Thin film photovoltaic module characterisation based in indoor and outdoor methods

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***Abstract*—Photovoltaic modules are normally tested under standard test conditions defined by the International Electrotechnical Commission, but these conditions are different from typical field condition. The standard test conditions for PV modules is specified as 1000 W/m^2 irradiance and 25°C cell temperature and reference spectral American Society for Testing and Materials (ASTM) G173. The light source may be natural or simulated, but it must match the reference standard as described in IEC 60904-3. The effect of spectral variations on the I-V measurements can may have a big impact on the accuracy of the performance measurements. This effect was quantified during in this the study at the Indoor and Outdoor PV testing facility in Council for Scientific and Industrial research, Energy Initiative Pretoria campus. Results show different spectral mismatch values were obtained when two different spectral reference cells were used on the indoor measurements of modules under test. The obtained spectral mismatch values were affected by the absence of true spectral data of modules under test. The irradiance corrected Isc outdoor measurement values were higher than measured uncorrected Isc measurements due to the first order impact from the measured irradiance in the plane of array. The spectral mismatch between the reference device and the PV module results in an additional error for thin film modules.**

Keywords—Thin film modules; Current-Voltage curve (I-V); Spectral response; Short circuit Current; Spectral mismatch.

I. Introduction

Substantial growth of the photovoltaic (PV) market has been maintained from more than a decade with global expansion reaching the total capacity closer to 400 GW. China is leading PV deployment by almost 54% of the total installed capacity in year 2017 [1]. In Africa, South Africa has installed utility scale of 1.47GW of PV in 2018 and more are still under construction [2], [3]. Most of these installations are either in project evaluation stage or have been delayed. This dramatic growth has led to the need for analytical tests of PV module reliability and performance [4], [5].

Crystalline silicon (c-Si) PV modules dominate the PV market globally with approximately 90-95% market share [6]. On the other end, thin film (TF) PV modules make up approximately 5-10% of the global market. Thin film modules present lower production costs and temperature coefficients relative to the c-Si and polycrystalline silicone modules [7]. Furthermore, thin film modules are attractive in applications where high ambient temperatures are reached. The most used production materials in this technology are copper indium gallium selenide sulphide (Cu (In, Ga) Se2, CIGS), cadmium telluride (CdTe), and amorphous silicon (a-Si) [8], [9]. The selection of best thin film technology for climatic condition of a location is crucial in order to improve the energy generated by PV system [4], [5].

II. Operation of PV Modules

A. Temperature and Irradiance

PV modules operate by converting light (irradiance) that is available into electric direct current using the photovoltaic semiconductors. The equivalent circuit of a PV module is shown in Figure 1.

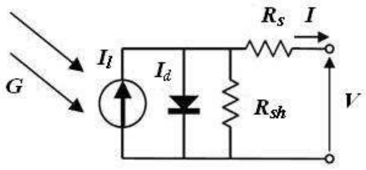

Figure 1: Equivalent circuit of a PV module [4]

The generated current from the module is determined using equation (1). Using Kirchoff's current law in Fig. 1:

$$I = I_l - I_d - I_{sh} \quad (1)$$

Where: I_l is the light generated current (A), I_d is the diode current (A) and is I_{sh} the current (A) flowing on the shunt resistance.

And in terms of single diode model, Eq. 1 can be rewritten as follows:

$$I = I_l - I_o\left[exp\left(\frac{V+IR_s}{\frac{nKT}{q}}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (2)$$

Where: I_o is the reverse saturation current (A), k is the Boltzmann's constant (1.381 x 10-23 J/K), n is the diode quality factor (-), q is the electronic charge (1.602 x 10-19 C), R_s is the series resistance (Ω), R_{sh} the shunt resistance (Ω)

The light generated current (I_l) can be expressed by,

$$I_l = \frac{G}{G_{ref}}\left[I_{ref} + \mu_i\left(T_c - T_{c,ref}\right)\right] \quad (3)$$

Where: μ_i is the cell's short-circuit current temperature coefficient (A/K), T_c temperature of the photovoltaic device (K), subscript *ref* shows the values at reference condition (T_c = 25°C and G = 1000W/m^2) and G is solar irradiance (kWh/m^2).

The diode reverse saturation current (I_o) is expressed by,

$$I_{o,ref} = \left(\frac{T_{c,ref}}{T_c}\right)^3 expo\left[\frac{qE_g}{nK}\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \quad (4)$$

Where: E_G is the band gap energy of the semi-conductor (eV).

The complete behaviour of single diode model PV cells, as shown in Eq. (2), is described by five model parameters (I_l, I_0, R_s, R_{sh}, n) which are representative of a physical PV cell/module. These parameters are in fact related to two environmental parameters i.e. solar insolation (irradiation) and temperature.

B. Solar Spectrum and Module Spectral Response

Solar spectrum is a second order effect that impacts performance and performance measurements of thin film and crystalline silicon modules. While the spectrum of sunlight is constant for any given time and place, the spectral response of the thin film module is different from the spectral response of crystalline silicon modules. The typical solar spectrum is shown in Figure 2 and spectral response of typical thin film and c-Si and multi c-Si PV modules is shown in Figure 3.

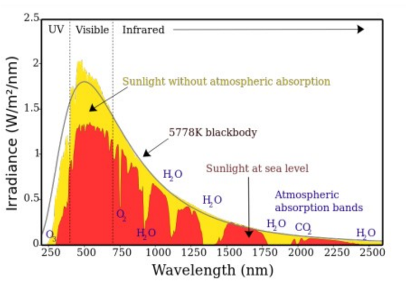

Figure 2: Typical Solar Spectrum [5]

The three distinctive spectral responses of the different types of PV technologies are shown in Figure 3. The c-Si, multi c-Si and CIGS have similar spectral response to each other. The CdTe and GaAs have similar spectral response. The dye sensitized solar cells and organic solar cells also have their own spectral response profile.

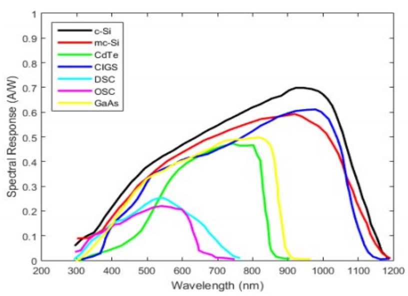

Figure 3: Different spectral response of different PV technologies [5]

The effect of the spectral variation will be validated through the indoor sun simulator as well as outdoor testing on thin film modules and c-Si modules [5], [10], [11].

III. Theoretical Frame work

Although thin-film PV modules have been in around for decades. The characterization of their performance, both under sun simulator and outdoors, remains a topic of dynamic research [4], [5]. There are different types of thin film technologies with each technology having its own spectral response, temperature coefficients and transient performances which make it difficult to get repeatable measurement results when measuring these PV modules even under simulated laboratory conditions. Also reference devices with matching spectral response are difficult to obtain [4]. These challenges lead to errors in the illumination levels and incorrect Isc measurements. Some of these technologies are high capacitive causing problematic dependence of results on the duration of illumination I-V curve sweeps.

A. Outdoor Measurements

The outdoor measurements have been done on the North facing fixed 25^{0}C tilted rooftop rack and the measurements have been carried out at solar noon $\pm$2 hours to minimize the angle of incidence and spectral effect. Current and Voltage (IV) curves of thin film modules were plotted using the peak power measuring device (PVPM) curve tracer. Solar spectrum was measured frequently over a range of air mass values in this study. Different pyranometers and crystalline Si reference devices are utilized in order to quantify the effect of the reference device used on the performance measurements. The module temperature was monitored. The spectral response was analysed from the measured solar spectrum device to quantify the effect of spectral variations on the performance of thin film modules.

B. Indoor Measurements

The indoor measurements are conducted on an artificial sun simulator where temperature and irradiance could be controlled with precision. However, the spectrum of the artificial sunlight does not match the natural sunlight or the reference spectrum perfectly, so the spectral mismatch factor was determined according to IEC 60904-7 international standards. The indoor measurement results are recorded and compared against the outdoor results in order to validate the spectral mismatch calculation, which can then be confidently used for indoor thin film I-V measurements with high accuracy and repeatable results.

IV. Measurements and results

A. Measurement Setup

Two dominant types of thin film PV module technologies (CdTe, CIGS) were selected from the available batches in the laboratory and from the outdoor testing racks. The modules specifications were registered on the created project workbook to capture the name plate ratings, technology name as per Table 1 shown below. From the participating thin film modules, one CdTe, five CIGS and two CIS thin film modules were selected and have been assigned conventional labels as "Module ID" attached to them for identification.

Table 1: Participating modules rating label

Module ID	Manufacturer	Cell Type	Pmp [W]	Isc [A]	Voc [V]	Imp [A]	Vmp [V]
18000-13	First Solar	CdTe	90	2.06	60.5	1.9	47.4
18000-14	Q-Smart	CIGS	85	1.68	73.1	1.49	57.2
18000-45	Q-Smart	CIGS	85	1.68	73.1	1.49	57.2
18000-46	Q-Smart	CIGS	85	1.68	73.1	1.49	57.2
18000-53	Solar frontier	CIS	175	2.2	114	1.96	89.5
18000-54	Solar frontier	CIS	175	2.2	114	1.96	89.5
18001-01	ZSW	CIGS	105	1.42	101.1	1.3	80.5
18002-01	ZSW	CIGS	105	1.42	101.1	1.3	80.5

These types have first all undergone the stabilization process as per IEC 61853 [4] where they were exposed to outdoor preconditions on the outdoor testing racks.

All the participating modules were then taken to the measuring stage both indoor and outdoor. Under outdoor test procedure, the modules were tested on the outdoor conditions. These modules were mounted on the North facing fixed 25^{0}C tilted rooftop racks and the measurements were taken on multiple sunny days. The available solar irradiance (1000W/m^2), weather data and the module thermal conditions files were crucial to this process. Therefore, the thermocouple sensor was attached to the backside of each module under test in order to measure the module temperature, and was connected to data logger to record the temperature measurements. The Silicon reference cells were incorporated and attached onto the same fixed tilt module rack to record real time plane of array irradiance data at the same angle as the module.

For indoor measurements, the rated Isc (short-circuit current) values and other rating label values were utilized in recipe creation on the sun simulator. These created recipes were used to accurately perform STC Current and Voltage measurement. Two available world PV scale (WPVS) monitor cells (Ref 055 and Ref 029) which were calibrated by international laboratories and were utilized to calibrate the sun simulator machine. The two Monitor cells were silicon reference cells with Ref 029 having a special K2 filter. The thin film modules tested at 25^{o}C thermal conditions using the incorporated thermal chamber of the sun simulator. In this indoor test measurements, an AAA h.a.l.m flashed solar simulator were utilized which is capable of providing a controllable testing laboratory condition. It generates 65 millisecond pulsed flashes from a high-precision xenon arc lamp and a flash duration of at least 45mS at irradiance of 200W/m^2 to 1100W/m^2. It has a thermal unit capable of creating a thermal condition ranging from 10^{o}C to 75^{o}C for temperature coefficient measurements, standard test condition measurements (STC) and normal operating module temperature measurements (NMOT). It has some PT100 temperature sensors which were placed at the back of the modules to measure the module temperature uniformity during testing. The unit was be periodically calibrated prior the measurements using WPVS monitor cell, to minimise measurement uncertainties due to unstable flash measurements and the traceability of the measurements.

The spectral mismatch factor was calculated using IEC 60904-7:2019 which describes procedure followed in spectral mismatch error correction used in testing PV module, caused by the mismatch between the flasher lamp spectrum, reference device spectrum, solar spectrum and the spectrum response of the device under test in order to achieve measurements uncertainties.

Upon the completion of the spectral mismatch factor, the correct spectral value was obtained for both WPVS reference cells as used (Ref 055 and Ref 029) on all the different participating module technologies used. These spectral values are used on indoor I-V measurements when measuring spectral unmatched devices in order to achieve repeatable and comparable measurements on thin film module technology.

Both these two methods (indoor and outdoor) should results in close short circuit current values for the same module technology used. This helps to have the correct spectral mismatch factor and will uplift thin film characterization and spectral mismatch factor capabilities.

B. Results

The outdoor measurements were measured from the 12th, 13th, 14th, 15th, 26th, 27th and 30th August 2019 at ±2 hours noon time using a Silicone reference cell device of the Peak Power measuring device as well as the Silicon reference cell. Both reference cells were mounted on the same plane of array irradiance as the modules under test. The measured data were filtered to include only the interval of Plane of array irradiance between 950W/m^2 and 1000W/m^2. The measured values were translated to STC conditions with a simple irradiance correction for short circuit current (Isc) excluding k-factor and r-series parameters, as per IEC Standard 60891. The measured uncorrected Isc values were compared against both STC corrected and irradiance corrected values as shown in Figure 4 below.

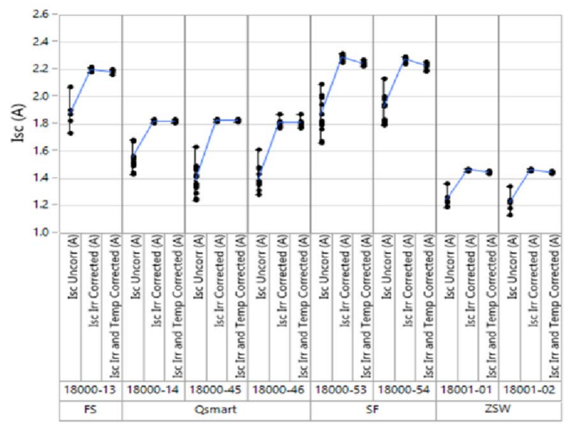

Figure 4: Isc measured vs Isc with irradiance correction and Isc with irradiance correction with temperature corrected outdoor measurements

The irradiance corrected Isc measurement values were higher than measured uncorrected Isc measurements due to the first order impact from the measured irradiance in the plane of array. The spectral mismatch between the reference device and the PV module results in an additional error for thin film modules. Therefore it is crucial to have a spectrally matched reference cell when measuring thin film modules under outdoor conditions in order to have accurate plane of array irradiance measurements.

During the indoor measurements PV modules were unmounted from the outdoor racks and measured on the indoor conditions same day and then measured again on the consecutive number of days. The WPV Si monitor cell (Ref 055) was used to calibrate sun simulator and used to measure the thin film PV modules at STC condition. The spectral mismatch factor was assumed to be unit (1). The three consecutive I-V measurements we taken on each module and the average measured Isc was reported. The WPVS monitor cells were interchanged and the K-2 filtered WPVS Si monitor cell (Ref 029) was used in order to observe the effect of the two mismatching reference devices.

The developed python script was used to calculate the spectral mismatch factor to compensate the differences between the global solar spectrum, reference device spectral response, spectrum of the sun simulator lamp and the spectral response of the test specimen. The global spectrum data was obtained from NREL website. The lamp spectral data was obtained from the sun simulator manufacturer and the spectral response data of the reference devices were obtained from the resent calibration documents. The spectral response of the modules was not available, instead webPlotDigitizer tool was utilized to obtain the spectral response data of the different participating thin film PV module technologies.

When Ref 055 was used on CdTe PV technology with the global solar spectrum and the spectrum of the illuminating flasher tube remain unchanged, the calculated spectral mismatch factor value of 0.989 was achieved. The corresponding spectral response charts were obtained as shown in Figure 5 below.

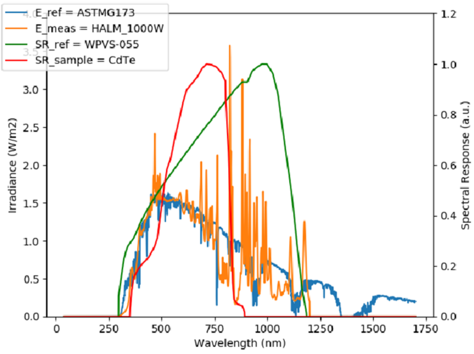

Figure 5: Spectral response of CdTe PV module technology when WPVS Ref 055 is used

When WPVS Ref 055 was interchanged with WPVS Ref 029 on the same CdTe PV technology with the global solar spectrum and the spectrum of the illuminating flasher tube remain unchanged, the calculated spectral mismatch factor value of 0.98820 was achieved. The corresponding spectral response charts were obtained as shown in Figure 6 below.

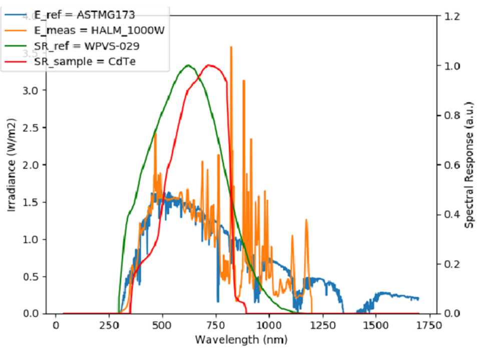

Figure 6: Spectral response of CdTe PV module technology when WPVS Ref 029 is used

When WPVS Ref 055 was used on the CIGS PV technology with the global solar spectrum and the spectrum of the illuminating flasher tube remain unchanged, the calculated spectral mismatch factor value of 1.01055 was achieved. The corresponding spectral response charts were obtained as shown in Figure 7 below.

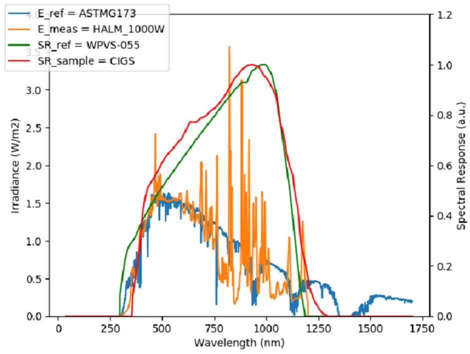

Figure 7: Spectral response of CIGS PV module technology when WPVS Ref 055 is used

When WPVS Ref 055 was interchanged with WPVS Ref 029 on the same on the same CIGS PV technology with the global solar spectrum and the spectrum of the illuminating flasher tube remain unchanged, the calculated spectral mismatch factor value of 1.00957 was achieved. The corresponding spectral response charts were obtained as shown in Figure 8 below.

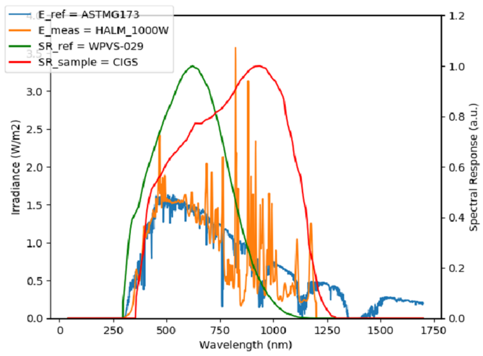

Figure 8: Spectral response of CIGS PV module technology when WPVS Ref 029 is used

The spectral mismatch values for all the different cases discussed above are shown in the Table 2 below

Table 2: Spectral Mismatch values comparisons

Module Technology	Reference Device	Spectral Mismatch Factor
CIGS	Ref 55	1.011
CIGS	Ref 29	1.010
CdTe	Ref 55	0.989
CdTe	Ref 29	0.988

The average of 3 consecutive Isc measurements measured values were on the indoor conditions were then corrected using the calculated mismatch factor values obtained on the individual PV module and by both WPVS reference devices as shown in Figure 9 below.

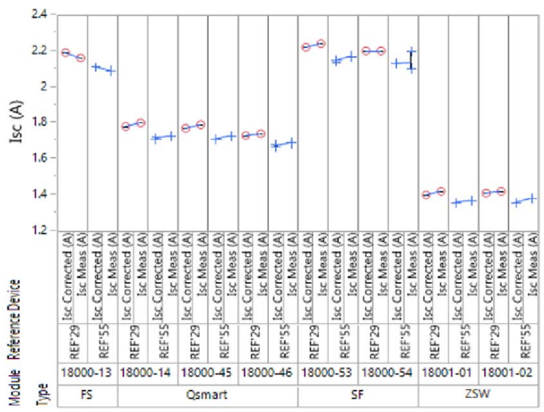

Figure 9: Isc measured vs spectral mismatched corrected Isc

The corrected Isc values were higher than the measured Isc for PV module First Solar for corrected measurements. All the Isc measurements of the Q-Smart PV module were observed to be close to each other on both for WPVS Ref 029 and WPVS Ref 055 as well as Solar Frontiers (SF) and ZSW PV modules.

The measured indoor and outdoor conditions Isc results were compared against the name plate rating using both the STC correction procedures (labelled as PVPM on the charts) and spectral mismatch factor values for both WPVS reference cells as shown in Figure 10 below.

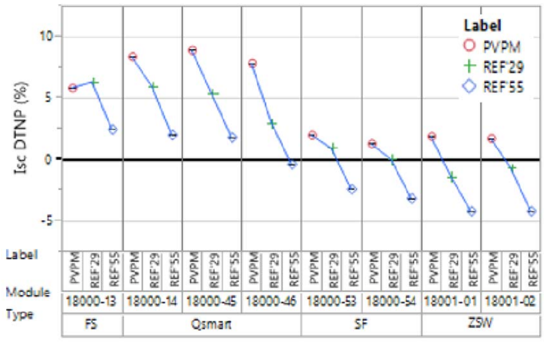

Figure 10: Delta to name plate Isc measurements on both indoor and outdoor conditions

All Solar Frontiers (SF) PV modules measured 0.5% above the nameplate on the outdoor (PVPM) and measured on target on one occasion with Ref 029 and -5% below nameplate with Ref 055 and ZSW PV modules measured 0.5% above the nameplate on the outdoor as shown in Figure 10 above.

First Solar (FS) and Q-Smart outdoor (PVPM) Isc measurements were above the nameplate by 5.81% and 8.88% respectively as shown in Figure 10 above as well as in Table 4 below.

Table 3: Outdoor Isc delta to nameplate comparison

Type	Module	N Rows	Mean (DTNP Outdoor Isc(%))
First Solar	18000-13	13	5.81
Q-Smart	18000-14	20	8.36
Q-Smart	18000-45	30	8.88
Q-Smart	18000-46	30	7.82
Solar Frontier	18000-53	27	1.96
Solar Frontier	18000-54	22	1.26
ZSW	18001-01	9	1.86
ZSW	18001-02	10	1.7

FS was noted to be above name plate by 6,311% in the Indoor condition and measured 5.81% above the nameplate as shown in Table 4 below.

Table 4: Indoor and Outdoor Isc of FS PV module delta to nameplate

Type	Module	Reference Device	N Rows	Mean (DTNP Indoor Isc(%))	Mean (DTNP Outdoor Isc(%))
First Solar	18000-13	REF'29	1	6.311	5.81

The indoor measurements are not the true representation of the spectral response of the module under test therefore these results will be validated when the actual spectral response is obtained from the PV manufacturers. The investigation on the measurement variations between the indoor and outdoor measurements will be carried out and the findings will be presented.

V. Conclusion

Outdoor measurements were affected the unavailability of spectrally matched reference cells correcting the Isc measurements has impact on the plane of array irradiance measurements. The absence of the true spectral response data of the PV modules has affected the indoor spectral corrections measurement for Isc. As a consequence there were notable cases where both indoor and outdoor conditions measured Isc values were above the nameplate. It is recommended to use the spectral response data provided by manufacturer when measuring Isc indoor sun simulator.

The indoor measurement I-V results were recorded and compared against the name plate in order to validate the spectral mismatch factor. The calculated spectral mismatch factor of each device was recorded and used to calculate the resultant Isc of the test specimen to quantify the effect of spectral variations on the performance of thin film modules.

Despite the unavailability of spectral mismatched reference device for thin film measurements, CSIR have developed some capabilities to accurately measure the short-circuit current of these devices on both indoor and outdoor conditions with the actual spectral response of the PV modules supplied.

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References

[1] Gaëtan Masson, IEA PVPS Task 1, Izumi Kaizuka, RTS Corporation and Carlotta Cambiè, Becquerel Institute, "iea-pvps.org - Preliminary Market Report," A Snapshot of Global PV (-2017-1992. [Online]. Available: http://www.iea-pvps.org/?id=266. [Accessed: 11-Oct-2019].

[2] M. Köntges, S. Kurtz, C. Packard, U. Jahn, K. A. Berger, and K. Kato, *Performance and reliability of photovoltaic systems: subtask 3.2: Review of failures of photovoltaic modules: IEA PVPS task 13: external final report IEA-PVPS*. Sankt Ursen: International Energy Agency, Photovoltaic Power Systems Programme, 2014.

[3] Minister of Energy, Jeff Radebe, "Energy Alert - 28 August 2018," Aug. 2018.

[4] T. J. Silverman, U. Jahn, G. Friesen, International Energy Agency, and Photovoltaic Power Systems Programme, *Characterisation of performance of thin-film photovoltaic technologies IEA PVPS task 13, subtask 3.1: final report IEA-PVPS T13-02:2014*. 2014.

[5] N. Taylor and Institute for Energy (European Commission), *Guidelines for PV power measurement in industry*. Luxembourg: Publications Office, 2010.

[6] I. P. Taks, "Trends 2018 in Photovoltaic Applications," p. 88, 2018.

[7] Pvps, Iea. (2018). 2018 SNAPSHOT OF GLOBAL PHOTOVOLTAIC MARKETS, "2018 Snapshot of Global Photovoltaic Markets."

[8] M. A. Munoz, O. Marin, M. C. Alonso-García, and F. Chenlo, "Thin Film Modules Characterization under Standard Test Conditions," p. 5, 2010.

[9] Q. Gao, Y. Zhang, Y. Yu, F. Meng, and Z. Liu, "Effects of I–V Measurement Parameters on the Hysteresis Effect and Optimization in High-Capacitance PV Module Testing," *IEEE J. Photovolt.*, vol. 8, pp. 710–718, Mar. 2018, doi: 10.1109/JPHOTOV.2018.2810852.

[10] A. Le Donne, V. Trifiletti, and S. Binetti, "New Earth-Abundant Thin Film Solar Cells Based on Chalcogenides," *Front. Chem.*, vol. 7, 2019, doi: 10.3389/fchem.2019.00297.

[11] A. Meflah, K. Rahmoun, A. Mahrane, and M. Chikh, "Outdoor performance modeling of three different silicon photovoltaic module technologies," *Int. J. Energy Environ. Eng.*, vol. 8, no. 2, pp. 143–152, Jun. 2017, doi: 10.1007/s40095-017-0228-6.