Journal of Renewable Energies 27 (2024) 173 – 189

DOI: https://doi.org/10.54966/jreen.v27i2.1178

Journal of Renewable Energies

Revue des Energies Renouvelables

journal home page: https://revue.cder.dz/index.php/rer

Research paper

Quantifying Measurement Uncertainty in Photovoltaic Module Performance at Standard Test Conditions: A Machine-Based Approach

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ARTICLE INFO

Article history:

Received April 15, 2024

Accepted October 16, 2024

Keywords:

Uncertainty calculation,
I-V characterization,
PV module,
Outdoor measurements,
Standard Test Conditions.

ABSTRACT

This paper presents an in-depth analysis of measurement uncertainty in the output parameters of photovoltaic (PV) devices, focusing specifically on measurements conducted under standard test conditions (STC). Accurate characterization of module I-V performance is crucial for PV manufacturers, researchers, and investors alike. The study provides a comprehensive overview of the measurement procedures for both performance and temperature coefficient of PV modules, with a strong emphasis on the detailed calculation of associated uncertainties. Notably, the research was conducted under real-world sunlight conditions, with special attention given to reference devices such as reference cells, modules, or pyranometers, which play a pivotal role in determining overall uncertainty components. By utilizing a diverse array of machines from various sources, the results obtained are applicable across a wide range of measurement configurations. Furthermore, adherence to the ISO/IEC 17025 series of standards ensures a standardized and reliable approach. The novelty of this research lies in its comprehensive approach to uncertainty analysis, encompassing both performance and temperature coefficient measurements under real-world conditions. By providing valuable guidelines for PV module characterization and reliability assessment, particularly in uncertainty estimation, this study contributes significantly to the advancement of photovoltaic technology.

1. INTRODUCTION

Outdoor measurements are essential for accurately determining the current–voltage (I–V) and current-power (I-P) characteristics of photovoltaic (PV) modules, as they are conducted under natural sunlight

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ISSN: 1112-2242 / EISSN: 2716-8247

conditions. Standard test conditions (STC) specify performance metrics at an irradiance of 1000 W/m², a module temperature of 25°C, and Air Mass 1.5 solar spectrum (Gaglia et al., 2017), with spectral data conforming to IEC 60904-3 (IEC60904-3, 2016).

Revati et al. (Revati & Natarajan, 2020). simulated the performance of PV modules under varying solar radiation and environmental temperatures, finding that higher solar radiation intensity leads to lower temperature and increased PV output. (Kumar et al., 2020) utilized MATLAB/Simulink to model and simulate a PV module, evaluating its performance under different working conditions. Their study demonstrated that changes in working temperature and solar illumination significantly affect the output current and voltage, and consequently the output power. Additionally, they discovered multiple power peaks on the power-voltage curve under partial shading conditions. The effective algorithm L-SHADED was used to identify unknown parameters in single-diode-based PV modules under different temperature and irradiance conditions.

The output performance, stability, and reliability of PV cells are influenced by material parameters, surface temperature, and radiation intensity. Previous research has mainly focused on the impact of these parameters on output power, often neglecting their effects on output stability and reliability (Zhang et al. 2021). Among these, the Monte Carlo method, based on sampling uncertainty propagation, stands out for its universal applicability and typical robustness (Palluotto et al. 2019, Zhang et al. 2020). This method has been widely adopted due to its effectiveness in addressing the uncertainties associated with PV module performance under standard test conditions (STC), which include specific temperature, spectral, and irradiance parameters.

Despite efforts to control module temperature and power during outdoor performance measurements, the electrical efficiency of PV modules is inherently impacted by ambient temperature variations, leading to efficiency reductions as temperatures increase (Bora et al. 2019). Given the inherent variability of natural solar systems, accurate uncertainty calculations for PV modules are crucial, especially for laboratories such as ours, the PVTL (Algeria), to ensure precise data analysis.

A number of test standards have been developed in the literature to guarantee the accurate characterization and evaluation of photovoltaic (PV) module performance. The IEC 61215 series, which outlines the testing specifications for crystalline silicon terrestrial PV modules, is one of the most well-known standards. A wide range of tests, including mechanical load tests, humidity-freeze tests, and thermal cycling tests, are included in this standard to assess the performance and durability of modules in various environmental settings (Seapan et al. 2020). IEC 61730, a crucial standard that addresses the electrical, mechanical, and fire safety of photovoltaic modules, is another important one (Golive et al. 2019). Furthermore, IEC 60904 specifies methods for measuring solar irradiance and I-V characteristics, guaranteeing precise performance assessment under standard test circumstances (STC) (IEC 60904-4, 2009)

In line with ISO/IEC 17025 (IEC 60891, 2021) standards, we strive to minimize corrections in I-V characterization, addressing specific challenges encountered in measuring temperature coefficients (TC) as documented in (Piliougine et al. 2021) and (M¨ullejans et al. 2009). Notably, these challenges are often overlooked in uncertainty estimations provided by laboratories.

Recent studies have expanded the understanding of PV module performance, particularly in outdoor environments. (Zellagui et al. 2021) explored the integration of PV distributed generators in electrical distribution systems, accounting for uncertainties in the presence of electric vehicle charging stations. Their findings demonstrate the importance of considering chaotic uncertainty algorithms in performance assessments. (Agroui et al. 2011) compared indoor and outdoor performance of thin-film photovoltaic modules, illustrating the variability between controlled and natural sunlight conditions. (Zaghba et al.

2023) focused on the performance of a grid-connected amorphous photovoltaic station in hot desert environments, showing that high ambient temperatures can significantly influence output stability and reliability. Furthermore, (Zarede et al. 2021) conducted a simulation of losses in photovoltaic systems, emphasizing the role of degradation in reducing overall energy production. These studies underscore the critical need for comprehensive uncertainty quantification, particularly in real-world conditions where temperature and irradiance fluctuations impact both the short-term and long-term performance of PV modules.

Over the years, the methodology for uncertainty calculation regarding ISC, VOC, PMMP, FF, and efficiency (ŋ) analysis at STC has been standardized (Emery, 2009, 2012; Dirnberger & Kraling 2013; Abdel-Basset et al. 2021, and Piliougine, 2021). This standardization has led to a defined uncertainty, promoting better agreement among measurement laboratories (Frank, 2018).

This paper presents an in-depth analysis of measurement uncertainty in PV devices' output parameters, focusing on measurements conducted under STC. We provide a comprehensive overview of measurement procedures for both performance and temperature coefficients of PV modules, emphasizing detailed uncertainty calculations. The research was conducted under real-world sunlight conditions, with special attention to reference devices such as reference cells, modules, or pyranometers, which are pivotal in determining overall uncertainty components. Utilizing a diverse array of machines from various sources, our results are applicable across a wide range of measurement configurations. Adhering to the ISO/IEC 17025 series of standards ensures a standardized and reliable approach.

The novelty of this research lies in its comprehensive approach to uncertainty analysis, encompassing both performance and temperature coefficient measurements under real-world conditions. By providing valuable guidelines for PV module characterization and reliability assessment, particularly in uncertainty estimation, this study significantly advances photovoltaic technology.

2. OVERVIEW OF KEY PV TEST STANDARDS FOR UNCERTAINTY ASSESSMENT

Table 1 provides a concise overview of the key standards used in photovoltaic (PV) testing, highlighting their specific focus areas. Each standard plays a crucial role in ensuring accurate, reliable, and consistent measurement procedures. For instance, **IEC 61215** focuses on the long-term durability of PV modules under varying environmental conditions, while **IEC 61730** addresses essential safety requirements. **IEC 60904** ensures precise I-V characterization under standard test conditions (STC), and **ISO/IEC 17025** emphasizes the importance of traceability and measurement accuracy in laboratory environments. Together, these standards form the foundation for accurate uncertainty calculations in PV testing.

3. EXPERIMENTAL PROCEDURES

3.1 Methodology

In order to determine and assess the measurement uncertainties for PV module tests in our laboratory, the experimental setup was carefully planned. The Renewable Energy Development Center (CDER) annex in Ben Aknoun City, Algeria, (Latitude: 36°44'44.94"N, Longitude: 3°00'46.80"E, Altitude: 236 meters) is where all calculations and tests were carried out. This site offered the perfect environment for our thorough uncertainty analysis and PV module performance evaluation.

3.2 Standard Test Condition Setup

A photovoltaic (PV) module's performance was successfully measured under outside direct standard test condition (STC) using ambient sunshine. This process is known to be easy, inexpensive, and quick. Through tracking measurements, the performance of a Poly-c-Si PV module was examined. An electronic load (Agilent, N3300A Keysight) was used to evaluate I-V curves in an outdoor setting.

Table 1. Overview of Key PV Test Standards for Uncertainty Assessment

Standard	Description	Focus Area
IEC 61215	Specifies tests for the design qualification and type approval of crystalline silicon PV modules.	Long-term durability and performance under environmental conditions (e.g., thermal cycling, humidity-freeze, mechanical load, UV exposure) (Seapan et al. 2020).
IEC 61730	Focuses on the safety of PV modules, covering electrical, mechanical, and fire safety standards.	Safety requirements to ensure protection in various applications (Golive et al. 2019).
IEC 60904	Provides methods for measuring I-V characteristics of PV devices and for calibrating reference devices.	Measurement of PV device performance under Standard Test Conditions (STC) (IEC 60904-4, 2009).
ISO/IEC 17025	Defines the competence of testing and calibration laboratories and emphasizes traceability and measurement accuracy.	Guidelines for ensuring accurate and reproducible uncertainty calculations in testing labs (IEC 60891, 2021).

We measured a number of important environmental factors in this study, such as wind direction, speed, relative humidity, sun spectrum, solar irradiance, and module temperature. An Algerian manufacturer's Poly-c-Si PV module was put through STC testing in order to adjust settings and examine uncertainties throughout the process. A simplified diagram of the STC test station's I-V curve characterization is shown in Figure 1. Figure 1 shows a complete configuration for tracking a photovoltaic (PV) module's performance in actual outdoor settings. When the PV module is exposed to sunlight, it produces electricity, and its I-V properties are examined. The output of the module is calibrated in relation to standard circumstances and measured for irradiance using a reference cell. Environmental sensors aid in determining how elements such as temperature rises or wind chilling impact the module's efficiency. Examples of these sensors are an emometer for wind speed and PT100 temperature sensors for surface temperature. Using an electronic load (N3300A) to dynamically mimic different load situations, the data collection system measures current, voltage, and power using a multi-channel acquisition unit (CHANEL N 3304) and a multimeter (34901A). LabVIEW software controls all of the components, enabling real-time data display and analysis, while a power supply guarantees the system's component parts function well. The precise characterization of PV module performance under varying environmental conditions is made easier by this configuration.

Figure 2 provides an overview of the equipment used for analyzing the I-V (current-voltage) and P-V (power-voltage) curves of photovoltaic (PV) modules, crucial for determining their electrical characteristics. The key parameters measured include the maximum power (Pmax), short-circuit current (Isc), open-circuit voltage (Voc), maximum power current (Imp), maximum power voltage (Vmp), and fill factor (FF). These parameters are essential for assessing the performance and efficiency of PV modules under different operating conditions.

The electronic load, specifically the Keysight N3300A, plays a central role in this setup by simulating varying load conditions to stress-test the PV module. It operates in two configurations: channel 3 (N3304A) alone for modules rated below 300W and channels 3 and 4 in parallel for modules with power ratings above 300W, ensuring that the system can handle different power levels efficiently. The flexibility of this setup allows for the characterization of both smaller and larger modules, ensuring that the data collected covers a wide spectrum of module ratings.

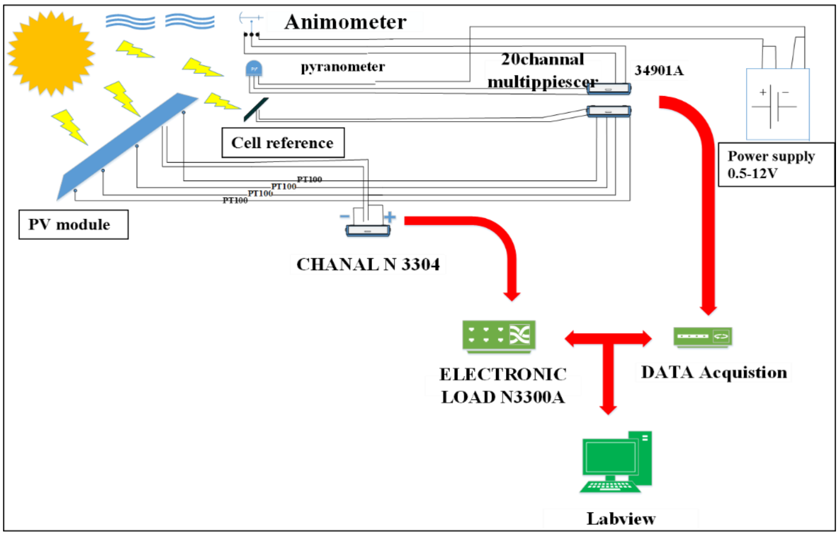

Fig 1. Simplified diagram of I-V characterization in STC test station.

The system also relies on a Keysight 34972A data acquisition unit, which gathers information from a variety of sensors, including those monitoring temperature, wind speed, and solar irradiance. This combination of environmental and electrical data is vital for accurate performance evaluation, as the performance of PV modules can vary significantly depending on external factors. By collecting and synchronizing all these measurements, the system provides a comprehensive analysis of the PV module's behavior under standard test conditions (STC) as well as under real-world environmental conditions. This approach helps identify efficiency losses and optimizes performance, leading to a more accurate and reliable characterization of PV modules.

In summary, the system shown in Figure 2 is reliable and adaptable, able to do comprehensive I-V and P-V assessments on a variety of PV modules, all the while guaranteeing accuracy by including environmental data. This configuration is critical to PV performance optimization, which is needed for both industrial and research applications.

Fig 2. Machines analysis of I-V curve (a)Data logger N3300A, front face and (b) bike side, Data acquisition , Keysight 34972A.

In order to precisely measure the temperature of the PV module, a careful setup is shown in Figure .3, which shows the positioning and arrangement of Pt100 temperature sensors on the backsheet. All of these sensors are located in the middle of each solar cell and are dispersed throughout the backside. The core region of a solar cell often receives more constant operating temperatures, which are crucial for performance assessments, hence this deliberate positioning is necessary to record an accurate depiction of the module's temperature. The even distribution of the sensors ensures a comprehensive temperature profile of the entire module, effectively capturing any potential temperature variations. Variations in temperature can occur due to a variety of factors, including fluctuations in environmental conditions, shading, and uneven power generation by individual cells. By monitoring temperature across the module, it is possible to detect thermal anomalies, such as hotspots, which can significantly impact both the performance and long-term reliability of the PV module.

The connection of multiple Pt100 sensors to a data acquisition system ensures that temperature data is continuously recorded and analyzed. This setup provides valuable insights into the thermal behavior of the PV module, allowing for the detection of issues that may not be apparent through electrical performance testing alone. For instance, higher temperatures typically result in reduced efficiency and can accelerate degradation, especially in localized hotspots.

Accurate temperature measurement is crucial for determining the thermal coefficient of the module, which describes how temperature changes affect its electrical performance. A precise understanding of these temperature effects allows for better control of operating conditions, leading to more accurate performance predictions and potentially extending the module’s operational lifespan. Ultimately, the configuration of Pt100 sensors depicted in Figure 3 offers a trustworthy way to gauge the thermal properties of the PV module. In order to ensure accurate performance evaluations, identify hotspots, and evaluate the module's long-term reliability, this thorough temperature monitoring is essential. It also helps to optimize the performance of PV systems and improves the overall dependability of the trial results.

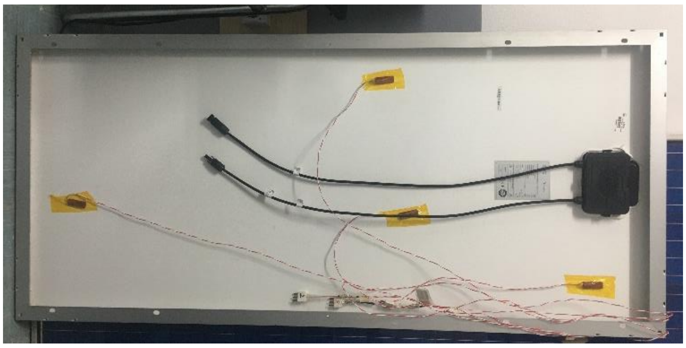

Fig 3. the temperature sensors on the back-sheet of PV module (glass-Tedlar®).

4. RESULTS AND DISCUSSION

4.1 Uncertainty analyses

Estimating uncertainty contributions to an impartial resulting value is a complex problem (Winter & Sperling, 2006; ISO/IEC-Guide98-3 2008; IEC:60904-1: 2006; and IEC 60891 2009). In uncertainty analysis, two commonly used types of uncertainty are type A and type B. At our laboratory, PVTL, which specializes in the credibility and verification quality of PV modules, all measurements require their associated uncertainty values. The measurement procedures for module I-V performance in the

Photovoltaic Test Laboratory (PVTL) are based on IEC standards (IEC:60904-4: 2011; ISO: Geneva, 1995; Li, 2021).

Table 2 summarizes the standard uncertainty components. All uncertainty components are given in percentages and are based on a 1-year calibration interval. The combined uncertainties were calculated according to Eqation (1) type B for each column. Type B uncertainties arise from the instruments used in measurement and their calibration histories. For a rectangular probability distribution with half-width a, the uncertainty is calculated as follows:

$$U_B = \frac{a}{\sqrt{3}} \quad (1)$$

It is important to note that, by following this procedure, all input quantities are treated as uncorrelated.

Table 2. list of materials including input uncertainty data of the machines and components used in the measurements and calculations standard uncertainties for the type B.

Components, machines	**Input uncertainty Data**	**Standard uncertainty**
Reference cell		1,73%
PT100	±0,003°C	U_{PT100} = 0,0017°C
Non-uniform temperature	≤3°C at STC	U_{T3}= 0,866°C
	≤7°C at other than STC	U_{T7}= 2,021°C
Data acquisition	*Accuracy (V_{DC}):* 0,0035% of reading + 0,0005% of range	U_{DAT}≤0,0023%
	Accuracy (temp): 0,06°C	U_T = 0,035°C
	Tc: 0,0005% of reading +0,0001%of range	U_{Tc} = 0,00035°C
Data logger	*Current accuracy* I(A):0,05%+10mA	U_I= 0,035%
	Voltage accuracy (V): 0,05%+8mV	U_V=0,033%
	Power accuracy P(W): 0,1%+0,6W	U_P=0,4%
	Tc: Current readback: 100ppm/°C+1mA/°C	U_{TcI}=0,0064%
	Voltage readback: 80ppm/°C+0,33mV/°C	U_{TcV}=0,0048%
Calibrated resistor	*Accuracy:* ±0,41%	U_{Res}= 0,24%

The standard uncertainty of each parameter's measurement can be calculated as:

$$U_B = \sqrt{(U_a)^2 + (U_b)^2 + (U_c)^2 + \cdots + (U_x)^2} \quad (2)$$

This comprehensive approach ensures that all potential sources of uncertainty are considered, providing a robust and reliable uncertainty estimation for the PV module measurements conducted in our laboratory.

4.1.1 Uncertainty in Isc

The uncertainty in the short-circuit current (Isc) is determined using standard uncertainty analysis methods, as described in references (Middlesex, UK, 1997, Li B 2022, Carrillo JM 2012). The uncertainty estimates for Pmax encompass both current and voltage measurements, reflecting the combined impact of these uncertainties on the power output. The PV module under investigation features 36 polycrystalline-Si cells with a nominal power of 150 Wp. The specific measurement conditions include an irradiance of G = 1000 W/m² and a temperature of T = 25°C.

The uncertainty in Isc, denoted as U_{Isc}, can be calculated using the following Equation (3):

$$U_{Isc} = \sqrt{(U_{DAS})^2 + (U_{Res})^2} \tag{3}$$

Here, U_{DAS} represents the uncertainty due to the data acquisition system, and U_{Res} represents the uncertainty due to the calibrated resistor. The uncertainty of Isc is expressed as a percentage, derived from the typical I-V data range and resolution, as shown in Table I. This method ensures precise uncertainty calculations tailored to the measurement conditions.

4.1.2 Uncertainty in Pmax

The determination of the maximum power (P_{max}) involves finding the maximum product of current and voltage under standard conditions. However, P_{max} can be influenced by factors such as contacting, owing to the distributed resistance nature of photovoltaics.

The uncertainty in U_{Pmax} can be calculated using the following Equation (4):

$$U_{Pmax} = \sqrt{(U_{Isc})^2 + (U_P)^2 + (U_{Voc})^2} \tag{4}$$

All uncertainties here, $UIsc$, UP, and $UVoc$ represent the uncertainties associated with short-circuit current, power, and open-circuit voltage, respectively. These uncertainties have been previously calculated and detailed in Table 1.

4.1.3 Uncertainty in Efficiency

The efficiency of a photovoltaic module, relative to standard reference conditions defined by temperature, spectral, and total irradiance, can be calculated using the formula in Equation (5) as follow:

$$\eta = \left(\left(\frac{Pmax}{surface}\right)/G\right) * 100 \tag{5}$$

The uncertainty in $U\eta$ can be determined by the Eq. (6) as follow:

$$U_\eta = 2\sqrt{\left(\frac{Rc}{\sqrt{3}}\right)^2 + \left(\frac{Pmax}{\sqrt{3}}\right)^2} \tag{6}$$

4.1.4 Uncertainty in FF

The fill factor (FF), is defined as:

$$FF = 100\,\frac{P_{max}}{V_{oc}\,I_{sc}} \tag{7}$$

The uncertainty U_{FF} in FF can be calculated as:

$$U_{FF} = 2\sqrt{(U_{Isc})^2 + (U_{Pmax})^2 + (U_{Voc})^2} \tag{8}$$

To comprehend a photovoltaic (PV) module's performance under standard test conditions (STC), Figure 4 displays the I-V (current-voltage) and P-V (power-voltage) curves of the PV module. A temperature of 25°C and an irradiance of 1000 W/m² are included in these parameters. The I-V curve is shown by the solid line, while the P-V curve is shown by the dotted line. Key information about the behavior of the module is provided by both curves.

The maximum power point (Pmax), maximum power voltage (Vmp), maximum power current (Imp), and short-circuit current (Isc) are important points in these curves. The maximum voltage (Voc) and maximum current (Isc) are represented when the voltage is zero (at open circuit and short circuit, respectively. Where the module is indicated by the Pmax point delivers the maximum power output, occurring at a specific combination of current (Imp) and voltage (Vmp). The PV module's electrical properties appear in the shape of the I-V curve, where high current and low voltage are represented by a comparatively flat section in the first segment. Near the Voc point, the current rapidly drops as the voltage rises. The Pmax point, where the module functions at maximum efficiency, is where the P-V curve peaks.

The significance of uncertainty estimates in the voltage and current measurements, which have an immediate impact on Pmax calculation, is also highlighted in this image. Variations in temperature, variations in irradiance, and inaccuracies in the apparatus can all lead to measurement uncertainties. Reliable performance evaluations depend on accurate uncertainty quantification, especially when describing modules for performance in various environmental scenarios. Researchers and engineers may choose and test PV modules more intelligently if they have a better understanding of these curves and the associated uncertainties. Through increased precision in performance evaluations, optimized module design, and improved dependability, this advances solar technology overall. In the end, understanding and reducing uncertainty contributes to ensuring that PV systems function as expected in practical applications, which increases trust in solar energy solutions.

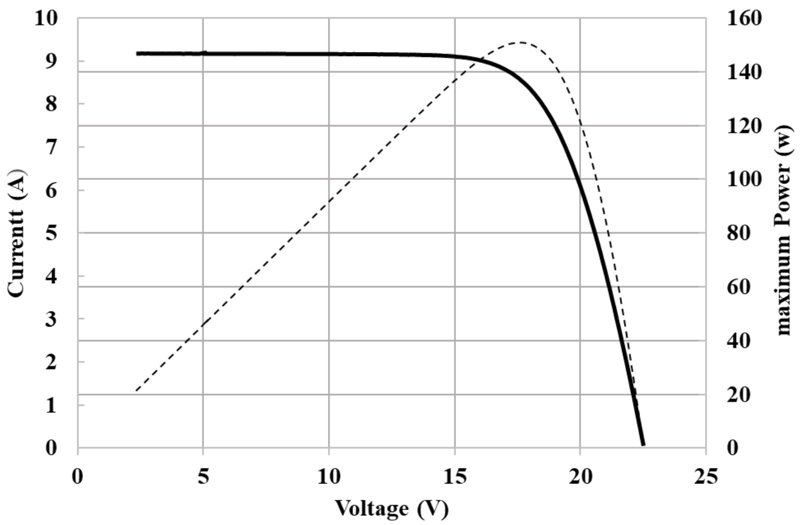

Fig 4. I–V and P-V characterization obtained under outdoor standard test conditions

The uncertainty estimation for the electrical I-V characterization parameters, as shown in Table .3, was conducted to assess the reliability of the measurements. The combined uncertainties were calculated following Equation (2), considering various factors such as irradiation intensity. In the columns for Pmax and FF, the standard uncertainty represents the root sum of squares for Isc and Voc, respectively.

For the outdoor I-V characterization measurement (Figure.4), the estimated uncertainties were ±0.47% for the short-circuit current (Isc), ±0.033% for the open-circuit voltage (Voc), and ±0.62% for the maximum power (Pmax). These uncertainties provide valuable insights into the accuracy of the measurements and highlight the precision achieved in characterizing the electrical parameters of the photovoltaic module under study.

Table 3. Results of the uncertainty estimation for electrical I−V characterization parameter.

parameters	Output data
Irradiation (w/m^2)	1000
Isc (A)	8.706 ±0.47%
Pmax (watt)	143.818 ±0.62%
Voc (V)	22.464 ±0.033%
η	14.37±3.19
FF	0.73 1.04%

4.2 Uncertainty on PV modules irradiations

Table 4 provides a detailed overview of the I-V characteristics of photovoltaic (PV) modules under outdoor Standard Test Conditions (STC), highlighting the measured, extrapolated, and interpolated data. The key parameters include module temperature (Tm), maximum power (Pmax), open-circuit voltage (Voc), short-circuit current (Isc), and irradiance (G). The focus of this discussion will be on the uncertainties associated with these measurements and the differences in irradiance. The measured data provide a baseline at the standard irradiance of 1000 W/m². Extrapolation adjusts the values to account for higher irradiance levels (1024-1069 W/m²), while interpolation spans a broader range of irradiance (928-1069 W/m²).

These adjustments allow for a more comprehensive understanding of the PV module performance under varying sunlight conditions (IEC 61853-1: 2011).

Table 4. I-V characteristics of PV modules under outdoor STC measurements and translated

Data	T_m(°C)	P_{max} (Wc)	V_{oc} (V)	I_{sc} (A)	G (W/m^2)
Measured	25	143,81±3.36	22,47±0.193	8,72±0.186	1000
Extrapolation	25	144,10±3.37	22,62±0.195	8,66±0.185	1024-1069
Interpolation	25	142,84±3.34	22,45±0.193	8,70±0.186	928-1069

The uncertainties in Pmax are relatively small, around ±3.36 to ±3.37 W, indicating a high level of precision in the measurements. The minor differences in uncertainty between measured, extrapolated, and interpolated data suggest consistent measurement techniques and reliable extrapolation and interpolation methods. The uncertainties for Voc are very small, around ±0.193 to ±0.195 V, demonstrating precise voltage measurements. This consistency is crucial for accurate performance characterization of PV modules. Similar to Voc, the uncertainties for Isc are small, around ±0.185 to ±0.186 A. The close agreement among measured, extrapolated, and interpolated values further indicates reliable current measurements.

4.3 Uncertainty on PV module temperature

Figure 5 shows the temperature coefficients of the following important electrical characteristics for a 150 Wp photovoltaic (PV) module: maximum power (P_{max}), maximum current (I_{mp}), maximum voltage (V_{mp}), short-circuit current (I_{sc}), and open-circuit voltage (V_{oc}). With linear trends based on actual data, the graph illustrates how temperature affects four crucial metrics that are crucial for assessing PV module performance in a range of temperature scenarios.

Current in Short Circuits (I_{sc}): The positive slope of the Isc (y = 0.0034x + 9.331) indicates a modest increase with temperature. The improved carrier production at higher temperatures is responsible for this small increase in Isc. Nonetheless, the overall variation is negligible, indicating that the short-circuit current is very little impacted by temperature. This is normal for photovoltaic modules, where the current is less affected by temperature compared to the voltage.

Open-Circuit Voltage (V_{oc}): The Voc shows a negative slope (y = −0.102x + 22.716) and a distinct and considerable reduction as temperature rises. Higher temperatures cause charge carriers to recombine more frequently, which lowers the voltage of the PV module. This behavior is well-known in PV modules. Reduced PV performance in hotter conditions is mostly caused by the fast fall in Voc.

Maximum Power (P_{max}): The strong negative slope (y = −1.0187x + 155.26) indicates that the power output (Pmax) decreases linearly with rising temperature. Together, the lowering Voc and the very stable but slightly increasing Isc cause a drop in Pmax. The module's power output decreases with increasing module temperature, as indicated by this negative temperature coefficient, which is an important factor to take into account for PV installations in high temperature region.

Maximum Current (I_{mp}): The positive slope (y = 0.0049x + 8.7337) indicates that the Imp only slightly increases with temperature. Similar to Isc, the Imp does not change considerably with temperature, suggesting that current is not greatly affected by temperature fluctuations. This trend indicates that the PV module's voltage is more significantly impacted by temperature than by current.

Maximum Voltage (V_{mp}): The Vmp has a negative slope (y = -0.1082x + 17.783) and thus declines with rising temperature, much like Voc. Because rising temperatures reduce the voltage available for producing power, the decline in Vmp affects the module's maximum power point. This highlights how crucial it is to take Vmp into account when examining the overall effectiveness of PV modules in various temperature settings.

This graph gives an in-depth understanding of how temperature affects the performance of PV modules. The major lesson here is that while the current-related parameters (Isc and Imp) stay mostly unchanged, temperature rises have a detrimental effect on the voltage-related parameters (Voc and Vmp). Because of this substantial drop in voltage, the PV module's total power output (Pmax) decreases with temperature. It is simpler to forecast the temperature behavior of the module under real-world settings thanks to the linear correlations shown by the fitted lines.

Designing PV systems requires an understanding of these temperature coefficients, especially in hot climates where high temperatures may significantly affect the efficiency and power output of the module. PV system performance can be adjusted for changing climatic circumstances by taking these temperature effects into consideration during system design and choosing modules with advantageous temperature coefficients. Furthermore, in order to improve the precision of performance forecasts, accurate temperature measurements are necessary due to the uncertainty in the temperature coefficients for Isc, Voc, Pmax, and FF. Temperature coefficient uncertainties can be reduced with appropriate calibration and precise sensor positioning, enhancing the dependability of PV module evaluations.

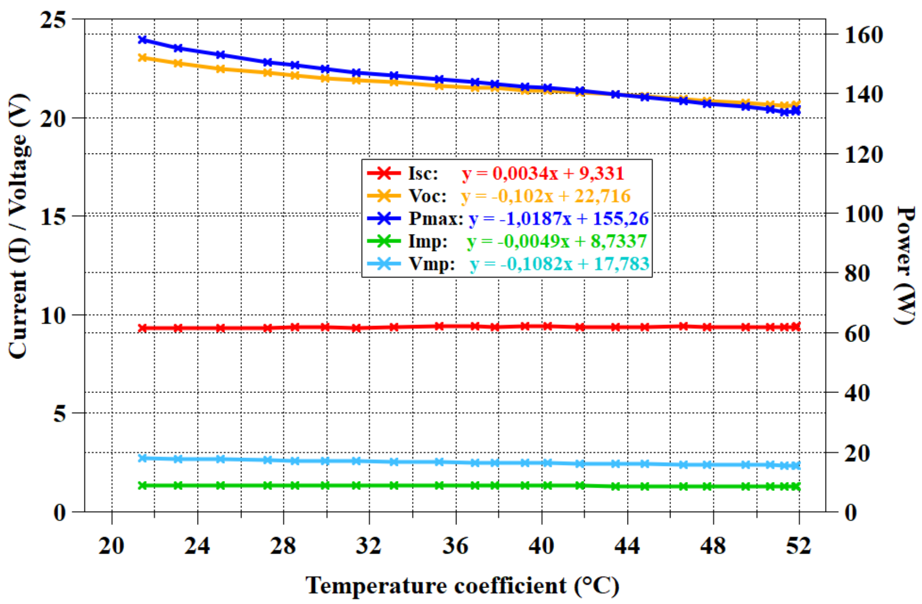

Fig 5. Evolution of Temperature coefficient measurement of PV module parameters.

The slopes determine the value of the corresponding temperature coefficients:

$$\alpha = \frac{1}{Isc}\frac{dIsc}{dTc} \tag{9}$$

$$\beta = \frac{1}{Voc}\frac{dVoc}{dTc} \tag{10}$$

$$\gamma = \frac{1}{Pmax}\frac{dPmax}{dTc} \tag{11}$$

The temperature coefficient of the *FF* (δ) can be obtained by:

$$\delta = \frac{1}{FF}\frac{FF}{dTc} = \gamma - (\alpha + \beta) \tag{12}$$

Table 5 represents the temperature coefficients of Isc, Voc, Pmax and FF. For a T_C ranging from 21 to 52°C, the results of the coefficients are: α = 0.038 %/°C, β = -0.45 %/°C, γ= -0.70 %/°C and δ = -0.29%/°C following Equation (9), (10), (11), and (12) respectively. Furthermore, the evolution time of T_C and the corresponding non-uniformity throughout the heating process.

The measurements taking without any precaution such as covering the back sheet of the module with a thermally-insulating foil as described in (M3003, Middlesex, UK, 1997) that there any difference in value of temperature coefficient.

The data presented in Table III refer to a single module, but, in most cases, are representative of a set of devices of the same type and technologies. Including detailed uncertainty calculations enhances the reliability of these observations, providing a comprehensive understanding of the module's behavior and aiding in the design of more resilient and efficient PV systems.

Table 5. Value of temperature coefficient calculated from experimental measurement

Tc	α (%/°C)	β (%/°C)	γ (%/°C)	δ (%/°C)
Error	±0.47%	±0.033%	±0.62%	±1.04%
Value estimation	0.038	-0.45	-0.70	-0.29

Figure 6 shows an "Organizational Framework Highlighting Key Contributions to Enhancing Photovoltaic Technology," which lists several key areas of concentration that must be addressed in order to progress PV technology. In order to improve PV module performance and dependability, this framework is designed to highlight the significance of accurate measurements, uncertainty calculations, and standardization. Let us examine each of the main components:

1. Standardization and Comparability (I): This element emphasizes the necessity of standardizing testing procedures for variables such as fill factor (FF), maximum power (Pmmp), short-circuit current (Isc), open-circuit voltage (Voc), and efficiency. Facilitating standard procedures in testing and assessment allows for greater international comparability. By guaranteeing uniformity between various locations and labs, this standardization fosters international collaboration. Consistent standards can make PV technology progress much more quickly as it enters new industries.
2. Temperature Coefficient Challenges (II): Improving the accuracy of PV module performance in varying climatic circumstances requires addressing the impact of temperature changes. The efficiency and power output of PV modules are strongly impacted by temperature variations, which make them extremely sensitive. By addressing these issues, the framework hopes to improve the adaptability of PV systems in a variety of situations by supplying more dependable data that accurately represents real-world operating conditions.
3. Enhancing PV Module Design (III): The foundation of this framework is research on material selection and design advancements. It focuses on creating more resilient, long-lasting, and effective PV modules. Particularly in harsh conditions, advances in material science and module construction can result in inventions that increase the lifespan of photovoltaic modules, lower their rate of degradation, and boost their overall efficiency. Better material selection also guarantees that the modules can withstand environmental deterioration and mechanical stress.
4. Assisting with Certification and Quality Assurance (IV): Adhering to ISO/IEC 17025 criteria improves measuring processes' credibility, which is important for fostering customer confidence and encouraging PV technology adoption on a larger scale. By ensuring that the measuring procedures are precise, repeatable, and dependable, these rules improve quality control.
5. Accurate Uncertainty calculate (V): Dependable performance evaluations are predicated on accurate uncertainty estimate. Research into novel PV materials, methods, and designs is encouraged by the framework, which offers an organized method for calculating uncertainty in important parameters. The foundation for future innovations in performance modeling is also laid by this procedure, which permits researchers to investigate more intricate and varied PV module designs while preserving accurate data on their output and efficiency.
6. Precise Performance Measurements (VI): Having precise performance measurements is essential to facilitating efficient energy management, which enhances energy storage and distribution options. The design of energy systems that incorporate PV modules is directly impacted by these metrics, which aid in maximizing power output and grid stability. When building renewable energy infrastructures, particularly those that incorporate smart grid and battery energy storage systems (BESS), the accuracy of these measures is crucial.
7. Facilitating Collaboration and Continuous Improvement (VI): The framework emphasizes how crucial it is to support cooperation between businesses, research facilities, and nations. The only ways to continuously innovate and develop PV technology are to collaborate on research projects, exchange expertise, and make cooperative advances in materials science and technology.

International cooperation guarantees that advances in material science, PV performance, and design are broadly accepted and put into practice while also quickening the innovation cycle.

8. Establishing the Foundation for Future Innovations (V): This section emphasizes the importance of conducting research centered on potential advancements in photovoltaic technologies. Through the framework, PV module analysis and design may be done in an organized manner, which promotes the investigation of new materials, technologies, and techniques to improve PV adaptability and efficiency. These kinds of breakthroughs will be essential to creating PV systems that function well in a variety of challenging and frequently harsh conditions, guaranteeing the long-term viability and expansion of the renewable energy industry worldwide.

Finally, Figure 6 offers a comprehensive overview of the elements essential to the development of PV technology. PV systems can be created in a way that provides reliability, efficiency, and flexibility in various conditions thanks to the emphasis on standardization, accurate uncertainty calculations, and exact performance measurements. The graphic highlights the significance of customer confidence and market growth by integrating quality assurance frameworks such as ISO/IEC 17025. Furthermore, the framework fosters constant innovation and cooperation, both of which are necessary for PV technologies, materials, and designs to continue to advance.

In the end, this methodical and multifaceted approach will help overcome the existing issues in PV module performance and design, which will support the global endeavor to increase the use of renewable energy sources and fight climate change.

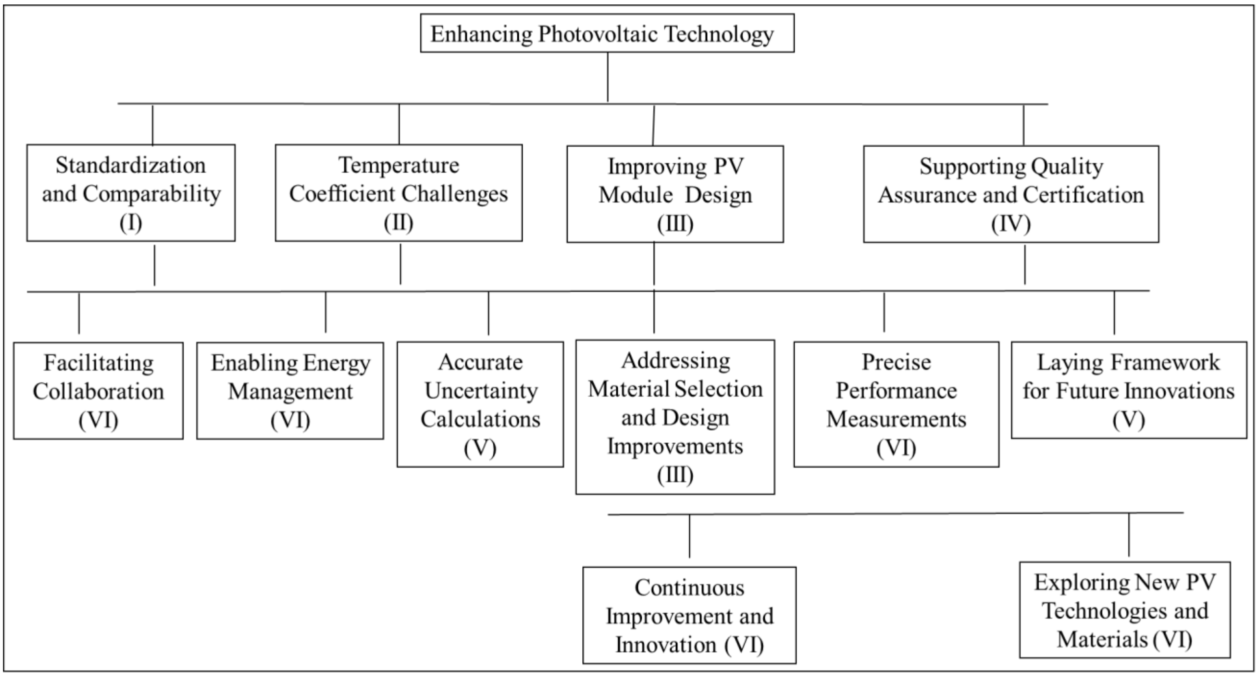

Fig 6. Organizational Framework Highlighting Key Contributions to Enhancing Photovoltaic Technology.

5. CONCLUSION

This study presents a comprehensive analysis of measurement uncertainty in the output parameters of photovoltaic (PV) modules, particularly under standard test conditions (STC). By employing rigorous uncertainty analysis methods, we have highlighted the significance of accurate I-V and I-P characterizations, which are crucial for the advancement of PV technology. The research, conducted under real-world sunlight conditions, emphasizes the importance of reference devices such as reference cells, modules, and pyranometers in determining overall uncertainty components.

Key contributions of this study include the development of standardized methodologies for uncertainty calculation related to ISC, VOC, PMMP, FF, and efficiency (η) analysis. These methodologies facilitate consistent and comparable results across different laboratories, fostering global collaboration and accelerating the development of PV technologies. Addressing temperature coefficient challenges, the study provides more accurate performance data under varying environmental conditions, contributing to the development of more resilient and efficient PV modules.

The optimization of measurement systems at STC and the subsequent phases of research, which involve estimating and optimizing the uncertainty of PV modules under outdoor conditions, underscore the importance of precise measurement and reliability. The detailed uncertainty calculations inform the selection of materials and design improvements, leading to the creation of more efficient and durable PV modules.

Adherence to ISO/IEC 17025 standards enhances the credibility of the measurements, which is vital for quality assurance and certification processes. This credibility is essential for gaining consumer trust and supporting the widespread adoption of PV technologies. Furthermore, the study provides a clear framework for future research and development, encouraging the exploration of new PV technologies, materials, and designs.

Accurate performance measurements enable better energy management and system optimization, contributing to the overall efficiency and reliability of solar energy systems. By providing valuable guidelines for PV module characterization and reliability assessment, particularly in uncertainty estimation, this study significantly advances photovoltaic technology. The organizational framework outlined in this paper highlights the key contributions to enhancing PV technology, emphasizing the importance of standardization, addressing temperature coefficient challenges, improving PV module design, supporting quality assurance, facilitating technological innovations, and enabling efficient energy management.

In summary, this study not only provides a robust methodology for uncertainty calculation but also addresses critical measurement challenges and promotes standardization. These contributions are essential for improving the accuracy, reliability, and efficiency of PV systems, thereby supporting the growth and development of the solar energy sector.

ACKNOWLEDGMENT

The authors acknowledge the support received by the “centre de développement des énergies renouvelables” through funding from the Ministry of higher education and scientific research.

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