Spectral Correction Method for Precise Solar Cell Characterization under Multi-Lamp Solar Simulators

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Abstract

The accurate determination of power conversion efficiency is paramount to the advancement of photovoltaic technologies. However, persistent spectral mismatch between solar simulators and the standard AM1.5G spectrum introduces significant, often unquantified, errors, particularly for emerging PV platforms like perovskites, organic, and multi-junction devices. Conventional correction techniques, such as the reference-cell and spectral-response methods, are fundamentally limited by their scalar nature; they aim to match the total integrated photocurrent but neglect its critical wavelength-by-wavelength distribution. This paper introduces a novel spectral correction paradigm: a wavelength-vector matching method. The approach is centered on minimizing a newly defined objective function, ΔN, which quantifies the root-mean-square deviation between the simulator-generated and the ideal AM1.5G-generated photocarrier profiles across the entire relevant spectrum. This vector-based criterion provides a rigorous measure of spectral fidelity. The proposed method offers three distinct advantages: (1) it obviates the need for physical reference cells, using the device under test as its own calibration standard via its external quantum efficiency (EQE); (2) it is universally applicable to any PV technology, from established silicon to nascent quantum dot cells; and (3) it uniquely resolves the calibration ambiguity inherent in modern multi-lamp solar simulators by identifying the single optimal combination of light sources. Experimental validation across nine distinct solar cell technologies, encompassing silicon, III-V, thin-film, and perovskite materials, confirms the method's superior accuracy and versatility. This work presents a robust and reliable standard for PV metrology, enhancing inter-laboratory data comparability and ensuring the credible evaluation of next-generation solar energy technologies.

Keywords: Solar cell efficiency, Spectral mismatch, External quantum efficiency, Solar simulator calibration, Multi-lamp simulator

1. Introduction

Accurate and reproducible efficiency measurements are essential for the development of emerging photovoltaic technologies. With the rapid rise of new solar cell types (perovskite, organic, multi-junction, etc.), even small errors in reported power conversion efficiency (PCE) can mislead research directions. In practice, solar cells are characterized indoors using solar simulators under Standard Test Conditions (1000 W/m², AM1.5G spectrum) to ensure consistency. High-quality Class AAA simulators typically employ xenon arc lamps, metal-halide lamps, or filtered light sources to approximate the solar spectrum. However, no artificial source perfectly replicates the AM1.5G solar spectrum at every wavelength, leading to spectral mismatch: differences between the simulator's spectral irradiance and the reference solar spectrum. These mismatches can introduce significant errors, especially for devices with narrow or atypical spectral response. For example, Shrotriya et al. (2006) reported that even when the total short-circuit current is matched between simulator and sun, differences in the spectral distribution can affect devices with metastable or trap states, underscoring the need for additional matching criteria in such cases.

Traditionally, two primary methods are used to correct for spectral mismatch in PV measurements. The reference-cell (RC) method employs a calibrated reference solar cell (usually silicon) alongside the test cell.

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A spectral mismatch correction factor M is determined based on the ratio of the test cell's response to the simulator vs. the reference cell's response under both the simulator and the standard spectrum. This factor corrects the measured current of the test cell. The RC approach assumes that the reference and test cells have identical spectral sensitivity; if not, the correction can be inaccurate. Indeed, Gavrik et al. (2020) noted that reference-cell methods are only reliable when the test and reference cells' absorption spectra closely coincide. The second approach is the spectral-response (SR) method, also known as the absolute EQE method. SR calibration involves measuring the test cell's external quantum efficiency (EQE) spectrum and adjusting the simulator's lamp output so that the measured short-circuit current under the simulator matches the calculated short-circuit current under the AM1.5G reference spectrum (obtained by convoluting the EQE with the standard solar photon flux). While the SR method avoids using a separate reference cell and directly accounts for the test cell's spectral response, it still forces agreement only in the total generated current and not in its distribution across wavelengths.

Recent studies have highlighted the limitations of these conventional methods in emerging PV characterization. Even advanced Class AAA solar simulators can yield non-negligible uncertainties for devices like perovskite or multi-junction cells if their spectral output is not well matched to the device under test. In 2020, Gavrik et al. introduced a "spectral tuning" technique in which a simulator's output was actively modulated to minimize measurement errors across different cell types. This underscores the importance of spectral matching. Nonetheless, a practical, broadly-applicable spectral correction method for multi-lamp simulators is still lacking.

In this work, we address these challenges by proposing a new spectral correction methodology for multi-source solar simulators. Our approach ensures that the wavelength-by-wavelength photogeneration rate in the test cell under the simulator matches that under the standard AM1.5G sun spectrum. In other words, we aim to equate not only the total number of charge carriers generated (which determines the photocurrent) but also the generation rate at each wavelength. By using the test cell's own EQE as the calibration reference, the method eliminates the need for separate reference cells and can adapt to any photovoltaic technology. The following sections describe the methodology in detail, the experimental validation of the technique, and a discussion of its advantages over traditional methods.

2. Methodology

Our spectral correction method uses the test cell's measured EQE together with the spectral output of available simulator lamps to compute and minimize a mismatch metric ΔN. The process involves four main steps, outlined below and illustrated in Figure 1.

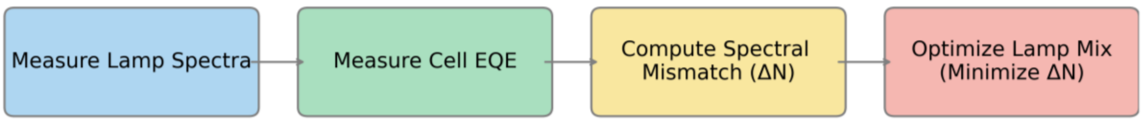

Figure 1: Workflow diagram illustrating the four-step spectral calibration procedure for a multi-lamp solar simulator. The steps are: (1) measure the spectral irradiance of each lamp (e.g. with a spectroradiometer), (2) measure the test cell's EQE as a function of wavelength, (3) compute the spectral mismatch metric ΔN for a given combination of lamp intensities, and (4) iteratively adjust the lamp power settings to minimize ΔN. This procedure yields the lamp intensity mix that best matches the AM1.5G reference spectrum for the specific test cell.

Step 1: Measure Lamp Spectra.

We first measure the spectral irradiance (photon flux as a function of wavelength) of each individual lamp or lamp type in the solar simulator. This can be done using a calibrated spectroradiometer or similar instrument for all lamp sources (xenon, metal-halide, halogen, LED, fluorescent, etc.) used in the simulator. If lamps are used in combination, the spectrum of each combination or controllable channel can also be characterized. The result is a set of spectral power distributions $E_{sim}(\lambda)$, where E_{sim} is the spectral photon flux (in units of photons·m^{-2}·s^{-1}·nm^{-1}) emitted by lamp at a reference power setting.

Step 2: Measure Cell EQE.

We next measure the test solar cell's EQE, denoted $EQE(\lambda)$, over the relevant wavelength range (typically 300–1200 nm for silicon and many thin-film cells, potentially extending further for multi-junction devices). $EQE(\lambda)$ is the fraction of incident photons at wavelength λ that are converted into collected charge carriers. This spectrum effectively captures the cell's wavelength sensitivity.

Step 3: Compute Spectral Mismatch Metric.

For any given combination of lamp intensities, we can compute the photogenerated current density I_{sc}^{sim} in the test cell under the simulator spectrum by integrating the product of the photon flux and the EQE over wavelength. If we let $E_{sim}(\lambda)$ be the combined spectral photon flux from all lamps (summing the contributions of each lamp scaled by their intensity settings), then:

$$I_{sc}^{sim} = q \int_{\lambda_1}^{\lambda_{end}} E_{sim}(\lambda) EQE(\lambda)\, d\lambda, \qquad \text{(eq. 1)}$$

where q is the elementary charge. Similarly, the reference short-circuit current density under the standard AM1.5G spectrum can be calculated as

$$I_{sc}^{ref} = q \int_{\lambda_1}^{\lambda_{end}} E_{ref}(\lambda) EQE(\lambda)\, d\lambda, \qquad \text{(eq. 2)}$$

using the AM1.5G spectral photon flux $E_{ref}(\lambda)$. By construction, if the simulator were perfectly matched to AM1.5G for the test cell, I_{sc}^{sim} would equal I_{sc}^{ref}. Traditional SR calibration ensures this equality of total current but does not guarantee that the integrands (the wavelength-specific generation rates) are equal at each λ.

To address this, we define an objective function *ΔN* that quantifies the difference in generated carrier density spectra between simulator and reference:

$$\Delta N = \sqrt{\int_{\lambda_1}^{\lambda_{end}} \left(E_s(\lambda)EQE(\lambda) - E_{ref}(\lambda)EQE(\lambda)\right)^2 d\lambda} \qquad \text{(eq. 3)}$$

In essence, *ΔN* is the root-mean-square deviation between the simulator-generated electron distribution and the reference distribution across all wavelengths. When *ΔN = 0*, the simulator is producing carriers in the cell at each wavelength in exactly the same way as the sun would, meaning a perfect spectral match for that cell. In practice, we compute *ΔN* numerically for any trial set of lamp intensity coefficients.

Step 4: Optimize Lamp Mix.

Finally, we vary the lamp intensity weights and repeat the calculation of *ΔN*, searching for the combination of lamp outputs that minimizes *ΔN*. This optimization can be performed using numerical algorithms (e.g., grid search for two-lamp systems, or more sophisticated optimization techniques for higher-dimensional lamp intensity space). The result is an optimal calibration setting for the simulator: the set of lamp intensities that yields the closest spectral match to AM1.5G for the given test cell. At this optimum, not only will the total short-circuit current be equivalent to that under the standard spectrum (as ensured by SR calibration), but the shape of the spectral response will also be as close as possible to the ideal. It is noteworthy that this approach makes the test cell itself the reference standard via its EQE, thus avoiding any need for separate reference cells. The method is broadly applicable to any PV technology and any combination of lamp types, so long as the cell's EQE is known and the lamp spectra are measured.

By following these steps, the solar simulator is calibrated in a cell-specific manner. The only required inputs are the measured lamp spectra and the test cell's EQE curve, both of which are commonly obtained in advanced PV laboratories. No additional hardware or reference devices are necessary.

3. Results and Discussion

We validated the proposed spectral correction method experimentally using a solar simulator equipped with five different lamp types (including broadband and narrowband sources). A total of nine solar cells spanning a range of PV technologies were tested: this set included crystalline silicon cells, III–V tandem cells, thin-film chalcogenide cells, and hybrid perovskite cells. The EQE spectra of these cells (used as inputs to the calibration) were taken from our previous work (Komilov et al., 2024) or measured directly for this study. For each cell, ΔN was computed as a function of the lamp power settings, and the calibration algorithm was executed to find the minimum ΔN condition.

In the case of a single-lamp simulator (using one lamp type at a time), conventional calibration methods (either RC with a well-matched reference cell or SR using the cell's EQE) generally suffice to ensure that the total short-circuit current I_{sc}^{sim} matches the AM1.5G reference I_{sc}^{ref}. Our method, when applied to single-lamp scenarios, confirmed that these standard calibrations were achieving near-optimal results for total current. However, the ΔN metric provides an additional check: it remained very low when the lamp spectrum inherently had a good spectral match to the cell (as is often the case with xenon for silicon cells, for instance), but it increased if the lamp's spectral output had gaps or excesses relative to the cell's spectral sensitivity. In such single-source cases, minimizing ΔN did not significantly change the lamp output beyond what the SR method set – it mainly served to verify that the spectral shape mismatch was negligible.

The benefits of our method became clear when combining multiple lamps. In a representative experiment, we used a two-lamp simulator consisting of a metal-halide (ML) lamp and a halogen (HL) lamp, each of which emits different portions of the spectrum. Conventional calibration could adjust the two lamps such that the total short-circuit current matched the standard (this essentially defines a line of solutions in the ML-vs-HL intensity space). In fact, there are infinitely many pairs of ML and HL intensities that yield the same total I_{sc}^{sim} equal to I_{sc}^{ref}. Figure 2 illustrates this situation: the red dashed line indicates the combinations of lamp powers for which the overall photocurrent is correct (i.e., $I_{sc}^{sim}/I_{sc}^{ref}$ = 1). Traditional calibration methods have no preference among these combinations since all give the correct total current. However, not all such combinations are equally good in terms of spectral shape. When we plotted the objective function ΔN over the two-dimensional space of lamp settings, we observed a distinct valley with a single clear minimum ΔN. For each tested cell, this minimum occurred at a unique combination of ML and HL power that made the simulator's composite spectrum closest to AM1.5G for that cell's EQE. Thus, our method selects one particular operating point (among the continuum of possibilities with correct total current) that optimizes the spectral match. In the experiment, we tuned the lamp outputs to this optimum point for each cell. As expected, the resulting I_{sc}^{sim} equaled I_{sc}^{ref} (by construction) and, more importantly, the spectral mismatch error was minimized — the cells behaved as if under true solar illumination more closely than under any other lamp setting.

Applying this procedure across the diverse set of nine solar cells, we found that each cell type had its own optimal lamp intensity mix. For example, a GaAs-based III–V cell required a higher fraction of ML (which has stronger output in the green part of the spectrum) compared to a silicon cell, in order to minimize ΔN. A perovskite cell, with sensitivity extending into the UV, benefited from increased weight on an ultraviolet-rich lamp channel to achieve its spectral match. These outcomes underscore that a one-size-fits-all lamp calibration (such as using a silicon reference cell) is suboptimal for cells with different spectral responses. By contrast, our EQE-based approach consistently identified the spectrally optimal calibration for each device.

The proposed spectral correction method offers several clear advantages over traditional RC and SR calibration techniques, particularly for multi-lamp solar simulators and novel PV devices:

1. Elimination of Reference Cell: By using the test cell's own EQE as the basis for calibration, the need for a separate reference cell is removed. This avoids errors due to material mismatch (e.g., using a silicon reference cell to calibrate a perovskite cell can introduce errors if their spectral responses differ). Each cell effectively becomes its own reference, ensuring the calibration is directly tailored to that cell's characteristics.

2. Unique Calibration for Multi-Lamp Systems: Conventional methods cannot distinguish between different lamp intensity combinations that produce the same total current. In contrast, our ΔN minimization yields a unique solution, identifying which combination of multiple lamps best emulates the solar spectrum for the cell in question. This is particularly valuable for simulators with many channels (such as LED-based solar simulators with various wavelength LEDs), where infinite combinations could give the correct total intensity but only one (or a few) give the correct spectral shape.

3. Improved Spectral Match Indicator: Our approach provides an intrinsic metric, ΔN, that quantifies how well the simulator matches the standard spectrum on a spectral basis. This can serve as a figure of merit for calibration quality. Under a nominal Class AAA simulator calibration (which ensures intensity and spatial uniformity within certain bounds), different labs might still have slightly different spectra. By reporting ΔN, labs have a common indicator of spectral match quality. This could improve inter-laboratory comparability: labs with different simulator types can adjust their settings to achieve similar ΔN (ideally minimizing it) for a given cell, rather than relying on potentially mismatched reference cells or assuming Class AAA alone is sufficient.

4. Generality and Future-Proofing: The method is applicable to any combination of lamps and any PV technology, as long as the EQE and lamp spectra are known. This means it can be readily applied to emerging technologies (tandem cells, quantum-dot solar cells, etc.) without needing specially calibrated reference devices for each new technology. As new lamp types (e.g. advanced LED simulators) or new solar cell materials emerge, the algorithm remains valid. It essentially repurposes information already available (the EQE curves used for standard spectral mismatch corrections) into a more powerful calibration tool.

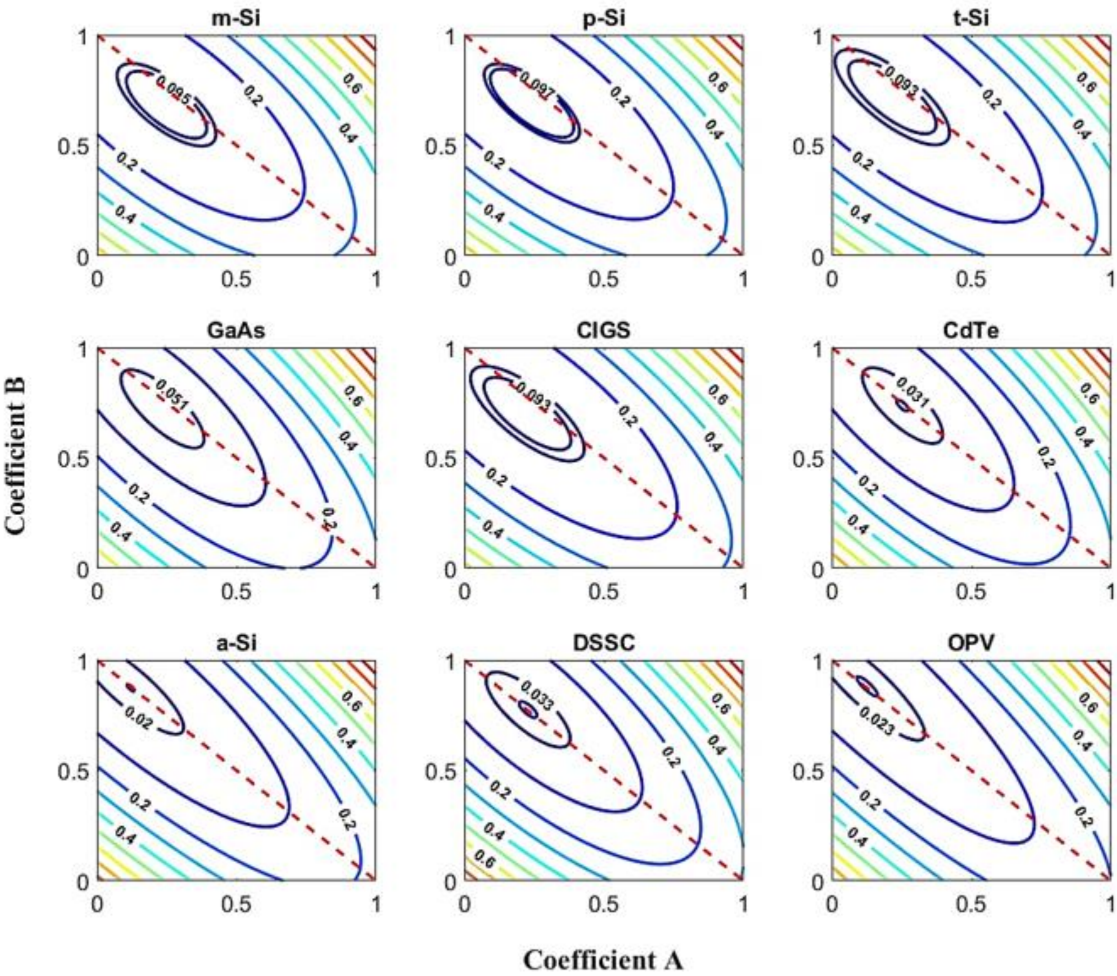

Figure 2: Objective function *ΔN* for a metal-halide + halogen dual-lamp simulator, shown as a function of the two lamps' relative power levels (A and B). The red dashed line indicates all combinations where the total short-circuit current is matched to the AM1.5G reference (conventional calibration criterion). The dark blue region marks the lowest *ΔN*, revealing a unique optimal spectral match at a specific lamp power ratio.

One potential drawback of our approach is the requirement for accurate spectral measurements (both of the lamp outputs and the cell's EQE). However, modern PV laboratories typically have the necessary equipment and procedures in place: spectroradiometers or calibrated spectrometers for lamp characterization, and EQE (or spectral response) measurement setups for solar cells. These measurements are often performed anyway to apply spectral mismatch factors in precision measurements. Our method simply uses that same information in a more comprehensive way. As with any calibration method, errors in the input data (e.g. a mis-measured EQE curve or lamp spectrum) would propagate to the calibration result. Thus, careful spectral measurements are important. In practice, we found that even with routine measurement precision, the ΔN optimization was robust and repeatable.

Looking forward, implementing this spectral correction in practice could be streamlined with software that takes EQE and spectral data to automatically recommend lamp settings. This would add only minimal overhead to the calibration process while significantly enhancing measurement accuracy. As the PV community pushes toward standardizing new technologies, adopting such cell-specific calibration methods could be key to ensuring that reported efficiencies are truly comparable and traceable to standard conditions.

4. Conclusion

We have developed a new spectral correction method for calibrating solar simulators, which matches the simulator's spectrum to the AM1.5G reference on a wavelength-by-wavelength basis using the test cell's own EQE. This vectorized spectral matching approach (quantified by the ΔN metric) combines the strengths of traditional reference-cell and spectral-response methods while addressing their weaknesses. It requires no reference cell and is capable of identifying optimal lamp intensity combinations in multi-lamp systems, something conventional methods cannot do.

Experimental validation across various lamp types and solar cells demonstrated that the method consistently finds the unique simulator settings that minimize spectral mismatch for each cell. By ensuring that both the total photocurrent and its spectral distribution align with the standard spectrum, the technique improves the precision of indoor PV measurements. This approach facilitates better consistency between different laboratories and simulator setups, as calibrations can be tuned for each cell type rather than relying on generic references.

In summary, the EQE-based spectral calibration method enhances the reliability of performance evaluations for both established and emerging PV technologies. It supports the ongoing standardization efforts in photovoltaic metrology and can be readily integrated into existing measurement workflows to yield more accurate and comparable efficiency data.

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