Spectrum Measurement of Variable Irradiance Controlled LED-Based Solar Simulator

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Abstract- Efficiency of photovoltaic devices are based on testing all equipment and systems used to produce devices in a healthy way, from electrical and optical points of view. Considering that photovoltaic devices which enable the generation of electric energy from solar energy as a renewable energy source are widely used solar simulators should be utilized to provide actual daylight spectrum distributions. The most considerable component of solar simulators in photovoltaic device research is the light sources they use. Due to their advantages over conventional light sources, such as compactness, low power consumption, and low cost, research and studies on solar simulators use LEDs took place as their illumination source. In this study, it is aimed to produce a low-cost Class A solar simulator with using six different type power LEDs, as specified in the IEC 60904-9 and ASTM E927-05 standards. At the end of the study with 24 power LEDs with six different wavelengths, the spectral match which is one of the three performance criteria of the solar simulator was obtained as Class A. This study shows that LED-based solar simulators provide great savings in terms of energy consumption as well as a huge advantage in cost, compared to the widely used xenon arc lamp solar simulators.

Keywords Solar energy; light emitting diodes; photovoltaic effects; simulation; spectroradiometers.

1. Introduction

The use of solar energy as a renewable energy source and of related photovoltaic systems is increasing day by day. Thus, to ensure the reliability of solar cells, testing their performance becomes the most important issue [1]. With rapidly developing technologies and studies, the transformation of photovoltaic solar cells into increasingly complex structures leads to difficulties in obtaining the current voltage (I-V) characteristics of solar panels. Therefore, the use of solar simulators, which have evolved in recent years, is inevitable to calibrate and test photovoltaic devices [2, 3]. The efficiency of photovoltaic devices depends on the electrical and optical testing of all equipment and systems used to produce cells [4]. Thus, considering the world's energy consumption, solar simulators that obtain the actual daylight irradiance are a necessity [5]. Photovoltaic panels convert solar energy to electric energy without frequent maintenance and have robust and uncomplicated designs that perform direct conversion. The most important characteristic parameters of photovoltaic devices, such as maximum power (P_{MAX}), the current voltage (I-V) curve, open circuit voltage (V_{OC}) and short circuit current (I_{SC}) are built under real atmospheric circumstances [6-9]. Solar simulators ensure optical and spectral ranges with a similar intensity to sunlight, and they are capable of testing basic-purpose solar cells and photovoltaic devices in a controlled manner, under standard conditions: 1.5 G air mass (AM 1.5 G) spectrum, 1000 W/m² solar irradiance, and 25 °C cell temperature [10-17]. The standards for energy applications of

photovoltaic devices are set out in a series of studies on two research lines supported by the Energy Research and Development Administration and the National Aeronautics and Space Administration. Standards for terrestrial photovoltaic measurement procedures were established after studies in the 1970s and include detailed descriptions of solar simulators [18-20]. These an air mass of 1.5 spectral parts when selecting a standard density of 1000 W/m², and the American Society for Testing and Materials (ASTM) standards use both values for commercial solar simulators [21]. The AM1.5 G spectral component is commonly used in concentrated solar system investigations (see Figure.1).

Solar simulators can simulate actual sunlight as terrestrial and out-of-atmosphere radiation [22]. The international standards for the solar simulation of photovoltaic tests (ASTM 927-05 [23], JIS C 8912 [24] and IEC 60904-9 [25]) are based on three criteria: temporal instability, spatial non-uniformity, and spectral match of the solar simulator [26, 27]. The amount of sunlight falling on the Earth's surface depends on geographical impact and seasonal parameters [22]. For photovoltaic panel testing, the air mass is standardized as AM 0, AM 1D, AM 1G, AM 1.5 D, AM 1.5 G, AM 2D, or AM 2G [28,29]. According to Al-Ahmad et al., "Solar simulation can be broadly classified into the irradiance above the atmosphere, i.e., with zero air mass (AM), AM 0, and air mass 1.5, corresponding to an optical path through the atmosphere of 1.5 times the vertical path of AM 1. AM 1.5 is further separated into AM 1.5 D for direct illumination of solar concentrators and AM 1.5 G, an integrated irradiance of 100 mW/cm² for global illumination inclusive of sky emission and scatter" [30]. Table 1 shows the international standard references for tests performed with solar simulators.

The aim of this study is to produce a low-cost Class A solar simulator with power LEDs of 6 different wavelengths and the IEC 60904-9 and ASTM E927-05 standards. For this purpose, wavelengths were measured in a mirror-covered box with 24 power LEDs, by means of a spectroradiometer that could also measure ultraviolet (UV) and infrared (IR) wavelengths. At the end of the study, spectral match one of the requirements for solar simulators specified in the IEC 60904-9 and ASTM E927-05 standard with 24 power LEDs and 6 different wavelengths was obtained at Class A. However, the 1000 W/m² requirement was not achieved. Future studies with revised features and combinations of LEDs should obtain this value.
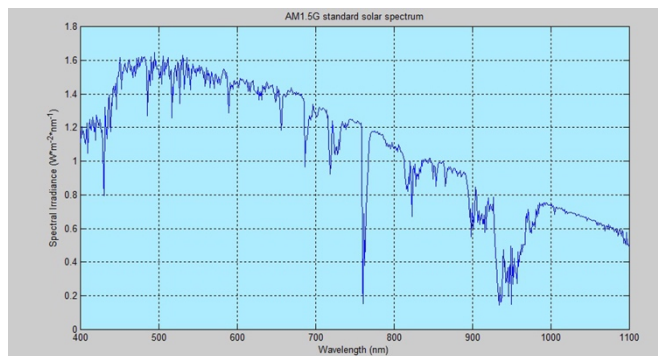

Fig. 1. AM1.5G standard solar spectrum

2. Solar Simulator for Photovoltaic Devices

2.1. Solar Simulator Classifications

A solar radiation level of 1000 W/m² was chosen as a unit (1 sun = 1000 W/m²). ASTM E927 and IEC 60904-9 classify the simulated performance of solar simulators as Class A, Class B, or Class C [35, 36]. These classifications specify three main criteria: spectral match, spatial non-uniformity, and temporal instability [37]. Table 2 lists these criteria [38].

To measure spectral match, the wavelength region is restricted to between 400 nm and 1100 nm and is divided into six bands [1], [23]. Each of these bands includes a specific percentage of the total radiation, as listed in ASTM E927-05. Table 3 shows the required light source radiation ratios for solar simulators, as specified in the standards.

As a performance criterion for solar simulators, spectral match is extremely necessary to ensure that the real world situation and test conditions are identical [39]. Spectral match is the ratio of the required irradiation percentage to the real percentage of light falling along the respective wavelength interval (Eq. 1) [40].

$$SM = \frac{\text{Actual Irradiance in the interval}}{\text{Required Irradiance in the interval}} \quad (1)$$

The "actual irradiance in the interval" required to find the spectral match is found by Equation 2:

$$\text{Actual Irradiance in the Interval} = \frac{\int_{\lambda_n}^{\lambda_{n+1}} S(\lambda)d\lambda}{\int_{400}^{1100} S(\lambda)d\lambda} \quad (2)$$

$S(\lambda)$ in Eq. 2 is the light source's spectral irradiation. Spectral irradiation is the distribution of light as a function of wavelength. λ_n is the starting point of the corresponding wavelength range, and λ_{n+1} is the ending point. The spectral matching is directly related to the light source used in the solar simulator. If the source's spectral composition source matches the spectral glow of the AM 1.5G reference spectral glow, then the spectrum will be an exact match. The ability to simulate the expected spectral coherence will be of great help in designing a solar simulator.

Mohan et al. explain spatial non-uniformity (S_{NU}) as "a difficult property that minimizes hot spots due to condensation of light in certain points, especially in simulators with large surface areas, affecting photovoltaic cell performance tests. S_{NU} is calculated in which E_{max} is the maximum intensity on the given test section and E_{min} is the minimum intensity" [40] (Eq. 3).

$$S_{NU} = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \times \% \, 100 \quad (3)$$

Table 1. International standards for solar simulator tests

Organization	Standard Number	Standard Name
IEC	60904-9	Solar Simulator Performance Requirements [25]
ASTM	G173-03	Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface [31].
ASTM	E927-05	Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing [23].
ASTM	E927-10	Standard Specification for Solar Simulation for Photovoltaic Testing [32].
ASTM	E948-16	Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight [33].
ASTM	E973-16	Standard Test Method for Determination of the Spectral Mismatch Parameter between a Photovoltaic Device and a Photovoltaic Reference Cell [34].
JIS	C 8912	Solar Simulators for Crystalline Solar Cells and Modules [24]

The third criterion used in classifying simulators is temporal instability. Bazzi et al. explained this concept as follows; "the temporal instability of irradiance is calculated in a manner similar to SNU but with E measured at a particular point on the test plane during the time interval of data acquisition" [41].

Table 2. Classifications of solar simulator performance

PERFORMANCE PARAMETERS	ASTM	IEC
Spectral match		
Class A	0.75 - 1.25	0.75 - 1.25
Class B	0.6 - 1.4	0.6 - 1.4
Class C	0.4 - 2.0	0.4 - 2.0
Spatial non-uniformity		
Class A	$\leq 3\%$	$\leq 2\%$
Class B	$\leq 5\%$	$\leq 5\%$
Class C	$\leq 10\%$	$\leq 10\%$
Temporal instability		
Class A	$\leq 2\%$	$\leq 2\%$
Class B	$\leq 5\%$	$\leq 5\%$
Class C	$\leq 10\%$	$\leq 10\%$

Table 3. Distribution of irradiance performance requirements

WAVELENGTH (nm)	PERCENTAGE OF TOTAL IRRADIANCE AM1.5G
400 – 500	18.4%
500 – 600	19.9%
600 – 700	18.4%
700 – 800	14.9%
800 – 900	12.5%
900 – 1100	15.9%

2.2. Light Sources Used in Solar Simulators

The most important part of a solar simulator's design is the light source. The lighting pattern, light flux stability, and light interval's spectral characteristics should be handled with precision when selecting the light source [42]. Different light sources are used to simulate sunlight according to ASTM standards [36]. Figure 2 shows the wavelengths of the light sources [22], [43–45].

Short and long arc xenon lamps are the most commonly used light sources in solar simulators. Some conventional solar simulator designs use metal halide arc lamps, carbon arc lamps, and quartz tungsten halogen lamps as light sources [29]. Nowadays, light-emitting diodes (LEDs) are used as light sources in solar simulator design due to their advantages over traditional light sources, such as their low cost, compactness, and lower power consumption [28, 46,47].
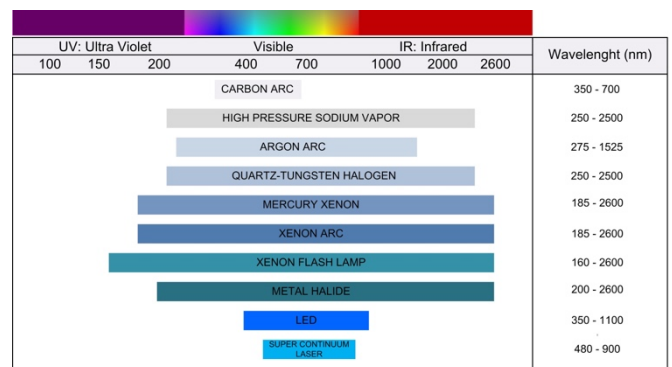

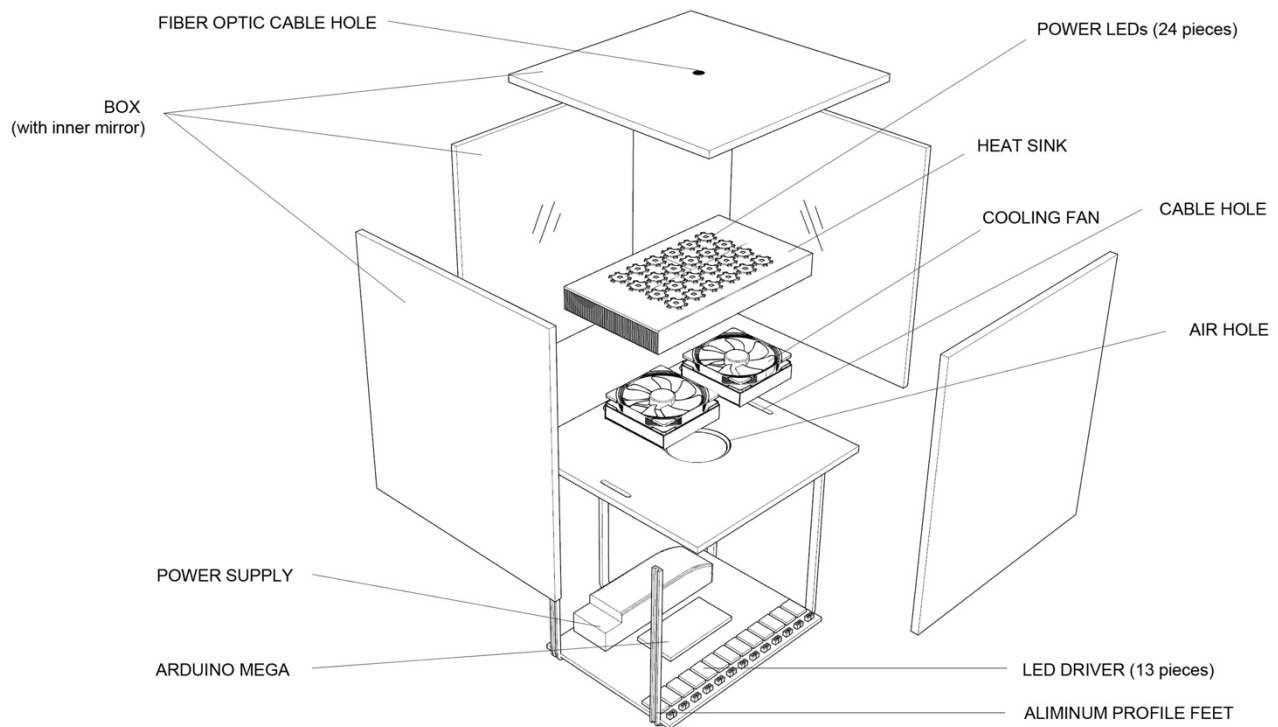**Fig. 2.** The wavelength range of light sources

Fig. 3. Solar simulator main components

3. Experimental Setup

3.1. Solar simulator main components

The main components of the solar simulator designed for this study are:

- ➢ A laser-cut wooden box covered with an inner mirror,
- ➢ An aluminum heat sink,
- ➢ Two cooling fans,
- ➢ A 75 W power supply,
- ➢ 13 LED drivers,
- ➢ An Arduino Mega 2560,
- ➢ Four 5500 K (Kelvin) cool white LEDs,
- ➢ Four 4000 K (Kelvin) warm white LEDs,
- ➢ Four 470 nm blue LEDs,
- ➢ Four 740 nm red LEDs,
- ➢ Four 850 nm infrared LEDs,
- ➢ Four 940 nm infrared LEDs and
- ➢ Aluminum profile feet.

A solar simulator was designed and manufactured using these materials. Figure 3 details all components of the solar simulator.

3.2. Experiment

A total of 24 LEDs in six different wavelengths were initially mounted with high sensitivity on single-star PCBs. The LEDs were then placed symmetrically on the aluminum heat sink. The heat transfer for the assembly process was high, and insulating tape was used (Figure 4). Two cooler fans were added under the aluminum heat sink and placed inside the main box. The LEDs, heat sink, and cooler fans were placed together, and the inner side of the box was covered with a mirror to allow for healthier wavelength measurement.

Appropriate LED drivers were chosen by considering the power and currents of the LEDs used. The LED drivers were regulated by an Arduino Mega 2560 microprocessor and software, so that the desired spectral values could be reached. The microprocessor, LED drivers, and power supply together formed a single power and control circuit in the lower part of the main box (Figure 5).
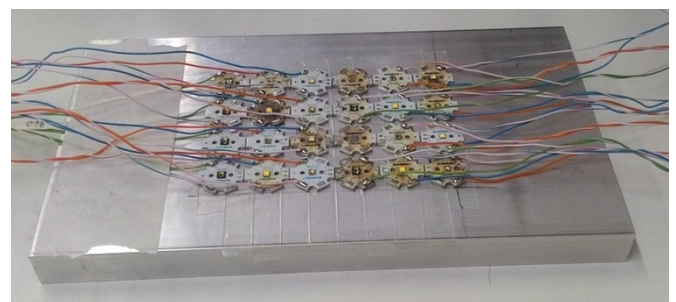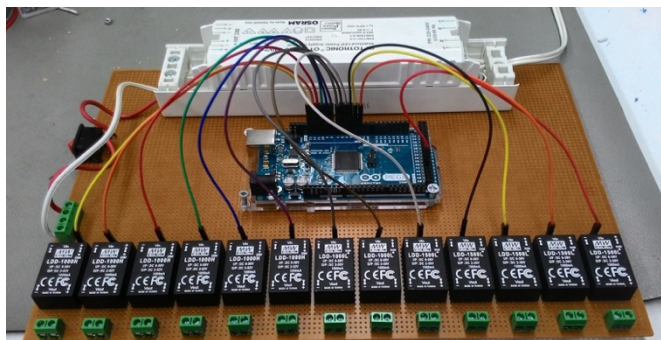

Fig. 4. LEDs placed on the aluminum heat sink

Fig. 5. LED driver board

3.3. *Spectral Match*

After the system components were assembled, the spectral match was tested. The IEC 60904-9 and ASTM E927-05 standards mandate the test described in the previous sections. For this reason, measurements were made with a Spectral Evolution SR-500 spectroradiometer. The fiber optic cable connected to the spectroradiometer was fixed to the other core, so that the LEDs outside the ceiling center of the main box containing the LEDs can be viewed at a 90° right angle. The test setup consisted of the solar simulator, a SR-500 Spectroradiometer, a fiber optic cable, and a laptop computer running DARWin SP software (Figure 6).

4. Result and Discussion

Using the measurements, the LEDs were driven with the drive circuit and the graphs and values in Figure 7 were obtained. According to the measurements, each LED has its own characteristic wavelength. Warm and cool white LEDs and blue LEDs obtained wavelengths between 400-700 nm. The 700-1100 nm chart was obtained with red, 850 and 940 nm IR LEDs. The comparison of the spectral match AM 1.5 G measured and calculated by the spectroradiometer is given in Table 4. Thus, the values obtained for all wavelength ranges expressed Class A, according to Table 1. The spectral matching value in the wavelength range of 600-700 nm was found to be at the boundary despite the Class A. In future work, it will be possible to obtain a more normal range by making appropriate changes to the number of warm white and red LEDs and their combinations. In Figure. 8, the orange lines show the range of Class A, and the dots show the range of the measured solar simulator values. Since the LEDs used in the study could only achieve an average light intensity of 350W/m^2, the other two performance criteria spatial non- uniformity and temporal instability were not calculated.

Table 4. Spectral match comparison for LED-Based Solar Simulator design (Using AM 1.5 global tilt)

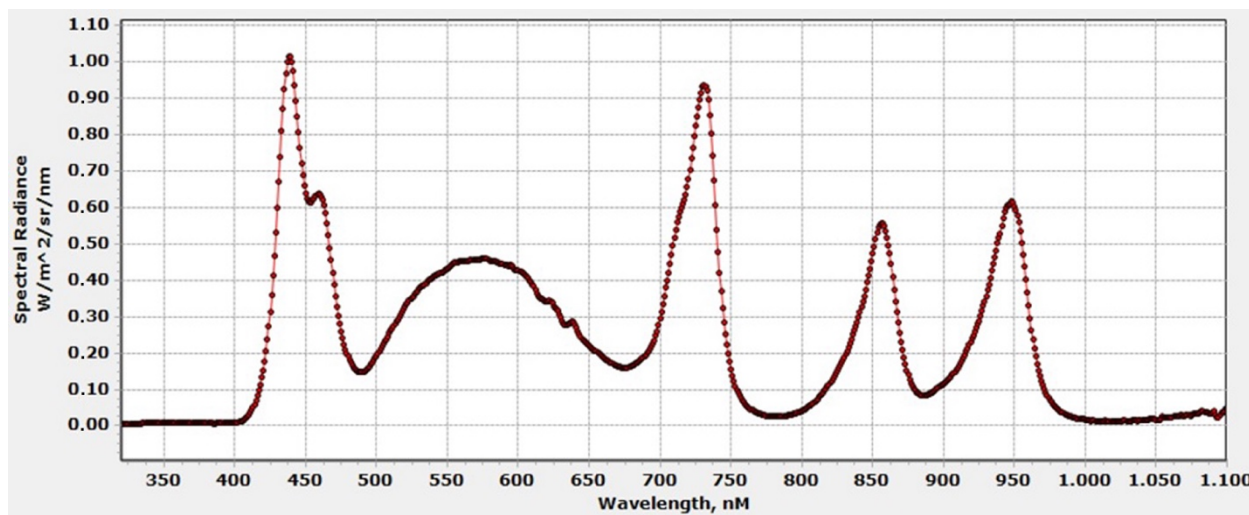| Wavelength Range	Class	AM1.5 Global Tilt	Irradiance	Spectral Match
400 – 500	A	18.4%	21.1%	1.14
500 – 600	A	19.9%	21.3%	1.07
600 – 700	A	18.4%	14.0%	0.76
700 – 800	A	14.9%	17.2%	1.15
800 – 900	A	12.5%	11.8%	0.94
900 – 1100	A	15.9%	14.7%	0.92

Fig. 6. Spectral match test setup

Fig. 7. Relative spectral irradiation measurements of the solar simulator design
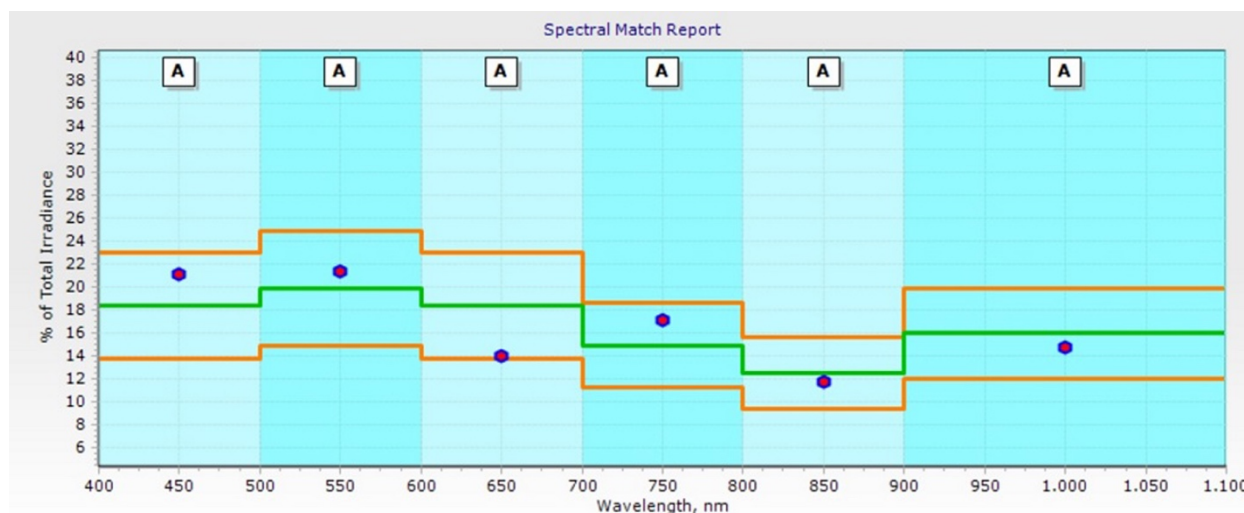

Fig. 8. IEC 60904-9 and ASTM E927-05 spectral match graph for the LED-based solar simulator design (using AM 1.5 global tilt)

5. Conclusions

In this study, a solar simulator was designed using LEDs with six wavelengths (cool white, warm white, 470 nm blue, 740 nm red, and 850 and 940 nm IR). The spectral match values obtained by spectroradiometer were as follows: 1.14 for 400-500 nm, 1.07 for 500-600 nm, 0.76 for 600-700 nm, 1.15 for 700-800 nm, 0.94 for 800-900 nm and 0.92 for 900-1100 nm. Based on these results, the designed LED-based solar simulator provided Class A for the spectral match, which is one of the three performance criteria according to IEC 60904-9 and ASTM E927-05. Thus, solar simulators designed for photovoltaic panel testing can achieve Class A spectral matching using LEDs of six wavelengths.

This study revealed the following:

➢ LED-based solar simulators provide great savings in terms of energy consumption as well as a huge advantage in cost, compared to the widely used xenon arc lamp solar simulators.

➢ LEDs reduce the cost of solar simulator production.

➢ Spectral match which is indicated in the IEC and ASTM standards, can be obtained at the Class A level in the solar simulators using LEDs.

➢ In future studies, 1000 W / m² irradiation intensity specified in IEC and ASTM can be achieved in solar simulators by changing led varieties and combinations.

➢ Spatial non-uniformity and temporal instability, which are indicated in the IEC and ASTM standards, can be obtained at the Class A level in the solar simulators using LEDs.

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