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Essential metrics for measuring indoor photovoltaics

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ABSTRACT

Indoor photovoltaics (IPVs) are emerging as sustainable power sources for low-energy electronics operating under ambient lighting. However, the absence of standardized measurement protocols and reporting conventions continues to limit meaningful comparisons and broader technological progress. In this Perspective, we synthesize insights from recent literature to identify key metrics and practical considerations essential for reliable IPV characterization. We outline reasonable guidelines—ranging from light source calibration and spectral matching to device masking and temperature control—that promote reproducibility and enable fair benchmarking. These recommendations aim to lay the groundwork for future efforts toward standardizing indoor photovoltaic testing.

INTRODUCTION

The proliferation of low-power electronics—including devices for the Internet-of-things (IoT), wireless sensors, smart wearables, and indoor environmental monitoring—has intensified interest in energy-autonomous operation under indoor lighting.[1–3] Unlike outdoor photovoltaics, which operate under the standardized AM1.5G spectrum at 100 mW/cm^2, indoor environments offer far lower irradiance (typically 10–1000 μW/cm^2) and light spectra tailored for human visual comfort rather than energy harvesting. Nevertheless, indoor photovoltaics (IPVs) have emerged as a promising solution, capable of converting ambient light into usable electrical power, thereby reducing battery dependence and electronic waste.[4–6] Recent advances in materials—such as wide-bandgap perovskites, organic semiconductors, and quantum dots—have enabled indoor power conversion efficiencies (PCEs) nearing 40% under certain conditions.[7,8] Yet, a persistent challenge remains: the absence of standardized measurement protocols. The diversity in spectral power distributions (SPDs) of indoor light sources—particularly light-emitting diodes (LEDs) and compact fluorescent lamps (CFLs)—along with their low intensities and narrow emission bands, introduces significant variability and potential sources of error in device characterization.

This variability affects multiple aspects of measurement. For instance, the use of photometric units such as illuminance (lux), which reflects human eye sensitivity, rather than radiometric quantities like irradiance (W/m^2), leads to ambiguous and non-comparable efficiency reports [Fig. 1(a)].[9] Two light sources rated at 1000 lux may yield vastly different results depending on their SPD. Additionally, the small photocurrents generated under low-light conditions increase susceptibility to noise, contact resistance, and parasitic leakage. The spectral mismatch between the reference cell and the device under test (DUT) also becomes critical under narrowband illumination, potentially leading to errors in calibrated irradiance if not corrected properly.

Although recent efforts have proposed classification schemes for indoor light sources, SPD-based irradiance conversions, and spectral mismatch correction methods, widespread adoption of these practices remains limited. A cohesive and universally accepted framework is still missing. In this Perspective, we address this gap by proposing a measurement-centric approach focused on essential metrics and best practices for IPV evaluation. Our goal is not to introduce new experimental results but rather to consolidate recent recommendations and technical insights from the literature into a practical framework. By emphasizing critical measurement variables—such as light source calibration, active area definition, temperature control, and electrical measurement stability—we aim to support more rigorous, reproducible, and transparent IPV characterization across the research community.

ESSENTIAL METRICS FOR INDOOR PVS AND PRACTICES

Accurate characterization of IPV devices requires more methodological precision than outdoor measurements due to the low

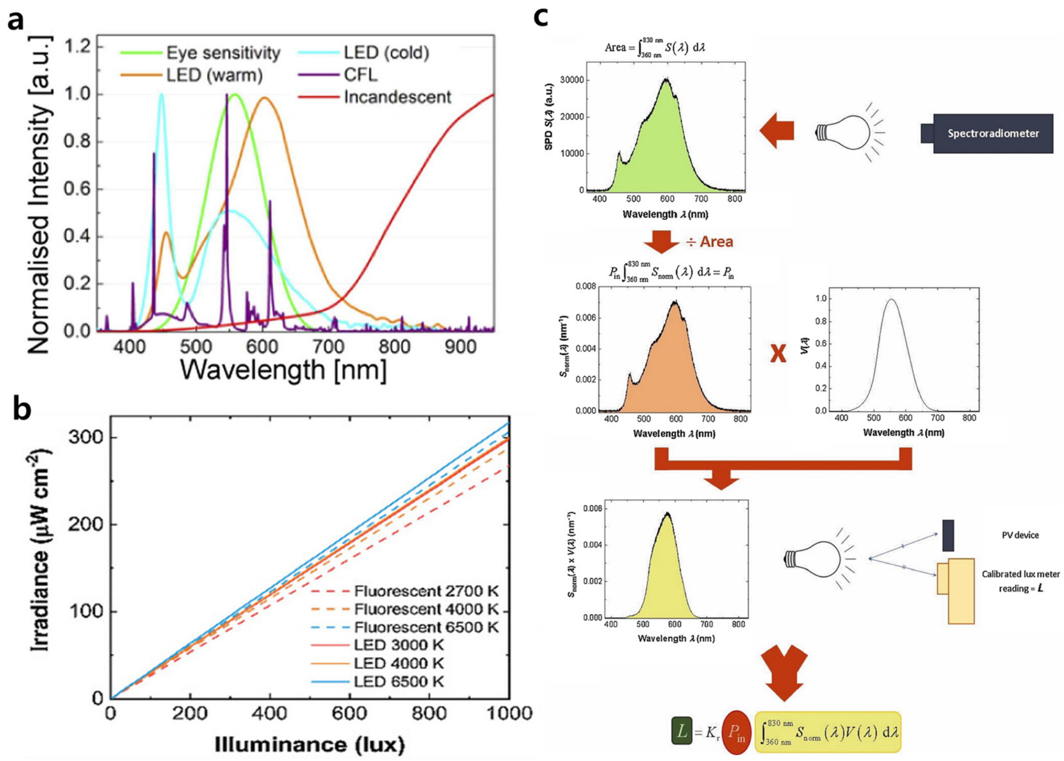

FIG. 1. (a) Normalized emission spectra of various indoor light sources, including a warm white LED (brown), cold white LED (cyan), compact fluorescent lamp (CFL, violet), and incandescent bulb (red), compared with the CIE 1931 standard photopic eye response (green). Spectra were measured using an ILT950 spectroradiometer.[9] Reproduced with permissions from Brown *et al.*, Nano Energy **128**, 109932 (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution License. (b) Theoretical relationship between illuminance (lux) and incident power (W/m^2) for different lighting technologies.[10] Reproduced with permission from Polyzoidis *et al.*, Adv. Energy Mater. **11**, 2101854 (2021). Copyright 2021 Wiley-VCH GmbH. (c) Schematic illustrating the method to calculate the incident power intensity P_{in} from a calibrated lux meter reading L. The yellow-filled area represents the integral of the spectral power weighted by the photopic response.[11] Reproduced with permission from Venkateswararao *et al.*, Mater. Sci. Eng. R **139**, 100517 (2020). Copyright 2020 Elsevier.

intensity, spectral complexity, and diffuse nature of indoor illumination. Standard protocols developed for outdoor solar simulators are insufficient under these conditions; instead, a tailored approach is needed. A primary requirement is the accurate quantification of incident light. While indoor illumination is often specified in *lux* (illuminance), this unit is weighted by the human eye's sensitivity and does not reflect the photon flux relevant to photovoltaic conversion. Instead, *irradiance*, measured in watts per square meter (W/m^2), is the appropriate metric for evaluating input power and calculating PCE. As many commercial light sources are rated only in lux, irradiance must often be inferred from the SPD and known luminous efficacy values. Indoor light sources vary widely in their spectral characteristics, which are often classified by their correlated color temperature (CCT)—a standard metric used to describe the color appearance of white light [Fig. 1(b)].[10] Typical domestic and commercial lighting falls into three general CCT categories: warm white (2700–3000 K), neutral or natural white (4000–4500 K), and cool white or daylight (5000–6500 K). Higher CCTs correspond to a greater contribution of short-wavelength (blue) light, resulting in significant changes to the SPD of the source. Given the spectral sensitivity of photovoltaic materials, such variation in SPD can substantially affect device performance.

To standardize testing across this diversity, we recommend defining a set of representative test conditions that span a range of CCTs and lighting technologies (e.g., LED, CFLs, and halogen). Since illuminance in lux does not directly correspond to the photon flux relevant for photovoltaic energy conversion, it is important to convert lux to irradiance using the SPD of the specific source. Furthermore, applying spectral mismatch correction factors—or at least reporting the degree of spectral overlap between the test light source and a standard reference spectrum—can improve comparability and transparency. Additional practical considerations should also be addressed. Some light sources (e.g., certain fluorescents or CFLs) require a warm-up period to reach steady-state output; thus, illuminance should be continuously monitored to ensure stable irradiance during measurement. Moreover, indoor lighting is often diffuse, with a significant portion of light reaching the device via reflections from surrounding surfaces. These reflections can alter both the intensity and the spectral content of the incident light. For reproducibility, the reflectance properties of the test environment should be kept consistent, as differences in wall color, surface finish, or proximity can lead to more than a 10% change in measured illuminance at the device plane.

Wong *et al.* proposed a method to convert lux into irradiance using a calibrated lux meter and SPD data [Fig. 1(c)].[11] Their study revealed that irradiance varies significantly not only by light source type and CCT but also across manufacturers and production batches for the same nominal light type. In a complementary study, Cui *et al.* compared three lux meters with an NIST-calibrated spectroradiometer and observed substantial discrepancies in measured illumination [Fig. 2(a)], underscoring the limitations of relying solely on commercial lux meters.[12] To address such inconsistencies, the International Electrotechnical Commission (IEC) recently released a technical specification—IEC TS 62607-7-2—outlining best practices for evaluating nano-enabled photovoltaics under indoor lighting.[13] This includes mandatory reporting of full SPD, CCT, and light source classification (e.g., LED-B4 or FL10) to contextualize device performance and enable reproducible comparisons across laboratories.

Another key issue is spectral mismatch between the reference cell and the DUT. Most PV measurements use a calibrated reference cell to determine the incident power, but indoor light sources often have narrow emission bands. If the spectral responsivity of the reference cell differs significantly from that of the DUT, large calibration errors can arise. This mismatch is quantified by the spectral mismatch factor (MMF), which must be calculated using the external quantum efficiency (EQE) spectra of both devices and the SPD of the light source. Whenever feasible, the reference cell should be chosen to closely match the DUT's spectral response. Reporting MMF and EQE curves is essential for transparency and inter-study comparison. The definition of the device's active area is equally critical. Unlike outdoor light, indoor illumination is typically diffuse and non-collimated, making measurements more sensitive to stray light and edge effects. Ma *et al.* showed that electrical edge effects are amplified in the absence of proper optical masking and can lead to significant overestimation of the short-circuit current density (J_{SC}) [Fig. 2(b)].[14] Optical masks help eliminate these effects by confining light absorption to a well-defined region. Cui *et al.* also demonstrated the influence of aperture size and mask alignment on J_{SC} accuracy [Fig. 2(c)].[12] To minimize these artifacts, masks should be

(1) optically opaque and non-reflective (preferably black),
(2) aligned perpendicular to the incident beam,
(3) slightly smaller than the active area, and
(4) consistently documented in reports.

Environmental control is another pivotal factor in the measurement process. Although indoor light sources generate lower thermal loads than solar simulators, temperature-sensitive materials such as perovskites and organics still exhibit performance fluctuations with minor changes in ambient temperature. Measurements should be performed under controlled conditions (typically $25 \pm 1\,^{\circ}C$), and the temporal and spatial stability of the light source should be verified. Cui *et al.* found that the output of a 6500 K LED bulb stabilized within 30 min, while a fluorescent lamp took over an hour to reach spectral

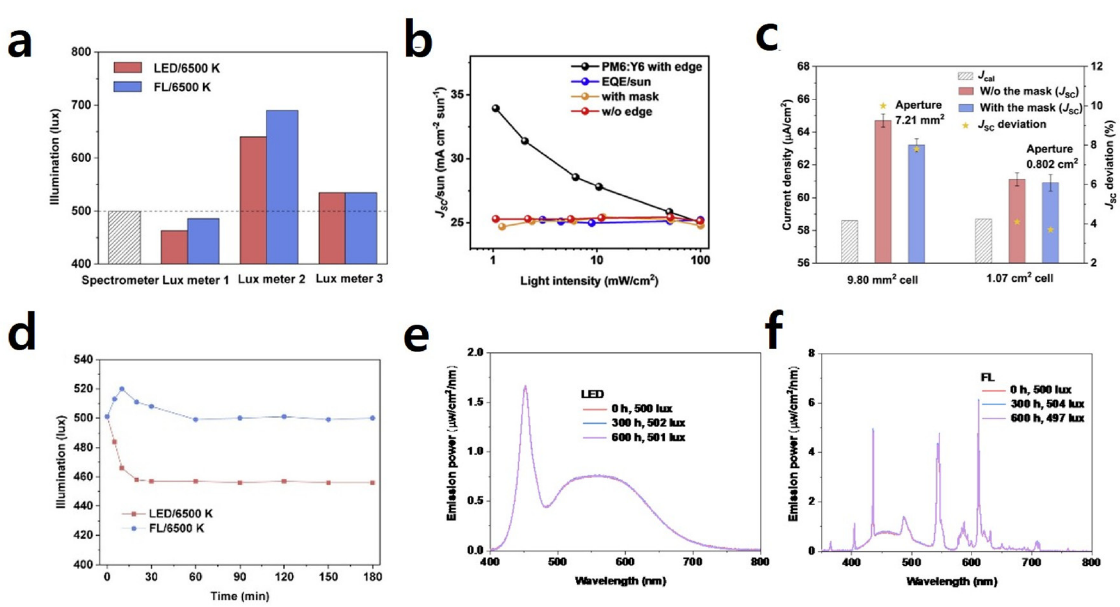

FIG. 2. (a) Comparison of illuminance measurements from three lux meters and a spectroradiometer under two light sources: a 6500 K LED bulb and a 6500 K fluorescent lamp (FL). All sensors were positioned identically during measurement to ensure consistency.[12] Reproduced with permission from Cui *et al.*, Joule **5**, 1011–1026 (2021). Copyright 2021 Elsevier. (b) Dependence of short-circuit current density normalized to AM 1.5G on light intensity for inverted PM6:Y6 devices measured under three configurations: with edge, with mask, and without edge. Also shown is the variation of external quantum efficiency (EQE) normalized to AM 1.5G (EQE/sun) as a function of light intensity for the same configurations.[14] Reproduced with permission from Zhou *et al.*, Joule **6**, 1–14 (2022). Copyright 2022 Elsevier. (c) The impact of the device active area on current density values. Error bars represent standard deviations of current densities. From left to right, the values are ±0.4, ±0.4, ±0.4, and ±0.5.[12] Reproduced with permission from Cui *et al.*, Joule **5**, 1011–1026 (2021). Copyright 2021 Elsevier. (d) Illuminance stability of 6500 K LED and fluorescent light over 3 h. Initial illuminance set to 500 lux; monitored continuously.[12] Reproduced with permission from Cui *et al.*, Joule **5**, 1011–1026 (2021). Copyright 2021 Elsevier. (e) Emission spectra of the 6500 K LED bulb after 300 and 600 h of operation. The light was turned off for 20 min every 3 h.[12] Reproduced with permission from Cui *et al.*, Joule **5**, 1011–1026 (2021). Copyright 2021 Elsevier. (f) Emission spectra of the 6500 K fluorescent tube after 300 and 600 h under the same on/off cycle.[12] Reproduced with permission from Cui *et al.*, Joule **5**, 1011–1026 (2021). Copyright 2021 Elsevier.

stability [$E_\lambda < 1\%$, Fig. 2(d)]. Once stabilized, both the LED [Fig. 2(e)] and FL [Fig. 2(f)] light sources showed negligible spectral drift over extended operation (>600 h), supporting their use in long-term IPV testing if properly conditioned.[12]

Electrical measurement protocols must also be adapted for IPVs. The low photocurrent under ambient light increases the influence of parasitic leakage, contact resistance, and instrumentation noise. Moreover, certain device architectures—particularly those based on perovskites—exhibit significant hysteresis and metastable behavior under I–V scanning. Dunbar *et al.* analyzed the effects of light soaking and sweep speed on $CH_3NH_3PbI_3$-based perovskite solar cells, distinguishing between fast- and slow-responding devices using a metastable timescale parameter, t_s.[15] Devices with longer t_s values exhibited significantly higher measurement variability due to delayed current stabilization and hysteresis. Among several tested protocols, the most accurate results were obtained using a dynamic steady-state method: devices were illuminated continuously during the I–V sweep, and current was recorded only after its variation fell below 0.2% per minute. While highly accurate, this approach is time-consuming and may be impractical for unstable devices. Two more efficient alternatives were proposed:

- **Repeat scan**: The device is held at open circuit for 30 min under ambient light, followed by multiple I–V scans (at 150 mV/s) until convergence.
- **V_{max}-soak-fast-scan**: The device is pre-conditioned at the maximum power point (MPP) for 10 min, then scanned rapidly in both directions.

These protocols were shown to reduce hysteresis and improve consistency. Pre-conditioning near MPP provided results closest to the true steady-state efficiency, whereas open-circuit pre-conditioning overestimated performance and short-circuit pre-conditioning underestimated it. Importantly, the optimal protocol depends on the device's t_s and operational stability. For fast-responding devices, quick scans minimize measurement time and thermal drift. For slow-responding or unstable devices, simpler measurements near the MPP—using coarse voltage steps—may be preferable.

To ensure robust characterization, the following measurement practices are recommended:

- Use high-sensitivity instrumentation for low-light conditions.
- Avoid rapid voltage scans and uncontrolled pre-biasing.
- Report both forward and reverse I–V curves.
- State scan rate, direction, stabilization time, and any pre-conditioning steps.
- Supplement with open-circuit voltage (V_{OC}) vs light intensity curves where appropriate, to extract ideality factors and assess recombination dynamics.

By systematically addressing illumination accuracy, spectral calibration, area definition, environmental stability, and electrical measurement rigor, researchers can lay a consistent foundation for evaluating indoor PV performance. However, precise measurement alone is insufficient. Transparent and standardized reporting of these metrics is equally vital for enabling reproducibility and meaningful comparison across studies. A summary of the essential parameters required for accurate measurement of IPVs is provided in Fig. 3. Since the indoor lighting environment indeed varies considerably across different use cases, such diversity must be reflected in any standardization effort for IPV performance assessment. In addition to adopting a one-size-fits-all approach for IPVs, we propose defining a set of application-specific testing scenarios that align with realistic deployment conditions. For instance,

- Smart home sensors (e.g., motion or environmental sensors) are typically used under warm-white LED lighting (∼2700–3000 K) with moderate illuminance levels (100–300 lux).
- Office-based IoT devices (e.g., occupancy or air quality monitors) are more likely to be exposed to neutral or cool white fluorescent/LED lighting (4000–6500 K) at higher illuminance levels (300–700 lux).
- Retail shelf labels and electronic price tags often operate under high-intensity, cool-white lighting (∼5000–6500 K), sometimes exceeding 1000 lux.
- Wearable or mobile indoor electronics may experience highly variable lighting, requiring multi-source or averaged exposure profiles to capture their use environment.

By aligning testing protocols with specific application domains, we believe future standardization efforts can yield more actionable, relevant, and realistic performance metrics for IPV technologies. These scenarios are selected based on common deployment environments reported in recent literature and standards development efforts.[16–18]

MATERIAL AND DEVICE CONSIDERATIONS FOR INDOOR PVS

Indoor PV performance is intrinsically linked to the optoelectronic properties of the absorber materials and device architectures. While general measurement protocols are essential for ensuring reproducibility and comparability, they must also be interpreted in the context of the materials being tested.

Maximizing spectral alignment between the absorber material and the emission profile of indoor light sources is critical for efficient energy harvesting. For instance, a polymer like poly[(5,6-bis(2-hexyldecyloxy)benzo[c][1,2,5]thiadiazole-4,7-diyl)-alt-(5,50–(2,5-difluoro-1, 4-phenylene)bis(thiophen-2-yl))] PDTBTBz-2F_{anti}, which exhibits a blue-shifted absorption spectrum, matches well with the output of LED lighting and can boost the J_{SC}.[19] Materials with optical bandgaps in the range of 1.7–1.8 eV are well suited for capturing a broad range of ambient light, while bandgaps between 1.9 and 2.0 eV are particularly advantageous under standardized 1000 lux indoor illumination. A material with a 1.9 eV bandgap, for example, can theoretically support a V_{OC} of up to 1.4 V in such conditions.[20] For optimal indoor photovoltaic performance, absorber materials should exhibit strong light absorption, controlled morphology, and be capable of forming relatively thick active layers to reduce leakage currents and improve parasitic shunt resistance (R_P) under low-intensity light. For device engineering, incorporating wide-bandgap interlayers can effectively reduce charge recombination by serving as energy barriers to block undesired counter-charges.

To generate approximately 1 mW of power under typical indoor illumination conditions (∼1000 lux) within a practical device footprint (∼10 cm^2), photovoltaic devices must achieve PCEs exceeding 30%. Equally essential is a high V_{OC}, which reduces the number of series-connected cells required to meet the voltage demands of IoT ecosystems—often around 2.65 V for battery-free, multisensor platforms.[21]

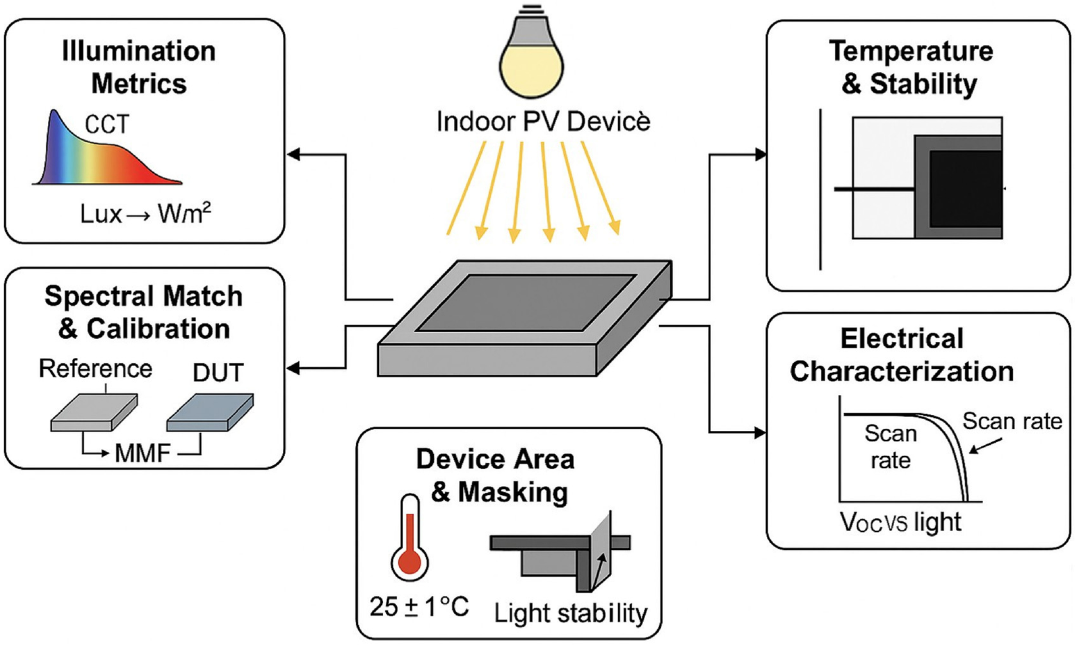

FIG. 3. The summary of essential metrics required for indoor PVs.

Recent advancements in emerging photovoltaic technologies—including dye-sensitized solar cells (DSSCs), organic photovoltaics (OPVs), and perovskite photovoltaics (PPVs)—have demonstrated V_{OC} values exceeding 1 V. Among these, perovskite-based devices have reported the highest indoor efficiencies, reaching up to 44.72% under 1000 lux fluorescent lighting.[22] Notably, an OPV device has achieved an indoor PCE of 37% at 1000 lux in an inverted structure.[7] DSSC-based indoor PVs have also made substantial progress, attaining efficiencies over 36% through strategies such as suppressing charge recombination via copper-based redox mediators, co-sensitization techniques, and the use of tailored ligand additives.[23]

OUTLOOK

The advancement of IPVs hinges not only on innovation in materials and device architectures but also—and perhaps more critically—on the adoption of rigorous and standardized measurement practices. Essential parameters such as irradiance calibration, spectral matching, precise active area definition, and environmental stability directly influence the accuracy, reproducibility, and relevance of reported device performance. Without addressing these factors, even the most promising materials risk being evaluated inconsistently, slowing both scientific progress and commercial translation. To accelerate the maturity of the field, coordination among academic researchers, industry developers, and standardization bodies is essential. Key steps include the development of certified indoor reference spectra that reflect real-world lighting conditions, round-robin benchmarking campaigns to assess inter-laboratory variability, and the establishment of shared calibration protocols for LED and CFL sources. Only through such collective efforts can a unified testing ecosystem emerge—one that parallels the robustness long established in outdoor photovoltaic standards.

Critically, the indoor environment introduces measurement challenges that are not merely technical but contextual. Indoor lighting conditions are user-specific, highly variable, and evolving with market trends in lighting technology. Therefore, measurement protocols must be not only accurate but also adaptable and clearly reported in a way that reflects end-use relevance. As the demand for autonomous, battery-free electronics continues to grow, the credibility of IPV research will increasingly depend on whether its testing conditions match real application scenarios. In sum, while breakthroughs in absorber design and device engineering will continue to expand the theoretical capabilities of IPVs, it is through careful measurement, contextual benchmarking, and transparent reporting that the field will build trust, foster collaboration, and deliver practical solutions. By adopting the essential metrics and best practices discussed in this Perspective, the IPV community can lay the groundwork for scalable, standardized, and commercially impactful energy systems designed specifically for the indoor world.

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AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

Author Contributions

Muhammad Ahsan Saeed: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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