Renewable and Sustainable Energy Reviews 77 (2017) 1240–1250

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Light sources of solar simulators for photovoltaic devices: A review

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ARTICLE INFO

*Keywords:*
Solar simulator
Photovoltaic devices
Light sources
Spectrum
Wavelength

ABSTRACT

As solar power usage is increasing nowadays, performance tests have become one of the most important topics in order to guarantee the security of photovoltaic tools. For photovoltaic panels to become efficient, there is need for health testing of all materials and technologies used in the production of the panels in electrical and optical aspects. Thus, when future energy standards are considered, it is imperative to use solar simulators that obtain near real sunlight spectrum values. The most important components of solar simulators used in photovoltaic panel tests are light sources. In this study, solar simulators were classified based on the light sources they use, and their history and technological development were investigated in line with the literature. Within the scope of this study, carbon arc lamps, sodium vapor lamps, argon arc lamps, quartz-tungsten halogen lamps, mercury xenon lamps, xenon arc, xenon flash lamps, metal halide lamps, LED and super continuum laser light sources were investigated. Additionally, to compare spectral deficiency among these light sources and solar simulators, multiple light sourced solar simulators were also covered under a separate title.

## 1. Introduction

Photovoltaic devices are non-linear energy sources with durable and simple designs that require little maintenance and convert solar radiation directly into electrical energy. It is very important that the characteristic values of photovoltaic devices such as current-voltage (I-V) curve, short circuit current ($I_{SC}$), open circuit voltage ($V_{OC}$) and maximum power ($P_{MAX}$) are determined under real atmospheric conditions [1–4]. In order to evaluate their performances, photovoltaic devices are rated under the so-called Standard Test Conditions (STC), corresponding to an irradiance of 1000 W/m$^2$, an AM (air mass) 1.5 spectrum and a device temperature of 25 °C [5]. I-V measurement is carried out under natural sunlight in the outdoor environment or in a closed laboratory environment with the help of a solar simulator [6]. The first option; is not preferable due to factors such as the intensity and the spectral distribution of solar radiation, geographical location, time, day of the year, climate conditions, composition of atmosphere, variation in altitude and weather conditions [7]. Instead, the second option is preferred for reasons such as simplicity, reproducibility and reliability [6]. For this reason, solar simulators are an integral part of current-voltage (I-V) characterization. This is because the I-V measurement requires a calibrated source that corresponds to real daylight and conditions that can be changed on demand to illuminate a photovoltaic panel [8,9]. Solar simulators are tools that provide spectral and optical composition similar to sunlight intensity. The fundamental aim of these tools is to test solar cells and photovoltaic panels under controlled laboratory conditions [10–14]. In today's world, as the usage of renewable energy resources has been increasing it is important for both photovoltaic tool producers and consumers that tests are conducted, due to photovoltaic tools having low efficiency [15]. A solar simulator mainly consists of three parts; light and power sources, an optical filter to change beam properties in order to fulfill requirements, and control elements to operate the simulator [1,16]. Carbon arc lamps, sodium vapor lamps, argon arc lamps, quartz- tungsten halogen lamps, mercury xenon lamps, xenon arc, xenon flash lamps, metal halide lamps, LED and super continuum laser light sources are investigated within the scope of the present study [11,17–22]. Xenon arc lamps are the most commonly used light sources among conventional solar simulators [22–24]. Since there are intensity and spectral component differences between natural sunlight and artificial light, xenon arc lamps are modified using filters to obtain the natural sunlight spectrum [25]. Test standards for the terrestrial application of photovoltaic panels have been presented in the research conducted by ERDA and NASA. A report published after the studies conducted in 1975 and 1977, provided a detailed explanation of solar simulators as well as the standard procedures for terrestrial photovoltaic measurement [26–28]. In this report, intensity was selected as 1000 W/m$^2$, AM 1.5 spectral component and 25 °C ambient temperature was chosen as a STC, however, in today's commercial solar simulators both of these are used as the ASTM (American Society for Testing and Materials)

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http://dx.doi.org/10.1016/j.rser.2017.03.062

Available online 29 March 2017

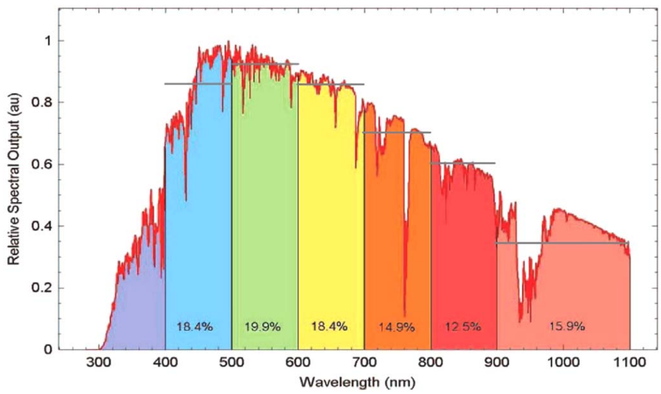


**Fig. 1.** IEC 60904-9 Reference solar spectrum irradiance distribution [14].

standards [29,30]. Solar simulators mainly simulate natural sunlight in two categories; space radiation and terrestrial radiation [31]. The ASTM 927-05 [32], JIS (Japanese Industrial Standard) C 8912 [33] and IEC (International Electrotechnical Commission) 60904-9 standards [34] for the solar simulation of terrestrial photovoltaic tests are accepted to evaluate three criteria; spectral distribution of solar simulator performance, spatial difference and temporal constancy [35,36]. The number of solar beams that fall on the Earth's surface depends on factors such as latitude, longitude, time of day and time of year [31]. The spectral distribution of the Sun on the Earth's surface is shown in Fig. 1 [14,37].

In the application the air mass for the photovoltaic panel test was standardized as AM 0 (the Sun's radiation in Space), AM 1 D (Direct), AM 1G (Global), AM 1.5 D, AM 1.5G, AM 2D and AM 2G [38,39]. According to Riordan and Hulstrom; air mass refers to the relative path length of the direct solar beam through the Atmosphere. When the sun is directly overhead (at zenith), the path length is 1.0 (AM 1.0). AM 1.0 is not synonymous with solar noon because the sun is usually not directly overhead at solar noon in most seasons and locations. When the angle of the Sun from zenith (i.e., the zenith angle, θ) increases, the air mass increases (approximately by secθ) so that at about 48° from the vertical the air mass is 1.5 and at 60° the air mass is 2.0 [8]. These AM values are shown in Figs. 2 and 3.

International standard references for solar simulator illuminations are stated below:

- IEC 60904-9 Solar Simulator Performance Requirements [34]

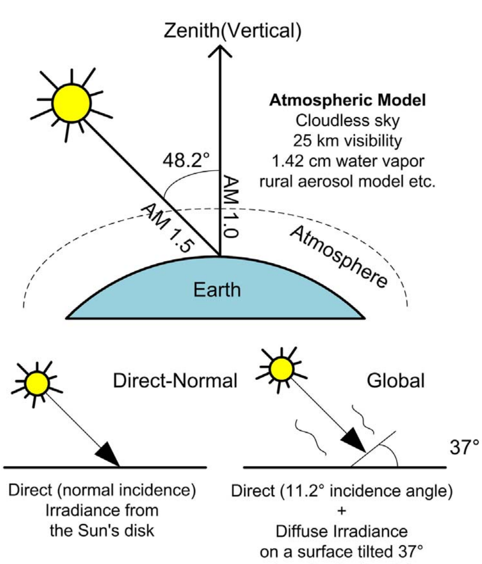


**Fig. 2.** Schematic of AM 1.5 reference spectral conditions [8].

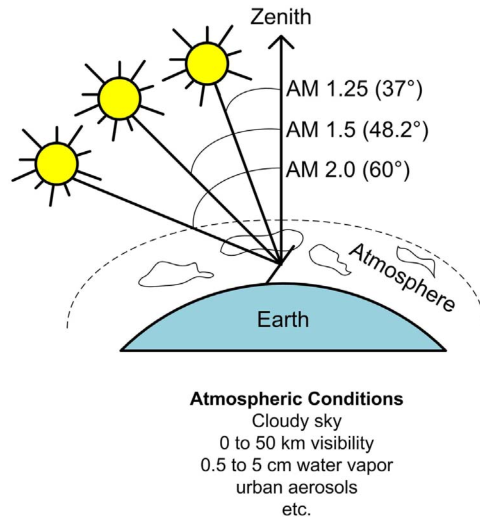


**Fig. 3.** Examples of other realistic atmospheric and air mass conditions compared to AM 1.5 (Fig. 2) [8].

- ASTM G173-03 Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface [40].
- ASTM E927-05 Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing [32].
- ASTM E927-10 Standard specification for Solar Simulation for Photovoltaic Testing [41].
- ASTM E948-16 Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight [42].
- ASTM E973-16 Standard Test Method for Determination of the Spectral Mismatch Parameter between a Photovoltaic Device and a Photovoltaic Reference Cell [43].
- JIS C 8912 Solar simulators for crystalline solar cells and modules [33]

In academic and commercial research, solar simulators are designed to comply with these solar spectrum standards. To achieve these standards in general, light sources are selected and different light sources are used depending on the purpose of use and the type of solar simulator. In this study, designed and implemented solar simulators as well as theoretical and practical applications were investigated. In order to contribute to the literature on solar simulators and provide reference for further studies, solar simulators are presented from a different perspective according to used light sources.

## 2. Solar simulator classes for photovoltaic devices

According to ASTM E927 (Standard Specifications for Solar Simulation for Terrestrial Photovoltaic Testing) and IEC 60904-9, simulation performances of solar simulators are defined under three classes; Class A, Class B and Class C [44,45]. This classification determines three main criteria; spectral match, spatial non-uniformity of irradiance and temporal instability [11,46,47]. These criteria are shown in Table 1 [14]. Under these criteria, the highest class is stated as Class A and the lowest class is stated as Class C [11].

Spectral match is important to provide one to one correspondence of real world situations and test conditions [45]. According to Mohan et al.; spectral match (SM) is calculated as the ratio of the actual percentage of irradiance falling on the interval of concern and the required percentage of irradiance [20]. This calculation is shown in Eq. (1)