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Error sources and measurement uncertainties in outdoor testing of BIPV modules

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Abstract: Although building-integrated photovoltaic (BIPV) systems have great potential, investment in this field is not at the desired level. There are two main reasons for this: the lack of technical analysis and economic reasons. Manufacturers and investors utilize datasheets of modules to determine the systems performance, which is determined at standard test conditions (STCs). However, there are apparent differences between STCs and outdoor measurements. Most studies in the field of BIPV system analysis have only focused on long-term outdoor measurements. Besides that, uncertainty of measurements is necessary to achieve scientific results. The aim of this study is to emphasize the importance of measurement uncertainty, to describe how measurement uncertainties are calculated, and to find out the uncertainty of an outdoor BIPV measuring system. In this study, different roof-integrated photovoltaic systems with 15°, 30°, and 45° inclination angles were tested in the Fraunhofer Institute for Wind Energy and Energy System Technology measurement field. Maximum power point current, voltage, power, and temperature of each system were measured. The uncertainty of current, voltage, and temperature was calculated as 0.29%, 0.05%, and 1.15%, respectively.

Key words: Building-integrated photovoltaic, error, measurement uncertainty, Type A and B uncertainty

1. Introduction

A building-integrated photovoltaic (BIPV) system consists of integrating photovoltaic (PV) modules into the building roof or facade. The PV modules do not only produce electricity; they also have many different features such as weather protection, thermal insulation, noise protection, and electromagnetic protection, depending on the design and implementation. If the PV modules have one or a few additional features, the PV modules are called BIPV modules [1]. Despite these additional properties, BIPV systems still remain small-scale compared to building-adopted photovoltaic systems (BAPV: rooftop installation). Technical barriers such as electrical, thermal, and mechanical characteristics of BIPV systems are the most effective factors on the market share growth. Besides that, the legal and administrative processes pose a problem [2]. The BIPV modules are produced as different types, such as glass-glass, glass-glass isolation, roof-tile, and metal-sheet. Even though the characteristics of the BIPV modules appear to be similar to those of PV modules, the most important difference is the operation temperature. The operating temperature of a BIPV system can reach 90 °C at a solar irradiation of 1000 W/m^2 when the ambient temperature is 30 °C, ventilation rate is 0 m/s, and backside temperature is 20 °C on the backside of the PV tiles [3]. However, the operating temperature of PV modules can only reach 50–60 °C when the ambient temperature is 30 °C due to the backside ventilation. This leads to different electrical, thermal, and mechanical properties of BIPV modules compared to standard modules or

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conventional building products [4]. Due to these reasons, accurate and confident measurements of thermal and electrical values such as current and voltage of the BIPV modules are very important.

No matter how carefully and scientifically measured, there is no measurement without errors. Therefore, the exact measurement results are never known, but the errors can be approximately calculated or may be estimated. It is important to define how large the measurement errors are to say something about scientific measurement results. There are two words that are confused with each other. These words are error and uncertainty. Error is the difference between the measured value and the true value that is not known. As for uncertainty, it is an estimate of the limit of the error. Thus, if the uncertainty is used for measurement, it means doubt about the validity of the result of the measurement [5]. Correctly, completely, and scientifically measured results need to be expressed with uncertainty, so estimating uncertainty is an important step in data reduction and expression of results.

Generally, errors of measurement consist of random (statistical) and systematic components [6]. Random errors are caused by unknown changes within the measuring instrument or by environmental conditions. Random errors vary in magnitude in each measurement under the same conditions. The magnitude of errors can be determined by performing multiple measurements. Systematic error is constant in each measurement of the same observation. Systematic errors may occur due to load accuracy of the measuring instrument or missing/old calibration [7].

Measurement uncertainties are generally defined using the GUM approach. GUM is commonly known as the "Guide to the Expression of Uncertainty in Measurement". This guide was published by the Joint Committee for Guides in Metrology (JCGM). The JCGM consists of seven international organizations and they prepared the GUM. There are two types of evaluations to determine the measurement uncertainty according to the GUM [8]. If the measurement instruments and accuracy of other equipment are not known clearly and different values are determined in repeated measurements, a statistical method called Type A can be used. When the complete accuracy of equipment is known, a systematic method called Type B is used. The aim of this study is to emphasize the importance of measurement uncertainty, to describe how measurement uncertainties are calculated, and to find out the uncertainty of an outdoor PV measuring system that uses an analog maximum power point tracker (MPPT) card. Error sources of measurement devices and the equipment have been determined, some error sources have been neglected and some assumptions have been taken into account, and the purpose of the neglect or assumption has been explained. In order to calculate measurement uncertainty both statistic (Type A) and systematic (Type B) methods have been used. Type A is used to determine the uncertainty of the MPPT card. The calculation of uncertainty for an analog MPPT card is very difficult so it takes a long time. If it has been calculated approximately the same value determined according to Type A will be found. Type B is used to calculate the uncertainty of temperature, voltage, and current measurements.

2. Fraunhofer IWES outdoor test field

In the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) field, three test roofs with 15°, 30°, and 45° inclination angles were installed to determine the performance of BIPV systems. The BIPV systems on three rooftops are seen in Figure 1. Each roof is mounted with a PV panel that has different technology [9].

The temperature, current, voltage, and the other environmental conditions such as solar radiation and wind speed are recorded to evaluate the operating characteristics, yield, and electrical characteristics of the system. Each module is operated by an analog MPP card developed at the Fraunhofer IWES. These MPP

Figure 1. Three BIPV systems on rooftops with different tilt angles.

cards determine the MPP voltage and current of the PV modules [10]. The surface temperature of these modules is measured at the back of the module simultaneously. Pt 100 (Class B) platinum-foil is used as a temperature sensor. The two different temperature sensors are installed at the back side of the module. One of them measures the operation temperature of the PV panel under loading and the other one measures the temperature of the PV panel with no electricity generated [11]. In addition, room temperature is detected in the test center. Each roof is equipped with a pyranometer, which determines the irradiation for each inclination. A wind sensor is installed on the central roof, which determines the wind speed and direction. Measurement data recording is performed using a data logger system at an interval of 15 s. An Agilent data logger is used in order to store measured data [12]. Current cannot be measured directly, so in order to measure current it is necessary to use a shunt resistor. A Manganin resistor bar as a shunt resistor, which has 0.2 error class, is utilized.

In this study, internationally accepted test methods, which are the Sandia National Laboratory (SNL) model [13] and the nominal operating cell temperature model [14], were used to evaluate to temperature, current, and voltage for BIPV modules. The measurement uncertainty was evaluated using GUM, which is an International Organization for Standardization (ISO) standard.

3. Measurement uncertainty

Measurement is a process of observing and recording the experimental studies that are collected as a part of a research effort. The aim of a measurement is to obtain the true value of the thing being measured. However, there is no measurement without errors. Error is the difference between the measured value and the true value. Errors fall into two categories: random error and systematic error. Like the true value, the error is not known for sure. Therefore, the quality of the measured result is characterized by uncertainty and the confidence level. Uncertainty is the parameter related to the measured thing that characterizes the dispersion of the values that could be referred to the measured thing. All measurements have a degree of uncertainty regardless of precision and accuracy. In order to compare two measured things, it is necessary to know the uncertainties [15].

The procedure for measurement uncertainty was created by the ISO/BIPM commonly referred to as GUM. According to GUM, measurement uncertainty can be classified as Type A and Type B. A Type A evaluation of uncertainty is based on statistical methods and it should be used in repetition measurement, whereas a Type B evaluation of uncertainty is based on scientific conclusion and it should be used when the measured value and assigned measurement uncertainty is known. A Type B evaluation includes measured data, information of calibration, uncertainties assigned to reference data, and experience with previous measurements [16].

Due to the many error sources in most measurement process, it is necessary to express all uncertainties at the same confidence level by converting them into standard uncertainties [17]. Standard uncertainty characterizes how well parallel measurements agree among themselves and it is denoted by u.

All the input quantities must be in the same units before they are combined. Therefore, it is necessary to convert an uncertainty component to the same units as the measurand. This conversion process is realized by using a sensitivity coefficient. The sensitivity coefficient shows the relationship of the individual uncertainty component and it is referred to as c_i.

In many cases the measurement results can be calculated from different input parameters. Therefore, the uncertainties need to be combined to calculate an overall uncertainty for the measurement. The combined standard uncertainty is the uncertainty of the output quantity, which takes into account the uncertainties of all the input quantities, and it is referred to as u_c.

The standard uncertainty provides a probability of 68.3% but this probability is too low for the researcher or customer. Thus, uncertainty results are presented with the expanded uncertainties. Expanded uncertainty is calculated by multiplying the standard uncertainty by the coverage factor (k). The coverage factor can have any value, but according to international acceptance the coverage factor is either 2 or 3. Coverage factors of 2 and 3 give a level of confidence approximately of 95% and 99.7%, respectively. Expanded uncertainty is referred to as U [18].

3.1. Calculation of Type A uncertainty

A Type A uncertainty is used when input quantities are repeatedly observed and where different values are determined under the same conditions for each measurement. Statistical methods are then used to calculate the results. First, the arithmetic mean (average) is calculated using an observed value and a number of measurements. Eq. (1) shows how to calculate the mean of measurement values.

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

Here, μ is a mean of measurement values, n is a number of measurements, and x_i is an individual observed value. Experimental standard deviation is calculated using Eq. (2).

$$\sigma_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i-\mu)^2} \tag{2}$$

Here, σ_x is a standard deviation. Especially if the value of measurements is low ($n < 10$), an alternative definition can be used for standard deviation. In this case, the value of n is replaced by n – 1. This gives more conservative results of σ_x [19].

If there is more than one measurement the standard deviation is divided by $\sqrt{n}$. [20], so the standard deviation of the mean is calculated by Eq. (3).

$$\sigma_\mu = \frac{\sigma_x}{\sqrt{n}} \tag{3}$$

This result can also be used as standard uncertainty of measurement $(u_{xi} = \sigma_\mu)$.

3.2. Calculation of Type B uncertainty

A Type B method should be used when all uncertainty estimates are obtained without the use of repeated measurements. The first step in the Type B method is to specify measurement uncertainty from the manufacturer's specification, calibration datasheet, and uncertainties assigned to reference data taken from handbooks, previous measurement data, or other certificates [19]. The measurement uncertainty can be given directly in the certificate. The standard measurement uncertainty is calculated by dividing the expanded measurement uncertainty by the coverage factor. In broad-range instruments, it is necessary to calculate the uncertainty for the reading or instrument range. There are three very important functions for the probability of occurrence. These are the rectangular, triangular, and normal distributions. The standard uncertainty for a rectangular distribution is calculated from Eq. (4).

$$u_{xi} = \frac{a}{\sqrt{3}} \tag{4}$$

The standard uncertainty for a triangular distribution is calculated from Eq. (5).

$$u_{xi} = \frac{a}{\sqrt{6}} \tag{5}$$

If three or more measured values are available, a normal distribution can be assumed as a good approximation. The standard uncertainty is found by dividing the expanded uncertainty by the coverage factor, k, appropriate to the stated level of confidence in the normal distribution. The standard uncertainty for a normal distribution is calculated from Eq. (6) [19].

$$u_{xi} = \frac{\text{expanded uncertainty}}{k} \tag{6}$$

Here, $k = 2$ if the reported level of confidence is 95%.

4. Method and material

4.1. Uncertainty of Fraunhofer ISET MPP meter

In this study, an analog MPPT card was utilized. The power of a PV cell increases depending upon increases of cell voltage up to the maximum power point (MPP). After this point the MPP decreases until the open circuit voltage is opened. Both voltage and current have same direction while the power increases. Nevertheless, voltage and current have different directions while the power decreases. Due to the deflection of current, the calculation of error value in the analog MPPT card is very hard and it takes a lot of time. For this reason, the uncertainty of the analog MPPT card has been determined using a solar simulator and statistic method. The output values of the MPPT card are known under defined conditions (irradiation, temperature, pressure, etc.). The difference between the real value and measured value is called the mismatch ratio. The mismatch ratio is obtained by dividing the actual power consumed by the load into the real MPP power of the module at the same moment. The PV simulator measures the I and V of the load and at the same moment it uses the values for I_{mpp} and V_{mpp} from the simulated PV-curve. The block diagram of the solar simulator is seen in Figure 2.

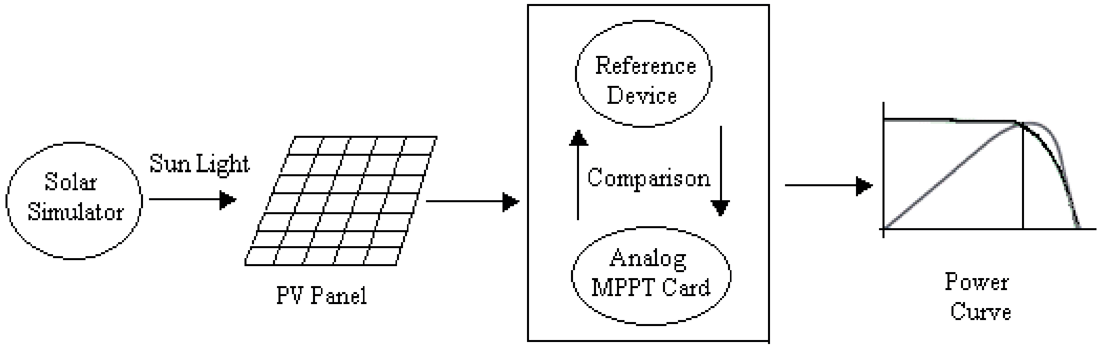

Figure 2. Blog diagram of solar simulator.

One hundred measurements have been carried out to determine the mismatch ratio. Measurements have been performed using different values of irradiation between 10 W/m^2 and 1000 W/m^2. It was found that the measurement results are close to each other at 50 W/m^2 and upper values. The measurement results are different and not stable under the value of 50 W/m^2. The measurement results are shown in Figure 3.

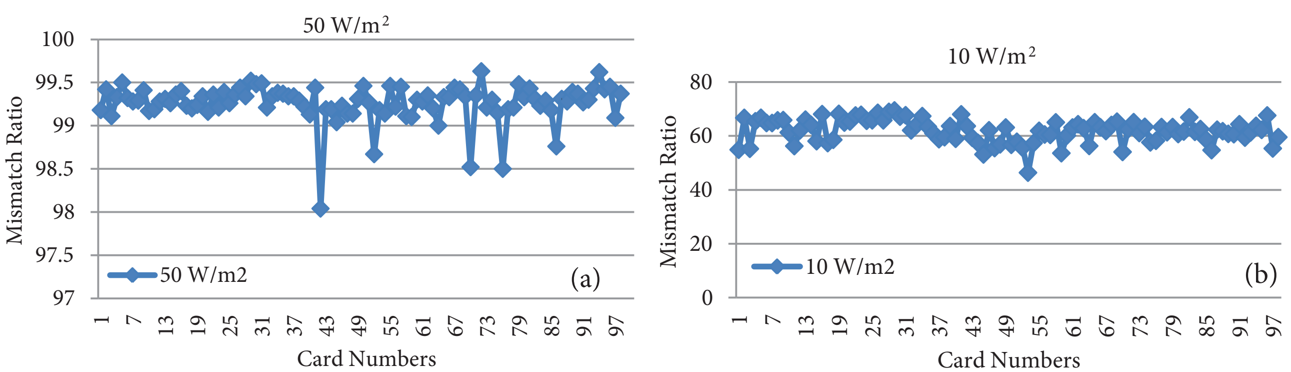

Figure 3. Mismatch ratio of MPP card: a) irradiation at 50 W/m^2, b) irradiation at 10 W/m^2.

Due to the big fluctuation in the measurement results at the above value of 50 W/m^2, the uncertainty has been calculated using a minimum of 50 W/m^2. The histogram of the measurement results at 50 W/m^2 is shown in Figure 4.

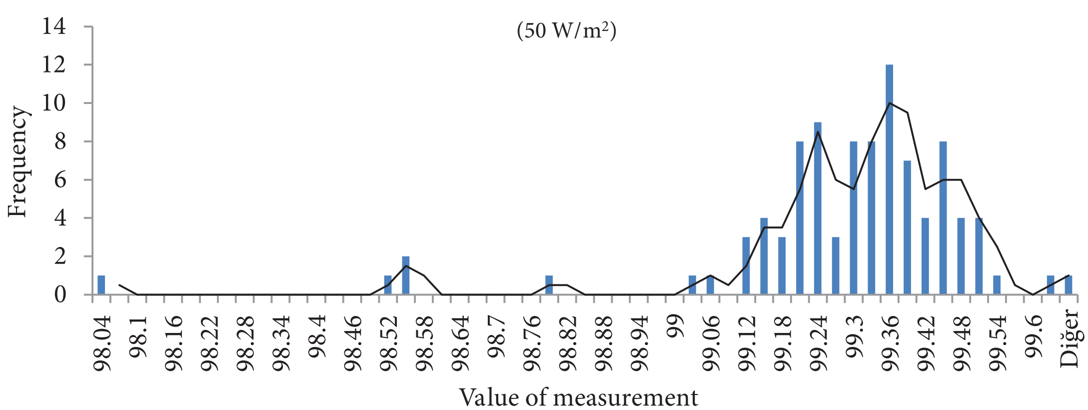

Figure 4. Histogram of the measurement results.

Axis x in Figure 4 shows the amount of deviation in percentage between the actual value and measured value. Axis y shows frequency, which is the realization frequency of the mismatch ratio. It can be seen from this figure that the accuracy rates of MPPT cards vary most between 99.06% and 99.6%. According to the histogram of the mismatch value it is convenient to use Gaussian distribution. The first step is to calculate the mean and determine if the data are scattered relatively evenly above and below the mean. The mean is calculated from Eq. (7).

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{7}$$

$$\mu = 99.2618$$

The standard uncertainty (u) for a Gaussian probability density function is represented by Eq. (8), where (σ) is the standard deviation of the sample readings and n is the number of readings.

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\mu)^2} \tag{8}$$

$$u_{mpp} = \sigma = 0.2286$$

4.2. Uncertainty of DC voltage measurement

The DC voltage is measured directly with the data logger, so it is necessary to use the specifications of the data logger in order to calculate the uncertainty of voltage measurement. Table 1 shows the accuracy of each voltage measuring range.

Table 1. Accuracy of voltage measuring range.

Function	Range	24 Hours 23 °C ± 1 °C	90 Days 23 °C ± 5 °C	1 Year 23 °C ± 5 °C	Temperature coefficient/°C
DC voltage	100 mV	0.0030+0.0035	0.0040+0.0040	0.0050+0.0040	0.0005+0.0005
	1 V	0.0020+0.0006	0.0030+0.0007	0.0040+0.0007	0.0005+0.0001
	10 V	0.0015+0.0004	0.0020+0.0005	0.0035+0.0005	0.0005+0.0001
	100 V	0.0020+0.0006	0.0035+0.0006	0.0045+0.0006	0.0005+0.0001
	300 V	0.0020+0.0020	0.0035+0.0030	0.0045+0.0030	0.0005+0.0003
±(% of reading + % of range)					

There are two accuracy values that are influenced by the uncertainty of the measurement value. One of them is the percentage of reading, where reading is the actual measured value, and the other one is percentage of range, where range is the name of the voltage scale. These accuracies include all measurement, switching, and transducer conversion errors [21].

The PV panel's voltage used in this study is a maximum of 40 V. Therefore, the range of 100 V is suitable. For this range, the 1-year accuracy is 0.0045% + 0.0006%. The data logger is utilized indoors. Hence, temperature drift is neglected. Accuracy of DC voltage measurement can be calculated be Eq. (9).

$$u_V = \left(\frac{0.0045}{100}40\right) + \left(\frac{0.0006}{100}100\right) = 2.4\,mV \tag{9}$$

This value can expressed in percentage form.

$$u_V = \frac{2.4\,mV}{40\,V} = 0.006\%$$

The accuracy describes the maximum error when using the data logger at ambient temperatures between 18 °C and 28 °C. If the data logger temperature is higher than the temperature drifts, errors should be considered. In this study the maximum temperature of the data logger was measured as 40 °C. It is seen in Table 1 that the drift error is 0.0005% reading + 0.0001% range. The contribution of drift error is calculated with Eq. (10).

$$u_{Vt} = {}^{(0.0005\% reading + 0.0001\% range)}/_{\circ} * (40^\circ - 28^\circ) \tag{10}$$

$$u_{Vt} = {}^{(0.0005\% reading + 0.0001\% range)}/_{\circ} * 12$$

$$u_{Vt} = 0.0060\% reading + 0.0012\%\, range$$

$$u_{Vt} = \frac{0.0060}{100} 40\,V + \frac{0.0012}{100} 100V$$

$$u_{Vt} = 0.0024 + 0.0012 = 3.6\,mV$$

This value can expressed in percentage form.

$$u_{Vt} = 0.015\%$$

Table 2 shows the results of uncertainty of voltage measurement.

Table 2. Uncertainty of voltage measurement.

Symbol	Uncertainty	Unit	Distribution	Factor	Standard MU	Sensitivity	Uncertainty contribution	Square uncertainty contribution
Data logger err.	6.0E-3	V	Rectangular	1.7321	3.5E-3	1.0E+0	3.5E-3	12.0E-6
Tem. drift err.	15.0E-3	V	Rectangular	1.7321	8.7E-3	1.0E+0	8.7E-3	75.0E-6
							MU / V	0.0093
	40.0E+0		Erw. factor	2			Erw. MU / V	0.0187
							Erw. MU /%	0.05%

4.3. Uncertainty of DC current measurement

The current is not measured directly with the data logger. In order to measure current it is necessary to utilize the shunt resistor. Indeed, the data logger measures voltage, which drops across the shunt resistor. The data logger verifies the current according to Ohm's law. There are four main error sources in measuring the current system. These are connection error, temperature error, accuracy of the resistor, and measurement instrument error.

- Connection error: The value of the resistor changes according to distances between measurement points and the resistance terminal. The best way to determine this error is getting different measurements from different points. However, if there is no measurement, the connection error can be assumed as 0.01% [22].

- Temperature error: The shunt resistor bar used in this study is made of Manganin. The resistance of the shunt rises 0.002% per each 1 °C, so the accuracy of temperature is 0.002%.

- Resistance accuracy: The biggest error across the shunt is resistance accuracy. This uncertainty is defined also from datasheet of the shunt resistor. According to the datasheet, resistance uncertainty is 0.2%.
- Data logger's error: The voltage drop is a nominal 60 mV on the shunt resistor. Therefore, the range of 100 mV is suitable. For this range, the 1-year accuracy is 0.0050% + 0.0005%. The data logger is utilized indoors. Hence, temperature drift for data logger is neglected. Accuracy of DC voltage measurement can be calculated by Eq. (11).

$$u_V = \left(\frac{0.0050}{100}60mV\right) + \left(\frac{0.0040}{100}100mV\right) = 0.007\,mV \tag{11}$$

This value can expressed in percentage form.

$$u_V = \frac{0.007\,mV}{60\,mV} = 0.0116\%$$

Table 3 shows results of uncertainty of current measurement.

Table 3. Uncertainty of current measurement.

Symbol	Uncertainty	Unit	Distribution	Factor	Symbol	Sensitivity	Uncertainty contribution	Square uncertainty contribution
Connection	10.0E-3	°C	Normal	2.0000	5.0E-3	1.0E+0	5.0E-3	25.0E-6
Temperature	2.0E-3	°C	Rectangular	1.7321	1.2E-3	1.0E+0	1.2E-3	1.3E-6
Resistor‘s error	200.0E-3	°C	Rectangular	1.7321	115.5E-3	1.0E+0	115.5E-3	13.3E-3
Data logger err.	11.6E-3	°C	Rectangular	1.7321	6.7E-3	1.0E+0	6.7E-3	44.9E-6
							MU / V	0.1158
	80.0E+0		Erw. factor	2			Erw. MU / V	0.2316
							Erw. MU / %	0.29%

4.4. Uncertainty of temperature measurement

The temperature cannot be measured directly. In order to measure the value of temperature, all the components and uncertainty of components must be considered. In this study, the Pt 100 resistance thermometer (tolerance class DIN B) was used. Eq. (12) shows the relationship between input quantities and measurement results for temperature measurements with Pt 100 resistance [23].

$$t_x = t_m + uM_F + uM_D + uM_{Th} + uV + ut_M + ut_W + u_B + uM_S + uM_H + uM_{RI} + uR_{RL} \tag{12}$$

In the equation, t_x is obtained temperature, t_m is temperature at the measurement point, uM$_F$ is measurement signal deviation caused by the heat-conduction error of the thermometer, and uM$_D$ is measurement signal deviation caused by the deviation of the sensor as per the EN 60 751 standard [24]. The permissible tolerance for a platinum sensor of class B is calculated by $\pm 0.3\ ^\circ$C + 0.005 T [25]. T is a measured temperature. In this study, the maximum temperature is 80 $^\circ$C. Therefore, the uncertainty (uM$_D$) is calculated as $\pm 0.7\ ^\circ$C, and uM$_{TH}$ is the measurement signal deviation caused by thermoelectric emfs. According to EN 60 751 specifics, if the measured temperature is 100 $^\circ$C, the measurement error (uM$_{TH}$) can be accepted as 0.05 $^\circ$, and uV is the indication of deviation of the evaluation electronics caused by supply variations. According to the datasheets of the transmitter, the thermometer, and the sensitivity of component, this uncertainty can be considered as 0.05 $^\circ$C. ut_M is the indication of deviation caused by fluctuating ambient temperature. The differences between the ambient temperature and the operating temperature are found and then this uncertainty is calculated using the datasheet. In this study this uncertainty is assumed as 0.1 $^\circ$C. ut_W represents the processing and linearization errors in the evaluation electronics. According to the datasheet, this uncertainty is 0.4 $^\circ$C. u_B is the indication of deviation caused by the influence of the input resistance, and uM_S is measurement signal deviation caused by insufficient stabilization. The sensors are at the same level for this measurement so this uncertainty can be neglected. uM_H is error caused by the self-heating error of the sensor. The error range of self-heating is about 0.1 mW at 0 $^\circ$C so this error can be accepted as 0. uM_{RI} is measurement signal deviation caused by inadequate insulation resistance. The Pt 100 is utilized in this study. This signal deviation can be neglected according to tolerance class DIN B. uR_{RL} is variation in the lead resistance. The lead resistance effect can occur if 2 core or 3 core cables are used between the thermometer and data logger. In this study, this uncertainty is not efficient because we used 4 core cables in our study.

Measurement uncertainty can be calculated using the information mentioned above. Whole error sources and their uncertainty, factor, distribution type, and sensitivity are shown in Table 4.

Table 4. Overall measurement uncertainty of temperature.

Symbol	Uncertainty	Unit	Distribution	Factor	Standard MU	Sensitivity	Uncertainty contribution	Square uncertainty contribution
uM_F	50.0E-3	$^\circ$C	Normal	2.0000	25.0E-3	1.0E+0	25.0E-3	625.0E-6
uM_D	700.0E-3	$^\circ$C	Rectangular	1.7321	404.1E-3	1.0E+0	404.1E-3	163.3E-3
uM_{TH}	50.0E-3	$^\circ$C	Rectangular	1.7321	28.9E-3	1.0E+0	28.9E-3	833.3E-6
uV	50.0E-3	$^\circ$C	Rectangular	1.7321	28.9E-3	1.0E+0	28.9E-3	833.3E-6
Ut_M	100.0E-3	$^\circ$C	Rectangular	1.7321	57.7E-3	1.0E+0	57.7E-3	3.3E-3
Ut_W	400.0E-3	$^\circ$C	Normal	2.0000	200.0E-3	1.0E+0	200.0E-3	40.0E-3
uB	100.0E-3	$^\circ$C	Rectangular	1.7321	57.7E-3	1.0E+0	57.7E-3	3.3E-3
							MU / V	0.4608
	80.0E+0		Erw. factor	2			Erw. MU / V	0.9215
							Erw. MU / %	1.15%

5. Conclusion and comments

The photovoltaic industry is improving quickly but BIPV systems are not improving like BAPV. Technical barriers such as electrical, thermal, and mechanical behaviors of BIPV modules are the most important factors for improvement. In this study, three types of roof systems were utilized. All PV panels are from the market so the study provides a real experience of current roof products' development. The PV modules that were utilized have c-Si technology with different configurations and different installation methods and PV panels were installed on three inclined roofs (15°, 30°, and 45°) without insulation layers. The module current, voltage, and module temperature were measured.

Measurement devices that have all the scientific qualifications were used in this study. However, there is no measurement without errors. For this reason, the analysis of measurement uncertainty was carried out. By this means, it was possible to say something about measurement results scientifically. The uncertainty of the MPP meter, current, voltage, and temperature were calculated as 0.2286%, 0.29%, 0.05%, and 1.15%, respectively. The study of uncertainty showed that the uncertainties of the MPP meter, DC voltage measurement, and DC current measurement are lower than the uncertainty of temperature measurement. The reason is that the temperature measurement needs additional elements such as sensors, cables, etc.

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