Light Sources and Irradiance Spectrum of LED Solar Simulator for Photovoltaic Devices: A Review

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Abstract- There is a growing demand for more applications for photovoltaic systems, which are a significant electricity source from renewable energy. Its performance test using a solar simulator is required. Light sources of solar simulator including halogen lamps and xenon lamps have been adapted to LED as a result of lamp technology. The goal of this article is to review LED solar simulator (LSS) light sources and spectrum for photovoltaic devices. Review articles from ScienceDirect and IEEE Explore from 2003 to 2022 were chosen as the basis for this analysis. The examination of spatial non-uniformity (S_{NE}), temporal instability, and spectral match (SM) under international standards was the result of the LSS's thorough investigation of the LED light sources design. The review discovered that LED-halogen solar simulators (LHSS) and LSS are the two main categories of solar simulator based on LED. The advantage of LHSS is that just one type of light source is required for the spectrum distribution on the infrared range. The drawback is that SM cannot be in class A. While LSS can reach class AAA and deliver good spectral coverage results in accordance with the new standard, IEC60904-9:2020, employing 10-23 LEDs of various wavelengths. The current state of LSS development is to design and build a modular LED array. S_{NE} is still an important indicator of LSS that is reflected in the source design that is stable, economical, and sustainable. The new IEC 60904-9:2020 A+ category is discussed. The future direction of LSS for PV applications is suggested.

Keywords- LED solar simulator, spatial non-uniformity, temporal instability, spectral match, irradiance spectrum.

1. Introduction

A solar simulator is a device that produces light with properties that have a light intensity and spectrum similar to natural sunlight [1]. It is an essential tool for research and industrial applications [2]. For testing any material, equipment or process is affected with a sunlight change, such as photovoltaic (PV) devices, solar collector, solar fuels, photo-electro chemistry, and photobiology [3-5].

An irradiance spectrum of the solar simulator for PV devices depends on the type of the light source. Generally, the xenon (Xe) lamp [6-8], metal halide (MH) lamp [9, 10], and quartz tungsten halogen (QTH) lamp [11-13] have been used, called "lamp-based system" [14]. Nowadays, solid state lighting is being used instead of a lamp-based system, namely, light emitting diodes (LED) [15-17]. The disadvantages of lamp-based system are that they produce light with poor temporal stability, shorter lifespan, and higher operating cost [18-20]. Whereas an LED-based system has advantages such as better stability, the adjustable light intensity in microsecond. Currently, LED based system can emit a multi-narrow spectrum to be a full spectrum of irradiance over 300 nm to 1850 nm [14, 21]. The properties of the Xe, MH, QTH, and LED for the solar simulator are shown in Fig. 1.

A good power supply of the lamp provides the best light stability [3]. LED thermal regulation system is necessary for maintaining irradiance, light intensity, and shift of spectrum. Therefore, LED thermal management for an LED solar simulators (LSS) should be considered appropriately [22]. Comparing the advantages of an LSS to a traditional Xe solar simulator: LSS is cheaper, smaller, and consuming lower power [23]. Using the proper monochromic LED mixed method, spectral irradiance can actually be generated according to the AM1.5G spectra at class A^{+} in the wavelength range between 350–1100 nm. Some of the advantages of LSS are fast intensity control and friendly interface with a variety of digitally controlled platforms, making it easy to research and development [14, 17].

As mentioned above, the LSS is very attractive in terms of stability, technology, control, and economic [24]. Furthermore, simulating AM1.5G spectra from LEDs has been a challenge and many researchers have developed over the past 20 years. Points of interest are; what is the target of the past LSS development? What will be the direction and trend in the future of LSS for PV applications?

This article aims to present the results of a review of the light sources and spectrum of LSS for photovoltaic devices to contribute to the synthesis of new knowledge that is useful in academia. The authors focus on a deeper study of the LED light source design and evaluation performance of LSS; there are spatial non-uniformity (S_{NE}), temporal instability (T_{IE}), and spectral match (SM) under international standards. To analyze the LED sources and the spectrum covers on the standard spectrum (AM1.5G) and presents the results and discuss for the benefit.

Fig. 1. The characteristic comparison of lamp-based system and LED-based system; modified from [14] and [18]

2. International Standard of Solar Simulator For Photovoltaic Devices

The international standards are used to evaluate the competency related to solar simulator for characterization of photovoltaic devices. They are following.

- IEC 60904-9 Solar simulator performance requirements [25]
- ASTM E927-10 Standard specification for solar simulation for photovoltaic testing [26]
- JIS C 8912 Solar simulators for crystalline solar cells and modules [27]

2.1 Performance Classification

A key point in the development of solar simulators for photovoltaic application is the development of a light source that synthesized the irradiance spectrum to be similar natural sunlight. The light source shall devise a spectrum of irradiance regarding the solar spectrum under AM1.5G as specified in IEC 60904-3 [28] and ASTM G173-03 [29]. The spectrum must have a light intensity equal to 1 sun or 1000 W/m^2 [30].

In Table 1, the highest performance indicator of all standards is defined in the same format. It is labeled as "class AAA". The letter AAA means that the solar simulator provides SM at class A, S_{NE} at class A, and T_{IE} at class A. The SM and long term instability (LTI) of all standards are the same numbers. The S_{NE} of JIS C 8904-9 on class B is 3%. It is lower than the other standard. Lastly, there is no short term instability (STI) assessment in ASTM E927-10. In this article, the IEC 60904-9 (2007) standard will be a reference because this standard is referred by the Thai Industrial Standards Institute (TIS), Ministry of Industry of Thailand.

2.2 IEC 60904-9 (2007)

IEC 60904-9 (2007) is a standard issued by the "International Electrotechnical Commission-IEC" [25]. It is to determine the required performance of a solar simulator used for I-V measurement and characterization of solar cells and radiation exposure studies. The important details include;

2.2.1. Wavelength Range

The spectrum range of solar simulator shall be the AM1.5G reference defined by IEC standard 60904-3 [28] and a wavelength range, 400–1100 nm, is divided into six ranges. The irradiance values of ranges, 400-500 nm, 500-600 nm, 600-700 nm, 700-800 nm, 800-900 nm, and 900-1100 nm, are 18.4%, 19.9%, 18.4%, 14.9%, 12.5%, and 15.9% respectively. They are the same percentage in ASTM, JIS, and IEC standards [14].

2.2.2. Spectral Match

The SM is defined by IEC 60904-3 [28], it is defined as a percentage of the total radiation exposure between 400-1100 nm. The SM is calculated as the ratio of the actual percentage of irradiation falling over the measured period and the percentage of reference irradiation [31]. If the calculation result is between 0.75-1.25, then the SM at the wavelength band is in class A (Table 2). To evaluate whether a solar simulator has an SM in class A, the SM evaluation results across all wavelengths must be class A. If not, the SM rating is based on the lowest value, probably B or C.

2.2.3. Spatial Non-Uniformity

The S_{NE} was measured on the test plane by measuring the maximum and minimum radiation exposure and calculating the radiation unevenness as shown in Eq. (1). IEC 60904-9 [25] stipulates that S_{NE} in class A, B, or C must result in S_{NE} calculation less than or equal to 2%, 5%, and 10%, respectively (Table 1). S_{NE} is an important parameter and the most difficult to control and keep in class A [32].

$$S_{NE}\,,T_{IE}(\%) = \left[\frac{\max.irradiance - \min.irradiance}{\max.irradiance + \min.irradiance}\right] \times 100 \qquad (1)$$

Table 1. Standard and performance specifications defined by ASTM E927-10 (2010), IEC 60904-9 (2007), and JIS C 8904-9 (2017) [25-27]

Performance parameters	ASTM E927-10	IEC 60904-9		JIS C 8904-9	
Spectral mismatch					
Class A	0.75 – 1.25	0.75 – 1.25		0.75 – 1.25	
Class B	0.60 – 1.40	0.60 – 1.40		0.60 – 1.40	
Class C	0.40 – 2.00	0.40 – 2.00		0.40 – 2.00	
Spatial non - uniformity					
Class A	≤ 2 %	≤ 2 %		≤ 2 %	
Class B	≤ 5 %	≤ 5 %		≤ 3 %	
Class C	≤ 10 %	≤ 10 %		≤ 10 %	
Temporal instability	LTI	LTI	STI	LTI	STI
Class A	≤ 2 %	≤ 2 %	≤ 0.5 %	≤ 2 %	≤ 0.5 %
Class B	≤ 5 %	≤ 5 %	≤ 2 %	≤ 5 %	≤ 2 %
Class C	≤ 10 %	≤ 10 %	≤ 10 %	≤ 10 %	≤ 10 %

LTI: long term instability, STI: short term instability, Class A/B/C denotes the solar simulator's level of performance.

Table 2. Classification of solar simulator on IEC 60904-9 (2020)

Class	Wavelength range	SM to all spectral band	S_{NE}	T_{IE}	
				STI	LTI
A+	300–1200 nm	0.875–1.125	1 %	0.25 %	1 %
A	400–1100 nm	0.75 – 1.25	2 %	0.5 %	2 %
B	400–1100 nm	0.6 – 1.4	5 %	2 %	5 %
C	400–1100 nm	0.4 – 2.0	10%	10%	10%

Table 3. Percentage of irradiance of IEC 60904-9 (2007) and IEC 60904-9 (2020)

Number	IEC 60904-9(2007) [26]		IEC 60904-9(2020) [31]	
	Wavelength (nm)	Percentage of irradiance	Wavelength (nm)	Percentage of irradiance
1	400 – 500	18.40%	300 - 470	16.61%
2	500 – 600	19.90%	470 - 561	16.74%
3	600 – 700	18.40%	561 - 657	16.67%
4	700 – 800	14.90%	657 - 772	16.63%
5	800 – 900	12.50%	772 - 919	16.66%
6	900 – 1100	15.90%	919 - 1200	16.69%

2.2.4. Temporal Instability

The T_{IE} according to IEC 60904-9 [25] requires two stages of temporal instability assessment.

a) Short term instability (STI) is the radiation stability measured during the sampling period of the data set for measuring the current-voltage (I-V) curves [33, 34] of solar cells. The flashing solar simulator gives a short period of flashing time. The stability of radiation exposure is calculated by Eq. (1).

b) Long term instability (LTI) is the measurement of the maximum and minimum values of radiation exposure over a period of used. The LTI is used for evaluating steady-state solar simulators which provide continuous lighting and then calculated by Eq. (1).

2.3 IEC 60904-9 (2020)

IEC 60904-9 (2020) [35] to keep up with the changes in LED technology and new material used in solar cells. Currently, there are many new types of solar cells such as tandem, multi-junction, and other compound materials such as Perovskite-Si solar cells [36-38]. These respond to a wider wavelength range of 400-1100 nm [28]. IEC 60904-9 (2020) contents improve as follows: 1) it presents class A+, 2) it extends the wavelength to be 300–1200 nm for class A+, and 3) it assesses spectral coverage and spectral deviation of AM1.5G.

2.3.1 Wavelength Range of Class A+

The most significant change in the new IEC 60904-9 (2020) standard is the introduction of a new A+ class, which takes advantage of the highest quality classification achieved by solar simulators. There are three criteria as same as version 2007. The wavelength range of IEC 60904-9 (2020) is covered 300nm to 1200nm. The details are shown in Table 2.

2.3.2. New Percentage of Irradiance of Class A+

Table 3 compares and demonstrates the irradiance percentages of these two standards. In 2020 version, the percentages of irradiance for all ranges are approximately the same, 16.61% to 16.74% that are different from the old version, 12.5% to 19.90%. The A+ designation is a major change in IEC 60904-9(2020), which has strict requirements. The remaining changes provide optional reporting metrics that will affect the quality improvement of solar simulator in the future.

2.3.3 AM1.5G Spectral Coverage

Spectral coverage (SPC) is the percentage of the spectrum between 300 nm and 1200 nm. The output of the solar simulator covers the bandwidth of the spectrum. IEC 60904-9: 2020 assumes bandwidth is "covered" by the solar simulator if the proposed spectrum is greater than 10% of the AM1.5G spectra at the same wavelength [35]. The method for calculating the percentage of SPC is to sum the region where the solar simulator emits the solar irradiance above 10% of the AM1 . 5 G reference spectrum and divides it by the total radiation value from 300 nm to 1200 nm. The SPC equation is explained in [35].

2.3.4. AM1.5G Spectral Deviation

Spectral deviation (SPD) refers to the percentage of the total deviation between the emitted spectrum of the solar simulator and the AM1.5G reference spectrum. The IEC 60904-9:2020 introduces the SPD as an additional method to simulate qualifies for the solar spectrum [35]. The spectral deviation of the solar simulator is assessed. SPD does not affect the classification at this time but it is reported under IEC 60904-9:2020. The SPD is calculated by summing up the absolute differences in irradiance of all wavelengths, multiplying by the optical bandwidth, and dividing by the total integral of the spectra, as explained in [35].

3. LSS Development Path Way

LEDs were first used for the solar simulator in 2003 reported by Kohraku and Kurokawa [39]. Next, they [40] presented the 4 LEDs colors to emit the significant spectra with AM1.5G and for the I-V characteristic of Si solar cells. Bliss *et al.* [41] developed a LHSS to emit the spectrum equivalent to AM1.5G. However, this LHSS to achieve LTI in class A should have a warm-up time of at least 15 min. Tsuno *et al.* [42] reported a new approach to LSS and compared them with a conventional solar simulator. They found that LSS performed better and the price is more cost-effective for longer use. Jang *et al.* [43] developed a method of thermal optimization of LSS to use LSS in I-V characterization analysis effectively.

Krebs *et al.* [44] proposed an LSS with self-calibrating intensity using a photodiode detector with maximum irradiance of 3000 W/m^2. They also developed LSS by extending the ultraviolet (UV) and infrared (IR) wavelengths, achieving an SPD mimic to AM1.5G spectra [45]. The following year, they developed an industrial-grade LSS of class AAA [46]. Plyta *et al.* [47] designed an LSS using the placement method, an LED array within class AAA, and an $S_{NE} < 0.3\%$ at 1.3 sun. They found that positioning the LED as hexagonal would result in the lowest S_{NE} value and would be a good choice for further designing the LSS.

Namin *et al.* [48, 49] designed the solar simulator for I-V characterization using blue, green, red, and white LEDs combined with halogen light. The solar simulator in [49] achieved class BBA. Bazzi *et al.* [50] used 6-colors LEDs that individually controlled the constant current dc-dc converter to achieve an LED spectral match to AM1.5G making the uniformity according to IEC standards. Grandi *et al.* [51] reported the low-cost LHSS, using 6-visible light combined with a QTH lamp. The SM achieved the B class of the 100 cm^2 test plane.

Linden *et al.* [24] first presented an LSS modular system with adjustable light intensity with a computer interface capable of expanding the light source size. The LED module of 10 cm × 10 cm achieved class AAA according to ASTM and IEC standards. They applied 23 different types of LED. Stuckelberger *et al.* [52] presented LSS for the steady-state I-V measurements. They found the highest characteristic better than class AAA of 18 cm × 18 cm test area. Vicente *et al.* [53] presented 5 LED types under low irradiance of 200 W/m^2, but they did not show the performance.

A compact-size LSS by Novickovas *et al.* [54] used 19 high-power LEDs in a hexagonal layout and 5 cm^2 circular light areas with class AAA. Mohan *et al.* [55] presented a simulation of 5 visible light LEDs by MATLAB, achieving SM at class B in 400–700 nm range. They later added a QTH lamp with LEDs to expand the SPD covering 400–1100 nm [56]. The SPD was in class A of SM. Saadaoui *et al.* [57] presented an LHSS similar to [51] with a narrower wavelength range for testing dye-sensitized cells.

Dafalla and Osman [58] developed a simple LSS for a university laboratory to test solar cells with Pasco Capstone. Caballero *et al.* [59] designed a low-cost LSS using 3 LED types: white, blue, and red over 400 nm to 700 nm. They used LabVIEW and a microcontroller to control irradiance at a maximum of 1200 W/m^2. Barar *et al.* [60] used the white LEDs with corrected color temperature (CCT) of 3000K to 6000K mixed with UV-LEDs to create a spectrum for the dye-sensitized solar cell test. Lopez-Fraguas *et al.* [61] developed a low-cost LSS for research. It achieved the AAA class, by used 14 monochromic LEDs. The irradiance was controlled by the LabVIEW interface on the area of 1 cm^2 diameter over 400 nm to 1100 nm. Watjanatepin [30] designed a 6 spectra LSS with a 900 cm^2 illuminated area that met class BBA. He applied chip-on-board (COB) LED combined with a high-power infrared LED; it could emit an irradiance of 1000 W/m^2.

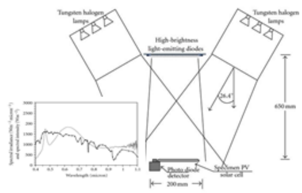
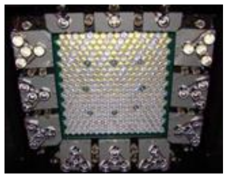
Al–Ahmad *et al*. [62] presented a modular base class AAA of LSS with a 20 cm^2 test plane. They used 6 LEDs spectra to emit irradiance of 100 mW/cm^2. The highlight of their LSS could be extended for various test planes by assembling multiple LED modules. They also developed 10 different LED colors and 266 units on a modular PCB [63]. The SM achieved class A under IEC standard and low-cost. Esen *et al*. [64] presented the LSS with a similar idea to [30] and [50] to achieve the SM of class A of IEC and ASTM standards. Subsequently, they also developed a large-scale LSS using 6 LED colors based on the original concept [65]. This solar simulator had the same size LED panel and a test area of 52 cm × 52 cm. It achieved class AAA under IEC 60904-9 and ASTM E927-10. Hofbauer *et al*. [66] presented the linear quadratic Gaussian (LQG) controller to control the light intensity of each LED spectra of LSS. Tavakoli *et al*. [67] used 19 different wavelengths of LED from 250 nm to 1000 nm and independently controlled each type of LED with a driver via a microcontroller. It was met class AAA of IEC and ASTM Standards.

Vosylius *et al*. [68] presented the LSS using 6 different LEDs over 400-1100 nm. The light source was designed with a double reflector. Their LSS met class AAA of IEC 60904-9. Sun *et al*. [69] proposed an LSS with a high-power LED of 16 different spectra and a hyper-hemispherical aplanatic lens with a multi-source integrated collimating system. Thanks to this technique, their LSS offered good spectral accuracy of AM1.5G and achieved class AAA at 100 mW/m^2 of irradiance. In their presentation of a rectangular LSS module, Watjanatepin and Sritanauthaikorn [3] used monochromic spectra from 6 LEDs placed symmetrically. It was simple to enlarge the large area of light sources and met class AAA on the 416 cm^2 test plane. The approaches by Al-Ahmad *et al*. [63] and Linden *et al*. [24] were the same.

4. Results and Analysis

The articles in international journals in ScienceDirect and IEEE explore were selected. The keywords were ‘LED’ and ‘solar simulator’ from 2003 to 2022. The authors made a meeting to consider the relevant articles by title, abstract, research goal, results, and conclusion. Subsequently, only articles that demonstrated the design and construction concept of LSS and tested performance under international standards were selected. There were 24 articles. After analysis, these articles were divided into two groups: 1) 3 articles on LHSS (Table 4) and 2) 21 articles on LSS. In the LSS group, the articles related to SPD compliance with AM1.5G were categorized into two groups: covered SPD and uncovered SPD (over 400 to 1100 nm) of 9 and 12 articles, respectively. The analysis results of the literature review as shown in Table 4 - 6.

Table 4. The LHSS main discovery, suggestion, and improvement.

Year	Reference	Objective	Method	Result	Suggestion and improvement
2012	Namin *et al*. [49]	To build and test simulator for solar cell. To combined the QTH and blue LED simulator.	• QTH lamps (120% rated voltage) with 468 nm blue LEDs. Blue LED array of 227.5 mm × 227.5 mm. QTH total in six lamps. • T-type LED 3 mm amount 1024 LEDs. • Cooling system; heat sink with cooling air.	 • IEC 60904-9 class; SM = B, T_{IE} = A, S_{NE}= B • Test solar cell at non – STC conditions. • Correction to STC using IEC 60891. • Test area 200 mm × 200 mm.	Method of testing solar cell under non – STC using correction method according to IEC 60891. It gives the same I–V curve as test from the AAA class solar simulator.
2012	Bliss *et al*. [70]	To discuss the pros and cons of using LEDs in a solar simulator. Development system is explained.	• LEDs array consist of 376 LEDs in 8 different colors combined with QTH lamps.	 • IEC 60904 – 9 class; SM = B, T_{IE} = A, S_{NE} = A • Test area 4.5 cm × 4.5 cm.	The SM meet to class B in the wavelength of 800 – 900 nm. To replace QTH lamps by using 28 LEDs may be coverage the wavelength of 300 to 1100 nm.

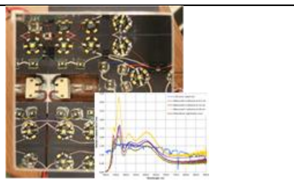
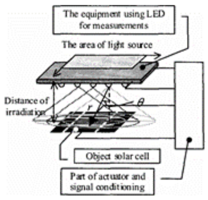
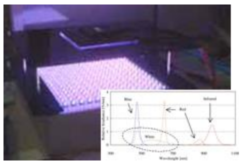
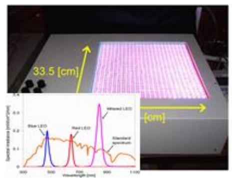
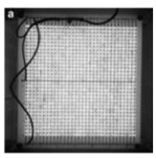
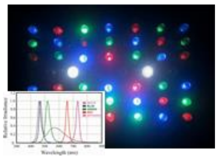
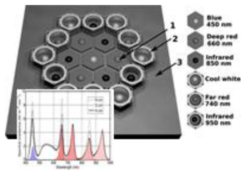
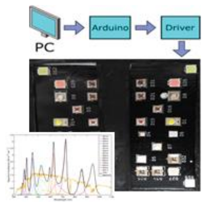
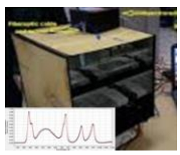
Year	Reference	Objective	Method	Result	Suggestion and improvement
2014	Grandi *et al*. [51]	To point out the simple and cheap rectangular aluminum light guide adopted with the LHSS. To achieve the satisfactory uniformity levels.	• 6 LEDs (blue, green, white, bluish green, and amber) combined with low voltage QTH lamp. • Performance test under IEC 60904 – 9.	 • S_{NE} meet class B by using light guides. • T_{IE} = class A and SM achieved class B. • Test area 10 cm × 10 cm.	The optimization procedure has been applied to design the class A of SM by introduce two of IR LED, there are 440 nm and 850 nm. The proposed spectral lack of SM in the wavelength of 900 to 1100 nm.

Table 5 The LSS with uncoverage spectral comparative of main discovery and improvement.

Year	Reference	Objective	Method	Result	Suggestion and improvement
2003	Kohraku and Kuroka-wa [39]	To examining the capability of evaluation methods the LED solar simulator for solar cell measurement.	• 4 LEDs color in square arrangement. • 6 LEDs color in hexagonal arrangement.	 • Unevenness using 4 and 6 LEDs is around 3% on the test area 100 mm × 100 mm.	"In the illuminant area as widens, the evenness is reduced." [39] The optimum of test area and distance of the light source affect to the unevenness.
2006	Kohraku and Kuroka-wa [40]	To propose the LSS to obtain the I-V curve and spectral response of the solar cell.	• 4 LEDs color (blue red, infrared and white) • Light source of 205 mm × 205 mm. • Measurement I-V curve at 1 sun.	 • I-V and SR characteristics of mono – crystalline cell do not depend on the intensity and wavelength. • Test measurement result less than calculated results.	"It is notable that the low intensity like LED can estimate the I-V characteristic under AM 1.5G." [40]
2008	Tsuno *et al*. [42]	To presented the new method for I-V characteristic by using LED solar simulator.	• 3 LEDs color (blue, red and infrared) Total of 2304 units as a light source. • Light source area of 335 mm × 335 mm. • Test I-V characteristic under non – STC and correction by SR.	 • Test area 100 mm × 100 mm. • I-V curve of solar cell under non – STC with correction by SR is much closed to I-V curve under STC.	"If 6 LEDs types allocation pattern is adopted, SR fitting formula will be very much improving [42]" The peak SPD over the AM 1.5G but average irradiance lower than 1000 W/m^2.
2012	Namin *et al*. [49]	Implement LSS as single-color of red, green, blue and white at 1000 W/m^2 and I-V testing under each LED's	• LED array of 227.5 ×227.5 mm^2, test area 150×150 mm^2. • LED array consist of 1024 LEDs. • I-V characterization under non -STC and correction by	 • Dynamic resistance could determine by blue or red LSS. • Uniformity and instability of	The SPD uncovered to AM1.5G of 400 to 1100 nm.

Year	Reference	Objective	Method	Result	Suggestion and improvement
		color To determine internal dynamic resistance of solar cell.	reference IEC 60891.	irradiance achieved class B. • I-V curve under non- STC and correction method by IEC 60891 is realization.	
2015	Vicente *et al.* [53]	To development of LSS in parameterization of PV module.	• 5 LEDs (blue, red, green, infrared and white) total are 53 units. • To test I-V of solar cell 1W, V_{oc} 6V and I_{sc} 250mA	 • Low irradiance of 200 W/m^2 • SPD range 400 to 800 nm but uncoverage AM1.5G of 400 to 1100nm • I-V curve showed good approximation closed to the standard I-V curve.	To build a new LSS with the large light area. Improvement of the irradiance to 1000 W/m^2.
2015	Novicko-vas *et al.* [54]	Design and construct a compact array LSS.	• 19 high – power LEDs 6 colors (450, 660, 740, 850, 940 nm and white).	 • IEC 60904-9 class AAA • Test plane 5 cm^2 • LED array 96 mm × 104 mm. • SPD uncoverage AM1.5G of 400 to 1100nm	"Significant photo current distribution non-uniformity change is predicted only for amorphous -Si-cell due to a much narrower efficient absorption spectrum" [54]
2019	Fraguas *et al.* [61]	Design and building a low – cost AAA – class of LSS, without any optical devices.	• 14 LEDs color on PCB 5 cm × 5 cm, 34 LEDs in total. • Control by LabVIEW. • MATLAB to design and simulation. • Calibrated by Si-solar cell by Newport (91150 – V) • Reference to IEC 60904-9.	 • S_{NE} class A on 1 cm^2 test area. • LTI and STI meet class A. • SM in class A. • Irradiance of 1.04 sun compact small LSS for small solar cell in research laboratory.	To improve the emission SPD by change the electrics control to achieve a perfect match with the AM 1.5G.
2020	Esen *et al.* [64]	To produce a low-cost class A of LSS with 6 different LEDs under ASTM E937-05 and IEC 60904-9.	• 6 LEDs (470, 740, 850, 940 nm, 4000 K, 5500 K) • LED drivers – current control by Arduino Mega 2560 • SM test under ASTM and IEC 60904-4 • Irradiance not achieved 1000 W/m^2	 • SM class A over 400 to 1100 nm. • SPD uncoverage AM1.5G and show lack of SPD on 600-700nm.	Improve irradiation intensity to 1000 W/m^2 S_{NE} and T_{IE} need to evaluate.

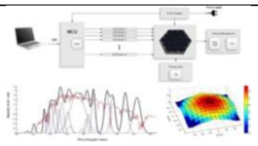
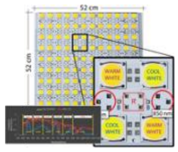
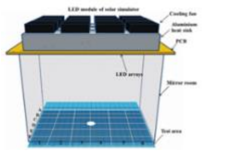
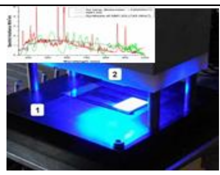
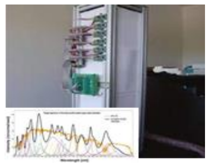
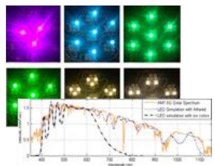
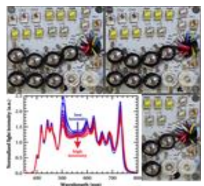
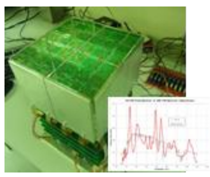
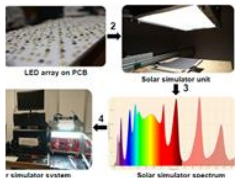
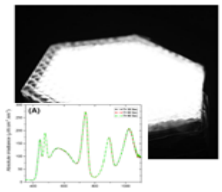
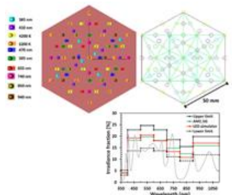
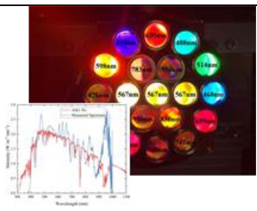
Year	Reference	Objective	Method	Result	Suggestion and improvement
2021	Tavakoli *et al.* [67]	To design of a tunable, versatile LSS the used 19 different wavelength of high - power LEDs, covering 250 to 1000 nm of AM 1.5G.	• 19 LEDs (265, 300, 365, 385, 395, 420, 451, 465, 495, 525, 565, 590, 625, 645, 660, 740, 760, 850, 940 nm) • LED array assembly on hexagonal MCPCB. • ASTM and IEC	 • Class AAA over 2.3 × 2.3 cm at distance 8.7 cm from LED array. • SPD uncoverage AM1.5G and lack of SPD in 700 nm. • SPD range of 250 nm to 1000 nm.	Appropriate for testing spectral responsibility in UV range of solar cell. To improve the LSS spectrum could be extending the LED in IR range.
2022	Esen *et al.* [65]	Design and construct a unique LED's board modular structure of LSS. To evaluate the performance under ASTM 927E – 10 and IEC 60904-9.	• 6 LEDs array (470, 730, 850, 940 nm, 2700 K, 5300 K) • Large LED array of 52 cm × 52 cm. • PWM control individually of LED power, Arduino based control.	 • Class AAA over 52 cm × 52 cm. • SPD range of 400 to 1100 nm of AM 1.5G at 1031 W/m^2. • SPD uncovered in range of 800 – 1100 nm.	"Use LEDs with faster response times instead of COB LEDs to develop LSS that can be flash tested in PV module test." [65] Increase the number of LED's board to powerful modules.
2022	Watjanatepin and Sritanauthaikorn [3]	To approach the construct of rectangular LED's module of a large – scale solar simulator. Demonstrate the performance of LSS under IEC 60904-9.	• 6 LEDs color (450, 525, 625, 730, 850, 940 nm) of 15 COB on PCB 30 cm × 40 cm. • Symmetrical LED positioning method. • IEC 60904-9	 • Class AAA on area 416 cm^2. • SPD uncoverage in 600-800 nm and 900-1100 nm. • SM class A over 400-1100 nm. • Irradiance 1004 W/m^2. • I-V curve of solar cell close match to I-V curve from standard solar simulator.	To create a large area LLS by using multiple rectangular module and study the impact of the irradiance on the overlap light area.
2022	Vosylius *et al.* [68]	To present a new rational design of scalable LSS and double reflector.	• 6 LEDs (warm white, cool white, 660, 740, 850, 940 nm) on LED array size of 16 cm × 16 cm. • Thermal control by forced air cooling. • Ray tracing simulation software was proposed. • Evaluate the performance of LSS under IEC 60904-9 ed2.	 • Class AAA over test plane 14 cm × 16 cm. • SM on AM1.5G of 400-1100 nm. • SPD uncoverage on wavelength 700 – 800 nm and 1000 – 1100 nm. • Double reflectors technique allowed this LSS to reach AAA class.	"The combination of individual reflectors with a common homogenizing mirror system processer further advantages due to lower losses." [68]

Table 6. The LSS with coverage spectral comparative of main discovery and improvement

Year	Reference	Objective	Method	Result	Suggestion and improvement
2010	Krebs *et al.* [44]	Design and construct a compact platform of LSS for testing a polymer solar cell.	• 18 LEDs types (390,410,445,465, 505,520,530,595,635, 660,690,700,740,810, 850,870,910,940 nm.). • Computer control with self-calibrating solar test platform. • IV-curve measurement by IPCE technique.	 • Test plane 19 mm×27 mm • Irradiance 743 W/m^2 approximate to AM1.5G coverage 350-1000 nm. • S_{NE} < 2% on xy-plane of ±12 mm. (variation in I_{SC} < 2%).	This platform is generally applicable to any solar cell characterization that response in 390-950 nm over mm^2 test plane.
2011	Kolberg *et al.* [45]	To develop a spectral tunable LLS covering the full Si-cells spectral range.	• 22 LEDs types over 350 to 1,100 nm. • Linear current regulator for LED driver. • Tunable control by computer software. • Thermal control: Passive air cooled	 • Class AAA of 1 sun coverage spectrum AM1.5G over 350 to 1100 nm. (IEC 60904-9). • Test plane 200mm×200mm.	The cooling technology could support of the full intensity and full-spectrum. To make a new light source for PV research with the unique features.
2012	Bazzi *et al.* [50]	To design LSS spectral, power convertor for LED drive and control.	• 6 LEDs (UV, blue, green, cyan, natural white, warm white). • Current mode control with feedback. • Cooling by natural air convection.	 • SM class A coverage 400-1,100 nm on test area 150mm× 150mm. • ASTM E927 • GUI for flexible control. • S_{NE} Class C over 100mm× 50mm.	LED could reduce the simulator size compare to commercial type. The user-friendly interface match to active control of the spectrum.
2014	Stuckel-berger *et al.* [52]	To design and construct a full LSS for light soaking and V-I measurement of a Si solar cells. Modular design of LED array.	• 11 LEDs (399, 417,457, 470, 500, 441 & 585, 596,624,658,685, 728 nm.) • Computer control by I^{2}C bus with MOSFET drive (LabVIEW based). • Calibrate LED SPD by current control the intensity. • Water cooled Al block.	 • SM class A^{+} coverage SPD of AM1.5G over 400-700 nm. • Test plane of 18cm×18cm. • T_{IE} class A^{++++} • Irradiance 487 W/m^2 over 400-750 nm. • S_{NE} class A under IEC standard.	"The modular design and low-cost component of this solar simulator allow for easy up-scalability" [52]. Water-cooled Al block show very good performance of light stability.
2014	Linden *et al.* [24]	To discuss electrical optical design, software driven GUI and development an adjustable	• 23 LEDs types covered 350 to 1,100 nm. • Modular building block design. • Computer control		The LED array is based on building block 10 cm×10 cm, that easy to assembly the large area solar

Year	Reference	Objective	Method	Result	Suggestion and improvement
		spectrum LSS. To characterize I-V cure of a standard size solar cell.	with GUI software. • Pulse control LSS.	• Class AAA of IEC 60904-9 and ASTM E927-10 • SPD coverage 350 to 1,100 nm of AM1.5G. • Test plane 20cm×20cm • I-V cure of Si solar cell 156mm× 156mm with a 100ms pulse control • Adjustable spectrum of each LED by fully computer control.	simulator.
2018	Al-Ahmad *et al*. [63]	"The optical design, construction and measurement of a novel LED based large area solar simulator Class AAA to replicate the solar spectrum is the aim." [56]	• 10 LEDs to achieve a class A of SM. • Modular of LED array on PCB of 32cm×9cm. • Performance test on IEC, ASTM and JIS standards.	 • Class AAA meet ASTM, IEC, JIS standards over ~ 760 cm^2 of test area. • SPD coverage AM1.5G on 350 to 1100 nm. • Low-cost ~ 200 AUD/10 cm^2.	Appropriate for scale-up of test plane by modular LED array from several cm^2 to m^2.
2019	Al-Ahmad *et al*. [62]	To development of low-cost LSS for test large area printed organic solar cell. To minimizing the number of LED with different wavelength.	• 6 LEDs (warm white, cool white and 478, 735, 887, 1008 nm.) • Simulate spectrum by Trace Pro software. • Hexagonal model of LED array. • Use mirror reflector and diffuser. • Force air cooling system.	 • Class AAA meet ASTM, E927-10 over 1,000 W/m^2 on test plane 20 cm^2. • SPD coverage AM1.5G. over 400 to 1,100 nm by used only 6 LEDs spectra.	This design will allow for large area solar simulator to be cheaply by multiple modules.
2022	Al-Ahmad *et al*. [71]	Present optical design, fabrication and evaluation of a low-cost LSS for PV devices testing.	• 10 LEDs (4,200K, 3,200k, 385,410, 470,505, 655, 740, 850, 940 nm) total 71 LED units. • Hexagonal unit LED cell with 50 mm. dimension. • Optical model within Trace Pro. • Thermal management by force air cooling.	 • Class AAA meet ASTM, IEC and JIS standards over 70 cm^2 of test plane. • SPD coverage AM1.5G. of 350 to 1,100 nm. • Irradiance of 1000 W/m^2 • I-V curve from this LSS not significant different from the standard solar simulator.	The hexagonal modular LED unit can be easily connected to multiple modules to increase the size of the test plane.
2022	Sun *et al*. [69]	To designs LED light source, optical system, light collecting	• 15 LEDs (415, 447,468, 488, 514, 567, 598, 659, 679, 708, 741, 783,826,		The LSS has widely application in PV industries, photobiology,

Year	Reference	Objective	Method	Result	Suggestion and improvement
		and collimating for LSS.	856, 950 nm.) and total of 19 LED's unit. • Thermal management: water cooled with Cu-heat pipe. • Constant voltage constant current control of LEDs. • LabVIEW real time active control. • Hyper-hemispherical aplanatic lens has been proposed.	 • Class AAA of IEC 60904-9. • T_{IE} < 0.3% • Irradiance of 1036W/m^2 SPD coverage AM1.5G over 400 to 1100 nm. • Test plane 50mm×50mm	photochemistry and other applications.

5. Synthesis and Discussion

5.1 LHSS.

According to Table 4, the LHSS in [49, 51] used 4 to 6 types of LEDs such as blue, green, orange, red, and white combined with a QTH lamp. While Bliss *et al.* [70] added more LED types to 8 types from UV to red wavelength, they did not specify how to control the LED. Performance of LHSS met to class BAA. Namin *et al.* [49] used the pulse control LED drive method, and the voltage control for the QTH lamp, to achieve class BBA. Grandi *et al.* [51] used a DC voltage control method for LED control. For the QTH lamp, it was the same method as [47].

The disadvantage of LHSS is that SM cannot be in class A, especially in the 900-1100 nm range. Because the QTH lamp provides a wide range of infrared, SPD may change when the control voltage of the lamp is changed. When the control voltage increases and the heat of the lamp increases, it results in poor stability of SPD and irradiance intensity [70]. The suitable control voltage and good light stability for QTH are from a constant-voltage DC power supply [48]. Another limitation is the physical characteristic of different LEDs and QTH lamps. This restricted the installation or position on the same light panel very difficult [49, 51, 70]. As a result, it is asymmetrical and thus negatively affects S_{NE} on the test plane. The advantage is that the SPD on the infrared range uses only one light source and is easier to control irradiance intensity than LEDs. After 2014, no researcher was interested in the development of the LHSS and multi-light sources solar simulator, but some researchers continued to focus on the development of single light sources, especially LSS.

5.2 LSS with Uncoverage Spectrum

An LSS classified as uncoverage SPD refers to an LSS that emits SPD that does not comply with the AM1.5G spectral coverage described in section 2.3.3. According to Table 5, the LSS almost developed in the early stages is made of 3 [39,40,42] to 6 types [3,48,53,54,64,65,68] LEDs. Sure, if 3-4 types of LED were used, the irradiance spectral in the 400 to 1100nm was not possible to follow the IEC specification because the less number of LED types did not emit the wideband spectrum. Some researchers [3, 54, 64, 68] presented an improvement the SPC in the 400 to 1100nm using 6 LED types comprising 3 of the visible spectra (450 to 470 nm, cool with and/or warm white and 660nm) and 3 of infrared spectra (740nm, 850nm, and 940nm). They designed the spectrum by the centralized spectral method;1 LED’s color for 1 wavelength range. When the SM of those light spectra was evaluated according to international standards [25, 26], they were achieved in class A [3, 54, 64, 65, 68]. The generated SPD had good continuity in visible wavelength coverage, but SPD in the infrared was uncovered, especially in the 700-800 nm and 900-1100nm (Fig. 2). Because they only used 3 types of infrared LEDs, it did not cover that wide wavelength range. This problem can be solved by adding more infrared LEDs (e.g. 4 - 5 types or more, more details were described in section 5.3.) by selecting the appropriate peak spectrum and covering the 700 to 1100 nm range.

Almost LSSs were developed for the I-V characterization of the Si-solar cells [3, 39, 40, 48, 52, 53, 54, 61, 65, 67]. If the irradiance spectral of SM was not in class A or SPD did not cover 400 to 1100 nm or irradiance intensity lower than 1000W/m^2, it could also be used to test solar cells under non-standard test conditions (non-STC) and then use the correction method by SR fitting formula [39,40, 42]. Alternatively, the correction methods specified in the IEC 60891 standard [72] presented by Namin *et al*. [48] that could adjust the I-V curve to the STC, but this made the analysis of the I-V curve more complicated. Thus, the researchers [3, 54, 61, 65, 68] developed their LSS under IEC 60904-9 [25] and ASTM E927-10 [26] at class AAA. Therefore, it could be used to test the I-V curve of solar cells under STC without modifying the curve.

The development of LSS with uncoverage spectral was closely related to the development of LED technology in each era. For example, from 2003 to 2012, thousands number of T-type LEDs were used to make an LED array [39, 40, 48, 57]. Since 2012, LED arrays have been widely used for high-power LEDs for LSS [54, 61, 63, 67]. From 2017 to the present, COB-LEDs were being built as a large modular light Source [3] For LSS. Some Of Them Used The High-Power combination with COB LED [30, 64, 68] for the same goals. The development's goal was to reduce the number of LEDs to tens to help simplify design and installation. Moreover, to increase the size of the new test plane was larger to test the PV module [3, 24, 61, 63].

The technique to control the LED intensity was precise and easy to adjust without access to the hardware of the LED driver. It was controlled by LabVIEW or a microcontroller with the pulse width modulation (PWM) technique [61, 64, 65, 67]. For the LED array of LSS construction schemes, most researchers had presented LED modular systems as rectangular modules [3, 61, 65, 68] and hexagonal modules [67] since 2019. The modular system could expand the modules to increase the size of the light source and test plane to be suitable for testing large PV modules. The largest LED module of LSS was 52cm×52cm presented by Esen *et al.* [65]. As for the thermal management technique for LED arrays, most researchers used an Al heat sink with air cooler [3, 39, 40, 48, 51, 54, 61, 64, 65, 67].

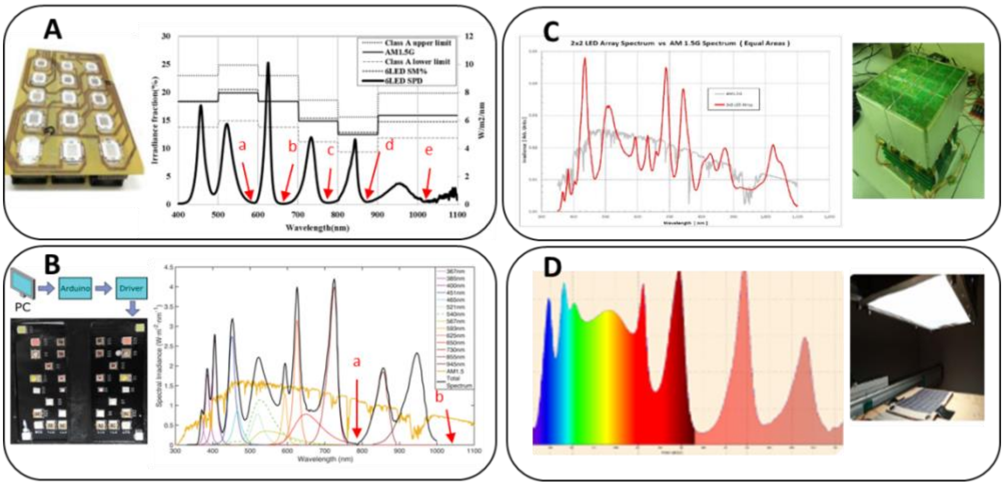


Fig. 2. The example of the LED light sources and spectrum coverage and uncoverage of LED spectrum from the reviewed (a) SPD of 6 LEDs show uncoverage at point a, b, c, d, and e [3], (b) SPD of 14 LEDs show uncoverage at point a, b [61], (c) Coverage spectrum from 23 LEDs [24], and (d) 10 LEDs [63].

5.3 LSS with Coverage Spectrum

According to Table 6, some researchers had developed the LSS to have an SPD-compliant AM1.5G spectral coverage (as described in section 2.3.3) to achieve good quality irradiance spectrum. The researchers [20, 43, 44, 60] presented a method using 10 to 23 different LED types to create an LLS capable of emitting irradiance spectra over 350 to 1100 nm (Fig. 2). Some researchers [40, 48] used 6 to 10 LED types to create irradiance spectral coverage of 400 to 750 nm for dye-sensitized solar cells. These LSSs are all rated for quality at class AAA under IEC [25] ASTM [26] or JIS [27].

An interesting discovery was that a high-power LED, SMD LED, was chosen as the light source of LSS [44, 45, 50, 62, 63, 69, 71] but COB LED was not used. Although, the COB–LED offered the advantage of reducing the number of high-power LEDs. For example, Linden *et al.* [24] used 400 LEDs for the test plane of 100 cm^2. Al-Ahmad *et al.* [63] used 71 high-power LEDs for the test plane of 70 cm^2 and 266 high-power LEDs for the LED module of 32×9 cm^2 [60]. The reason for using only one type of high-power LED may be the physical characteristics of each LED spectrum are the same. Therefore, the design process and simulation make it more convenient. Because a high-power LED mathematic model or information was contained in the software library, it was no need to redevelop it. At the same physical characteristics, the placement of the LEDs on the PCB or the heat sink of the light source module can be installed in the same space harmoniously. The issue also affects the design of the LED cooling system. This setup allows the distance between the LEDs to be symmetrical. It results in good consistency for the S_{NE} and T_{IE} of the LSS and has better stability. However, for thermal management for LED arrays, our review found that most researchers used an Al heat sink with air-cooler [24, 44, 45, 48, 62, 63, 71], making T_{IE} met to class A. Interestingly, a water-cooled aluminum block from [51] made T_{IE} more stable up to class A^{++++}.

Lighting design and spectrum simulation; some researchers used MATLAB and TracePro software [62, 63, 71]. The irradiance of LEDs or tunable control was controlled via a computer [24, 44, 45, 48, 51] with LabVIEW [51]. A graphical user interface program [24, 49] was used for precise control and easy use in a user-friendly interface. Most researchers presented the LED modular system as a rectangular module [24, 45, 51, 63] and some of them proposed the hexagonal module [62, 71]. To expand the module to increase the light source size, it was found that expanding the test plane by increasing the number of rectangular modules was more reasonable than hexagonal modules. Because their characteristics were consistent with the characteristics of PV modules, the largest LED module for LSS with a coverage spectrum measures 18cm×18cm [51].

6. Conclusion

It is generally accepted that the LSS is stable, flexible, and accurate. Its spectrum is more similar to the AM1.5G than the Xe-lamp-based simulator in terms of PV device response quality. Although the LEDs have an extended lifetime, low cost, and low power compared to lamp technology. Since 2003, the LSS for PV devices is constantly evolving which can be divided into two types according to the nature of the light source; LHSS and LSS. The weakness of the past LHSS is that this system cannot meet class AAA, especially SM value. While LSS is built from the high-power LED using 10 to 23 LEDs with different wavelengths have strengths, they can enter class AAA and provide good SPC results in line with the new standard, IEC60904-9 (2020). These LSSs have test plane sizes ranging from several mm^2 to hundred cm^2. The current development of LSS tends to design a modular based LED array for a test plane of PV modules. After 2017, there is a trend of more applications of COB-LED for large area solar simulators. S_{NE} is still an important indicator of LSS that is still reflected in the study of the design of the source which is stable, economical, and sustainable light source.

Future challenges are interesting issues that lead to research problems and have an impact on academic circles such as

- Development of LSS that meets IEC 60904-9 (2020) standard, especially expanding the LED spectrum to cover wavelength of 350 nm to 1200 nm, with performance class A+A+A+.

- Is it possible to use COB-LED as an LED array to reduce the number of high-power LEDs and simplify the control system?

- How to optimally minimize the number of LED types to generate the irradiance spectral with the most SPC and the least SPD?

- Development of a programmable LSS system capable of generating time-varying irradiance spectrum similar to that of natural sunlight.

- Development of irradiance control with computer for accuracy and optical feedback.

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