Interlaboratory comparison of solar cell measurements under low indoor lighting conditions

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***Abstract*--In recent years, industrial demand for energy harvesting from the indoor environment using photovoltaic (PV) solar cells has grown substantially. Much of this demand is focused on powering Internet of Things devices such as remote sensors and actuators because their power requirements can be easily met by indoor PV cells that convert otherwise wasted indoor light energy into low power electricity. However, accurate measurement of PV cells' indoor performance is challenging because there are currently no broad consensus approaches or standards for doing such measurements. Here, we have taken the first steps towards establishing such a consensus by performing an interlab comparison (ILC) of measurements of a photovoltaic solar cell under three distinct low illumination reporting conditions. In this bilateral comparison, each laboratory uses a different technique for reporting the performance parameters of the cell under a fixed set of agreed upon illumination conditions. Our results demonstrate good agreements under some reporting conditions and divergent results under another. Yet, first steps have been taken towards understanding the challenges of establishing a universally-acceptable method of measurement.**

***Index Terms*—Ambient light, interlab comparison, current vs voltage measurements, indoor photovoltaics,**

I. INTRODUCTION

Photovoltaic cells are commonly rated by their power output under the standard test conditions (STC, air mass 1.5 global / 25 ºC / 1000 Wm^{-2}) [1]. Although these conditions are rarely achieved in practice (except in the laboratory), this characterization provides a reasonable basis for comparing different types of solar cells under outdoor conditions, and bilateral or multilateral interlaboratory (interlab) comparisons have taken place among international metrology laboratories under the STC [2]. However, the STC is not relevant for indoor ambient applications. Typically, the light intensity (or irradiance) under artificial lighting conditions found in commercial offices and residential buildings is less than 5 Wm^{-2} as compared to the outdoor conditions which typically range in irradiance from 100 Wm^{-2} to over 1000 Wm^{-2}. The light intensity indoors depends on the type of light source and its distance from the cell. Moreover, the spectrum can be totally different from the outdoor solar reference spectrum (e.g., AM1.5G). The indoor spectrum depends on the type of light source, but also on the presence of reflected and diffused light. Unfortunately, no international standards exist to characterize solar cells for indoor applications. This situation is not acceptable because the popularity and use of PV energy harvesting from ambient lighting has grown substantially recently [3]–[5].

Recent work, for example, has shown that high power conversion efficiencies (PCE) are expected for PV materials with bandgap energies of 1.8 eV to 2 eV under visible light sources such as commercial white light emitting diodes (LEDs) and fluorescent tube lighting [6], [7] and a large variety of organic [8], hybrid [9] and inorganic [10], [11] PV materials are well suited for energy harvesting under these lighting conditions. Given a lack of clear universal characterization standards, impressive work has already been made towards accurate measurements [12], [13], including module characterization [14]. Still, the need for clear standards is greater than it has ever been and steps are being taken to address this issue [15], [16].

Recently, ITRI developed International Electrotechnical Commission and International Organization for Standardization (ISO/IEC) 17025-certified indoor light measurement system and has started to offer calibration services to interested customers based on the approach outlined in two recent SEMI standards and other publications [17]–[19]. NIST has also developed a reference solar cell-based method for calibrating solar cells under low artificial lighting although it has not yet settled on an illumination standard [16]. Therefore, NIST and ITRI initiated a bilateral

Date Submitted:

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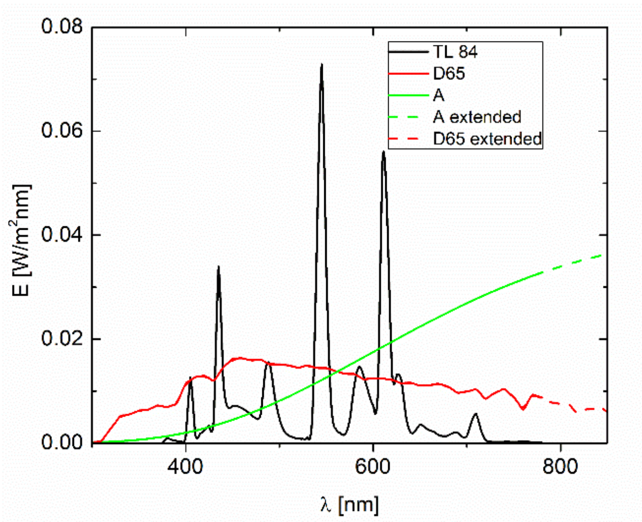

Fig 1. The reference spectra of the three standard light sources used for this interlab comparison. The irradiance values are calculated such that the illuminance produced by each spectrum is exactly 1000 lx.

interlab measurement project to compare the ability of their respective approaches to measure the current vs voltage (I-V) curve parameters of a carefully chosen solar cell under a set of mutually agreed-upon illumination conditions. The illumination sources that were proposed by ITRI as described below were used in this study.

A variety of standardized indoor light sources exist for metrology purposes. The International Commission on Illumination (CIE) is responsible for publishing standards for different types of light sources, called illuminants. In accordance with an agreement between ISO and CIE standards are published as double logo standards by ISO. CIE Standards are therefore a primary source of internationally accepted data defining aspects of light and lighting, for which international harmony requires a unique definition.

A standard illuminant represents a mathematical table of relative energy versus wavelength, used for colorimetric calculations. It is a (theoretical) source of visible light with a set spectrum, determined by convention, and therefore provides a worldwide basis for comparing images under different lighting. For performance characterization of indoor photovoltaics (IPVs), it is useful to adopt some of these illuminants as a standard PV illumination source and establish methods to compare measurement results between different laboratories. We consider several widely-used light sources for indoor environments (residential and commercial) and relate them to an appropriate illuminant (standard). One very widely recognized indoor light source is the common incandescent light bulb. The CIE has agreed upon a standard for the incandescent light bulb, called "illuminant A" [20]. This illuminant is intended to represent typical, domestic, tungsten-filament lighting. Its relative spectral power distribution is that of a Planckian radiator at a color temperature of approximately 2856 K. Technically, illuminant A is only defined over the spectral region from 300 nm to 780 nm. However, it can be extended further into the near infrared (NIR) regime using Planck's law for a black body source at a temperature of 2856 K. Furthermore, we have chosen illuminant D65 and illuminant TL84 as additional light sources for the purpose of this ILC between NIST and ITRI. Illuminant D65 is a CIE standard illuminant corresponding to average daylight with a correlated color temperature (CCT) of 6500 K, and TL84 represents a narrow tri-band fluorescent lamp with CCT of 4000 K. Upon agreement to use the three illumination sources (illuminants A, D65, TL84) defined above at 1000 lx of illuminance and a device temperature of 25 °C, each laboratory proceeded with the measurements using its own method. Illuminance of 1000 lx was chosen for the reporting condition in order to remain consistent with previous precedence in many literature reports [7], [10], [14], [15]. Before we present the findings, we briefly review each laboratory's methodology. It should be noted that the terms "solar cell" and "IPV cell" are sometimes used interchangeably throughout this paper.

II. NIST EXPERIMENTAL SETUP

Current versus voltage (I-V) curve measurements were performed in a dark box under a well characterized indoor low light simulator comprised of a white LED projector with a measured CCT of 3262 K. The I-V measurements were obtained using a common source-measure unit in sweep mode with sweep direction from 0 V towards the open circuit voltage, V_{oc}. The simulator light intensity (irradiance) is controlled by a precision LED driver and the light source is very stable during the course of the measurement (under 0.1 % fluctuations). The fan-cooled LED is operated in dc mode and illuminates a temperature controlled measurement stage comprised of two solar cells mounted side-by-side: one cell is a calibrated reference solar cell with the ID#10510-0777 and the other cell is the device under test with the cell ID# NIST 1005. The reference cell is a silicon solar cell packaged inside a world photovoltaic scale (WPVS)-styled holder [21] with a KG-5 glass window cover. The test cell is a GaInP IPV cell, procured from a commercial manufacturer and wire-bonded and packaged by NIST inside a similar WPVS-style holder with a plain quartz window. The energy band gap of this material, 1.82 eV, makes this an attractive candidate for measurements under (mostly) visible light sources. The GaInP device is also very stable in air, making it an ideal candidate for a bilateral comparison that took weeks to conclude. Both cells are nominally 20 mm × 20 mm in size and are contacted with the common 4-wire electrical connections and a thermocouple for temperature measurements, features that greatly facilitate an interlab comparison. All measurement results are reported at 25 °C.

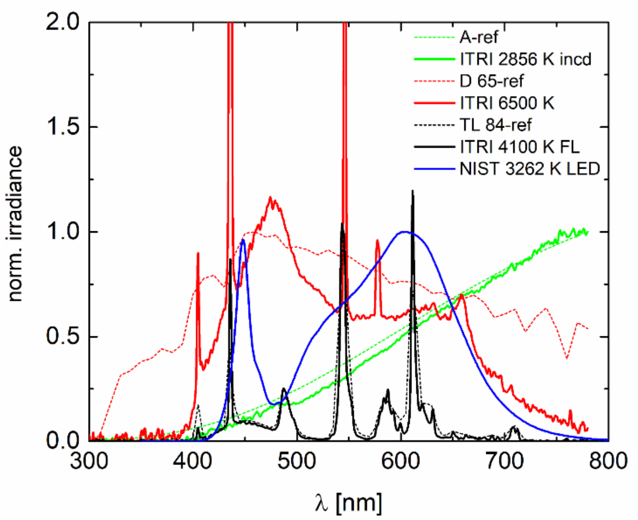

Fig 2. The normalized spectra of the three light sources used in ITRI's indoor lighting simulator and the white LED used in NIST's simulator. The reference spectra are shown in dashed lines for comparison.

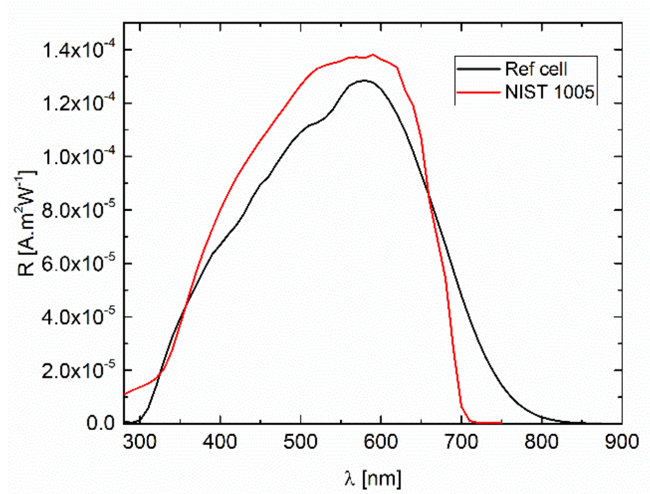

Fig 3. The irradiance-mode spectral responsivity functions of the KG-5 filtered Si reference cell and the GaInP (NIST 1005) test solar cells.

III. ITRI EXPERIMENTAL SETUP

I-V curve measurements were performed under a custom indoor lighting simulator that includes a number of commercial light sources designed to reproduce some of the CIE standard illuminants, including D65 (6500 K fluorescent tubes, Average North USA sky daylight), TL84 (4100 K, European shop fluorescent tubes), CWF (4150 K, cool white fluorescent, shop lighting), U30 (3000 K, shop lighting), and illuminant A (2856 K, typical halogen home lighting). The light intensity is adjustable (ranging from 0 lx to 2500 lx), with non-uniformity of less than 2 % (at 20 cm × 20 cm) and temporal instability of less than 2 %. The simulator light intensity (irradiance) is controlled by an NML (National Measurement Laboratory, Taiwan)-traceable lux meter (HIOKI, model FT3424 [22]). The test IPV cell used during this interlab comparison measurement is the cell ID# NIST 1005 as mentioned above. All measurement results are reported at 25 °C.

Figure 2 shows the normalized spectral irradiance of all the indoor light sources used for the reported measurements. While ITRI uses three distinctive light sources to establish a match to each reporting condition, NIST only used one light source, a white LED with a color temperature of 3262 K to perform all three sets of measurements. In this case, spectral corrections must be applied as described below. In Fig. 2, the normalized reference spectra are also shown again, as light dashed lines, for comparison.

IV. THE NIST METHOD

NIST's measurement methodology is based on the use of calibrated reference solar cells for setting the effective irradiance value at the plane of the measurement [16]. To this end, an appropriate reference solar cell is chosen and calibrated under each of the reporting spectra (i.e., illuminant A, D65 and TL 84). This calibration method establishes the short circuit current, $I_{r,r}$ of the reference cell under each reference spectrum according to Eq (1):

$$I_{r,r} = \int_{\lambda \min}^{\lambda \max} E_r(\lambda) R_{r,\mathrm{irr}}(\lambda) d\lambda \qquad (1)$$

where $E_r(\lambda)$ is the spectral irradiance function of the reference spectrum, $R_{r,\mathrm{irr}}$ is the spectral responsivity (SR) function of the reference cell in irradiance mode, and λ is the wavelength of light in nm. The reference cell is used during the I-V measurements of the test IPV cell to measure and establish the effective irradiance to which the test cell is exposed. The normalized spectral distribution of the three reference spectra used for this interlab comparison have been published in Appendix 2 of the SEMI PV80-0218 standard, covering the spectral band from 300 nm to 780 nm [17]. These three spectra, scaled to represent the absolute spectral irradiance of each illuminant producing an illuminance of 1000 lx at the measurement plane, are shown in Fig. 1. Since the spectral distribution of illuminant A and D65 do not drop to 0 at the upper value of 780 nm, the spectral responsivity $R_{r,\mathrm{irr}}$ of the reference solar cell should ideally be strictly within this spectral range in order for the integral computation in Eq (1) to be valid. Typical silicon (Si) reference solar cells with a regular quartz or glass window are not appropriate for this purpose because their spectral responsivity function typically extends to 1200 nm, well past the tabulated spectral distribution of the reference illuminants. For this purpose, we instead chose a KG-5 filtered Si solar cell, with spectral responsivity given in Fig. 3. The KG-5 window significantly eliminates the NIR spectral responsivity contributions of silicon and is therefore an appropriate reference cell under these 3 reference light sources. Even as such, we discovered that a very small

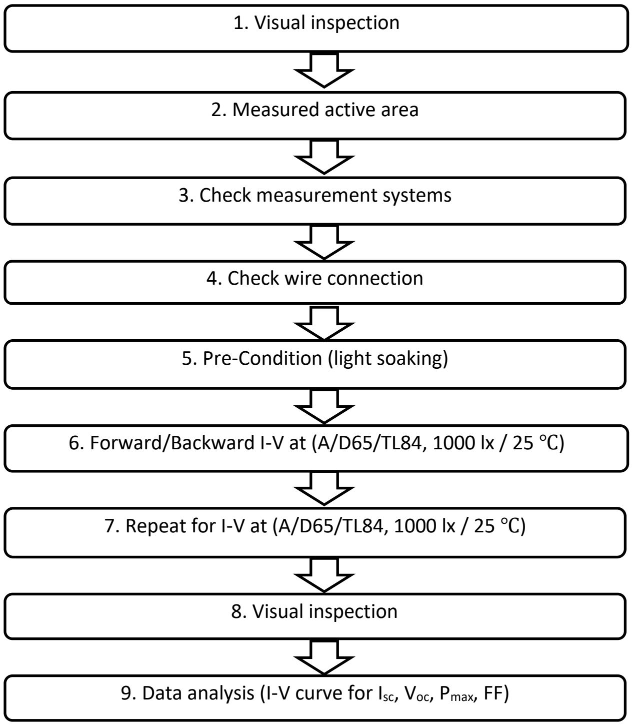

Fig 4. Testing flow-chart and protocol followed by ITRI

contribution to the $I_{r,r}$ of the reference cell will come from the 780 nm to 830 nm region, for which tabulated data are missing in SEMI PV80-0218. For the sake of reducing errors as much possible, we manually extended the illuminant A and the D65 spectral distribution to 830 nm as shown by the dashed lines in Fig. 1. For illuminant A, we simply extended the distribution according to Planck's black body law with the same parameters defining CIE's illuminant A [23]. For D65, we took the spectral distribution of the IEC 60904-3, representing the standard sun under the air mass 1.5 global irradiation, and matched it to the D65 spectrum using appropriate scaling factors. This approach allowed us to extend the D65 from 780 nm to 830 nm. This artificial extension of the two spectra, illuminant A and D65, increases the short circuit current of the reference cell by 1 % and 0.2 %, respectively, compared to the integration in Eq. (1) from 300 nm to 780 nm. Therefore, it would not constitute a large source of error in the measurements if we had ignored it. The TL84 spectrum was used as provided in the SEMI PV80-0218 standard since it fully drops to 0 at 780 nm.

The rest of the measurement protocol is identical to that presented in reference [16] and we invite the reader to consult that work for detailed analysis. In brief, a spectral mismatch parameter, *M*, is calculated and the effective irradiance, *F*, is measured and adjusted so that *F*=1 for each of the three cases. The computation of *M* as described in Eq. 3 of Ref. [16] involves measurements of the spectral responsivity of the reference cell, the spectral responsivity of the IPV cell, the irradiance of the indoor simulator and the irradiance of the reference spectra. The calculated M is directly used in Eq. 5 of Ref. 16 to compute *F*, which in turn is used in Eq. 7 to report the I-V curve of the IPV cell under the given reporting condition.

Table 1: calibrated reference cell currents and the spectral mismatch parameter for each of the three illumination conditions

Reference light source	Indoor sim light	$I_{r,r}$ (ID: 10510-0777)	*M*
Illuminant A	WLED-3262K	454.63 µA	1.16
D65	WLED-3262K	445.5 µA	1.025
TL84	WLED-3262K	319.46 µA	0.983

Table 1 provides the $I_{r,r}$ and *M* values for each of the reference light sources. Notice that the *M* value for the illuminant A case is significantly larger than unity, representing the large mismatch that exists due to the use of an LED indoor simulator to represent illuminant A conditions. Nevertheless, the results of this interlab comparison as outlined below demonstrate that the reference cell method works very well in practice. Matching of the indoor simulator light to a particular reference spectrum is not strictly needed although it can reduce overall uncertainties. For the reported short circuit current, I_{sc}, values and the maximum power, P_{max}, our estimated expanded uncertainties (k=2) in this work are approximately 2.2 % and 2.5 % respectively.

V. THE ITRI METHOD

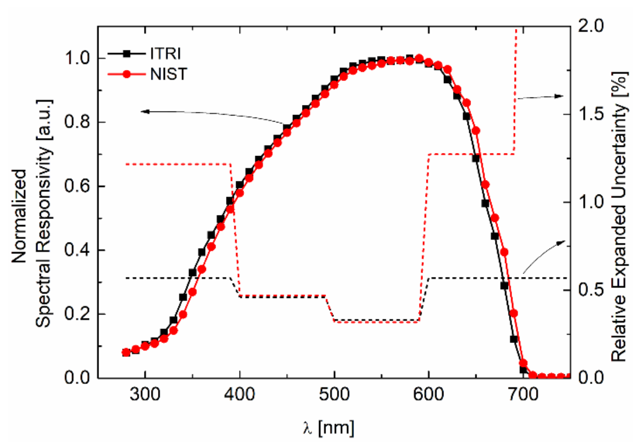

Fig 5. The normalized spectral responsivity curve of the NIST 1005 test cell as measured by NIST and ITRI. Relative expanded uncertainties are also reported.

ITRI's measurement methodology is based on the flowchart shown in Fig. 4, which adheres to the protocols outlined in the SEMI PV57-1214 and SEMI PV89-0219 standards [17], [18]. In this method, a reference device is also required for monitoring the light intensity. However, unlike the NIST method where a calibrated reference cell is used for spectrally corrected irradiance measurements, ITRI uses a calibrated Lux meter and a spectrometer to measure and adjust the light intensity and spectrum. This I-V method is called the step-wise dynamic I-V or asymptotic I-V method,

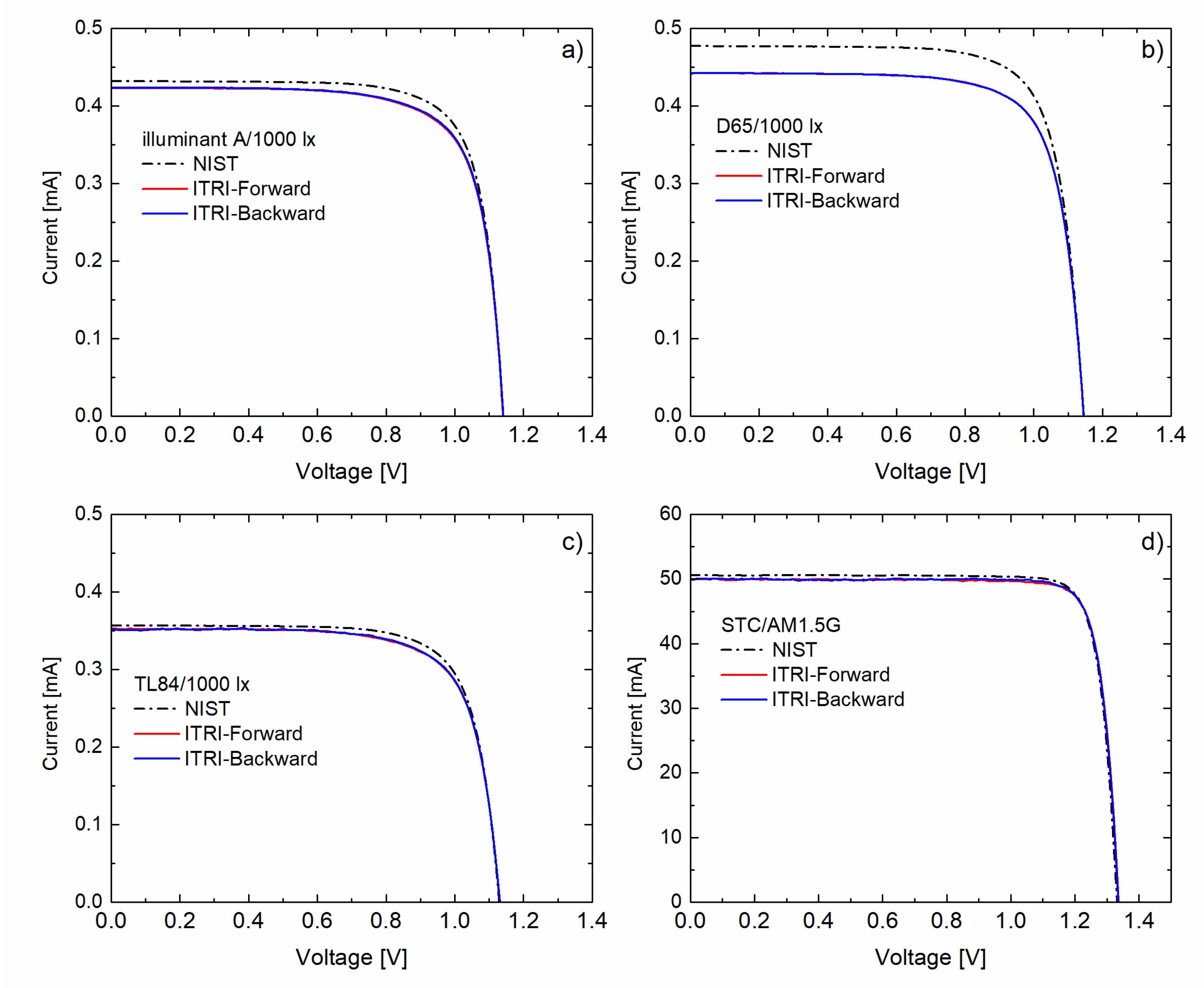

Fig 6. The summary of I-V curve measurements reported by each laboratory under 4 different reporting conditions.

where current is monitored at each voltage point along the I-V curve for stability or capacitive effects instead of a fast sweep of current vs voltage. The asymptotic method is the only method that allows slow-responding and rapidly-degrading devices to be accurately measured, where the maximum bias rate to avoid hysteresis is unknown and eliminates any artifacts due to metastability, or prior thermal or bias history. These issues, however, are not a concern with the test cell used during this intercomparison. Finally, the expanded uncertainties (k=2) for I_{sc} and P_{max} measurements are approximately 3.1 % and 3.5 % respectively.

VI. BILATERAL PROTOCOL AND MEASURANDS

The study was carried out in the following manner: NIST prepared a WPVS-style IPV cell and performed measurements on it. Results of its measurements were withheld as the unit was shipped to ITRI for measurement under its procedure. After the final measurements at ITRI, both sides revealed their measurement results simultaneously. The specific measurands for the purpose of the comparison were the short circuit current of the test cell, I_{sc}, the open circuit voltage, V_{oc}, the maximum power, P_{max}, and the fill factor, *FF* of the cell under each of the three illumination sources (i.e., illuminant A, illuminant D65 and illuminant TL84) at 1000 lx and with the cell held at a temperature of 25 °C. Furthermore, results under STC were also reported.

VII. RESULTS

Figures 5 and 6 summarize the ILC measurements for the normalized spectral responsivity and I-V curves under the four reporting conditions. Accurate measurement of the SR of the test cell (Fig. 5) is critical to the calculation of the mismatch parameter in NIST's method, though not so

Table 2: spectral match between each laboratory's simulator and the reference spectra over three spectral bands.

Spectral Band (nm)	ITRI ratio to A	ITRI ratio to D65	ITRI ratio to TL84	NIST ratio to A	NIST ratio to D65	NIST ratio to TL84
300-450	0.55	0.86	1.04	2.02	0.32	0.51
450-650	0.94	1.24	1.01	1.96	1.48	0.99
650-780	1.07	0.60	0.81	0.25	0.59	2.38

important for the ITRI method. We have provided these data merely for the sake of completion. The most important figure of merit for an interlab comparison of this kind, however, is the I_{sc} of the cell under each reporting condition. In two of the three low-light cases (illuminant A and TL84), we report an agreement to better than 2 %, within the margin of uncertainty for both labs. Considering that the NIST indoor simulator (a white LED) is spectrally unmatched to any of the three reference spectra, this interlab agreement is remarkable and provides further evidence for the validity of the reference-cell based I-V measurement method [16] The D65 measurements produce the largest discrepancy between the two labs with I_{sc} differences of ≈ 7 % and P_{max} differences of ≈ 8 %.

We attribute this larger disagreement to the difficulty in establishing a matched spectrum to the D65 illuminant with the ITRI indoor simulator. This statement is better illustrated by Table 2 where we have taken fractional irradiance values of each lab's simulators over three narrow spectral bands and divided them by the fractions calculated for the three reference light sources. Therefore, a ratio of 1 over each band would mean the closest match between the simulator's spectra and the reference spectra. ITRI's TL84 and illuminant A fractions are mostly close to unity, particularly in the spectral region of 450 nm to 780 nm where most of the cell's photocurrent generation takes place. However, significant deviations from unity are observed for the ITRI D65 ratios over this region, which could lead to a larger error in determining the cell's parameters under the D65 source. At the present, ITRI's luxmeter-based protocol, as described in the SEMI standards, does not accommodate any additional corrections to the I-V curves when a mismatch is present between the simulator and the reference spectra but further investigation is needed to explore these issues. Table 2 also shows that all the NIST ratios are significantly different from unity. However, since NIST applies spectral mismatch parameter corrections to its I-V curves through the reference cell-based protocol, these large ratios do not appear to be an impediment to accurate measurements. As can be seen in Fig. 6, we also observe a recurring offset in the I_{sc} values between the two labs that could be related to an unidentified source of error in either laboratory. Identifying the reasons for this offset will likely require more extensive interlab-measurements with other participants.

Table 3 in appendix gives the measurands from the two laboratories for the 4 reporting conditions. Clearly, the STC measurements under AM 1.5 G conditions gives the best agreement between the two labs due to the long-established norms and standards for performing these measurements. Other differences in measurements, such as the FF parameter, could potentially be related to the different I-V sweep methods at the two labs and should elicit future investigation. Measurement improvements in the future should focus on the accuracy of the I_{sc} measurements. In situations when the indoor simulator's light source is spectrally different than the reference spectrum, spectral mismatch errors must be carefully considered and applied. Furthermore, measurements at other light intensities (i.e., 500 lx, 100 lx etc.) are of great interest to the community but the linearity of current with irradiance of the reference devices must be carefully verified prior to such measurements. The collimation of the light source and angular mismatch issues will also likely play a role in accuracy of the electrical characterization of IPV cells.

VIII. CONCLUSIONS

In summary, we have presented results of the first international bilateral interlab comparison of an IPV cell's electrical performance parameters under a set of agreed upon reporting conditions suitable for low intensity indoor lighting. The three illumination sources have been adapted from the CIE illuminants and the measurement results were reported under an illuminance of 1000 lx and a cell temperature of 25 °C. Despite using different methodology to measure and report the cell parameters, the two labs agreed to within 2 % for I_{sc} measurements in two of the three reporting conditions (illuminants A and TL84). The last reporting condition (illuminant D65) resulted in an approximate 7 % discrepancy in I_{sc}, a result that will be explored further by each laboratory. Given that this interlab comparison was the first of its kind and that there are currently no well-established international standards and protocols for these measurements, the results suggest that the standard lighting conditions used in this work could form the basis of an approach to characterize performance under indoor illumination. Additional engagement by other international metrology institutes could help facilitate reaching a universally acceptable standard for characterizing indoor PV.

APPENDIX

Table 3: A summary of the I-V curve parameters reported by each laboratory is presented in Table 2. % difference is defined as (1-(ITRI/NIST))×100 %.

A	V_{oc} (V)	I_{sc}(A)	P_{max} (W)	Fill Factor (%)
NIST	1.140	0.000432	0.000378	76.80
ITRI	1.142	0.000424	0.000367	75.78
% diff	-0.20 %	1.77 %	2.92 %	1.32 %

D65	V_{oc} (V)	I_{sc}(A)	P_{max} (W)	Fill Factor (%)
NIST	1.145	0.000477	0.000418	76.50
ITRI	1.145	0.000444	0.000385	75.59
% diff	-0.04 %	6.93 %	8.01 %	1.19 %

TL84	V_{oc} (V)	I_{sc}(A)	P_{max} (W)	Fill Factor (%)
NIST	1.130	0.000357	0.000304	75.50
ITRI	1.132	0.000351	0.000295	74.28
% diff	-0.16 %	1.59 %	2.95 %	1.62 %

AM 1.5G	V_{oc} (V)	I_{sc}(A)	P_{max} (W)	Fill Factor (%)
NIST	1.331	0.0507	0.0574	85.20
ITRI	1.337	0.0501	0.0572	85.38
% diff	-0.43 %	1.07 %	0.41 %	-0.21 %

REFERENCES

[1] *IEC 60904-3, "Photovoltaic Devices – Part 3: Measurement Principles for Terrestrial Photovoltaic (PV) Solar Devices with Reference Spectral Irradiance Data*. 2008.

[2] S. Winter *et al.*, "Calibration of reference solar cells at standard test conditions," *Metrologia*, vol. 58, no. 1A, p. 02001, Jan. 2021.

[3] I. Mathews, S. N. Kantareddy, T. Buonassisi, and I. M. Peters, "Technology and Market Perspective for Indoor Photovoltaic Cells," *Joule*, vol. 3, no. 6, pp. 1415–1426, Jun. 2019.

[4] A. Venkateswararao, J. K. W. Ho, S. K. So, S.-W. Liu, and K.-T. Wong, "Device characteristics and material developments of indoor photovoltaic devices," *Mater. Sci. Eng. R Reports*, vol. 139, no. June 2019, p. 100517, Jan. 2020.

[5] A. S. Teran *et al.*, "AlGaAs Photovoltaics for Indoor Energy Harvesting in mm-Scale Wireless Sensor Nodes," *IEEE Trans. Electron Devices*, vol. 62, no. 7, pp. 2170–2175, Jul. 2015.

[6] M. Freunek, M. Freunek, and L. M. Reindl, "Maximum efficiencies of indoor photovoltaic devices," *IEEE J. Photovoltaics*, vol. 3, no. 1, pp. 59–64, Jan. 2013.

[7] N. H. Reich, W. G. J. H. M. van Sark, and W. C. Turkenburg, "Charge yield potential of indoor-operated solar cells incorporated into Product Integrated Photovoltaic (PIPV)," *Renew. Energy*, vol. 36, no. 2, pp. 642–647, Feb. 2011.

[8] Y. Aoki, "Photovoltaic performance of Organic Photovoltaics for indoor energy harvester," *Org. Electron.*, vol. 48, pp. 194–197, Sep. 2017.

[9] M. Freitag *et al.*, "Dye-sensitized solar cells for efficient power generation under ambient lighting," *Nat. Photonics*, vol. 11, no. 6, pp. 372–378, Jun. 2017.

[10] I. Mathews, P. J. King, F. Stafford, and R. Frizzell, "Performance of III–V Solar Cells as Indoor Light Energy Harvesters," *IEEE J. Photovoltaics*, vol. 6, no. 1, pp. 230–235, Jan. 2016.

[11] K. A. Haque and M. Z. Baten, "On the prospect of CZTSSe-based thin film solar cells for indoor photovoltaic applications: A simulation study," *AIP Adv.*, vol. 9, no. 5, p. 055326, May 2019.

[12] X. Ma, S. Bader, and B. Oelmann, "Characterization of Indoor Light Conditions by Light Source Classification," *IEEE Sens. J.*, vol. 17, no. 12, pp. 3884–3891, Jun. 2017.

[13] B. Minnaert and P. Veelaert, "A Proposal for Typical Artificial Light Sources for the Characterization of Indoor Photovoltaic Applications," *Energies*, vol. 7, no. 3, pp. 1500–1516, Mar. 2014.

[14] A. Sacco, L. Rolle, L. Scaltrito, E. Tresso, and C. F. Pirri, "Characterization of photovoltaic modules for low-power indoor application," *Appl. Energy*, vol. 102, pp. 1295–1302, Feb. 2013.

[15] S. Winter, "Characterization and Power Measurement of IPV Cells," in *Indoor Photovoltaics*, Wiley, 2020, pp. 115–131.

[16] B. H. Hamadani and M. B. Campanelli, "Photovoltaic Characterization Under Artificial Low Irradiance Conditions Using Reference Solar Cells," *IEEE J. Photovoltaics*, vol. 10, no. 4, pp. 1119–1125, Jul. 2020.

[17] *SEMI PV80-0218 Specification of Indoor Lighting Simulator Requirements for Emerging Photovoltaic*. 2018.

[18] *SEMI PV57-1214, "Test Method for Current-Voltage (I-V) Performance Measurement of Organic Photovoltaic (OPV) and Dye-Sensitized Solar Cell (DSSC),."* 2014.

[19] T.-C. Wu, Y.-S. Long, S.-T. Hsu, and E.-Y. Wang, "Efficiency Rating of Various PV Technologies under Different Indoor Lighting Conditions," *Energy Procedia*, vol. 130, pp. 66–71, Sep. 2017.

[20] *CIE S 014-2, "CIE Colorimetry - Part 2: Standard Illuminants for Colorimetry,."* 2006.

[21] C. R. Osterwald *et al.*, "The world photovoltaic scale: an international reference cell calibration program," *Prog. Photovoltaics Res. Appl.*, vol. 7, no. 4, pp. 287–297, Jul. 1999.

[22] "Certain commercial equipment, instruments, software, or materials are identified in this paper to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.." .

[23] M. R. Luo, Ed., "CIE Standard Illuminant A," in *Encyclopedia of Color Science and Technology*, New York, NY: Springer New York, 2016, pp. 179–179.

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