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TRENDS IN SOLAR SIMULATORS: A REVIEW

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ABSTRACT

Solar simulators are major characterization tools yielding the performance values of solar cells or modules. They are used in photovoltaic industries and academia for researches in photochemistry, biosensors, sunscreen testing and so on. Solar simulators have been facing many challenges in terms of design, construction, and characterization as well as in their being used to characterize other devices. In this article, problems faced by engineers and scientists in developing, and characterizing solar simulators are presented.

Keywords: Spectral mismatch, Irradiance, Characterization, LED

INTRODUCTION

As a result of the decline in fossil fuels and increase in global warming, sources of sustainable energy have started gaining more consideration as substitute energy sources. Clean energy becomes necessary for the outlook of our planet. The sun is the best natural accessible energy that we have. Photovoltaic solar cells convert the sun energy into electricity at continual improved efficiencies. Mainstream technologies exhibit close to 20% efficiencies while record efficiencies have surpassed 40% showing the potential for further advancement of technological and increase in efficiency (Samir et al., 2020). Photovoltaic cells can be characterized either outdoors or indoors. However, outdoor characterization of solar cells is affected by some uncontrollable parameters such as solar energy variation, geographical location, time, day of the year, climate conditions, composition of atmosphere, variation in altitude and weather conditions (Kockott & Schoenlein, 2012), (Esen et al., 2017). The indoor photovoltaic cell characterization is performed with the aid of the so-called solar simulator.

Solar simulator is an artificial device that can provide intensity and spectrum close to or mimic the natural sunlight. It is widely used in the indoor testing and research of solar photovoltaic (PV) cells, plastics, polymers, and other materials which are sensitive to the sunlight (Tavakoli et al., 2020). Solar simulator produces the operating conditions which are imperative for the solar cell to work. Hence a solar simulator is considered as a fundamental instrument for the characterization of the solar cell. These systems are basically big, bulky, and costly but a small solar simulator can be a good contribution to test small device manufactured in research scale (Trentadue et al., 2021).

1.1 Need for Solar Simulator

The impact of determining the health status of solar photovoltaic modules leads to the development of special test equipment. It's usually to achieve reproducible results under outdoor conditions. In order to overcome this challenge, indoor tests are incorporated, providing a controlled environment under laboratory conditions for testing, usually called solar simulator (Cortés- et al., 2021). The purpose of the solar simulator is to provide a controllable indoor test facility under laboratory conditions, used for the testing of solar cells, sun screen, plastics, and other materials and devices (Mankar et al., 2018).

1.2 Standard for Solar Simulators

Solar simulators are characterized by a three-letter code that classifies each of the three criteria. The first code classifies spectral match, the second code classifies spatial non-uniformity, and the third code classifies temporal instability. Class A is the most stringent requirement and therefore indicates better performance than Class B, which is better than Class C. For example, a Class AAA solar simulator meets Class A requirements for all criteria, whereas a Class ABA solar simulator meets Class A requirements for spectral match and temporal instability but Class B requirements for spatial non-uniformity (Newport Corporation, 2011). The three compliance standards that define solar simulator performance are:

i. International Electrotechnical Commission (IEC) Standards.
ii. Japanese Industrial (JIS) Standards.
iii. American System for Testing and Materials (ASTM) Standards.

Each standard's requirements for spectral match, spatial non-uniformity and temporal instability are described below:

Table 1: IEC 60904-9 Compliance Standards

	Spectral Match	**Non-uniformity of irradiance**	**Temporal Instability (Short Term)**	**Temporal Instability (Long Term)**
Class A	0.75-1.25	2%	0.5%	2%
Class B	0.6-1.4	5%	2%	5%
Class C	0.4-2.0	10%	10%	10%

Table 2: JIS C8904-9 Compliance Standards

	Spectral Match	Non-uniformity of irradiance	Temporal Instability (Short Term)	Temporal Instability (Long Term)
Class A	0.75-1.25	±2%	0.5%	2%
Class B	0.6-1.4	±3%	2%	5%
Class C	0.4-2.0	±10%	10%	10%

Table 3: ASTM E 927-10 Compliance Standards

	Spectral Match	Non-uniformity of irradiance	Temporal Instability
Class A	0.75-1.25	2%	2%
Class B	0.6-1.4	5%	5%
Class C	0.4-2.0	10%	10%

In each of the standards, the minimum class required of a solar simulator is C.

This paper reports the trends and the challenges in solar simulators and their designs as well as construction.

2. Trends in Solar Simulators

Research on solar simulators can be traced back to the early 1960s with a series of research programs sponsored by National Aeronautics and Space Administration (NASA) in which a solar simulator was used to re-provide the extraterrestrial solar radiation (Nygren, 2014). There were subsequent series of developments of solar simulators by various researchers and institutions all in an effort to intensify researches in solar simulation and to develop a solar simulator that can give spectral components much closer to the natural sun. Light sources are the most important in the design and construction of a solar simulator. Thus, most of the solar simulators have been developed by simply moving from one light source to another or hybrid of the sources for improved spectrum.

Jang and Shin (2010) fabricated a solar simulator and employed numerical thermal analysis to investigate the increase in the junction temperature of the LEDs, which remains a challenge when they are utilized as the light source in the development of the solar simulators. The authors demonstrated that the junction temperature of the LED module can be significantly decreased by optimization of several design parameters. The schematic of the fabricated LED solar simulator is shown in the fig.1.

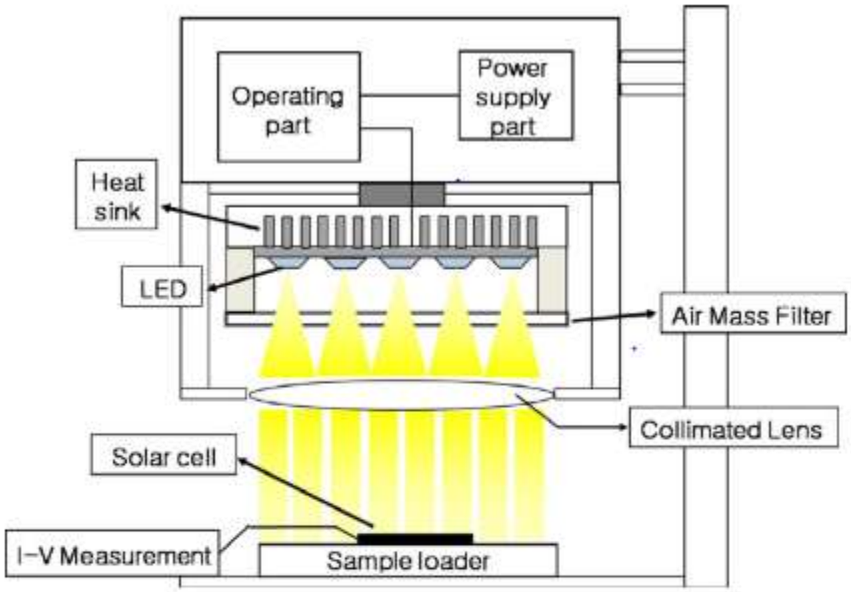

Fig. 1. Schematic LED Solar simulator (Jang & Shin, 2010).

Codd et al.(2010) employed three dimensional approach of the Newton-Raphson method and designed, built and characterized a low cost, high flux, large area solar simulator for the study of optical melting and light absorption behavior of molten salts. The authors were able to show that this approach to multi-source simulator could be easily extended to four or more sources desirable for the next generations of multi-junction solar cells. The approach is an improvement over the past practice where only one source could be adjusted on one sub-cell at a time.

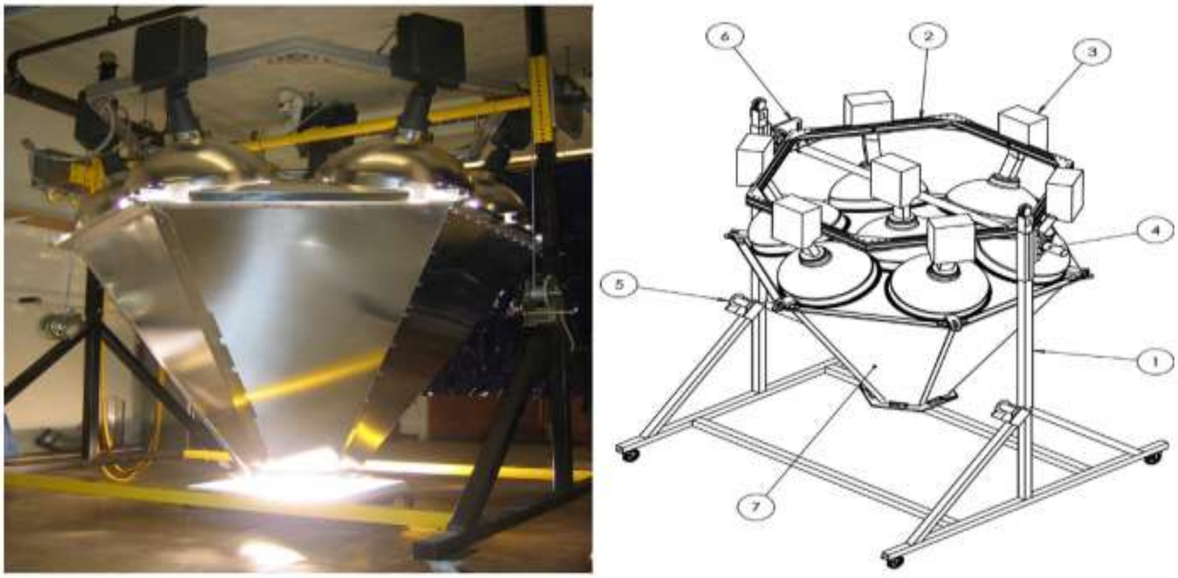

Figure 2: MIT metal-halide CSP solar simulator (Codd et al., 2010)

Due to low intensity limitations of LED-based solar simulators, in (Namin et al., 2012), the authors developed a solar simulator by adopting tungsten, halogen and monochromatic red, green, blue and white LEDs as the light source. High irradiance not previously obtained by tungsten halogen lamps and LEDs has been realized.

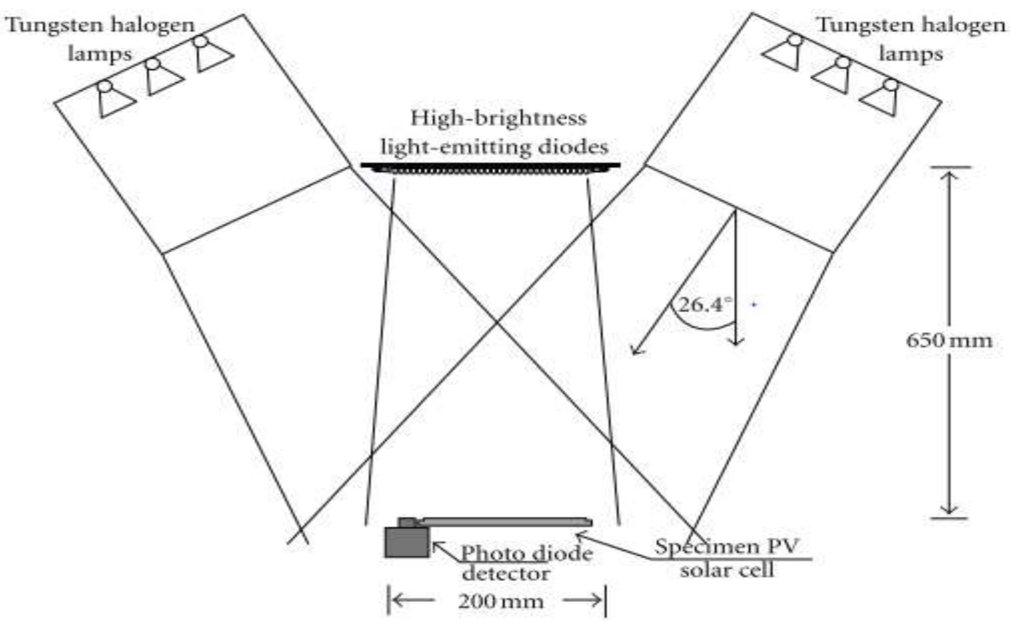

Figure 3: A schematic structure of combined tungsten halogen and blue LED solar simulator (Namin et al., 2012)

In an attempt to overcome the narrower output spectral width challenge in LEDs, Georgescu et al., (2013) employed a numerical approach to determine the LEDs central wavelengths and relative intensities so that their cumulated spectrum can follow the solar one to certain degrees of precision, using both the distribution as defined in the ASTM E927-05 Standard and the measured solar spectrum as a calibration reference.

In another research study, Hamdani et al., (2013) developed a large area solar simulator by intermixing of many LED light rays and power delivery in the form of a synthesized air mass (AM) 1.5 spectrum. However, the developed simulator could not produce expected high intensity.

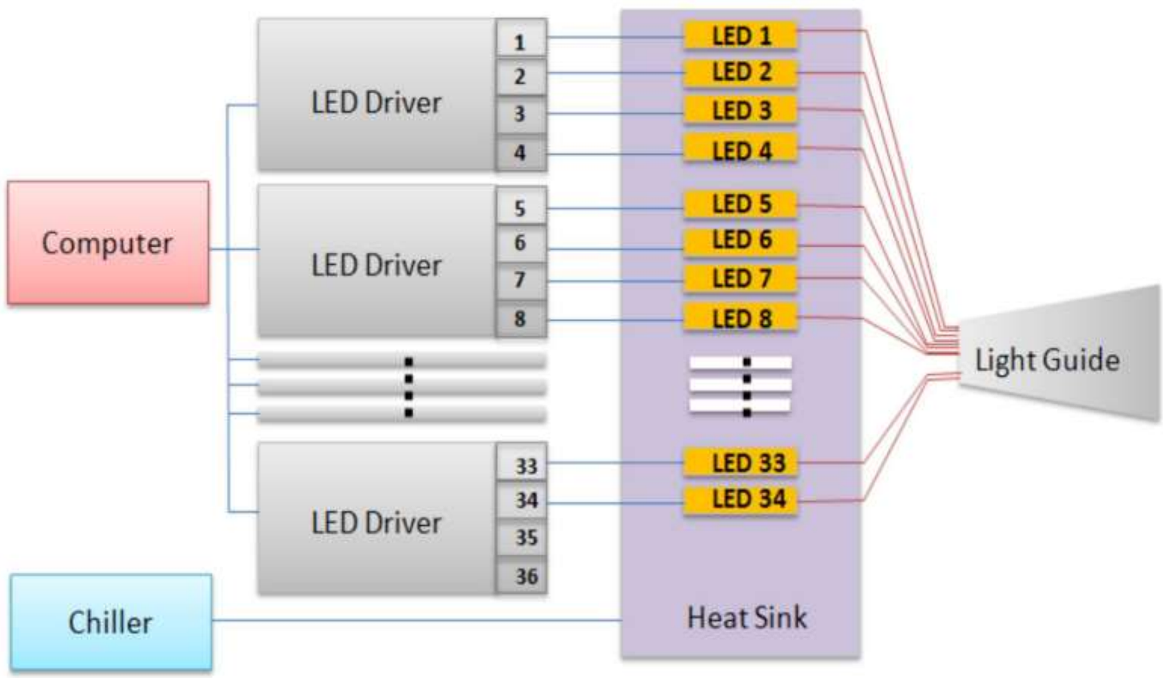

Figure 4: A schematic structure of the solar simulator (Hamadani et al., 2013)

Mekys, (2015) designed a LED-based solar simulator by employing 19 high power LEDs in a compact array. The author demonstrated that these LEDs were sufficient to achieve high light flux density with A class spectral distribution match, A class irradiance non-uniformity, and A class temporal instability for the test area of at least 5 cm diameter.

To overcome the challenge of narrowed range parameters of some solar simulator, Xu et al., (2016) developed a solar simulator by employing seven independent xenon arc lamps each consuming 10Kw. The simulator was able to simulate highly concentrating solar systems. Most of the solar simulators developed in previous researches were small scale solar simulators.

Figure 5: The assembled group of seven xenon arc lamps (Xu et al., 2016)

To bring an end to small scale solar simulator, Ahmad et al., (2018) developed a large area solar simulator employing a modular array of light emitting diodes of six different wavelengths. The simulator reached AAA class.

Some light sources such as Quartz Tungsten Halogen (QTH) lamp suffer bulb overheating which leads to the degradation decrease in the lamp intensity. Salam et al., (2019) developed a solar simulator using QTH lamps as the light source and implemented a controlled mechanism to overcome the overheating in the QTH. The simulator has successfully been realized.

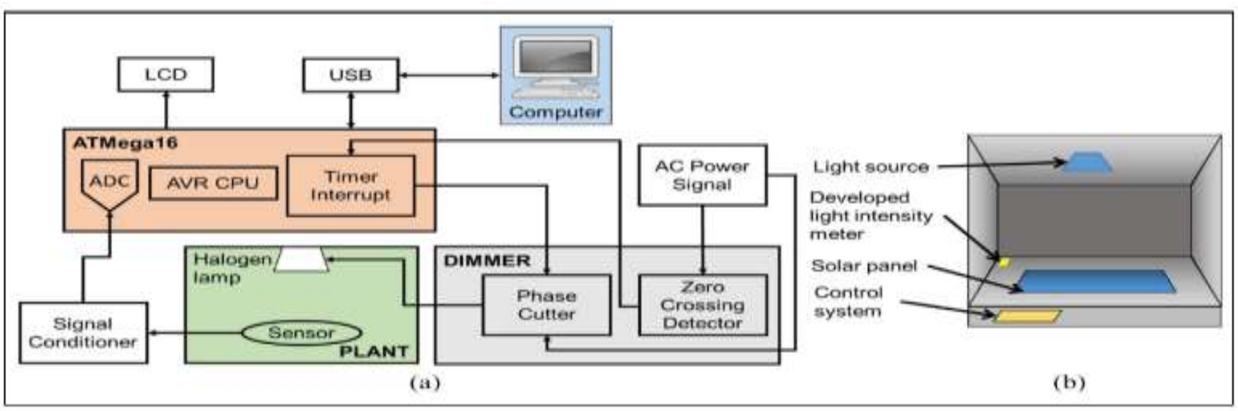

Figure 6: (a) Block diagram of developed solar simulator and (b) its layout in a box (Salam et al., 2019)

Relying solely on LED light alone in the development of solar simulator hardly makes the simulator to achieve standardized intensity (Bodnár et al., 2020). For the improved intensity the authors designed and constructed a solar simulator employing halogen-LED as the light source. The authors were able to achieve good intensity.

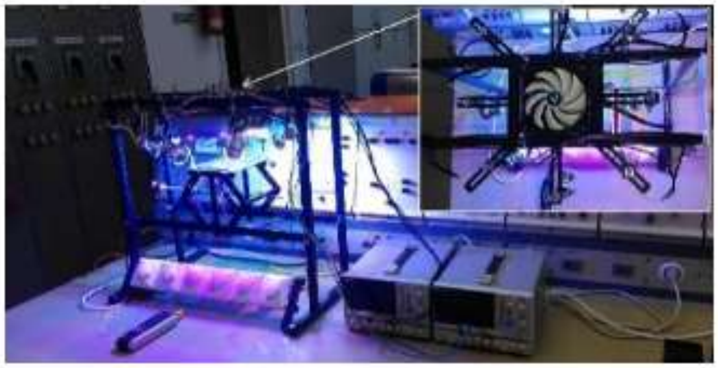

Figure 7: Complete Solar Simulator (Bodnár et al., 2020)

Due to the need for large area solar simulator, Meshram and Yadav (2021) developed a large area uniform illumination for larger cells characterisation by intermixing different LED rays. However, the design fell short of the standard solar AM 1.5 G intensity.

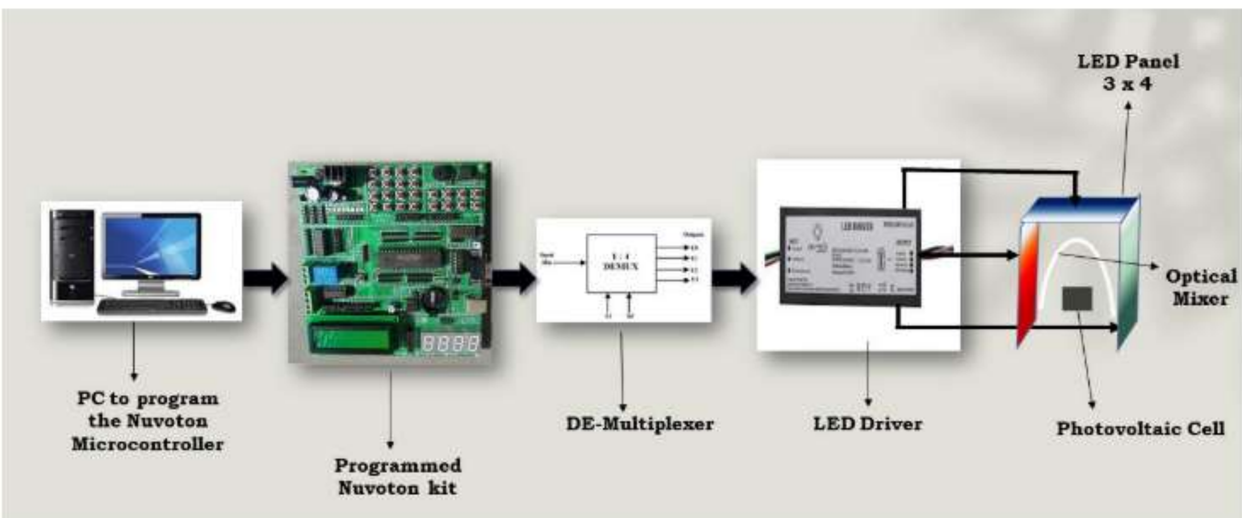

Figure 8: Detailed diagram of the LED based Solar Simulator showing all the functioning blocks (Meshram & Yadav, 2021).

The table 1 below gives the summary of the reviewed articles on solar simulator.

Table 1: Summary of the previous works on solar simulators

S/N	Reference	Problem/Challenge	Materials/Method	Focus	Contribution
1	(Jang & Shin, 2010)	Using LEDs as the sources of light in solar simulators leads to the increase in junction temperature of the LEDs	96 LED packages, Collimated lens, Air mass filter (1.5D), Power driver unit. Numerical thermal analysis of the LED modules was performed for the thermal optimization.	Thermal analysis of the LED modules employed in the solar simulator.	Demonstrated that the junction temperature of the LED module can be significantly decreased by the optimization of several design parameters.
2	(Codd et al., 2010)	It is critical for the correct current be produced on each junction to produce accurate I-V curves for multi-junction solar cells.	The Newton-Raphson method which uses the derivative of a function to extrapolate to a solution.	Adjusting multi-source solar simulators	Showed that this approach to multi-source simulator may be easily extended to four or more sources desirable for the next generations of multi-junction solar cells.
3	(Namin et al., 2012)	Number of research works were published on LED simulators, all showing low intensity limitations of LED-based simulators.	Employed tungsten, halogen and monochromatic red, green, blue and white LEDs	High irradiance	Achieved high irradiance in the developed solar simulator.
4	(Bazzi et al., 2012)	Design of LED platform combined with power electronics and control establishes a missing link in the literature, where these aspects are treated independently.	LED spectra, power converters for LED drive, and control. Visible light of a standard solar spectrum was	Designing a LED-based simulator with control mechanism.	A LED based solar simulator with flexible control and energy conversion was realized.

			simulated using six LED colors.		
5	(Georgescu et al., 2013)	Using LEDs in the construction of a solar simulator poses a number of difficulties mainly because of the narrower output spectral width.	Employed the numerical approach to determine LEDs central wavelengths and relative intensities using Gaussian distributions for accurate approximation of the LED output characteristics.	Obtaining a spectral distribution closely matched to that of the sun, by using LEDs for which their spectra were calculated by means of Gaussian distributions, functions which could permit an excellent correlation with the experimental determinations.	It has been shown that a calibration based completely on the ASTM Standard can cause significant local deviations in case of LED solar simulators.
6	(Hamadani et al., 2013)	Large-area uniform illumination more suitable for larger cells and module measurements still remain a challenge today.	Used high power LEDs as the source of light.	Design of a large area solar simulator for larger solar cell characterization.	Fabricated large area solar simulator.
7	(Mekys, 2015)	The light intensity insufficiency problem in other light sources.	Employed 19 high-power LEDs for a usable illuminated area of at least 5 cm in diameter with at least 1 sun irradiance.	Designing a class AAA simulator.	The compact LED- based AAA class solar simulator, was demonstrated for test areas of up to 5 cm in diameter.

8	(Xu et al., 2016)	Narrowed ranges of parameters (radiative fluxes, temperatures, and spot sizes) of some solar simulators.	Employed seven independent xenon arc lamps as the light source. Each lamp consumes 10kW electricity and has its own reflector.	Provide wide range parameters of the solar simulators.	Designed and constructed a solar simulator that simulates the radiation characteristics of highly concentrating solar systems and serves as an experimental platform for investigating the thermo- chemical processing of solar fuels and for testing advanced high-temperature materials.
9	(Ahmad et al., 2018)	Laboratory characterisation of large area (> 1 m^2) solar modules using simulated solar illumination remains an ongoing issue.	The simulator uses a novel configuration of LED modules positioned in a hexagonal geometry design.	Development of large area solar simulator.	The class AAA LED solar simulator was designed in accordance with the standards of ASTM E-927-10 to measure the I-V characteristics of solar cells.
10	(Salam et al., 2019)	Decrease in light intensity leading to overheating and long-term degradation of the bulb and filter	Employed QTH lamps as the light source, an alternating current phase-cut dimmer, a light intensity meter, and an ATMega328p	Control mechanism to overcome overheating of the source.	A QTH lamp–based solar simulator has been success-fully developed. A control

			microcontroller with a computer and a liquid crystal display.		mechanism was implemented in the solar simulator to overcome the decrease in the QTH lamp light intensity due to the bulb overheating and long-term degradation.
11	(Bodnár et al., 2020)	Inability to achieve light intensity required for standardized examinations by relying solely on LED lights.	Employed a hybrid halogen-LED as the light source with reflector.		Designed and constructed a solar simulator which achieved good uniformity.
12	(Meshram & Yadav, 2021)	Large-area uniform illumination, more suitable for larger cells and module measurements still remain a challenge today.	Used phosphor converted LEDs to cover a good spectral response over the standard irradiance spectra.	Designing a large area uniform illumination.	Successfully developed a simulator on lab scale basis.

3. FINDINGS

Many research works related to solar simulators have been studied and extensively reviewed. From the review it can be seen that there were series of solar simulator developments solving one problem or the other and, in some researches, leading to the emergence of new challenges. In most of the researches, light sources are the most challenging aspects of the simulator as a standardized light need to be produced for photovoltaic cell characterization and other testing requiring the spectrum close to or matches that of the sun. Apart from the standard light intensity challenge, the review also highlights the need for small scale solar simulator developments. There is also for optimal light control in the development of solar simulator.

4. CONCLUSION

The paper presents a literature review on solar simulators. Various problems faced by researches in the design and developments of solar simulators have been presented. From the report it is clear that robust researches need to be carried out especially in the design of small scale solar simulators which is capable of producing a standard light intensity required for photovoltaic cell characterization and other devices testing according to American System for Testing and Materials (ASTM), International Electrotechnical Commission (IEC) or Japanese Industrial Standard (JIS).

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