kept as close as possible to the module temperature. To accomplish this, PVMT01 comes with two solar clips and two polyester tapes per pack.

Recommended is to fasten the solar edge clips at the following locations:
1. above the sensor
2. next to the cable connector

Use (extra) cable ties to secure the cable to the solar clips.

Recommended is to fasten the polyester tape at the following locations
1. near the sensor
2. ± 20 cm along the cable, use as little tape as possible.

4.4 Electrical connection

PVMT01 must be connected to a measurement and control system, typically a so-called data logger. The Pt1000 is a standardised type of temperature sensitive resistor. To use a PRT, its electrical resistance must be measured. The resistance is measured by applying a small excitation voltage or current. To prevent heating of the PRT, care must be taken to apply only low-power excitations. Most commonly used data logger systems have preprogramed functions to calculate temperature from a temperature sensitive resistance. For more information, refer to the user manual of the data logger used.

PVMT01 can be read out in a 2-wire or 4-wire configuration. The 2-wire configuration accuracy decreases, relative to the 4-wire, as function of the cable length. The 4-wire configuration eliminates the electrical resistance of the cable from the measurement and is the most accurate way to measure this sensor.

Figure 4.4.1 shows the circuit diagram for a 2-wire configuration. When possible, connect the two wires at each end of the PRT to reduce resistance.

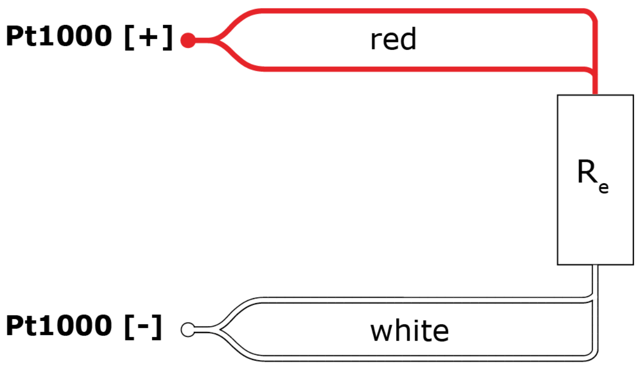

Figure 4.4.1 *2-wire circuit diagram, R_e represents the sensor resistance.*

Figure 4.4.2 shows the circuit diagram for a 4-wire configuration. A 4-wire configuration is recommended. For extension, always use a shielded cable.

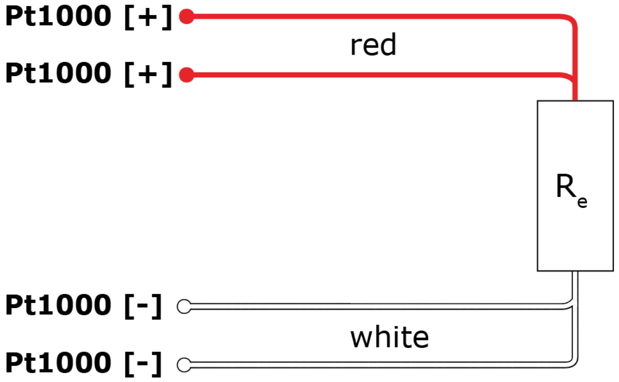

Figure 4.4.2 *4-wire circuit diagram, R_e represents the sensor resistance.*

NOTICE
Putting more than 5 Volt across any of the sensor wires may lead to inaccurate readings or permanent damage to the sensor.

5 Maintenance and trouble shooting

5.1 Recommended maintenance and quality assurance

PVMT01 requires minimal maintenance. Unreliable measurement results are detected by scientific judgement, for example by looking for unreasonably large or small measured values.

Table 5.1.1 *Recommended maintenance of PVMT01.*

MINIMUM RECOMMENDED PVMT01 MAINTENANCE			
	INTERVAL	SUBJECT	ACTION
1	1 month	data analysis	compare measured data to maximum possible / maximum expected temperatures and to other measurements nearby, for example nearby stations or redundant instruments. Also, historical seasonal records can be used as a source for expected values. Look for any patterns and events that deviate from what is normal or expected. For analysis: use nighttime data of cloudy nights with high windspeeds (> 3 m/s) without rain/snow: under these conditions, all measured temperatures of ambient air temperature, panel temperature should be the same.
2	1 year	inspection	inspect the sensor for wear and damage, cable quality, inspect correct attachment to the PV panel, correct fitting of connectors, inspect location of installation. Check electrical connections at the data logger.
3	10 years	lifetime assessment	judge if the instrument will be reliable for the next years, or if it should be replaced.

5.2 Trouble shooting

Table 5.2.1 *Trouble shooting for PVMT01.*

General	make sure spare sensors are available on-site. inspect the quality of installation, attachment of the sensor to the PV panel. inspect the sensor for any damage. inspect if the connectors are properly attached. check for possible moisture intrusion in connectors check the connection of extension cables to the data logger look if neighbouring sensors work exchange extension cables with those of nearby sensors that work. decouple the sensor from extension cable and put a spare sensor in its place.
The sensor does not give any signal	a quick test of the instrument can be done by using a handheld multimeter. check the electrical resistance of the sensor at the connector. Measure between pin 1-3 or 2-4. See Figure 4.2.1. Use a multimeter at the lowest range larger than 1000 Ω. Measure the sensor resistance. The typical resistance of the wiring is 0.13 Ω/m. Typical resistance should be the typical sensor resistance of 1000 Ω plus 0.26 Ω for the total resistance of two wires (back and forth) of each 1 m. Infinite resistance indicates a broken circuit; zero or low resistance indicates a short circuit. measure electrical resistance of the sensor at the connector between pin 1-2 and 3-4. See Figure 4.2.1. Use a multimeter at the 100 Ω range. Measure the wire resistance. The typical resistance of the wiring is 0.13 Ω/m. Typical resistance should be the total resistance of two wires (back and forth). Infinite resistance indicates a broken circuit. connect the extension cable. Repeat the 2 measurements.
The temperature signal is unrealistically high or low	check the cable condition looking for cable breaks. check the Pt1000 measurement by replacing it with a 1000 Ω resistor with 4-wire connection. The result should be 0 °C. for analysis: use nighttime data of cloudy nights with high windspeeds (> 3 m/s) without rain/snow: under these conditions, all measured temperatures of air temperature, panel temperature should be the same.
The sensor signal shows unexpected variations	check the presence of strong sources of electromagnetic radiation (radar, radio) or switching of high-power equipment. check the condition of the sensor cable. check if the cable is not moving during the measurement. check the condition of the connector.

6 Appendices

6.1 Appendix on uncertainty evaluation

There is no general consensus on uncertainty evaluation of back-of-module temperature measurements. IEC 61724-1 does not give an estimate of the total measurement uncertainty, implicitly recognising that this depends on sensor design and environmental factors such as POA. The user should make his own assessment. Table 6.1.1 summarises the main contributions to the uncertainty budget of the entire measurement from T_{CELL} to the T_{BOM} as used for calculating PV performance indices.

Table 6.1.1 *Uncertainty budget of PV module temperature measurements; the accepted uncertainty under IEC 61724-1 compared to PVMT01 performance.*

	UNCERTAINTY BUDGET	**COMMENT**	**IEC 61724 ACCEPTANCE**	**PVMT01 SPECIFICATION**
[#]	[contribution]	[description]	[interval]	[interval]
1	T_{BOM}-T_{CELL}	depends on the composition of the module and is often assumed to be proportional to POA	expected: (1 to 3) °C at 1000 W/m^2	N/A
2	PRT	sensor accuracy class	requirement: ± 1 °C	< ± 0.5 °C -40 °C to +150 °C
3	$\lvert T_{SEN} - T_{BOM} \rvert$	depends on multiple factors is often assumed to be proportional to POA	no requirement	< 2 °C at 1000 W/m^2 POA (nominal)
3.1	thermal resistance of adhesive	is often assumed to be proportional to POA Uncertainty is included in $T_{SEN} - T_{BOM}$	requirement: < 2 x 10^{-3} K/(W/m^2)	< 0.2 x 10^{-3} K/(W/m^2)
4	non-uniformity	over a PV power plant the module temperature is variable	not quantified	N/A
5	electronics	measurement uncertainty of the electronic measurement system	not mentioned	N/A
6	recalibration	in case a sensor is not stable, recalibration is needed to keep uncertainty within required limits	requirement: sensor is replaced or recalibrated as per manufacturer’s requirements	no requirements

Ad 1: Table A1 of IEC 61724-2 and IEC 61724-1 clause 9.1 note 1 mention thermal resistances between cell and back-of-module of (1 to 3) x 10^{-3} °C /(W/m^2), in °C per W/m^2 POA irradiance. This means 1 to 3 °C difference T_{CELL} - T_{BOM} at a POA of 1000 W/m^2. Table A1 gives a value of 3 x 10^{-3} °C /(W/m^2), in °C per W/m^2 POA irradiance for the most common "open rack" glass-cell-glass modules and glass-cell-polymer modules.

An independent estimate by Hukseflux leads to an estimate in the order of 0.6 °C, so much lower than the IEC estimate of 3 °C, at 1000 W/m² POA irradiance for both module types:

Glass-cell-glass modules typically use 2 glass plates, each of 2 mm thick. A glass-cell-polymer module typically has a 3 mm thick glass plate and a 0.3 mm thick polymer sheet. Both have 2 glue layers of approximately 0.2 mm each. The silicone PV cell material has negligible thermal resistance. Glass thermal conductivity is approximately 1 W/(m·K), polymer and glue both 0.2 W/(m·K). Assuming that silicon absorbs 60 % of incoming solar irradiance, reflects the rest and that 20 % of the incoming solar irradiance is converted to electrical power, we estimate that 40 % is converted to heat. We estimate for both panels thermal resistances between cell and the combined 2 surfaces of 1.5 x 10^{-3} °C /(W/m^2). The thermal resistances between cell and back-of-module are 3 and 2.5 x 10^{-3} °C/(W/m^2), with the lower thermal resistance for the polymer backsheet. However, with 40 % heat conversion and assuming the heat going in two directions, the net effect estimated by Hukseflux is in the order of 0.6 °C at 1000 W/m^2 POA irradiance for both module types.

Ad 2: for the temperature sensor IEC 61724-1, clause 9.1 accepts ± 1 °C or better. Class A platinum resistance temperature sensors are a factor 2 better. The uncertainty specification is $\pm(0.15 + 0.002\cdot|T_{SEN}|)$, which is ± 0.45 °C at 150 ° C.

Ad 3: IEC 61724-1 does not give an estimate of the total measurement uncertainty of the T_{BOM} measurement, implicitly recognising that this depends on sensor design and environmental factors such as POA and wind direction. The error resulting from 3.1, thermal resistance of the adhesive, is one of the contributors to the uncertainty of the T_{BOM} measurement.

Ad 3.1: for the adhesive IEC 61724-1, clause 9.1 accepts a minimum of 500 W/(K m^2) thermal conductance, which is equal to a maximum of 2 x 10^{-3} °C /(W/m^2) thermal resistance. Assuming that silicon absorbs 60 % of incoming solar irradiance, reflects the rest and that 20 % of the incoming solar irradiance is converted to electrical power, we estimate that 40 % is converted to heat. Taking a 50-50 distribution of heat flux between the front and rear of the solar module, this means a contribution to the difference T_{BOM} - T_{SEN} at a POA of 1000 W/m^2 of 0.4 °C. For a maximum irradiance of 1500 W/m^2 this contribution is of the same order as what IEC 61724-1 calls "*on the order of approximately 1 °C*".

Ad 4: the variability of module temperatures is mentioned in IEC 61724-1, clause 9.1 "*module temperature varies across each module and across the array. Temperature sensors shall be placed at representative locations to capture the range of variation, and allow determination of an effective average*." Also, the required minimum of 3 sensors per measurement station (table 2 of IEC 61724-1), is meant to make it possible to determine a meaningful average. Under given solar conditions, important factors in variability of module temperature are panel orientation, and exposure of the module to wind, i.e. local wind speed and direction.

Ad 5: consult the electronics manual to estimate the contribution of the measurement by the electronics to the uncertainty budget.

Ad 6: modern temperature sensors have a good record of stability. The decision to replace or recalibrate after a certain time interval of use is left to the user.

Ad 1, Ad 3: these errors are caused by thermal resistances and all contribute to a measured temperature that is lower than cell temperature (unless sensors are thermally insulated, which is exceptional). They are often assumed to be proportional to POA. However, accurately correcting for these errors is not easy because at a certain POA the distribution of heat losses between the front and rear sides of a PV module may change. This distribution depends on the exposure of the panel to wind, in particular wind direction.

6.2 EU declaration of conformity

We, Hukseflux Thermal Sensors B.V.,
Delftechpark 31, 2628 XJ, Delft,
The Netherlands

hereby declare under our sole responsibility that:

Product model	PVMT01
Product type	PV module temperature sensor

conform with the following directive(s):

2011/65/EU, EU 2015/863	The Restriction of Hazardous Substances Directive

This conformity is declared using the relevant sections and requirements of the following standards:

Hazardous substances	EU RoHS2 (2011/65/EU) and EU 2015/863 amendment known as RoHS3

Eric HOEKSEMA
Director
Delft, 01 February, 2024