INTRODUCTION

The relevance of determining the health status of Solar PhotoVoltaic Modules SPVM leads to the development of specialized test equipment. These tests are classified according to the electrical and environmental characteristics, that is, online, offline, indoor, and outdoor tests. Outdoor tests are employed to determine the electrical behavior of the SPVM under real atmospheric conditions. However, outdoor tests are subject to variable environmental conditions; therefore, it is unusual to achieve reproducible results. In order to overcome this challenge, indoor tests are incorporated, providing a controlled environment under laboratory conditions for testing, usually called...
solar simulator. This machine is capable of controlling the irradiance received by the SPVM. It should be noted that both indoor and outdoor testing can be conducted either online or offline.

Organizations such as the International Electrotechnical Commission IEC and the American Society for Testing and Materials ASTM have developed the following international standards IEC 60904-9:2007 and ASTM E927-19:2019 in order to classify the performance of solar simulators. These standards classify the performance of the solar simulator according to three categories (a) spectral match, (b) spatial nonuniformity of irradiance, and (c) temporal instability of irradiance. Spectral correlation measures the deviation of the integrated spectral irradiance in a particular wavelength band, when compared to a reference value in the same wavelength band. Spatial nonuniformity of the irradiation determines the deviations in the irradiance on the plane of the SPVM. Finally, the temporal instability of irradiation is related to the power supply of the solar simulator, identifying irradiance oscillations through disturbances in the current and voltage input. It is important to note that the IEC standard divides the temporal instability of irradiance into short-term instability STI and long-term instability LTI. This is not so in the ASTM standard. Each of the three performance indicators is subclassified into Classes A, B, or C, where Class A is the closest to the reference value.

The wavelength of light on the surface of the SPVM is determined by two main factors (a) the primary light source and (b) the light filter. Common artificial light sources are xenon-based lamps, light-emitting diodes (LED), and quartz-tungsten halogen (QTH) lamps. Xenon lamps provide a light spectrum similar to the one generated by the sun. However, the high price of the xenon lamps exceeds greatly the price of LED lights or QTH lamps, making it difficult to acquire them. LED lights provide a low-irradiance light spectrum that depends on the color of the light emitted. Therefore, a proper combination of LEDs can generate a light spectrum similar to the sun spectrum. On the contrary, QTH lamp provides a light spectrum concentrated in 800-1200 nm. For this reason, QTH lamps tend to raise the temperature of the surroundings in a brief time. Despite these disadvantages, QTH lamps are presented as a suitable alternative for the development of a solar simulator, since their price per bulb is low and are capable of generating a high light intensity.

There are different types of solar simulators presented in the state of the art. These simulators usually use LED lights, xenon-based lights, or QTH lamps. Gheorghian et al proposed a solar simulator that uses two different lights sources: four floodlights halogen lamps and two lamps arrangements, both of them capable of producing a nonuniformity of irradiance under 10% over an area of 31 × 31 cm². Salam et al developed a solar simulator based on QTH lamps filtering part of the infrared spectrum with a water tank diluted with blue dye placed between the light source and the SPVM. Nevertheless, Salam et al did not indicate the performance parameters of the proposed solar simulator when validating the behavior by means of electrical measurements on the current-voltage plane, usually referred to as IV curve. Aristizabal et al proposed a solar simulator using QTH lamps, infrared filters, and daylight filters as the primary source of light over an area of 5 × 5 cm². The filters implemented by Aristizabal et al reduce the level of irradiance from 3500 to 200 W/m² on the surface of the SPVM tested. The performance of the solar simulator implemented by Aristizabal et al presented a spatial nonuniformity of irradiance under 10%. Hussain et al constructed a solar simulator using 23 × 500 W halogen Philips lamps, covering an area of 123 × 53 cm². The performance of the solar simulator constructed by Hussain is measured only in terms of its nonuniformity of irradiance at different levels, ranging from 7.8% for an irradiance of 804 W/m² up to 8.9% for an irradiance equal to 466 W/m². Yandri et al designed a solar simulator that offers a nonuniformity of irradiance under 5% over a surface of 9.1 cm², employing incandescent tungsten lamps coupled with paper filters. Also, Yandri et al indicated in the state of the art a set of solar simulators that use QTH lamps.

Other studies suggest that incorporating LEDs in a QTH bulb array improves the spectral match. An example of this can be seen in the solar simulator developed by Baguckis et al, which uses a tungsten halogen bulb combined with six types of LED lights acting as the primary light source. In a similar manner to what was proposed by Baguckis, Grandi et al developed a solar simulator that incorporates QTH bulbs and LED lights. The difference between these studies is that the simulator developed by Grandi et al have a larger working area than the design proposed by Baguckis et al; however, as the area increases, the spectral correlation deteriorates.

Table 1 summarizes the solar simulators that use QTH lamps. It is appreciated that most QTH solar simulator designs are generally of small size. This fact presents a disadvantage for solar simulators, since it limits indoor testing to photovoltaic solar cells, which typically have a size of 156 × 156 mm². In addition, it is important to note that several studies do not measure the spectral match, so it is difficult to quantify the impact of light filters. Finally, the state of the art usually lacks details on the construction methodology of the solar simulator reported.

This article proposes a novel methodology to design an optimal solar simulator, which uses commercial QTH lamps and a filter composed of a mixture of water and...
cyan ink. The methodology includes the characterization of the irradiation of a QTH lamp, the mathematical model of irradiation, and the design and construction of a solar simulator. It should be noted that the studies mentioned above are based on the assumption that the light sources are powered by direct current, which aspect is discussed in this article. The performance of the solar simulator is evaluated according to international standard criteria, such as spectral match, spatial nonuniformity of irradiance, and temporal instability of irradiance. In addition, the behavior of the solar simulator is verified by calculating the root-mean-squared error RMSE of IV curves measured under indoor and outdoor conditions, using six samples of the SPVM JS10P. The rest of the article is divided as follows: Section 2 examines in detail the performance parameters of a solar simulator, Section 3 indicates the methodology to characterize the performance of a single lamp, Section 4 develops the design and construction methodology of the solar simulator, and Section 5 studies the performance of the constructed solar simulator. Finally, Section 6 concludes the article.

2 SOLAR SIMULATOR STANDARD PERFORMANCE REQUIREMENTS

International solar simulator standards usually divide the performance of solar simulators into three aspects: (a) spectral match, (b) spatial nonuniformity of irradiance, and (c) temporal instability of irradiance. Several institutions are in charge of defining the calculation method and the classification of the performance indicators. Some of these institutions are the IEC, the ASTM, and the Japanese Industrial Standard JIS. This research is based on the indications from the IEC 60904-3 and ASTM E927-19 standards.

It is important to note that the methodology for calculating the performance parameters is similar regardless the institution. The calculation method for the performance indicators is developed in the following subsection.

### Table 1: Summary of solar simulators employing halogen bulbs as a primary light source

| Author               | Year   | Area             | Spectral match $R_{SM}$ | Spatial nonuniformity of irradiance (%) | Temporal instability of irradiance (%) |
|----------------------|--------|------------------|-------------------------|----------------------------------------|----------------------------------------|
| Salam et al<sup>15</sup> | 2014   | $≤1.1 \times 0.5$ m$^2$ | N/A                     | N/A                                    | N/A                                    |
| Aristizabal et al<sup>16</sup> | 2011   | $≤5 \times 5$ cm$^2$    | N/A                     | $≤10$                                  | $≤6$                                   |
| Hussain et al<sup>17</sup> | 2011   | $≤123 \times 53$ cm$^2$ | N/A                     | $≤8.9$                                | N/A                                    |
| Yandri et al<sup>18</sup> | 2018   | $≤9.06$ cm$^2$        | N/A                     | $≤9.7$                                | N/A                                    |
| Baguckis et al<sup>28</sup> | 2016   | $≤1.5$ cm radius     | $0.75 \leq R_{SM} \leq 1.25$ | $≤2$                                  | $≤0.1$                                 |
| Grandi et al<sup>29</sup> | 2014   | $≤10 \times 10$ cm$^2$ | $0.60 \leq R_{SM} \leq 1.40$ | $≤5$                                  | $≤1$                                    |

### Figure 1: Standard air mass 1.5 hemispherical spectral solar irradiance for $37^\circ$ sun-facing tilted surface. Detailed information can be found in the IEC 60904-3 standard<sup>30</sup>

#### 2.1 Spectral match

The methodology for calculating the spectral correlation consists of comparing the light spectrum of the solar simulator with respect to a reference light spectrum. In the first instance, the IEC and ASTM institutions report their reference light spectrum in the IEC 60904-3<sup>30</sup> and ASTM G 173-03<sup>31</sup> standards. As the solar modules primarily use the visible spectrum of the sun’s energy, the reference light spectrum is divided into six segments which ranges from 400 nm to 1100 nm. Figure 1 indicates the behavior of the global solar spectral irradiance indicated in the IEC 60904-3 standard. It can be seen from the Figure 1 that the spectral irradiance is divided into six wavelength bands, each one corresponding to the spectral bands indicated by the standards. The cumulative global irradiance at the wavelength boundaries of these spectral bands is indicated in Table 2. Based on the data indicated in Table 2, the standards calculate the percentage of total irradiance of each wavelength ranging from 400 to 1100 nm. The percentages of each spectral band used for IEC and ASTM standards are presented in Table 3 (also referred
as spectrum ratio). It can be seen that these percentages differ from the third significant figure, as a result of differences in the cumulative global integrated irradiance. It is important to note that the cumulative integrated irradiance is calculated by means of the trapezoidal integration technique using the data provided by the IEC 60904-3 and ASTM G 173-03 standards.

As soon as the behavior of the reference spectrum is obtained, the light spectrum produced by the solar simulator must be measured. For this purpose, the IEC and ASTM indicate a series of recommendations, for example, measurements should be in the range of 400-1100 nm with a difference between two successive measurements below 10 nm. Finally, the comparison between the reference light spectrum and the measured light spectrum for each $X$ wavelength range is determined according to Equation (1). In this equation, $R_{SM,X}$ represents the spectral correlation for the wavelength range $X$, while $P_{meas,X}$ and $P_{ref,X}$ indicate the percentages of total irradiance over the measured and reference wavelength range $X$, respectively.

$$R_{SM,X} = \frac{P_{meas,X}}{P_{ref,X}}$$

### 2.2 Spatial nonuniformity of irradiance

Spatial nonuniformity of irradiance $S_{NE}$ indicates the dispersion of irradiance over the plane of the SPVM illuminated by the solar simulator. For this purpose, the international standards calculate the nonuniformity of irradiance by means of the maximum and minimum value of the entire irradiance data set $I_S$ or short-circuit current data set $I_{SC}$, as indicated in Equation (2). Furthermore, the ASTM standard includes the calculation of the standard deviation of spatial nonuniformity $\sigma_{NE}$ using the mean value of short-circuit current $\langle I_{SC} \rangle$, determined as indicated in Equations (3) and (4). In order to properly measure the irradiance distribution produced by the solar simulator, it is recommended to divide the test area into 64 equal sections.

Similar to the spectral match methodology, $S_{NE}$ can be classified into Classes A, B, C, or U. Table 5 indicates the Class distribution for the IEC and ASTM standards.

$$S_{NE} = \frac{\max \{ I_S \} - \min \{ I_S \}}{\max \{ I_S \} + \min \{ I_S \}} \times 100\%$$

$$\langle I_{SC} \rangle = \frac{1}{n} \sum_{i=1}^{n} I_{SC} [i]$$

$$\sigma_{NE} = \frac{1}{\langle I_{SC} \rangle} \sqrt{\frac{\sum_{i=1}^{n} (I_{SC} [i] - \langle I_{SC} \rangle)^2}{n - 1}} \times 100\%$$

### 2.3 Temporal instability of irradiance

Temporal instability of irradiance $T_{IE}$ indicates fluctuations in the power grid, which are reflected in irradiance variations on the solar simulator plane or the short-circuit current of a SPVM illuminated by the solar simulator. The IEC 60904-9 standard divides the temporal instability of
irradiance into a short-term instability (STI) and a long-term instability (LTI). On the one hand, the STI corresponds to the variability in the irradiance when tracing an IV curve. On the other hand, LTI affects the result of the test performed in seconds or milliseconds.

The TIE measurement can be performed at any place in the area of the solar simulator. Finally, the classification of TIE is segmented into Classes A, B, C, or U. Table 6 indicates the requirements of each class regarding IEC and ASTM standards.

### 3 | LIGHT SOURCE CHARACTERIZATION

The light source of the solar simulator is mainly dependent on the light source technology, shape of the light source, external light filters, and electrical characteristics. Since each commercial light source has a distinctive radiation distribution, it is useful to have a preliminary setup for testing purposes. In this study, QTH lamps are selected as the light source due to the fact that this technology has (a) high level of irradiance and (b) low price when compared to other light sources. The selected QTH lamp corresponds to the commercial LINEAL 220V/300W-118 R7S ELFA. It is important to consider that this type of light source presents a high level of infrared radiation; therefore, the effect of a water filter mixed with different levels of cyan ink is studied in order to address this issue.

After the light source technology is determined, the preliminary experimental setup is designed. The design considers a filter system that offers a partial control over the light spectrum. Figure 2A,B indicate the front and lateral view of the preliminary experimental setup. In order to minimize the light contamination produced or reflected by other objects, a perimeter is closed around the preliminary experimental setup with a blackout curtain. A detailed review of the selected power supply, the effect of the dyed water filter on the spectral profile produced by the QTH lamp, and the mathematical modeling of irradiance over the preliminary experimental setup is described in the following subsections.

### 3.1 | Power supply

The power supply of the light source must be able to regulate different voltage levels. This can be achieved by (a) alternating current (AC) excitation or (b) direct current (DC) excitation. The AC power supply is indicated in Figure 3A, where it can be seen that the source is composed of the three-phase utility grid and an autotransformer (usually called variac). It should be noted that the selected light source only needs to be powered by one phase of the variac. The DC power supply incorporates a rectification stage consisting of a diode bridge rectifier and a capacitor bank in comparison with the AC scheme, as shown in the Figure 3B.

In order to determine the power supply for the light source, the electrical voltage at the terminals of a SPVM will be registered over time. The ED10-6M SPVM will be used for this purpose. The illuminated SPVM is connected to a variable resistor and placed in the testing area of the preliminary experimental setup. The voltage of the SPVM is measured with the CT2593 differential probe and the information retrieved is stored by the DSOX3014A digital oscilloscope. The voltage used in this paper corresponds to a normalized voltage with respect to the mean value of the measured data.

The voltage response generated by the SPVM over time is registered when the 50 Hz AC power supply scheme is used. Results are plotted in Figure 4A (red dashed line

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**Table 4** Spectral match $R_{SM}$ indicated by the IEC and ASTM institutions

| Classification | IEC 60904-3 | ASTM G173-03 |
|----------------|-------------|--------------|
| Class A        | $0.75 \leq R_{SM} \leq 1.25$ | $0.75 \leq R_{SM} \leq 1.25$ |
| Class B        | $0.60 \leq R_{SM} \leq 1.40$ | $0.60 \leq R_{SM} \leq 1.40$ |
| Class C        | $0.40 \leq R_{SM} \leq 2.00$ | $0.40 \leq R_{SM} \leq 2.00$ |
| Class U        | N/A         | $R_{SM} > 2.00$ |

**Table 5** Spatial nonuniformity of irradiance $S_{NE}$ indicated by the IEC and ASTM institutions

| Classification | IEC 60904-3 (%) | ASTM G173-03 (%) |
|----------------|-----------------|------------------|
| Class A        | $\leq 2$        | $\leq 2$         |
| Class B        | $\leq 5$        | $\leq 5$         |
| Class C        | $\leq 10$       | $\leq 10$        |
| Class U        | N/A             | $> 10$           |

**Table 6** Temporal instability of irradiance $T_{IE}$ indicated by the IEC and ASTM institutions

| Classification | IEC 60904-9 | ASTM G173-03 |
|----------------|-------------|--------------|
|                | STI (%)     | LTI (%)      |
| Class A        | $\leq 0.5$  | $\leq 2$     |
| Class B        | $\leq 2$    | $\leq 5$     |
| Class C        | $\leq 10$   | $\leq 10$    |
| Class U        | N/A         | $> 10$       |
It can be seen from the fast Fourier transform (FFT) in Figure 4B (red dashed line with circle markers) that the harmonic content of the voltage has a frequency of 100 Hz and is mainly driven by a continuous component. This continuous component is generated by the mean value of the irradiance on the SPVM surface. The 100 Hz harmonic is associated with the on/off cycle of the light source, representing approximately 12% of the continuous component; therefore, it should not be neglected in the electrical analysis. These results indicate that the transient response of monocrystalline silicon SPVMs is larger than the 50 Hz on/off cycles for QTH lamps.

When the SPVM is excited by the DC power supply, the voltage response over time produces a continuous harmonic component, as seen in Figure 4A (blue dashed line with asterisk markers). The application of the FFT, indicated in Figure 4B (blue dashed line with asterisk markers), confirms this fact. Considering this background, the power supply of the light source follows the DC scheme.

### 3.2 | Dyed water filter

In order to investigate the effects of the dyed water filter on the QTH lamp spectrum, different concentrations of cyan ink are tested and analyzed. This study uses the VSP-EM Vernier spectrometer to perform the measurements. However, a disadvantage of this spectrometer is that it is only capable of measuring the spectral band between 400 and 900 nm. Therefore, the spectrum ratio is redefined according to the guidelines of the IEC 60904-9 standard. Table 7 indicates the adapted spectrum ratio for the spectral bands a–e. It should be considered that, since measurements are not being made in the infrared band, an unexpected performance of some photovoltaic technologies could be influenced.

The dyed water fills a transparent glass cube up to a height of 1.48 cm, which is located between the light source and the spectrometer. The ink used in this study corresponds to a commercial sample of the HP GT52 cyan ink and is mixed with 4 L of distilled water throughout this study. Table 8 indicates the different filter combinations used, including the case when no filter is considered.

Figure 5 indicates the normalized spectral responses for filter combinations $W_{raw}$, $W_{0.0}$, and $W_{1.4}$. It can be seen that the inclusion of distilled water has no major impact on the overall spectral response. However, the inclusion of cyan ink reduces the spectral bands b and c in relation to a, d, and e. This allows to precisely manipulate the QTH lamp spectrum distribution.

The spectral match for each band of the experimental filters is indicated in Table 8. It can be appreciated that the cyan ink increases the spectral match for bands a, d,
and e. On the contrary, for bands b and c, the ink tends to decrease the spectral match. This fact suggests that the incorporation of the HP GT52 cyan ink mainly absorbs the wavelengths in the 500–700 nm range. Therefore, the dyed water filter allows the original QTH spectrum comply with Class C spectral match of the IEC and ASTM standards requirements.

3.3  

Mathematical model of irradiance

The mathematical model of the spatial nonuniformity of irradiance is calculated by measuring a grid of 432 equally spaced points over the test area. Irradiance measurements are acquired by using the LICOR200R pyranometer, which technical characteristics indicated in. The collected data are stored in a CR300 datalogger. Figure 6 shows that the measured irradiance has a Gaussian distribution.

Since the test area is smaller than the area covered by the irradiation produced by the light source, some irradiation values are not measurable. In order to solve this challenge, the behavior of the irradiance is modeled using an arbitrary x–y coordinate system. The MATLAB curve fitting toolbox is used. The selection of the model is determined based on the highest correlation coefficient for the polynomial degree combinations indicated in Table 9. It can be seen that the second-degree polynomial is suitable for the Y axis and the fourth-degree polynomial for the X axis in order to properly describe the behavior of the irradiation. Equation 5 indicates in a matrix form the irradiance on the x–y plane $I(x,y)$.

$$I(x,y) = \begin{bmatrix} 1 & x^2 & x^3 & x^4 \\ \end{bmatrix} \begin{bmatrix} P_{00} & P_{01} & P_{02} \\ P_{10} & P_{11} & P_{12} \\ P_{20} & P_{21} & P_{22} \\ P_{30} & P_{31} & 0 \\ P_{40} & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ y \\ y^2 \end{bmatrix}$$ (5)

4  

Solar Simulator Design and Construction

The solar simulator design is based on the light source irradiance model. The design procedure of the solar simulator is detailed below, and the results of spatial nonuniformity and temporal instability are indicated.

**TABLE 7**  
Adapted spectrum ratio using the global reference solar spectral irradiance indicated in IEC 60904-3

| Wavelength band | Wavelength range (nm) | Spectrum ratio (%) |
|-----------------|-----------------------|--------------------|
| a               | 400 → 500             | 21.892             |
| b               | 500 → 600             | 23.687             |
| c               | 600 → 700             | 21.839             |
| d               | 700 → 800             | 17.754             |
| e               | 800 → 900             | 14.828             |

**FIGURE 4**  
SPVM voltage response over time when the utility grid has a fundamental frequency of 50 Hz

**FIGURE 6**  
SPVM voltage response over time when the utility grid has a fundamental frequency of 50 Hz

(A) Normalized voltage.

(B) Normalized voltage FFT.
The optimal distribution of the light sources resides in minimizing the $S_{NE}$ variable, which is subject to the amount of light bulbs ($n_x$ and $n_y$), and distance between them ($d_x$ and $d_y$) on the X axis and the Y axis. This work explores a range of 3-5 light bulbs, as indicated in Equation (6). On the contrary, the minimum value of $d_x$ and $d_y$ is determined by the case where two light bulbs are in contact (12 cm between light bulb centers), while its maximum value is defined when the modeled irradiance of two adjacent light sources is zero (71 cm). Equation (7) indicates the $d_x$ and $d_y$ constraints. Figure 8 shows the optimization flowchart applied to one of the three light bulbs indicated in Figure 9. The optimization algorithm is designed to locate a $27 \times 54$ cm$^2$ section with the lowest spatial irradiance nonuniformity within the total illuminated area of the simulator. To achieve this, two data matrices are used ($M_a$ and $M_d$) to register the performance of the different irradiance distributions.

The results of the optimization for the different layouts are shown in Table 11. It can be appreciated that a higher solar simulator class is achieved by the “b” layout. This layout is composed of 20 QTH lamps and is suitable to reach a $S_{NE}$ Class B in both IEC and ASTM standards. The irradiance distribution can be appreciated in Figure 10, where the dimension of the test area is near $140 \times 150$ cm$^2$. In addition, the design is capable of transforming the bell-shaped irradiance profile to a single light unit, generating an uniform irradiance zone.

### Optimization model

The optimal distribution of the light sources resides in minimizing the $S_{NE}$ variable, which is subject to the amount of light bulbs ($n_x$ and $n_y$), and distance between them ($d_x$ and $d_y$) on the X axis and the Y axis. This work explores a range of 3-5 light bulbs, as indicated in Equation (6). On the contrary, the minimum value of $d_x$ and $d_y$ is determined by the case where two light bulbs are in contact (12 cm between light bulb centers), while its maximum value is defined when the modeled irradiance of two adjacent light sources is zero (71 cm). Equation (7) indicates the $d_x$ and $d_y$ constraints. Figure 8 shows the optimization flowchart applied to one of the three light bulbs indicated in Figure 9. The optimization algorithm is designed to locate a $27 \times 54$ cm$^2$ section with the lowest spatial irradiance nonuniformity within the total illuminated area of the simulator. To achieve this, two data matrices are used ($M_a$ and $M_d$) to register the performance of the different irradiance distributions.

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$$3 \leq n_x, n_y \leq 5$$

$$12 \leq d_x, d_y \leq 71$$

### Fabrication

In order to manufacture the solar simulator, a previous design of the “b” layout is performed. Subsequently, the structure of the solar simulator is constructed using 30 mm$^2$ CNC structural T-slot aluminum profiles. Figure 11A,B presents the constructed prototype, where the “b” layout can be appreciated. It is important to note that the distance between the light source and the testing area is the same as indicated in Figure 2A.

### Scalability

After $d_x$ and $d_y$ are calculated, it is important to investigate the spatial nonuniformity of irradiance for different number of bulbs. To achieve this, the performance of five
squared light sources arrays composed of 4, 9, 25, 64, and 169 units is explored. It can be seen in Figure 12 that the optimal $d_x$ and $d_y$ values are capable of generating a solar simulator that match a Class B spectrum. Furthermore, the Class B area increases as the number of light sources increases.

**FIGURE 6** Measured irradiance on the testing area

**TABLE 9** Correlation coefficients for the polynomials under study

| deg(y) | deg(x) | 2  | 3  | 4  |
|--------|--------|----|----|----|
| 2      | 0.9715 | 0.9721 | 0.9908 |

**TABLE 10** $p$-coefficients of the irradiance model

| Coefficient | Value   | 95% Confidence interval      |
|-------------|---------|------------------------------|
| $p_{10}$    | $3.47 \times 10^2$ | $3.34, 3.59 \times 10^2$  |
| $p_{10}$    | 2.51    | 2.19, 2.82                  |
| $p_{10}$    | 2.32    | 2.21, 2.42                  |
| $p_{10}$    | $-2.16 \times 10^{-2}$ | $-2.47, -1.85 \times 10^{-2}$  |
| $p_{11}$    | $1.87 \times 10^{-2}$ | 1.71, 2.03 $\times 10^{-2}$   |
| $p_{12}$    | $-5.23 \times 10^{-3}$ | $-5.45, -5.02 \times 10^{-3}$  |
| $p_{12}$    | $8.46 \times 10^{-3}$ | 7.18, 9.74 $\times 10^{-3}$    |
| $p_{12}$    | $-5.42 \times 10^{-3}$ | $-6.14, -4.70 \times 10^{-3}$  |
| $p_{12}$    | $-4.02 \times 10^{-3}$ | $-6.14, -3.72 \times 10^{-3}$  |
| $p_{12}$    | $-1.25 \times 10^{-7}$ | $-1.43, -1.07 \times 10^{-7}$  |
| $p_{12}$    | $8.19 \times 10^{-9}$ | $-3.45, -19.8 \times 10^{-9}$  |
| $p_{22}$    | $1.10 \times 10^{-7}$ | 1.02, 1.19 $\times 10^{-7}$    |

5 | EXPERIMENTAL RESULTS

In this section, the performance of the constructed solar simulator is investigated from three perspectives: (a) the spatial non-uniformity of irradiance, (b) temporal instability, and (c) thermal evaluation of the solar simulator.

5.1 | Nonuniformity of irradiance

The irradiance profile of the solar simulator is measured in order to verify the optimized light distribution. The dyed water filter is included in this test, which limits the solar simulator area to $27 \times 54 \text{ cm}^2$. Therefore, the irradiance is measured over 190 equidistant points, spaced 3 cm
from each other. Figure 13 shows the solar simulators irradiance distribution.

To identify the largest area that satisfies the class indicated by the IEC and ASTM standards, a look-up code is applied to the measured irradiance. Three specific suitable test areas are found, one of class indicated in the international standards. Table 12 resumes the output of the analysis, where it can be seen that an area of $270 \times 270 \text{ mm}^2$ matches Class A.

5.2 | Temporal instability of irradiance

Temporal instability of the irradiation is measured over the duration of an IV curve with a solar reference cell. The IV curves are measured using the CetisPV-Outdoortest equipment distributed by h.a.l.m. elektronik gmbh. Figure 14 shows the irradiance measured in five trials, where each trial is composed of 250 measurements at time intervals of 75 ms. The irradiance is normalized according to its mean value. The solar reference cell is placed randomly on the test area. Table 13 indicates the temporal instability of irradiance, where it can be seen that the statistical maximum value oscillates nearly 0.07% from the mean irradiance.

5.3 | IV curve measurement

The measurement analysis compares outdoor and indoor IV curves for the same irradiance and cell temperature. However, since the indoor and outdoor irradiance and cell temperatures do not perfectly match, an error is propagated through the IV curves measurements. These measurements are performed by testing six samples of the
JS10P SPVM, which technical characteristics are indicated in Table 14. In addition, IV curves are measured with the CetisPV-Outdoortest equipment at the Universidad Técnica Federico Santa María, Santiago, Chile.

Figure 15 indicates the behavior of three IV curve samples measured in outdoor and indoor conditions. Here, the mean irradiance equals 825 W/m², and mean cell temperature \( T_{\text{c},\text{out}} \) equals 38.1°C. From this figure, it is possible to appreciate that the shape of both IV curves remains similar, as well as the short-circuit current and open-circuit voltage values.

The error of the IV curve measurements of the SPVMs 1, 2, and 3 is indicated in Figure 15D, where the error presented is the deviation of the PV current for the same PV voltage. It can also be appreciated from the figure that a maximum PV current deviation of 0.07 A is reached. Furthermore, an alternative way to obtain the errors is to calculate the RMSE of the measured data set. The RMSE is normalized by means of the short-circuit current. Table 15 resumes the information of the six SPVM samples. The percentage deviations of the irradiance and cell temperatures of the tests are indicated in Table 15. It can be observed that the tested SPVMs display the greatest deviations in irradiation and cell temperature exhibiting an increased RMSE. Regardless of the propagation error mentioned above, the maximum value of RMSE is under 3%.

6 | CONCLUSION

A novel methodology to build an optimal solar simulator has been developed in this article. The proposed
methodology considers the characterization of the light source in order to design a solar simulator according to international standard requirements. The light source is composed of a 4 × 5 array of commercial QTH bulbs. A DC power supply is used as the silicon-based SPVMs are able to detect the 50 Hz frequency power grid. In addition, a filter is included in the experimental setup to adjust the spectral match. The filter is composed of a mixture of distilled water and cyan ink, reducing the predominance of the spectral band in the 500-700 nm range. The addition of the filter allows the light source to match the Class C spectral match standard requirement. Finally, a mathematical model of the light source irradiance is performed, measuring a grid of 432 equally spaced points over the test area.

After defining the optimal amount and distribution of QTH lights, a mathematical solar simulator model that
complies with the Class B spatial nonuniformity of irradiance. In addition, the scalability of the solar simulator is demonstrated, achieving a Class B test area over 2 m² when a 13 × 13 array of commercial QTH bulbs is used. On the contrary, the constructed solar simulator exhibits a spectral match of 1.69%, a spatial nonuniformity of irradiance of 1.66%, and a temporal instability of irradiance under 0.1% over a 75 ms interval. Discrepancies between the designed and constructed solar simulator are attributed to unexpected rotations of the QTH light sources and reflecting structures.

The reported RMSE of the IV curves is <2.7% under indoor and outdoor conditions. Environmental conditions for indoor and outdoor tests should be considered, since variations may introduce unexpected errors in the RMSE calculation. Finally, a 270 × 270 mm² Class CAA solar simulator is achieved, according to the IEC and ASTM standards. The constructed solar simulator is able to test
small-sized solar photovoltaic modules, enabling scalability by means of the proposed methodology.

Further works must consider improvements in the optimization algorithm, such as the implementation of a metaheuristic search method. Furthermore, other light technologies can be studied, such as LEDs, xenon lamps, or combinations of different technologies. Finally, it is possible to study several light filters in order to achieve a higher spectral match class.

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NOMENCLATURE

AC alternating current
APE absolute percentage error
ASTM American Society for Testing and Materials
DC direct current
FFT fast Fourier transform
IEC International Electrotechnical Commission
JIS Japanese Industrial Standard
LED light-emitting diode
LTI long-term instability
MAPE mean absolute percentage error
QTH quartz-tungsten halogen
RMSE root-mean-squared error
SPVM solar photovoltaic module
STI short-term instability

ACRONYMS

NE

VARIABLES

WS working space area
$I_{S,out}$ measured outdoor irradiance data set
$T_{c,out}$ measured outdoor cell temperature
$\sigma_{NE}$ spatial nonuniformity of irradiance (standard deviation)
$d_x, d_y$ distance between two consecutive bulb
$I_S$ irradiance data set
$I_{SC}$ short-circuit current data set
$n_x, n_y$ amount of bulbs
$p_{\text{meas},X}, p_{\text{ref},X}$ percentage of total irradiance over wavelength range $X$
$p_{\text{xx}}$ $p$-coefficient determined for the measured light source irradiance profile
$R_{\text{SM,X}}$ spectral match over wavelength range $X$
$R_{\text{SM}}$ spectral match
$S_{\text{NE}}$ spatial nonuniformity of irradiance

$T_{IE}$ temporal instability of irradiance
$W_n$ study case when water filter is mixed with n ml of dye
$W_{\text{raw}}$ study case when no filter is used
$M_{n,\text{d}}$ optimization algorithm data matrix

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

ORCID

Rodrigo Barraza https://orcid.org/0000-0002-6737-9145
Patricio Valdivia Lefort https://orcid.org/0000-0002-7457-1346

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