Resolving Spectral Mismatch Errors for Perovskite Solar Cells in Commercial Class AAA Solar Simulators

Perovskite solar cells (PSCs) have achieved astonishing feats with their power conversion efficiencies (PCEs) because of their excellent optoelectronic properties. The certified PCEs in state-of-the-art PSCs have dramatically improved to 25.2%, which is now strikingly comparable to single crystalline silicon (c-Si) solar cells. As certification at accredited test centers is time-consuming and costly, it is extremely challenging and highly unrealistic to impose certification for every published PSC efficiency. Hence, commercial Class AAA solar simulators are widely utilized as a reliable simulated air mass (AM) 1.5 global (G) solar emission source. Most reported PCEs of PSCs are usually evaluated using commercial Class AAA solar simulators with a total spectral irradiance of 1.00 sun or 100 mW cm\(^{-2}\) measured with a c-Si reference cell. This is generally regarded as a prevailing measurement methodology for PSCs. The measured spectral irradiance of a solar simulator (\(S_{\text{msd}}\)) is deemed to reach a corresponding standard level under the reference condition of AM 1.5 G (\(S_{\text{std}}^0\)) when the short-circuit photocurrent of the c-Si reference cell measured in the solar simulator (\(J_{\text{sc}}\)) is equivalent to its certified value (\(J_{\text{sc}}^0\)) recorded under “standard conditions” in a public research center. In this Viewpoint, we highlight the inherent challenges of perovskite solar cell characterization using this methodology and present an alternative, straightforward approach that achieves reliable and comparable measurements across various Class AAA solar simulators.

The reliability of the current measurement approach using commercial Class AAA solar simulators for PSCs remains an open question. Measurement errors derived from the spectral mismatch of Class AAA solar simulators are rarely reported or discussed in PSC literature. To enable fair comparison and reproducibility of published results from various research groups, it is imperative to conduct reliable measurements with these commercial solar simulators. Herein, we first examine possible measurement uncertainties in representative PSCs arising from three typical industry standard Class AAA solar simulators (brands A, B, and C). Despite conforming to the International Electrotechnical Commission (IEC) standards, the spectral mismatch of specific solar simulators can result in measurement uncertainties over 10% for PSCs (relative to the ideal AM 1.5 G condition). Our results indicate that the specific spectral mismatch of the Class AAA solar simulators yield non-negligible measurement uncertainties in the short-circuit current density (\(J_{\text{sc}}\)) and PCE of the PSCs. The difference of the measured \(J_{\text{sc}}\) of the typical MAPbI\(_3\)–xCl\(_x\) (MA = CH\(_3\)NH\(_3\), \(x \approx 0.2\)) based PSC could even reach up to \(\pm 6.4\) mA cm\(^{-2}\), leading to a measurement difference in PCE as high as \(\pm 5.3\%\) (absolute difference). In other words, the Class AAA rating of solar simulators should not be taken for granted as a safeguard against measurement errors of PSCs due to the spectral mismatch. Careful error assessment and calibration are crucial and indispensable. To minimize such errors, we propose calibrating the effective irradiance of solar simulators in the spectral response range of PSCs (\(S_{\text{eff}}\)) to the identical standard level under the reference condition of AM 1.5 G (\(S_{\text{std}}^0\)) when evaluating PSCs under the Class AAA solar simulators. This can be achieved via adjusting \(S_{\text{msd}}\) to \(\frac{1}{M}S_{\text{msd}}^0\), where \(M\) is the spectral mismatch factor reported elsewhere. This means that the irradiance measured with a c-Si reference cell should be adjusted to 1/M sun instead of the traditional 1 sun. Consequently, the measurement differences of \(J_{\text{sc}}\) and PCE of the studied MAPbI\(_3\)–xCl\(_x\) based PSC under the Class AAA solar simulators successfully improved to an acceptable and negligible level of \(\pm 0.2\) mA cm\(^{-2}\) and \(\pm 0.1\%\), respectively. In addition, the related measurement values are more reliable because of a better approximation of the measured \(J_{\text{sc}}\) to the integrated one calculated from the external quantum efficiency (EQE) of the PSC.

The normalized irradiance spectra of the reference AM 1.5 G solar emission and the studied commercial Class AAA solar simulators (denoted by Sol A, Sol B, and Sol C) are illustrated in Figure S1, and the corresponding extracted parameters including irradiance distribution, spectral match, and classification of the solar simulators are summarized in Table 1. According to the IEC standards, the spectral match in the entire wavelength range of the Sol A solar simulator completely conforms to A grade, indicating a rigorous Class A spectral match. For the Sol B and Sol C solar simulators, both their spectral match are tentatively assessed as approximate Class A (~A), considering that their spectral match in most wavelength ranges except the range 900–1100 nm can achieve A grade. It is also noted that the relative irradiance distributions of the Sol A solar simulator are slightly above and below the corresponding AM 1.5 G reference levels in the visible and...
The SRJ of a photovoltaic device under illumination at a specific wavelength is defined as

$$\text{SRJ}(\lambda) = \text{SI}(\lambda) \cdot \text{SR}(\lambda)$$

(1)

where SI(\lambda) is the spectral irradiance of the illumination and SR(\lambda) is the spectral response of the device. Therefore, SI_{ss}^{\text{mad}} and SI_{mad}^0 can be described by

$$\text{SI}_{\text{mad}}^{\text{ss}} \propto \int_{\lambda_1}^{\lambda_2} \text{SRJ}_{\text{mad}}^{\text{ss}}(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} \alpha_s \text{SI}_{\text{ss}}(\lambda) \beta \text{SR}_{\text{ss}}(\lambda) d\lambda.$$  

(2)

and

$$\text{SI}_{\text{mad}}^0 \propto \int_{\lambda_1}^{\lambda_2} \text{SRJ}_{\text{mad}}^0(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} \alpha_0 \text{SI}_{\text{ss}}(\lambda) \beta \text{SR}_{\text{ss}}(\lambda) d\lambda.$$  

(3)

where SI_{\text{ss}}(\lambda) and SI_{\text{ss}}^0(\lambda) are the respective spectral irradiance of the solar simulator and AM 1.5 G solar emission with relative scale (i.e., the irradiance intensity is a relative value); SR_{\text{ss}}(\lambda) is the relative spectral response of the c-Si reference cell; \(\alpha_s, \alpha_0, \beta\) are constants to correct the relative value to absolute. Similarly, SI_{\text{eff}} and SI_{\text{eff}}^0 can be expressed as

$$\text{SI}_{\text{eff}} \propto \int_{\lambda_1}^{\lambda_2} \text{SRJ}_{\text{eff}}(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} \alpha_s \text{SI}_{\text{ss}}(\lambda) \gamma \text{SR}_{\text{PSC}}(\lambda) d\lambda.$$  

(4)

and

$$\text{SI}_{\text{eff}}^0 \propto \int_{\lambda_1}^{\lambda_2} \text{SRJ}_{\text{eff}}^0(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} \alpha_0 \text{SI}_{\text{ss}}(\lambda) \gamma \text{SR}_{\text{PSC}}(\lambda) d\lambda.$$  

(5)

where \(\text{SI}_{\text{eff}}\) is the measured short-circuit photocurrent of a PSC under the solar simulator and \(\text{SI}_{\text{eff}}^0\) is an assumed ideal value under the reference condition of AM 1.5 G or certified value recorded under "standard conditions" in a public research center; SR_{\text{PSC}}(\lambda) and SR_{\text{PSC}}^{0}(\lambda) are the corresponding SRJ values of the PSC under illumination of the solar simulator and AM 1.5 G solar emission; SR_{\text{PSC}}(\lambda) is the relative spectral response of the PSC; \(\gamma\) is a constant to correct the relative value to absolute. Dividing eq 2 by 3 or eq 4 by 5 gives

$$\frac{\text{SI}_{\text{mad}}^{\text{ss}}}{\text{SI}_{\text{mad}}^0} = \frac{\alpha_s}{\alpha_0} \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda}.$$  

(6)

or

$$\frac{\text{SI}_{\text{eff}}^{\text{ss}}}{\text{SI}_{\text{eff}}^0} = \frac{\alpha_s}{\alpha_0} \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}.$$  

(7)

According to eqs 6 and 7, we obtain

$$\frac{\alpha_s}{\alpha_0} = \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda} \cdot \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}.$$  

(8)

namely

$$\frac{\text{SI}_{\text{eff}}^{\text{ss}}}{\text{SI}_{\text{eff}}^0} = \frac{\text{SI}_{\text{eff}}^{\text{ss}}}{\text{SI}_{\text{eff}}^0} = \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda} \cdot \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}.$$  

(9)

As the spectral mismatch factor \(M\) has been defined by 23–27

$$M = \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{ss}}(\lambda) d\lambda} \cdot \frac{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}^0(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \text{SI}_{\text{ss}}(\lambda) \text{SR}_{\text{PSC}}(\lambda) d\lambda}.$$  

(10)

expression 9 can also be abbreviated to

$$\frac{\text{SI}_{\text{eff}}^{\text{ss}}}{\text{SI}_{\text{eff}}^0} = \frac{1}{M} \frac{\text{SI}_{\text{eff}}^{\text{ss}}}{\text{SI}_{\text{eff}}^0}.$$  

(11)

Because SI_{mad}^{\text{ss}} is adjusted to be equal to SI_{mad}^0 in terms of the prevailing method, the relation between SI_{eff}^{\text{ss}} and SI_{eff}^0 can then be written as

$$\text{SI}_{\text{eff}}^{\text{ss}} = M \cdot \text{SI}_{\text{eff}}^0.$$  

(12)

For the purpose of intuitively displaying the prevailing irradiance calibration, the relative irradiance intensities of the studied solar simulators and the reference AM 1.5 G solar emission are proportionally adjusted to achieve an identical
relative value of 328 for both $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{Si}}(\lambda) \, d\lambda$ and $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{Si}}^0(\lambda) \, d\lambda$, suggesting the validity of $SI_{\text{msd}} = SI_{\text{msd}}^0$ based on eqs 2 and 3. In addition, the corresponding relative values of $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{PSC}}(\lambda) \, d\lambda$ and $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{PSC}}^0(\lambda) \, d\lambda$ can be deduced from the specific relative irradiance spectra, accompanied by the spectral response curve of the PSC. The related results are shown in Figure 1 and Table 2 (Cal I). It should be noted that the relative values of $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{PSC}}(\lambda) \, d\lambda$ are inconsistent with the reference $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{PSC}}^0(\lambda) \, d\lambda$, revealing a likelihood of $SI_{\text{eff}} \neq SI_{\text{eff}}^0$ in spite of $SI_{\text{msd}} = SI_{\text{msd}}^0$. In order to further illustrate the nonconformity between $SI_{\text{eff}}$ and $SI_{\text{eff}}^0$, the $M$ factors of the studied solar simulators are calculated by utilizing eq 10 to determine the actual formulas of $SI_{\text{eff}}^0$ and $SI_{\text{eff}}^0$ on the basis of eq 12. As a result, the $M$ factors of the Sol A, Sol B, and Sol C solar simulators are 1.12, 0.83, and 0.85, respectively, which indicates that the corresponding $SI_{\text{eff}}^0$ can actually reach 1.12$SI_{\text{msd}}^0$, 0.83$SI_{\text{msd}}^0$, and 0.85$SI_{\text{msd}}^0$ when $SI_{\text{msd}}$ is uniformly adjusted to $SI_{\text{msd}}^0$ (Table 2, Cal I). This demonstrates the non-negligible uncertainties of $SI_{\text{eff}}^0$ relative to $SI_{\text{eff}}^0$ (Table 2, Cal I), which clearly results in overvalued or undervalued measurement values for PSCs.

To perform more reliable measurements for PSCs using commercial Class AAA solar simulators, we hereby propose to adjust the irradiance intensities of the solar simulators to achieve $SI_{\text{eff}} = SI_{\text{eff}}^0$ according to eqs 4 and 5. As predicted, the corresponding relative values of $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{PSC}}(\lambda) \, d\lambda$ calculated from the specific relative irradiance of the solar simulators and the spectral response of the c-Si reference cell
deviate from the reference $\int_{\lambda_1}^{\lambda_2} SRJ_{\text{Si}}^0 (\lambda) \, d\lambda$. This suggests that the $SI_{\text{msd}}^{\text{ss}}$ must be adjusted beyond the reference $SI_{\text{msd}}^0$ in order to achieve $SI_{\text{eff}}^{\text{ss}} = SI_{\text{eff}}^0$. Considering $SI_{\text{eff}}^{\text{ss}} = SI_{\text{eff}}^0$, the explicit relation between $SI_{\text{msd}}^{\text{ss}}$ and $SI_{\text{msd}}^0$ can be determined by

$$SI_{\text{msd}}^{\text{ss}} = \frac{1}{M} SI_{\text{msd}}^0$$

(13)

inferred from eq 11. Furthermore, the computed $M$ factors of the Sol A, Sol B, and Sol C solar simulators in this situation (Table 2, Cal II) are in accordance with those obtained under the aforementioned calibrated irradiance (Table 2, Cal I). This is consistent with the previous conclusion that the $M$ factor is not restricted to the absolute spectral irradiance.\textsuperscript{24} Consequently, the $SI_{\text{msd}}^{\text{ss}}$ of the Sol A, Sol B, and Sol C solar simulators are equivalent to 0.89$SI_{\text{msd}}^0$, 1.20$SI_{\text{msd}}^0$, and 1.18$SI_{\text{msd}}^0$, respectively (Table 2, Cal II), calculated via eq 13. As noted, $SI_{\text{msd}}^0$ is designated as a standard sun (100 mW cm$^{-2}$) and can be judged by the certified $f_{\text{sc}}$. Accordingly, the $SI_{\text{msd}}^{\text{ss}}$ should be separately calibrated to 0.89 sun, 1.20 sun, and 1.18 sun for the Sol A, Sol B, and Sol C solar simulators by adjusting the relevant $f_{\text{sc}}$ to 0.89$f_{\text{sc}}^0$, 1.20$f_{\text{sc}}^0$, and 1.18$f_{\text{sc}}^0$ to realize the irradiance calibration of $SI_{\text{eff}}^{\text{ss}} = SI_{\text{eff}}^0$. Moreover, it is noteworthy that the specific irradiance spectra of the solar simulators in the spectral response range of the PSC (or visible wavelength range) with the irradiance calibration of $SI_{\text{eff}}^{\text{ss}} = SI_{\text{eff}}^0$ are more conformant with that of the reference AM 1.5 G solar emission than the traditional one with the irradiance calibration of $SI_{\text{msd}}^{\text{ss}} = SI_{\text{msd}}^0$ (Figures 1a and 2a). This indicates that the measurement for PSCs under the solar simulators with the irradiance calibration of $SI_{\text{eff}}^{\text{ss}} = SI_{\text{eff}}^0$ will be more reasonable and reliable.

To further assess the reliability of the two irradiance calibration criteria for PSCs using commercial solar simulators, we evaluated a typical PSC with a configuration of ITO/MAPb$_{1-x}$Cl$_x$-Cu(Tu)/PCBM/BCP/Ag, where ITO is the indium tin oxide transparent anode, MAPb$_{1-x}$Cl$_x$-Cu(Tu)I is
a hybrid layer of the MAPbI$_3$$_{x}$–Cl$_x$ perovskite and the trap state passivator Cu(thiourea)$_2$I reported previously, PCBM [6,6]-phenyl-C$_6$H$_4$-butyric acid methyl ester serves as an electron transporting layer, BCP bathocuproine has the role of hole blocking layer, and Ag is the silver cathode. The detailed construction and characterization of the PSC are described in Methods (Supporting Information). The PSC refers to the MAPbI$_3$$_{x}$–Cl$_x$ based device unless otherwise specified. The related measurement results of the PSC are illustrated in Figure 3 and Table 3. Predictably, the measured $J_{SC}$ and PCE of the PSC are rather contradictory for Sol A, Sol B, and Sol C solar simulators with the widely irradiance calibration of $S_{sun}^\text{eff} = S_{sun}^0$ (or $S_{sun}^\text{eff} = 1.00$ sun) via a calibrated c-Si reference cell. The average $J_{SC}$ and PCE of 8 separate devices under the Sol A solar simulator can be as high as 23.8 ± 0.4 mA cm$^{-2}$ and 21.0 ± 0.6% which is almost acceptable. However, the relative uncertainties for the CsPbIBr$_2$ and PEA$_{0.08}$FA$_{0.92}$SnI$_3$ based PSC, the improved relative uncertainties are within ±3%, which is almost acceptable. However, the relative uncertainties for the CsPbIBr$_2$ and PEA$_{0.08}$FA$_{0.92}$SnI$_3$ based PSC can still reach as high as ±6% and 9%, respectively, which are non-negligible. This implies a considerable measurement difference of up to ±6.4 mA cm$^{-2}$ for $J_{SC}$ and ±5.3% for the PCE (absolute difference) depending on the model of the solar simulator. Furthermore, all these measured $J_{SC}$ values deviate greatly from the integrated one extracted from the EQE spectrum of the device (Figure 3c), which further demonstrates poor reliability of these measurement results. Intriguingly, the measurement differences of $J_{SC}$ and PCE improves to a negligible level of ±0.2 mA cm$^{-2}$ and ±0.1% upon adopting the irradiance calibration of $S_{sun}^\text{eff} = S_{sun}^0$ (or $S_{sun}^\text{eff} = 1.00$ sun). The measured $J_{SC}$ also approximates to the integrated one, indicating a more reliable measurement result.

To validate the applicability of our calibration method to various perovskite materials with different bandgaps, we tested it on a relatively higher-bandgap perovskite CsPbIBr$_2$ and a lower-bandgap perovskite PEA$_{0.08}$FA$_{0.92}$SnI$_3$ [PEA = C$_{2}$H$_4$(CH$_2$)$_2$NH$_3$, FA = CH(NH$_2$)$_2$]. The device structures and the detailed fabrication procedures are described in Methods (Supporting Information). The relevant irradiance calibration and photovoltaic characterization results are shown in Figures S3–S8. The extracted $M$ factors are summarized in Table 4. Similarly, the relative measurement uncertainties for both CsPbIBr$_2$ and PEA$_{0.08}$FA$_{0.92}$SnI$_3$ based PSCs are non-negligible using the prevailing irradiance calibration approach. Instead, our proposed approach successfully minimizes the relative measurement uncertainties.

### Table 3. Photovoltaic Parameters of the PSC under Illumination of Various Solar Simulators with $S_{sun}^\text{eff} = 1.00$ sun or $S_{sun}^\text{eff} = 1/M$ sun

| solar simulator | $S_{sun}^\text{eff}$ (sun) | $V_{OC}$ (V) | $J_{SC}$ (mA cm$^{-2}$) | FF (%) | PCE (%) |
|-----------------|-----------------------------|-------------|-------------------------|--------|---------|
| Cal I           | Sol A 1.00                  | 1.15±       | 24.1                     | 79.2   | 21.9    |
|                 | Sol B 1.00                  | 1.1 ± 0.01d | 23.8 ± 0.4               | 78 ± 1 | 21.0 ± 0.6 |
|                 | Sol C 1.00                  | 1.12 ± 0.01 | 17.6                     | 80.9   | 16.2    |
|                 | Cal II                      | Sol A 0.89  | 1.13 ± 0.01              | 21.3   | 9.3     |
|                 | Sol B 1.20                  | 1.13 ± 0.01 | 21.0 ± 0.2               | 79 ± 1 | 18.6 ± 0.5 |
|                 | Sol C 1.18                  | 1.13 ± 0.01 | 20.8 ± 0.2               | 79.8 ± 0.9 | 18.7 ± 0.2 |

$^a$ $V_{OC}$ is the open-circuit voltage. $^b$ FF is the fill factor. $^c$ The data are based on the champion device. $^d$ The data including the standard deviation are average values calculated from 8 separate devices.

### Table 4. Statistics of the $M$ Factors and Relative Uncertainties of the Studied Solar Simulators Based on Various Perovskite Materials, with Si or KG5-Si as the Reference Cell

| reference cell | light source | $M$ | $M$ |
|----------------|--------------|-----|-----|
|                |              | $M$ | $M$ |
| Si             | Sol A 1.15 (15%) | PEAM$_{0.08}$FA$_{0.92}$SnI$_3$ | 1.12 (12%) |
|                | Sol B 0.75 (25%) | PEAM$_{0.08}$FA$_{0.92}$SnI$_3$ | 0.83 (17%) |
|                | Sol C 0.87 (6%) | PEAM$_{0.08}$FA$_{0.92}$SnI$_3$ | 0.85 (15%) |
| KG5-Si         | Sol A 1.02 (2%) | PEAM$_{0.08}$FA$_{0.92}$SnI$_3$ | 0.99 (1%) |
|                | Sol B 0.94 (6%) | PEAM$_{0.08}$FA$_{0.92}$SnI$_3$ | 1.03 (3%) |
|                | Sol C 1.03 (3%) | PEAM$_{0.08}$FA$_{0.92}$SnI$_3$ | 1.00 (0%) |

$^a$ Values in parentheses are the relative uncertainties.
start of the experiments and after 7 months of operation. As shown in Figure S10 and Table S1, the variation of the irradiance spectrum is extremely small and the relative deviations of the resulting M factors are within ±2%, which is negligible. Nevertheless, the irradiance spectrum of the solar simulator should still be periodically recorded (e.g., once a month) for the M factor calculation.

Lastly, as PSCs are sensitive to air, encapsulation is recommended to ensure good parallelism between the efficiency and spectral response tests and achieve precise M factors. The tests in this work were conducted either in an inert atmosphere or with encapsulated devices. For instance, the efficiency and spectral response cycle test results based on encapsulated PEA$_{0.08}$FA$_{0.92}$SnI$_3$ PSC are illustrated in Figure S11. Both the current density–voltage curves and spectral response curves between the two tests are almost overlapping, and the calculated M factors are nearly identical (Table S2), which indicates that encapsulation is an effective way to achieve good parallelism between the efficiency and spectral response tests.

In summary, measurement uncertainties in PSC characterization arising from the spectral mismatch of specific commercial Class AAA solar simulators are demonstrated to be considerable when employing the prevailing irradiance calibration approach of $S_{11}^{	ext{ref}} = S_{11}^{	ext{std}}$ (or $S_{11}^{	ext{ref}} = 1.00$ sun) via a calibrated c-Si reference cell. The measurement differences of $J_{SC}$ and PCE of a typical MAPbI$_3$Cl$_x$ based PSC using three commercial Class AAA solar simulators were found to be as high as ±6.4 mA cm$^{-2}$ and ±5.3% (absolute difference), respectively. To ensure the reliability of PSCs measurement results using commercial solar simulators, it is recommended to periodically assess and calibrate the spectral mismatch errors of commercial solar simulators even though their spectral match conforms to the A grade according to the IEC standards. Alternatively, the related errors can be minimized by leveraging a modified irradiance calibration procedure of $S_{11}^{	ext{ref}} = S_{11}^{	ext{std}}$ (or $S_{11}^{	ext{ref}} = 1/M$ sun). Finally, we hope that this Viewpoint will help mitigate some of the underlying challenges facing the community in PSC device characterization using widely available commercial Class AAA solar simulators.

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ASSOCIATED CONTENT
1 Supporting Information
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Methods including device fabrication and characterization, spectral irradiance of studied light sources (Figure S1), X-ray diffraction (XRD) pattern of MAPbI$_3$$_{1-x}$Cl$_x$–Cu(Tu)I (Figure S2), irradiance calibration analysis and photovoltaic characterization of CsPbBr$_2$Cl$_4$ (Figures S3, S4, and S7) and PEA$_{0.68}$FA$_{0.32}$SnI$_3$ (Figures S5, S6, and S8) based devices, spectral response of c-Si reference cell without or with a KG5 filter (Figure S9), spectral irradiance (Figure S10) and M factor statistics (Table S1) of Si and B solar simulator at the start of the experiments and after 7 months of operation, efficiency and spectral response cycle test results for the PEA$_{0.08}$FA$_{0.92}$SnI$_3$ based device (Figure S11) and corresponding M factor statistics (Table S2) (PDF)

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Notes
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