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Selection of Light Source Solar Simulator for different Spectral Distributions Research

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Abstract: The PV modules are characterized using solar simulators under Standard Test Condition (STC, AM 1.5). To ensure reproducibility, International Electrotechnical Commission (IEC) are followed. Nevertheless, the PV conversion efficiency depends on the sun's spectral irradiance value and the climatic conditions, the selected PV technology and the incident sunlight wavelength. This paper analyses the Xenon arc and metal halide MSR lamps adequateness as a light source to characterize solar cells of different commercial technologies. Three different solar spectral distribution (Clear, Cloudy and AM 1.5) have been simulated and analysed. The spectral contributions in the near ultraviolet, the visible and the infrared wavelength ranges are studied separately. As results, the solar simulator lamps effectiveness to characterize different commercial PV technologies is assessed. The Xenon arc lamp appears as suitable for mono and polycrystalline first-generation PV technologies. However, the MSR lamp shows a stable performance for all the tested technologies, even reaching a spectral match B class according with the IEC 60904-9 standard.
Keywords: Solar spectra irradiance, Metal halide lamp MSR, Xenon arc lamp, Solar simulator, Spectral match

I. INTRODUCTION

It is well known that energetic production capability (or conversion efficiency, η_G) of PV modules is measured under Standard Test Condition (STC) [1][2]. These controlled conditions are defined by a solar irradiance of 1000 W/m^2, a cell temperature of 25ºC and a 1.5 air mass reference solar spectral irradiance (AM 1.5). The AM 1.5 corresponds to the total distribution of the sunlight (including the direct and diffuse component) to an integrated irradiance of 1000 W/m^2 on a sun-facing plane surface tilted 37º to the horizontal, under the U.S. specific atmospheric conditions [3].

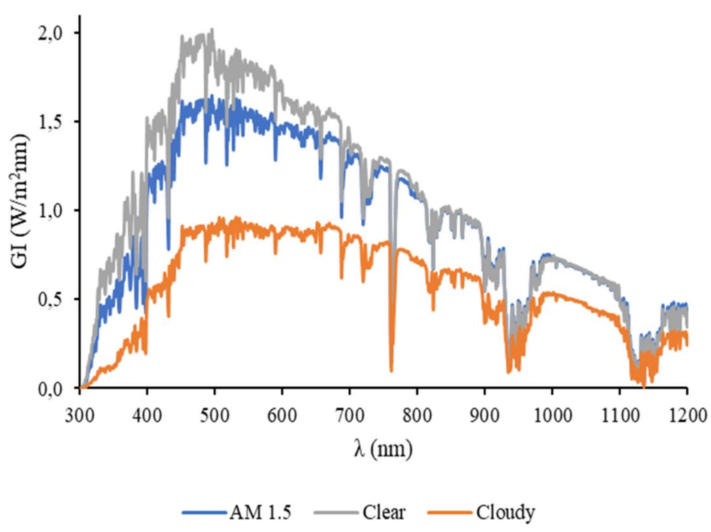

Figure 1. Global spectral irradiance distribution for AM 1.5 reference, clear and cloudy conditions.

However, the shape of the solar global spectral irradiance distribution varies worldwide depending on the atmospheric conditions and the sun position. Thus, a mismatch of the local spectrum with the AM 1.5 may appear, resulting in a variation of the conversion efficiency. This topic has been discussed in several papers under different climatic conditions and results corroborate this hypothesis. As example, Atacama Desert solar spectrum [4] shows, in the ultraviolet range [5], a solar global irradiance, GI, 28.8% higher than the reference AM1.5 spectra. Figure 1 shows the spectral irradiance distribution for the Clear and Cloudy climatic conditions plus the AM 1.5 reference spectrum in the 300-1200 nm wavelength region [6]. The observed differences are especially remarkable in the 300-500 nm wavelength region. The observed behaviour reveal that, in addition to the temperature and solar radiation, the solar spectrum shape must be considered to assess the PV cells efficiency dependence.

On the other hand, from the quantum efficiency, QE, of each PV technology it is possible to observe that the efficiency depends of the wavelength [7][8]. Even if the shape could slightly change depending on the manufacturer, the QE variation with wavelength for the main commercial PV technologies is shown in Figure 2. Using the ISO-21348-2007 wavelength ranges [5] to analyse the Figure 2 plot, a high QE variation can be seen for all the analysed technologies in the near ultraviolet, NUV, interval (300-400 nm). A nearly constant quantum efficiency is measured in the solar visible irradiance range (400-760 nm) for all the PV technologies except for the amorphous silicon (a-Si). In the infrared IR-A interval (760-1200 nm), only the silicon-based mono and polycrystalline technologies show a comparable performance. Moreover, the p-Si looks less spectrum-dependent than the monocrystalline silicon (m-Si) in the 300-450 nm wavelength range (NUV to Purple) and for wavelengths over 800 nm. This lower dependence may lead to the lower efficiency loss of the p-Si. These result has been experimentally demonstrated elsewhere [9][10]. This adequateness of the p-Si, due to its capability to withstand high temperatures, may be also related with the solar cell quantum efficiency [11] and the incident solar spectrum.

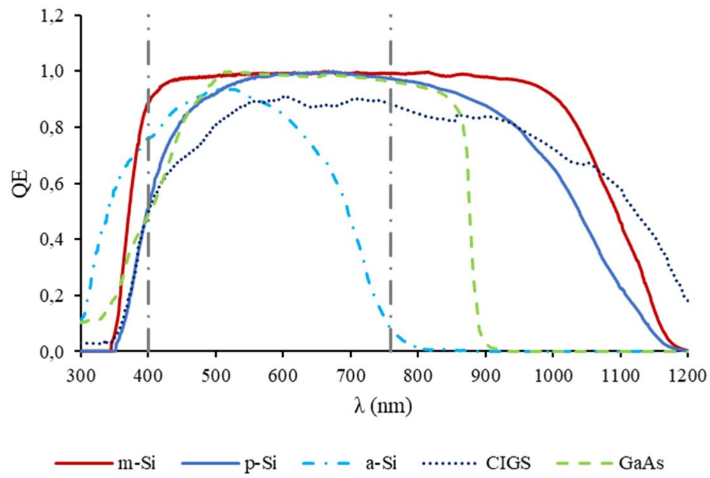

Figure 2. Typical quantum efficiency for commercial PV technologies: Polycrystalline silicon (p-Si), Monocrystalline silicon (m-Si), Amorphous silicon (a-Si), Copper-Indium-Gallium-Selenide (CIGS) and Gallium Arsenide (GaAs).

Although the previous considerations, PV modules manufacturers provide, for simplicity, a single efficiency value under the AM 1.5 spectrum. This single efficiency value of commercial PV modules is measured under STC by laboratory-controlled indoor tests instead of real sun. These STC are generated with the use of Solar Simulator devices (hereafter, SSD). According to the International Electrotechnical Commission (IEC) [12], a solar simulator is characterised and rated as A, B or C on three categories: spectral match, spatial non-uniformity of irradiance on the test plane and temporal instability. This analysis will focus on the SSD spectral match, defined as the deviation between the simulator spectrum and the AM 1.5 reference [1]. For the spectral match estimation, the IEC standard considers six wavelength intervals from 400 nm to 1100 nm to calculate the percentage of total irradiance on each range (Table 1). However, it must be noticed that this 400-1100 nm interval, historically selected as it almost covers the mono and polycrystalline absorption region, does not comprise the full absorption region of the most common commercial PV technologies [13].

This IEC standard limitation in terms of analysed interval can be seen after Figure 1 and Figure 2 plots, where the adequateness of increase the solar simulator interval to the 300-1200 nm range can be visualized. Figure 2 shows that, for all the tested technologies, the absorption band starts in the 300-400 nm interval. In addition, the silicon-based mono and polycrystalline technologies plus the CIGS cells extend this band until the 1100-1200 nm interval. The effect of different solar irradiance spectra, especially remarkable in the NUV and the IR-A regions, can be seen in Figure 1. This climate-spectral dependence can be seen when comparing the AM 1.5 with the Clear spectrum in the NUV range and with the Cloudy spectrum in the IR-A interval. These results demonstrate the interest of increasing the SSD wavelength range to the 300-1200 nm interval as well as including different spectral irradiances in the analysis.

Table 1. Global reference solar spectral irradiance distribution (IEC 60904-3 [1])

Interval	Wavelength range (nm)	Total irradiance in the (400-1100 nm) wavelength range (%)
1	400 – 500	18.4
2	500 – 600	19.9
3	600 – 700	18.4
4	700 – 800	14.9
5	800 – 900	12.5
6	900 – 1100	15.9

The most common solar simulators use two types of high-intensity discharge lamps, xenon arc or metal halide, as a light source [14][15][16][17][18][19]. A recent researches identified lower differences with respect to the AM 1.5 for the metal halide lamp spectrum [20] but, to date, no SSD has been constructed to simulate different climatic conditions, hence no studies of PV technologies efficiency as a function of the spectral distribution have been carried.

On this basis, an SSD to simulate different climatic conditions is under development by the LabSolar (Certification Laboratory of Photovoltaic Solar Energy Systems Devices) located in the Federal University of Bahia, Brazil [21]. This simulator aims to provide a PV module efficiency value for clear sky conditions with high irradiance values in the NUV region (mainly desert and hot climates), and another for cloudy conditions, prevalent in temperate and cold climates with high diffuse radiation.

In this paper the adequateness of characterize a PV module providing a single solar cell efficiency value measured under Standard Test Condition (STC, AM 1.5) is evaluated. For that, the PV efficiency dependence with the solar AM.1.5 spectrum shape will be compared with a typical spectral irradiance distribution for the Clear and Cloudy climatic conditions [6]. Within this context, the suitability of including the solar spectrum characteristics in the solar cells' efficiency calculation will be analysed. Additionally, this work assesses the xenon arc and metal halide MSR lamps as light source of a Solar Simulator. For that, the deviation with respect to the AM 1.5, the Clear and the Cloudy spectral distributions will be studied. In both cases, as they increase the final economic and energetic cost, no additional filters have been considered. In order to ensure the highest possible characterization reliability, results will be separately evaluated for the most common commercial technologies. The obtained results, will allow selecting the most suitable solar simulator, depending in both selected technology and climatic conditions.

II. METHODOLOGY

The following methodology aims to evaluate how the solar spectrum variations modify the solar cells efficiency and, therefore, affect to the PV system's sizing calculation. In view of this, an SSD able to reproduce different solar spectra under laboratory conditions is required to analyse in detail these variations. Two commonly-used SSD lamps will be evaluated and classified to select the optimal in terms of spectral match and photoelectric effect cross-section for each tested PV technology. SSD lamps have not filtered during the full evaluation.

A. Effect of solar spectrum on PV technologies efficiency

To measure the spectrum effect on the tested PV technologies, its contribution on different intervals for the spectral irradiances plotted in Figure 1 is calculated to be compared with the quantum efficiencies from Figure 2. By dividing the solar spectrum in the three previously defined natural wavelength ranges, NUV, Visible and IR-A, the reference percentage of irradiance, RPI, is calculated for the spectral distributions under study (AM 1.5, Clear and Cloudy) using Eq. 1. This RPI value allows quantifying the spectrum relative contribution on each wavelength range.

$$\mathrm{RPI} = 100 \cdot \frac{\sum_{i=a}^{b}(\mathrm{GI_i})}{\sum_{i=300}^{1200}\mathrm{GI_i}}\ (\%) \qquad \text{Eq. 1}$$

where GI_i is the spectral global irradiance for the *i* wavelength value and (*a*, *b*) is the wavelength range.

To assess the solar spectrum dependence with the climatic conditions, the relative difference, $RD_{Climate}$, of the Clear and Cloudy climate spectra with respect to the AM 1.5 reference is calculated using Eq. 2, where $RPI_{Climate}$ stands for the RPI value for the Clear or Cloudy conditions and $RPI_{AM\ 1.5}$ refers to the reference RPI value.

$$RD_{Climate} = 100 \cdot \frac{RPI_{Climate} - RPI_{AM\ 1.5}}{RPI_{AM\ 1.5}}\ (\%) \qquad \text{Eq. 2}$$

The relative efficiency value $\langle\eta\rangle_{Rel}$ of each technology calculated with Eq. 3, convolutes each PV technology quantum efficiency value, QE_i^{PV}, for the *i* wavelength value in the (*a, b*) range with the RPI value (Eq. 1).

$$\langle\eta\rangle_{Rel} = 100 \cdot \frac{\sum_{i=a}^{b}\left(QE_i^{PV} \cdot GI_i\right)}{\sum_{i=300}^{1200} GI_i}\ (\%) \qquad \text{Eq. 3}$$

B. Spectral Match (SM) classification of xenon arc and MSR lamps

Two different lamp types are considered as a light source for the SSD, the Medium Source Rare-Earth (MSR) metal halide lamp [22], and the Q-Flash xenon arc lamp, typically used to illuminate samples during photoconductance lifetime measurement. Figure 3 shows the relative spectral energy distribution for the MSR (reported by manufacturer), and for the xenon arc lamps [23]. The AM 1.5 solar global spectrum reference distribution is used for comparison.

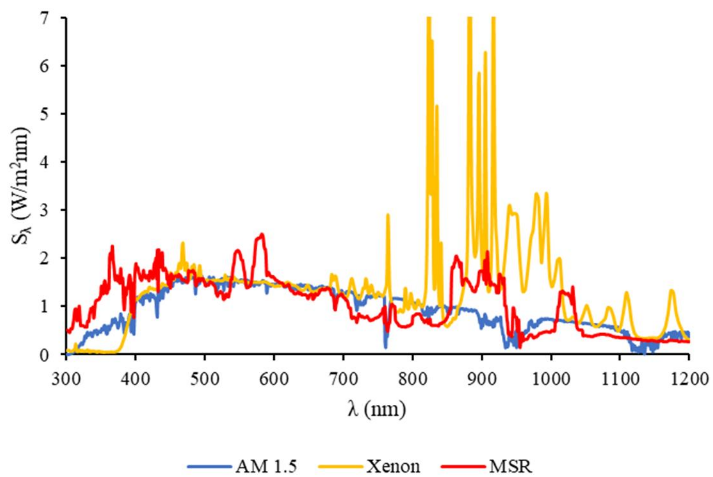

Figure 3. Comparison of xenon arc and metal halide MRS lamps spectral irradiance distribution with AM 1.5 reference.

In the spectrum visible region (400-760 nm), a good compatibility of the xenon arc lamp with the AM 1.5 reference is observed. As carrying the evaluation in the full 300-1200 nm region, the MSR lamp cannot be dismissed. In the NUV interval (300-400 nm), the xenon arc lamp shows lower energy values than the AM 1.5 reference while the MSR shows higher values until the 450 nm. Even so, this MSR lamp energy excess in the NUV range can be filtered to values close to the AM 1.5 reference. Analysing the IR-A region (760-1200 nm), the xenon arc lamp shows energy peaks close to 7 W/m^{2}nm, while the MSR lamp barely surpasses the 2 W/m^{2}nm value, only twice the AM 1.5 reference value.

The spectral match, SM, is defined in Eq. 4 as the ratio between the simulated percentage of irradiance, SPI, and the RPI value (defined in Eq. 1). The SPI value is calculated using Eq. 5, where S_λ is the spectral irradiance of the light source in the (*a, b*) wavelength interval. The perfect match of a lamp with the reference equals the SM value to 1. The spectral match classification as a function of the SM values range is presented in Table 2.

$$SM = \frac{SPI}{RPI} \qquad \text{Eq. 4}$$

$$SPI = 100 \cdot \frac{\sum_{i=a}^{b}\left(S_{\lambda,i}\right)}{\sum_{i=300}^{1200} S_{\lambda,i}}\ (\%) \qquad \text{Eq. 5}$$

Table 2. SSD spectral match classification intervals definition.

Spectral Match to all intervals	Classifications
0.75 – 1.25	A
0.6 – 1.4	B
0.4 – 2.0	C

Using a similar procedure to the Clear and Cloudy spectra relation with the AM 1.5 reference (Eq. 2), the relative efficiency of each lamp with respect to the AM 1.5 spectrum, RD_{Lamp}, can be calculated following Eq. 6. This value allows determining which lamp better simulates each spectrum for the different PV technologies.

$$RD_{Lamp} = 100 \cdot \frac{RPI_{Lamp} - RPI_{Climate}}{RPI_{Climate}} \ (\%) \qquad \text{Eq. 6}$$

III. RESULT AND DISCUSSION

A. Commercial PV technologies efficiency dependence with wavelength

The reference percentage of irradiance (Eq. 1) for the AM 1.5, Clear and Cloudy spectra and the relative difference (Eq. 2) in the NUV, Visible and IR-A intervals are presented in Table 3. Results show that the solar spectrum variations mainly appear in the NUV and IR-A regions. In the NUV region of the Clear sky spectrum, with high direct solar radiation values, an RD of 28.1% with respect to the AM 1.5 reference is measured. This result is compatible with the Atacama Desert measured variations [5]. When considering the Cloudy spectrum, a decrease of up to 45% appears with respect to the reference.

Table 3. Spectra variation on wavelength intervals for different climatic conditions.

Wavelength ranges	AM 1.5	Clear		Cloudy	
	RPI	RPI	$RD_{Clear-AM1.5}$	RPI	$RD_{Cloudy-AM1.5}$
NUV	5.4%	7.0%	28.1%	3.0%	-45.5%
Visible	60.1%	62.2%	3.5%	58.7%	-2.2%
IR-A	34.5%	30.8%	-10.6%	38.3%	11.1%

The relative quantum efficiency contribution on each wavelength interval for the tested PV technologies is presented in Table 4. Results show that spectral variations in the NUV range will remarkably affect to the a-Si technology, as a 16% of its total quantum efficiency appears on this interval. Besides, the amorphous silicon, frequent in building integration, is also totally inadvisable in regions with a high spectral contribution in the IR-A region.

Table 4. Relative contribution of PV technologies efficiency with wavelength intervals.

Wavelength ranges	m-Si	p-Si	a-Si	CIGS	GaAs
NUV	3.7%	1.9%	16.1%	2.2%	5.1%
Visible	50.4%	55.1%	83.2%	48.6%	71.5%
IR-A	45.9%	43.0%	0.6%	49.2%	23.5%

To assess the solar cells efficiency variation of the climate-dependent spectra with respect to the AM 1.5 reference, the relative difference of each PV technology $\langle\eta\rangle_{Rel}$ value (calculated with Eq. 3) in the 300-1200 nm interval is calculated in Table 5. Results show that the difference between the Clear and Cloudy spectra with respect to the AM 1.5 reference are barely noticeable with exception of the amorphous silicon, which presents a 12% variation between the Clear and Cloudy conditions due to its nearly zero production in the IR-A range.

Table 5. Relative difference between technologies efficiency under Clear and Cloudy condition respect AM 1.5.

$RD_{Climate}$	m-Si	p-Si	a-Si	CIGS	GaAs
$RD_{Clear-AM\ 1.5}$ (%)	-0.3	-0.6	6.2	-1.1	1.3
$RD_{Cloudy-AM\ 1.5}$ (%)	1.2	1.6	-6.5	2.1	-0.5

These results allow concluding that, on first approximation, the conversion efficiency value under AM1.5 constitutes an adequate descriptor of the performance of a solar cell unless for the a-Si technology. However, the extreme climate conditions require an additional analysis as high ultraviolet or infrared solar spectra remarkably affect to the PV technology performance. Therefore, it can be stated that only for large-scale installations located in extreme climate locations or for PV systems requiring a high reliability, the optimal characterization of a solar cell should include the efficiency value for the predominant solar spectrum in the PV system location.

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B. Spectral Match Classification Of Xenon Arc And Msr Lamps

The evidence of the spectral distribution effect on the PV technologies efficiency makes crucial to classify the SSD spectra using the standard normative. For this purpose, the simulated percentage of irradiance is calculated for the AM 1.5, Clear and Cloudy spectra in 100 nm intervals using Eq. 5. The SPI results, required to calculate the lamps' Spectral Match (Eq. 4), are presented in Table 6.

Table 6. Percentage of total irradiance of AM 1.5 reference, Clear and Cloudy spectral distributions.

Interval	Wavelength range (nm)	Percentage of total irradiance (SPI) in the wavelength range 300 – 1200 nm		
		AM 1.5	Clear	Cloudy
1	300 – 400	5.4 %	7.0%	3.0%
2	400 – 500	16.7%	18.4%	14.6%
3	500 – 600	18.1%	19.1%	17.6%
4	600 – 700	16.7%	16.5%	17.2%
5	700 – 800	13.5%	12.9%	14.8%
6	800 – 900	11.3%	10.2%	12.3%
7	900 – 1000	6.7%	5.9%	7.5%
8	1000 – 1100	7.7%	6.9%	9.0%
9	1100 – 1200	3.8%	3.1%	4.1%

Compared with the AM 1.5 reference spectrum, the Clear sky spectrum shows a higher SPI share in the 300-600 nm interval while the Cloudy spectra presents higher SPI contributions than the AM 1.5 spectrum for wavelengths over 600 nm. These results allow to conclude that PV technologies with higher sensitivity to wavelength values under 600 nm, such as a-Si, are advantageous in Clear sky conditions. Furthermore, technologies with a wider functioning wavelength interval, like the m-Si, p-Si and CIGS, show a better performance for Cloudy conditions.

Table 7. MSR and xenon arc lamp Spectral Match (according IEC60904-9).

Interval	Range [nm]	AM 1.5				Clear				Cloudy			
		SM_{MSR}		SM_{Xenon}		SM_{MSR}		SM_{Xenon}		SM_{MSR}		SM_{Xenon}	
1	300 – 400	2.207	-	0.304	-	1.723	C	0.237	-	4.051	-	0.558	C
2	400 – 500	1.046	A	0.766	A	0.947	A	0.693	B	1.193	A	0.874	A
3	500 – 600	0.988	A	0.698	B	0.936	A	0.662	B	1.015	A	0.718	B
4	600 – 700	0.827	A	0.699	B	0.835	A	0.706	B	0.803	A	0.679	B
5	700 – 800	0.606	B	0.766	A	0.635	B	0.803	A	0.556	C	0.704	B
6	800 – 900	1.044	A	1.572	B	1.158	A	1.744	C	0.959	A	1.445	C
7	900 – 1000	1.322	B	3.058	-	1.519	C	3.514	-	1.191	B	2.755	-
8	1000 – 1100	0.871	A	0.972	A	0.971	A	1.083	A	0.746	B	0.832	A
9	1100 – 1200	0.852	A	1.316	B	1.053	A	1.626	C	0.794	A	1.227	A
Class (all ranges)		-		-		C		-		-		-	
Class (without interval 1)		B		-		C		-		C		-	

The numerical value of the xenon arc and MSR lamps spectral match for each wavelength range, calculated with Eq. 4, along with their classification according to the IEC 60904-3 standard [1] is presented in Table 7. For the lamps' classification, the worst-case match is used. Considering the 300-1200 nm interval, only one class C classification is obtained in the Clear condition for the MSR lamp. The other cases lead to spectral match values out of range, hence, no classification can be calculated. By removing the 300-400 nm interval for the analysis, the MSR lamp classification can be calculated for the three spectra, achieving a B class for the AM 1.5 and a C class for the Clear and Cloudy conditions. Moreover, no spectral match classification can be calculated for the xenon arc lamp due to its energy excess in the 900-1000 nm interval. This first result shows that the MSR lamp better matches the analysed spectra than the xenon arc lamp.

C. Optimal Solar Simulator For Different Pv Technologies

This section analyses the SSD lamps response with respect to the AM 1.5 reference for the different PV technologies under study. For it, the RD_{Lamp} value is calculated (using Eq. 6) for each $\langle\eta\rangle_{Rel}$ technology value (Eq. 3) in the 300-1200 nm interval. Numerical results are presented in Table 8 and plotted in Figure 4, where the inadequateness of the xenon arc lamp for the GaAs and the a-Si technologies can be seen (Figure 4a). However, it shows relative differences smaller that 2% for m-Si and p-Si technologies. Meanwhile, even if the $RD_{Xenon\text{-}AM\ 1.5}$ values are higher, the MSR lamp presents a better uniformity and reliability in terms of response (always within a 10% deviation range), having a wide applicability range (Figure 4b).

Table 8. Relative difference of PV technologies efficiency for xenon arc and MSR lamps with respect to the AM 1.5 reference.

RD_{Lamp}	m-Si	p-Si	a-Si	CIGS	GaAs
$RD_{Xenon\text{-}AM\ 1.5}$ (%)	1.9	0.2	-30.4	2.3	-21.1
$RD_{MSR\text{-}AM\ 1.5}$ (%)	-4.0	-6.1	1.9	-5.9	-9.9

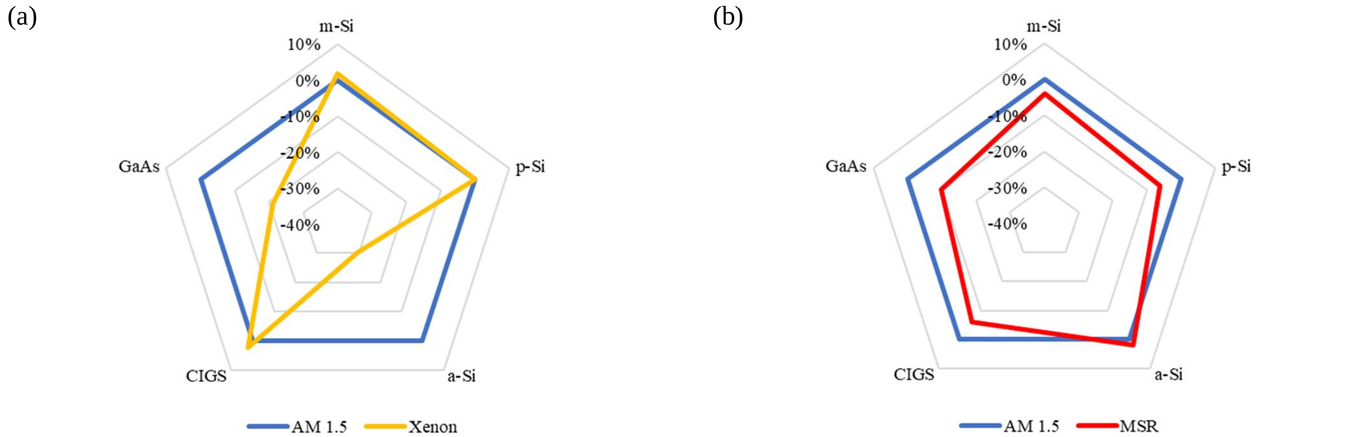

Figure 4. Relative difference of PV technologies efficiency for xenon arc and MSR lamps with respect to the AM 1.5 reference.

In addition, both SSD lamps performance variations has been analysed using Clear and Cloudy spectra. Figure 5 shows the results obtained by a simple convolution between technologies efficiency and the different solar spectra distributions. A practically negligible dependence from the solar spectra is observed. As general result, the xenon arc lamp is a suitable SSD for first generation PV technologies (m-Si and p-Si) with an RD_{Lamp} value under 2.2%. For the CIGS technology, this relative difference increases to 3.5%. The xenon arc lamp is not advised for the GaAs and the amorphous silicon PV technologies as showing relative differences from 20% to 35%. Furthermore, the MSR lamp shows a more uniform relative difference value for all the technologies (between 1.9% and 11.1%). For the Cloudy spectrum (Figure 5c), an average RD_{Lamp} underestimation of -5.8% is measured for all the technologies, but an irradiance increase would meliorate the MSR simulation of this climatic condition.

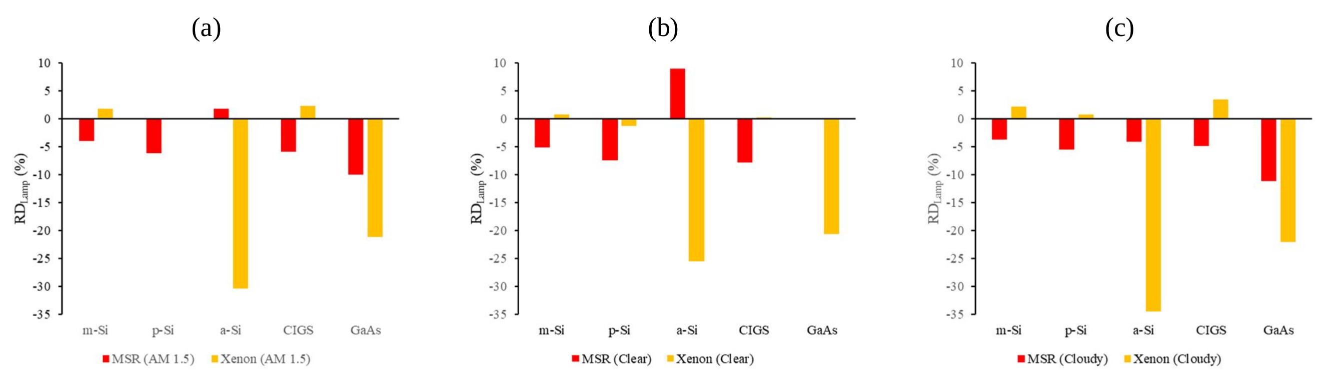

Figure 5. Relative difference between technologies efficiency under Xenon arc and MSR lamps respect (a) AM 1.5 reference, (b) Clear sky and (c) Cloudy.

IV. CONCLUSIONS

The adequateness of two sources of light solar simulator lamps, Xenon arc and metal halide RMS, have been analyses. Their performance is evaluated for three different solar spectra distribution, typical Cloudy and Clear spectra and the AM 1.5 reference spectrum. The most common commercial PV technologies are analysed.

The contribution of the quantum efficiency percentage in relation to its total share for commercial PV technologies in the analysed spectrum regions has been initially evaluated. To this end, the percentage of the Clear and Cloudy climatic conditions spectra with respect to the AM 1.5 reference has been compared. Results show that the AM 1.5 average efficiency value constitutes, on first approximation, a good estimator for the performance PV technologies in terms of efficiency, with a 2% difference with the climate-dependent analysed spectra, unless for the amorphous silicon PV technology(6% variation is observed). Therefore, it can be stated that only for large-scale installations located in extreme climate locations or for PV systems requiring a high reliability, the optimal characterization of a solar cell should include the efficiency value for the predominant solar spectrum in the PV system location.

The adequateness of the xenon arc and the metal halide MSR lamps in standard AM 1.5 solar simulators has been analysed. As they increase the final economic and energetic cost, non-use of additional filters is considered in the analysis. Results show the good performance of the xenon arc lamp to characterise silicon-based first generation PV technologies (mono and polycrystalline silicon solar cells). For the thin-layer second generation technologies, the xenon arc lamp results show inaccuracies higher than 20%. Conversely, the metal halide MSR lamp appears as an adequate light source for solar simulator for the tested PV technologies as it presents a more stable irradiation distribution, with inaccuracies between 1,9% and 11,1%.

The IEC standard classification method rates the MSR lamp as class B for the AM 1.5, and class C for the Clear and Cloudy spectra. However, this method does not provide information about the PV technology to be tested despite its proven relevance for the solar simulation procedure. For this reason, an IEC standard review is suggested to increase the wavelength range to the 300-1200 nm where some new technologies, as the a-Si, will offer a promising contribution on the quantum efficiency performance. In addition, include some typical reference spectra from extreme climates with high and a low UV irradiance contribution is suggested. This revision would provide additional information about the solar cell performance dependence with the climatic conditions, improving both the PV performance and sizing optimization.

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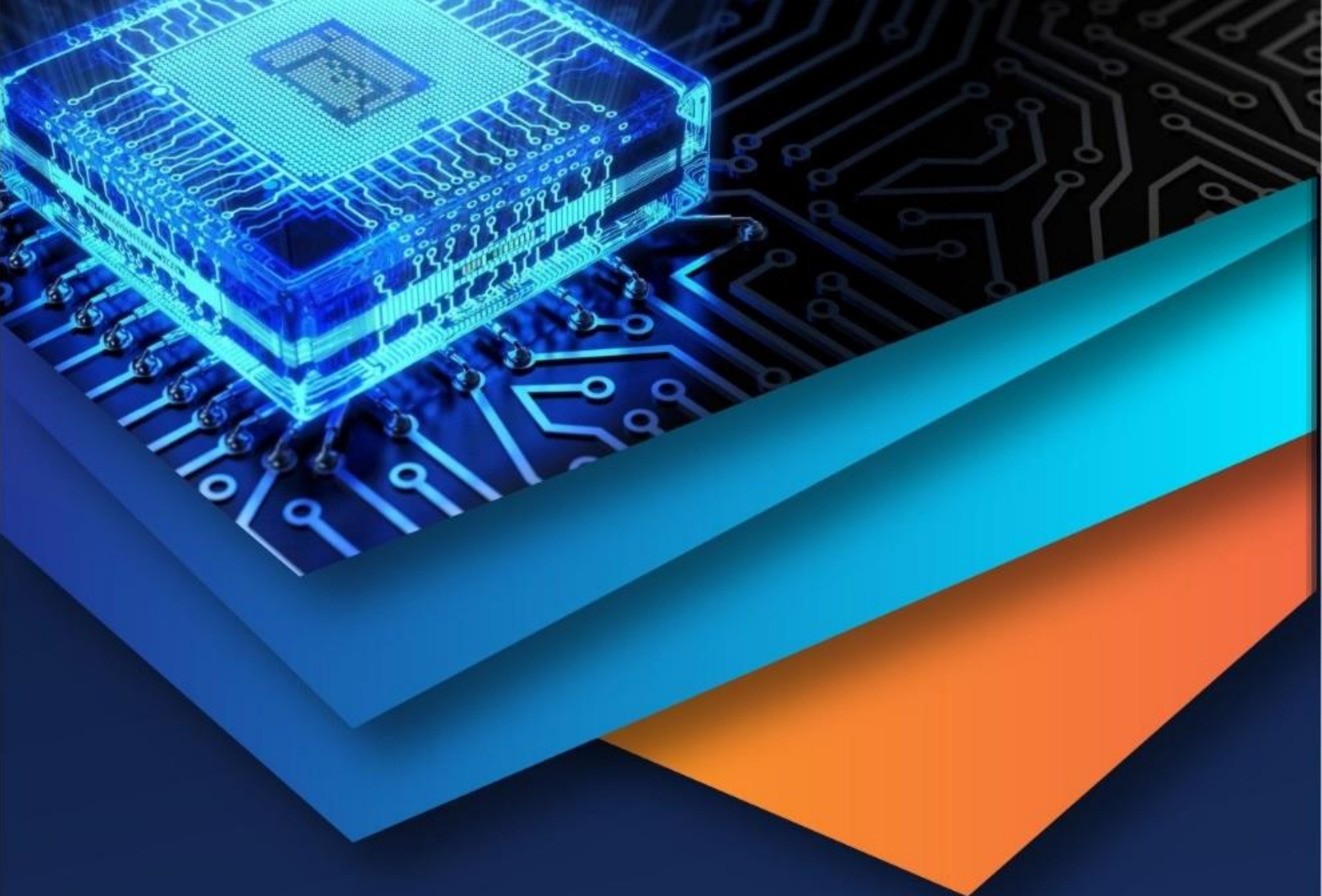

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