XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

SOLAR METROLOGY: PHOTOVOLTAIC MODULE PERFORMANCE MEASUREMENTS

J. Dubard[1]*, J.-R. Filtz*[1]*, V. Cassagne*[2]*, P. Legrain*[3]
[1] *LNE, 29 avenue Roger Hennequin, France, Paris Area, 78197 Trappes*
[2] *TOTAL, 2 place Jean Millier - La Défense 6, France, Paris Area, 92078 Paris La Défense*
[3] *TENESOL, 12 allée du Levant, France, Lyon Area, 69890 La Tour-de-Salvigny*

LNE, LCM (LNE-CNAM), Photonics and Energy Division, France, jimmy.dubard@lne.fr

Abstract: The performance of a photovoltaic module is mainly defined by the maximum power P_{max}, which is measured under standard conditions (1000 W/m², AM 1.5, 25°C) using a sunlight (natural or simulated) and a calibrated reference device. This reference photovoltaic device, placed in the same lighting conditions than the module under test, allows the measurement of the sunlight levels through the monitoring of the maximum power of these devices. As a key metric for photovoltaics economy, the measurement of P_{max} must be a subject of a strong attention. This paper describes the metrology applied and the typical levels of uncertainties achievable by National Laboratories as well as in the Industry.

Keywords: Solar Energy, Photovoltaic module, Power measurement, Metrology, Traceability, Uncertainty

1. INTRODUCTION

Photovoltaic (PV) is one of the most promising renewable energy to meet the objectives of the sustainable development worldwide. The actual business market growth was about 35%/yr. over the last 10 years and is 50% with 16.6 GW installed in 2010 worldwide (7.2 GW in 2009) leading to 40 GW cumulated [1]. This rate will continue during the next decade and later with production costs decreasing, leading to PV electricity costs equivalent to classic production means (grid parity) and a significant share in the energy mix in most countries. Europe is today the leading region for PV market with more than 13 GW installed in 2010.

PV performance measurement methods are well known and are applied by National Laboratories or Metrology Institutes, Testing Laboratories and production lines. The results of the measurements are given for a set of irradiance and environmental parameters that are standardized [2] and are strongly dependent upon the measurements conditions. Traceability to SI units is critical and should be demonstrated. It is similar to the traceability set for the calibration of PV devices [10].

An overview of the current status of the measurement of PV module performance, the measurements methods used, the traceability routes and the uncertainty budgets are hereafter presented.

2. MEASUREMENT METHODS

The main quantity to be measured for module performance evaluation is the maximum power P_{max} commonly expressed in Watt peak (Wp). It is determined from the I-V characteristics of the module. This implies the measurement of the current and the voltage at the outputs of the module. I-V characteristics should be measured under illumination using either continuous light (natural or artificial) or pulsed light [2].

Measurement under continuous light can be performed using the sun as a source or a sun simulator based on lamps such as HMI lamps.

Measurement under pulsed light uses a flash lamp sun simulator based on a xenon arc lamp which spectrum is close to the sun spectrum. The pulse duration is about 2 ms to 10 ms.

Measurement using simulated sun light is typically limited to module with length less than 3m. Measurement under natural sun light is mandatory for large modules and photovoltaic concentrator.

To measure the I-V characteristics a resistive load should be connected to the module in order to vary the voltage drop between the terminations.

P_{max} of a module is determined from the I-V curve as the highest product IxV, it is done for a set of standardized conditions that are:

- Irradiance at 1000 W/m²
- Sun spectrum: AM 1.5
- Junction temperature: 25°C

The junction temperature is not accessible, but usually estimated as equal to the module temperature. Then, the module should be stabilized at the reference temperature and the measurement of the complete I-V curve should be performed under a short period of time (less than 1s).

However each data point of the I-V curve should be acquired under this short period of time. Therefore a pulsed sun simulator is usually used to measure the performance of a module. Figure 1 shows the typical I-V curve of a module.

P_{max} is determined for a level of irradiance of 1000 W/m². This irradiance measurement is given by the short circuit current of a reference device (cell or module).

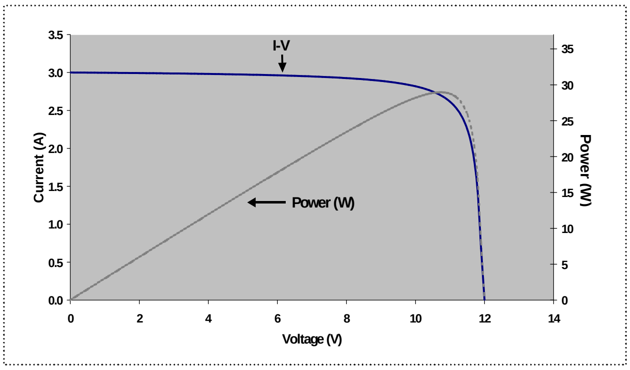

Figure 1: I-V curve of a PV module

The spectral characteristics of the reference device can be different from the one of the module under test. Therefore a spectral mismatch correction should be calculated to take into account this difference and the difference between the spectrum of the light source used and the spectrum of the sun AM 1.5. This implies the measurement of the relative spectral response of the module under test. The spectral mismatch MM is computed [7] from the following equation (1):

$$MM=\frac{\int E_{ref}(\lambda)S_{ref}(\lambda)d\lambda\int E_{meas}(\lambda)S_{DUT}(\lambda)d\lambda}{\int E_{meas}(\lambda)S_{ref}(\lambda)d\lambda\int E_{ref}(\lambda)S_{DUT}(\lambda)d\lambda} \qquad (1)$$

Where $E_{ref}(\lambda)$ is the sun reference spectrum, $E_{meas}(\lambda)$ is the spectrum of the source used, $S_{ref}(\lambda)$ is the spectral response of the reference device and $S_{DUT}(\lambda)$ is the spectral response of the PV module under test.

The performance of a PV module may be dependent upon the level of irradiation received by the module prior to the measurement of the I-V characteristics. The preconditioning is then an element for the repeatability of the measurements. This is the case particularly for some PV technology (thin film modules like amorphous silicon (a-Si), CIGS, and some mono-crystalline silicon cells) for which P_{max} is sensitive to this level of irradiation.

The performance of a thin film module should be measured after a period of pre-conditioning which should be determined by the laboratory or the manufacturer of the module [4]. The time during which the module is kept in the dark prior to the measurement is critical and should be determined also.

For most crystalline silicon technology it has been demonstrated that pre-conditioning is not necessary.

3. TRACEABILITY

To evaluate the performance of a module under standard conditions the following quantities have to be measured:

- The irradiance in the plane of the module (irradiance level and spectrum of the light source)
- The electrical characteristics: current and voltage
- The temperature of the module

Traceability of the electrical and temperature measurements can easily be done through calibrated instruments such as ammeter and voltmeter for current and voltage, and probe such as Pt100 for temperature. For irradiance measurement the traceability to SI is more complex.

3.1. Traceability of measurement under simulated sun light

When using a sun simulator for module performance measurement, the level of irradiance is determined from the short-circuit-current Isc of a reference device. This device should be calibrated according to the International Standard [5].

Four calibration methods are described:

- **G**lobal **S**unlight **M**ethod (GSM)
- **D**irect **S**unlight **M**ethod (DSM)
- **D**ifferential **S**pectral **R**esponse (DSR)
- **S**un **S**imulator **M**ethod (SSM)

For the GSM and DSM methods the traceability is achieved through the use of a pyranometer and/or a pyrheliometer that are traceable to the **W**orld **R**adiometric **R**eference (WRR) [6,7].

The calibration of the reference device is completed by the characterisation of the relative spectral response of the device and by the characterisation of the relative spectrum of the natural sun. The traceability chain is as shown in figure 2.

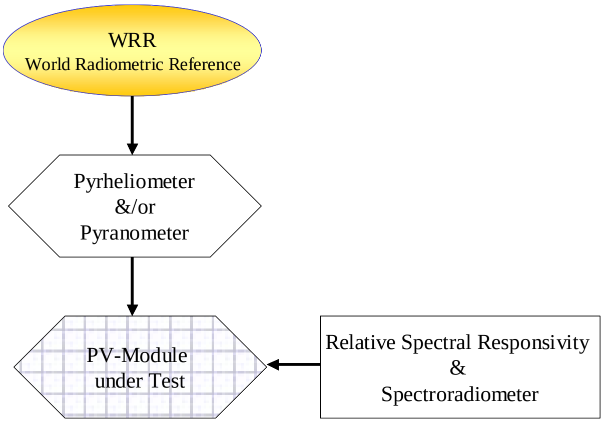

Figure 2: Traceability chain for GSM and DSM measurement method

Calibration of a reference device using the DSR method [8] is based on the comparison of the device response to the response of a standard detector which is directly traceable to the cryogenic radiometer. This method has been used to define the **W**orld **P**hotovoltaic **S**cale (WPVS) that has been established following the PEP'93 international comparison [9]. This scale is made by a set of PV mono-crystalline silicon cells for which Isc is the result of the average of measurements performed by selected reference laboratories.

The traceability chain for the DSR method is as shown in figure 3.

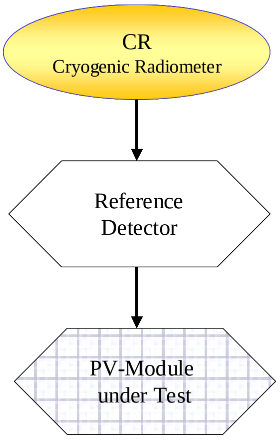

Figure 3: Traceability chain for DSR measurement method

The SSM method is based on the measurement of the absolute spectrum of the source used. This measurement relies on the calibration of a spectroradiometer.

The traceability is then achieved through the spectroradiometric scale which is set on the Black Body Cavity Radiation or the Synchrotron Radiation. This absolute spectrum of the source is completed by a characterization of the relative spectral response of the PV reference under calibration.

The traceability chain for the SSM method is as shown in figure 4.

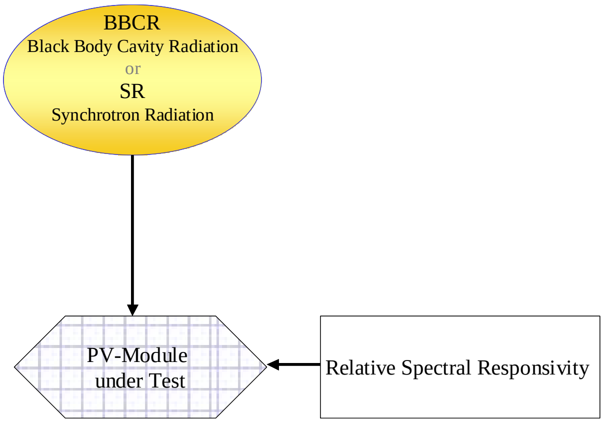

Figure 4: Traceability chain for SSM measurement method

3.2. Traceability of measurement under natural sun light

For measurement under natural sun light the level of irradiance can be measured by:

- A pyranometer. The traceability is the one described for GSM method.
- A PV reference device. The traceability is the one described for the method used for the calibration of the reference device.

4. UNCERTAINTY EVALUATION

Uncertainty evaluation of PV module performance should take into account the following contributions:

Standard cell calibration: Actual WPVS cell are calibrated with an uncertainty of 0.75% which relates directly to the irradiance level and Pmax uncertainties.

Spectral mismatch: Uncertainty due to the spectral mismatch has been evaluated [10] to be on the order of 0.5% for simulated sun light and 0.2% for natural sun light. This uncertainty takes into account the uncertainty of spectrum measurement of the light source and the relative spectral response of the reference device and the module under test.

Temperature: The contribution of the temperature should be evaluated taking into account the temperature coefficient of the reference device (irradiance level measurement) and the temperature coefficient on voltage and current of the module under test.

The uncertainty on the temperature takes into account the uncertainty on the ambient temperature and the temperature uniformity of the module.

For indoor measurement, the uncertainty on temperature can be as low as 0.5°C whereas for outdoor measurement temperature uniformity can be as large as 2°C. This leads to an uncertainty on P_{max} of 0.1% and 0.7% respectively.

Electrical measurement: The voltmeter and the shunt are calibrated with uncertainties less than 0.1%. This leads to an uncertainty of 0.15% on P_{max}.

Beam uniformity: For a class AAA simulator the beam uniformity over the maximum irradiance area specified by the manufacturer is ± 1%. This uncertainty can be adjusted depending on the actual size of the module under test. Uncertainty due to beam uniformity is neglected when performing the test under natural sun light.

Alignment of the module: The module can be aligned normal to the light beam within an uncertainty of ± 2°. The position of the module with respect to the reference device is adjusted within ± 1cm. The effect of this misalignment on the irradiance level and therefore on P_{max} is small (less than 0.1%).

Cable and connections effects: The effect of cable and connections should be evaluated by determining the Fill Factor (FF). The variation of FF has to be kept lower than 0.2%.

Finally the expanded uncertainty for $\mathbf{P_{max}}$ of a module is as low as 2.8% and 2.6% respectively for indoor and outdoor measurements. This uncertainty evaluation is valid for crystalline silicon technology. For thin film technology the effect of pre-conditioning on the uncertainty should be evaluated.

How to reduce the uncertainties?

Indoor measurement: in particular by improving the beam uniformity, the reference cell calibration and the evaluation of the mismatch factor.

Outdoor measurement: in particular by improving the temperature control of the module that will have also an impact on the measurement repeatability.

5. FEEDBACK FROM INTER-LABORATORY COMPARISONS

As in all metrological assessment, laboratories inter-comparison round robins are useful and have been set-up. Table 1 summarizes results issued from the main comparisons identified during the last 15 years.

Inter-laboratory comparison **Name**	**Date**	**Nb of devices**	**Nb of lab**	**Dispersion in Pmax**
PEPô87 [11]	1987-1989	20	8	2% sc-Si 3-4% mc-Si 4-7% a-Si
ASTM E1036 [12]	1992-1994	6	4	6.7% Si
2^{nd} International module Inter-laboratory comparison [13]	2006	6	9	7.3% Si 9-16% a-Si 7.5% CdTe 10% CIGS 9.5% III-V
FP6-PERFORMANCE [14]	2007	5	6	2-4% Si (Thin Film results not published)

Table 1: Results of PV cells and Modules comparisons

All these comparisons show a significant spread of the results. For crystalline Si cells and modules, the best dispersions are around 2-3% which fits well with the theoretical uncertainty calculation. But it is common to find a 6-8% dispersion and for thin film it can reach 10%.

These dispersions are often larger than the uncertainties claimed by the participants.

Therefore these inter-laboratory comparisons may show some under evaluation of some uncertainty components for some laboratories.

Particularly the calculation of spectrum mismatch which has a small influence for crystalline Si technology (low band gap, usual references and long experience) may be a strong contribution for thin film technologies particularly for high band gap materials and multi-junctions cells if the reference cell is not properly chosen.

No inter-laboratory comparison results were published in the last 2 years whereas the worldwide market has more than doubled during that period of time.

6. MODULES POWER MEASUREMENT AT INDUSTRIAL SCALE

At industrial scale, the metrological traceability is often longer. The factory flasher is calibrated using a device traceable to an accredited laboratory (the reference device).

To minimize the uncertainty the reference device should be of the same type than the module to be measured. If this condition is fulfilled then many uncertainty components can be reduced (spectral mismatch, temperature, alignment, cable and connections). Attention should be paid on beam uniformity contribution if the spatial response of the modules is not uniform and varies from one module to the others.

On the production line the irradiance stability of the flasher could be an issue: stability within the pulse and pulse to pulse stability. This could lead to an uncertainty associated to the repeatability of the measurement on the order of 1%.

In the factories ñdaily metrology methodsò are applied: a secondary reference (usually a production type module) is made from the reference device via local sun simulator. This secondary reference can be used daily to recalibrate the sun simulator or to monitor it with a maximum drift allowed (for example 1%) leading a new calibration with the reference device.

The uncertainty associated to the characteristics of the sun simulator (usually a class A) is about 2 to 4% depending on the PV technology. The final uncertainty is 2.5 to 5% coming from:

- Reference device: 2 to 3.5%
- Calibration of the flasher: 0.5 to 1.1%
- Calibration of a secondary reference module and daily recalibration of the flasher or monitoring of drift (1% max): 1 to 2.5%
- Measurement of the production module: 1 to 2.5%
- Total Budget: 2.5 to 5.1% assuming a normal distribution.

In case of class B sun simulator, this uncertainty can be in the range of 5 to 10%. Evaluation of the drift of the reference device would need further investigation.

Finally it is noticed that the uncertainty value is in the range of the module sales margin and so a better control of uncertainty can have a positive impact of the photovoltaic economy chain for all actors.

7. CONCLUSION

Photovoltaic module performance evaluation at laboratory and industrial levels implies complex measurement traceability routes to SI and WMO (World Meteorological Organization). Today uncertainty for crystalline silicon reference module is as low as 2.0% while uncertainty for production line PV module is 2.5 to 10%, practically 3-5% and few percents more for thin films technologies. Lower uncertainties can be achieved for any technologies by choosing adequate measuring devices: reference cell or module, high beam quality (spatial uniformity and spectral distribution). Improved uncertainty is a key factor for the fast growing PV market and has a huge impact on the economy and environment.

8. REFERENCES

[1] European Photovoltaic Industries Association, ñGlobal market outlook for photovoltaics until 2015ò, EPIA, 2011

[2] IEC 60904-1, ñPhotovoltaic devices ï Part 1: Measurement of photovoltaic current-voltage characteristicsò, September 2006

[3] IEC 60904-7, ñPhotovoltaic devices ï Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devicesò, ISBN 978-2-88910-324-9, November 2008

[4] IEC 61646, ñThin-film terrestrial photovoltaic (PV) modules ï Design qualification and type Approvalò, ISBN 2-8318-9746-7, May 2008

[5] IEC 60904-4, ñPhotovoltaic devices ï Part 4: Reference solar devices ï Procedures for establishing calibration traceabilityò, ISBN 978-2-88910-323-2, June 2009

[6] H. Müllejans, W. Zaaiman, F. Merli, E. D. Dunlop, H. A. Ossenbrink, Comparison of Traceable Calibration Methods for Primary Photovoltaic Reference Cellsò, Prog. Photovolt: Res. Appl., DOI: 10.1002/pip.625, 2005

[7] H. Müllejans, W. Zaaiman, E. D. Dunlop, H. A. Ossenbrink, òCalibration of photovoltaic reference cells by the global sunlight methodò, Metrologia 42 360ï 367, 2005

[8] J. Metzdorf, ñCalibration of Solar Cells. 1: The Differential Spectral Responsivity Methodò, Applied Optics, 26(9), 1701 (1987).

[9] C. R. Osterwald, S. Anevsky, A. K. Barua, P. Chaudhuri, J. Dubard, K. Emery, B. Hansen, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, Y. X. Wang, T. Wittchen, W. Zaaiman, A. Zastrow, J. Zhang, ñThe World Photovoltaic Scale: An international reference cell calibration programò, Progress in Photovoltaics, Vol 7, Issue 4, p. 287-297, July/August 1999

[10] H. Müllejans, W. Zaaiman, R. Galleano, ñAnalysis and mitigation of measurement uncertainties in the traceability chain for calibration of photovoltaic devicesò, Measurement Science and Technology, 20, 2009

[11] J. Metzdorf, and al., ñObjectives and results of the PEP'87 round-robin calibration of reference solar cells and modulesò, Proc. 21st IEEE PVSC, 21-25 May 1990, p. 952 - 959 vol.2

[12] C. Osterwald, ñResults of 1992 ASTM Cell and Module Measurement Intercomparison,ò, Proc. 23rd IEEE PVSC, 1993, 1102

[13] S. Rummel and al., ñResults from the Second International Module Inter-Comparisonò, Photovoltaic Energy Conversion, Conference 2006 IEEE 4th World Conference, 7-12 May 2006, p. 2034 ï 2037

[14] W. Herrmann and al., ñAdvanced intercomparison testing of PV modules in European test laboratoriesò, 22nd EPVSEC, 3ï 7 September 2007