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Design and construction of a solar simulator for characterization of photovoltaic modules

Diseño y construcción de un simulador solar para caracterización de módulos fotovoltaicos

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Abstract

This work comprises the design, development, characterization and implementation of a solar simulator prototype for photovoltaic modules, implementing LED lamp technology as artificial lighting. First, we designed the prototype in AutoCAD, and then we built it using a box (100×100×35cm) made of sheet metal as a cabin. We used a super polished sheet as a reflective surface inside the cabin. Inside the cabin, we placed 8 LED lamps of 200 and 50 Watts in order to have a constant irradiance. An Arduino UNO board and a SPLITE2 pyranometer were used to measure lamp irradiance, along with a MATLAB data acquisition system. As a result, a functional prototype of a CB type solar simulator with an area of 1m^2 was got with a constant irradiance of 200 W/m^2 at a height of 30cm and with a homogeneity of 98.6 W/m^2 difference between peaks.

Solar simulator, Irradiance, LED technology, Characterization, Prototype

Resumen

Este trabajo consiste en el diseño, desarrollo, caracterización e implementación de un prototipo de simulador solar para módulos fotovoltaicos, implementando tecnología de lámparas LED como iluminación artificial. Primero se realizó el diseño del prototipo en AutoCAD, posteriormente, se construyó utilizando una caja (100×100×35cm) de lámina como cabina, la cual en el interior cuenta con lamina superpulida utilizada como superficie reflejante. En el interior de la cabina se colocaron 8 lámparas LED de 200 y 50 Watts con la finalidad de tener una irradiancia constante. Se utilizó un piranómetro SPLITE2 adaptado con una tarjeta Arduino UNO para caracterizar la irradiancia de las lámparas dentro de la cabina, así como un sistema de adquisición de datos en MATLAB. Como resultado se obtuvo un prototipo funcional de un simulador solar tipo CB de área de 1m^2 con una irradiancia constante de 200 W/m^2 a una altura de 30cm y con una homogeneidad de 98.6 W/m^2 de diferencia entre picos.

Simulador solar, Irradiancia, Tecnología LED, Caracterización, Prototipo

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Introduction

To properly understand the operation of the solar cell, it is necessary to take into consideration the influence of the two main external factors: the ambient temperature (Perpiñán, 2015) and incident illumination

Solar simulators are indispensable tools in the characterization of photovoltaic modules. These simulators present controlled conditions of radiation and temperature. For these reasons laboratory tests, under controlled conditions, can provide more reliable information, the radiation variation of a solar simulator can be performed by different techniques depending on the technical characteristics of the lamps used. (Bodnár, 2020)

In order to perform experimental tests with photovoltaic modules, an operation must be maintained under established standards, in standard measurement conditions SCT (Standard Test Conditions), which correspond to an irradiance in the module plane of 1,000 W/m2, module temperature of 25 ºC and a spectral distribution of irradiance according to the air mass factor AM 1.5 (Canales, 2004).

The aim was to develop a prototype solar simulator for the characterization of photovoltaic modules based on LED lamps, seeking to approach commercial versions. These devices present a good correlation compared to a solar simulator with a xenon lamp. Such a device presents a low cost and, in particular, an easy way to control the luminous flux.(Grandi, 2014).

Something to keep in mind, is the LED light emission spectrum. For a white LED, the normalized emission spectrum measured at room temperature consists of a blue peak located at approximately 450 nm emitted by the LED chips and a broad yellow peak at ~560 nm emitted by the phosphor particles. (Jeong, 2012) As shown in Figure 1.

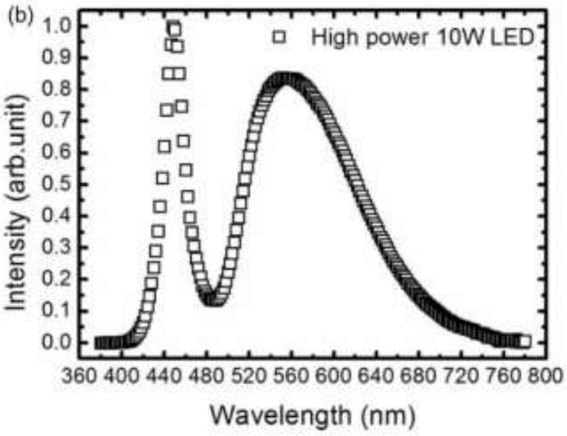


Figure 1 Emission spectrum White LED (Jeong, 2012)

The requirements for solar simulators are found in the American Standard for Testing and Materials (ASTM) E972. According to this standard, solar simulators can be classified by three main aspects and into different classes, A, B or C (Table 1) based on the three aspects mentioned above (Jeong, 2012). However, any solar simulator should be able to provide the average surface light intensity (AM 1.5) with a maximum value of 1000 W/m^2 (Jeong, 2012).

	Class A	Class B	Class C
Spectral conformity	75-125%	60-140%	40-120%
Spatial uniformity	≤2%	≤5%	≤10%
Temporary stability	≤2%	≤5%	≤10%

Table 1 Classification of solar simulators (Bodnár, 2020)

The spectrum is also characterized by the percentage of irradiance in eight wavelength intervals. Table 2 shows the standard terrestrial spectra of AM 1.5G (Global) and AM 1.5D (Direct) and the extraterrestrial spectrum AM 0. (Wang, 2014)

Length	Total irradiance percentage		
[nm]	AM1.5 D	AM1.5G	AM0
300-400	Not specified	Not specified	8.0%
400-500	16.9%	18.4%	16.4%
500-600	19.7%	19.9%	16.3%
600-700	18.5%	18.4%	13.9%
700-800	15.2%	14.9%	11.2%
800-900	12.9%	12.5%	9%
900-1100	16.8%	15.9%	13.01%
1100-1400	Not specified	Not specified	12.2%

Table 2 Percentage irradiance by wavelength. (Grandi, 2014)

In this work, the design, construction, characterization and implementation of a first version of a solar simulator prototype for the characterization of photovoltaic modules, implementing LED lamp technology as artificial lighting, was carried out.

Methodology to be developed

For the construction of the system, a square wooden box of 1m per side and 35 cm high was used. Two different types of LED lamps were used at the bottom, two GOGOLITE GL-FG013 and six ZL-RS-50W. The height above the lamps was calculated to obtain a more uniform irradiance at a multiple of 1000 W/m2. To measure the irradiance inside the box, a Kipp and Zonen SP-Lite 2 pyranometer and a multimeter were used to interpret the values obtained by the pyranometer. Inside the box, aluminum foil was placed on each of the faces, in order to have a reflective effect which helps to have a better concentration of light (Figure 2a).

Three openings were made through which the pyranometer could be introduced and placed inside the analysis quadrants to perform the measurements inside the system. These openings are 30 cm high every 5 centimeters, in order to measure irradiance at 6 different heights and thus determine homogeneity (figure 2b).

Figure 2 A) inside of the test box. B) opening for the introduction of the pyranometer

Connections were made for the lamps powered by two 110V sources, one for the 6 ZL-RS-50W lamps (large) and the other for the GOGOLITE GL-FG013 lamps (small). Each of the arrays was connected in parallel, resulting in the arrangement shown in Figure 3.

Figure 3 Lamp connection arrangement

With the location and distribution of the lamps and the dimensions of the box, we worked on the virtual design using the AutoCAD program shown in figure 4.

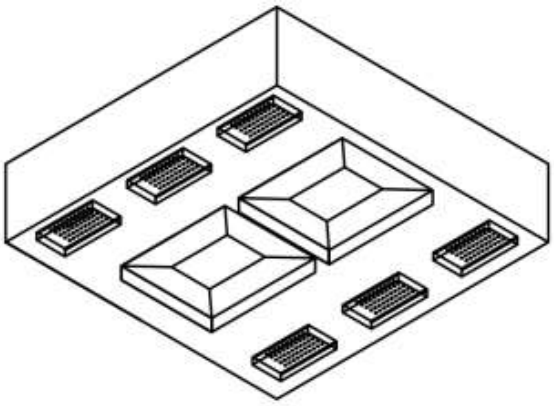


Figure 3 Arrangement of lamp connections

As spectroscopy tests, the pyranometer and a set of cellophane paper of different colors (red, yellow, green, blue and purple) were used to obtain the irradiance passing through each color, in order to speculate its irradiation spectrum (Figure 5).

Figure 5 Blue and purple spectroscopy tests

Subsequently, the construction of the simulator was carried out using the 1 meter per side and 35 centimeters high sheet metal box. Inside the box super polished foil was placed on the 4 walls (Figure 6a) which will do the same job as the aluminum in the test box, i.e., as a reflective surface to help have a more homogeneous radiation inside the system.

Figure 6 A) cutting of super polished sheet for solar simulator walls. B) fixing of lamps inside the box

As can be seen in Figure 6b, angles and screws were used to fix the lamps, which go directly to the structure of the sheet metal box.

The irradiance measurements were repeated in the 9 quadrants in which the simulator surface was divided and where a more homogeneous irradiance was obtained at a height of 30 cm. Once the lamps were installed, the pyranometer and an Arduino were used to perform the measurements and analyze the data obtained more precisely (Figure 7a and 7b).

Figure 7 A) Final irradiance measurement. B) Pyranometer data collection

For the implementation stage, a photovoltaic module model EPCOM PRO1012 was used, obtaining its I-V characteristic curves by means of a PROVA 200A curve tracer (Figure 8), with which the 5 electrical parameters were obtained.

Figure 8 Characterization of photovoltaic module

Results

Graphs 1a, 1b, 1c and 1d show the distribution of irradiance emitted by the set of lamps within an area delimited by the 9 quadrants. The measurements were performed in a 3×3 coordinate system.

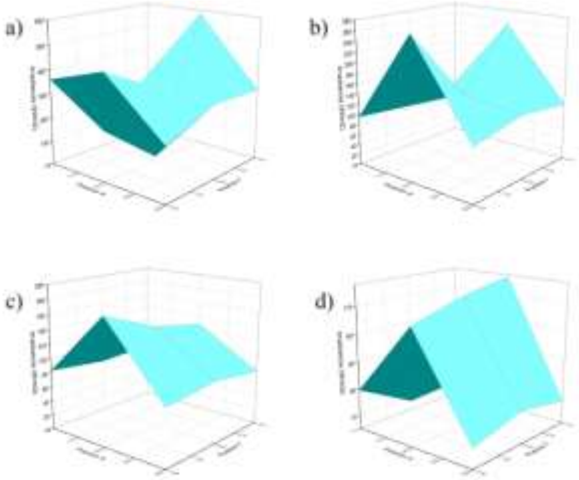


Figure 9 A) Irradiance distribution at 10 cm. B) Irradiance distribution at 20 cm. C) Irradiance distribution at 30 cm. D) Irradiance distribution at 35 cm

Graph 1 shows the irradiance intensities measured on the test prototype in the form of surfaces. It is observed that for surfaces A, B and D, there is non-uniformity in the irradiance and that in the case of surface C the irradiance becomes more uniform, at an average value of about 100 W/m2 (Annex A).

Analysis of measurements of the electromagnetic spectrum of LED lamps

The graph in Figure 10 shows the irradiance emitted by the white light of the two LED lamps, passing it through the colored cellophanes and recording its intensity with the pyranometer.

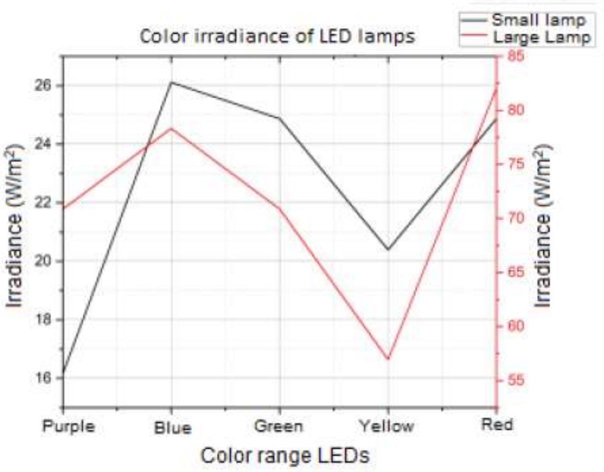


Figure 10 Characterization of the photovoltaic module

From figure 10 it is possible to observe the similar behavior for both lamps, which means that the LEDs are the same and only differ in the quantity that each lamp has, this because the difference between both curves is the intensity.

On the other hand, for both cases, the predominant presence of blue, green and red colors, emitted by the white LED lamps, stands out. This behavior is consistent with Figure 1 where the theoretical emission spectrum of a white LED is observed.

Regarding the homogeneity of the irradiance in the system, the graph in Figure 11 shows the distribution of irradiance emitted by the array of LED lamps inside the solar simulator prototype, measured at a height of 30 cm above the lamps.

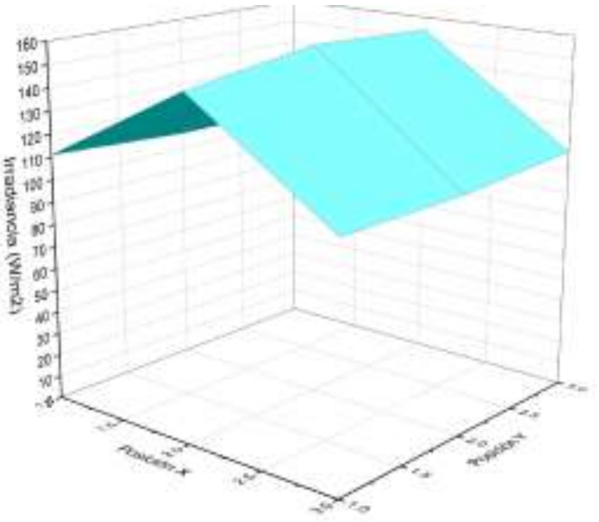


Figure 11 Irradiance distribution of the built solar prototype

As can be seen, the distribution in the prototype of the constructed solar simulator is more uniform than the irradiance distribution of the test prototype. In addition, an increase in the irradiance emitted by the LED lamps is observed due to the use of the super polished sheet on the walls of the system, despite maintaining the same arrangement of lamps.

Table 3 shows the irradiance measurements in each of the 9 quadrants of the solar simulator.

Quadrant	Irradiance (W/m^2)
1	111.1
2	149.2
3	105.2
4	106.9
5	157.3
6	105.2
7	106.3
8	154.2
9	108.6
Average	122.66

Table 3 Irradiance measured per quadrant of the prototype

Temperature analysis of the solar simulator prototype

The graph in Figure 12 shows the time variation curve of the temperature inside the solar simulator prototype. As can be seen, the adjustment shows an increase in the internal temperature of 1.46°C/minute, with this value it is possible to get an idea of how long the system has to be allowed to cool down to perform the next module characterization.

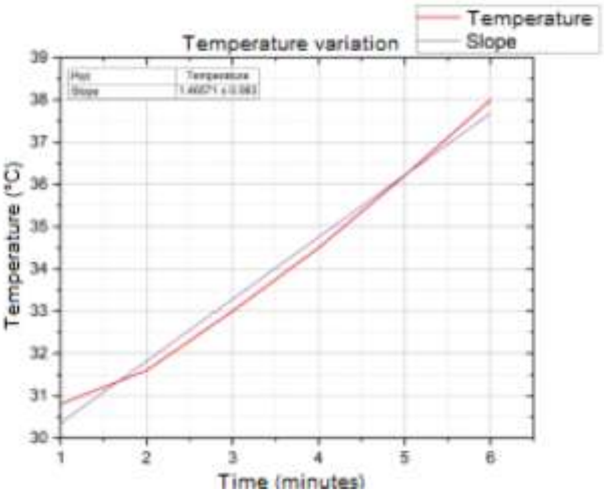


Figure 12 Temperature variation of the prototype

Characterization of the solar simulator prototype

Table 4 shows the wavelength irradiance percentages of the prototype compared to the irradiance of the sun at AM0 conditions. It is observed that the spectral conformity of the prototype is 53.57% which is a value corresponding to class C, the inequality of the prototype is 7.43% which corresponds to class B, so the final classification of the solar simulator prototype is class CB according to Table 1.

Wavelength [nm]	Percentage of total irradiance	
	AM0	Prototype
300 - 400	8%	11.48%
400 - 500	16.40%	9.57%
500 - 600	16.30%	23.37%
600 - 700	13.90%	
700 - 800	11.20%	9.35%
800 - 900	9%	
900 - 1100	13.10%	
1100 -1400	12.20%	
Spectral conformity with respect to sunlight	100%	53.77%
Class	A	C
Spatial inequality	0%	7.43%
Class	A	B

Table 4 Comparison with AM0 values of the irradiance per wavelength

Implementation of the system on a photovoltaic module

The graph in Figure 13 shows the I-V characteristic curve of a photovoltaic module model EPCOM PRO-1012 irradiated with the prototype built with the solar simulator, the values obtained are compared with the curve at STC conditions of its data sheet (see Annex B).

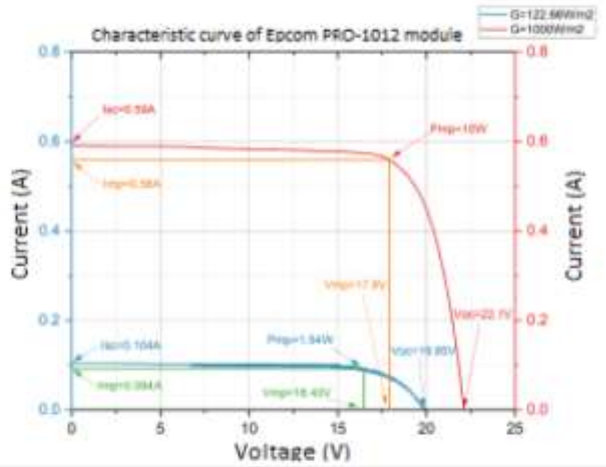


Figure 13 Characteristic curves of the photovoltaic module

As can be seen, the characteristic curve obtained with the use of the solar simulator has the same behavior as the characteristic curve provided by the technical data sheet of the photovoltaic panel. With this it can be concluded that the simulator has a uniform irradiance and works to obtain the values of the parameters used for the definition of the characteristic curve at a lower irradiance.

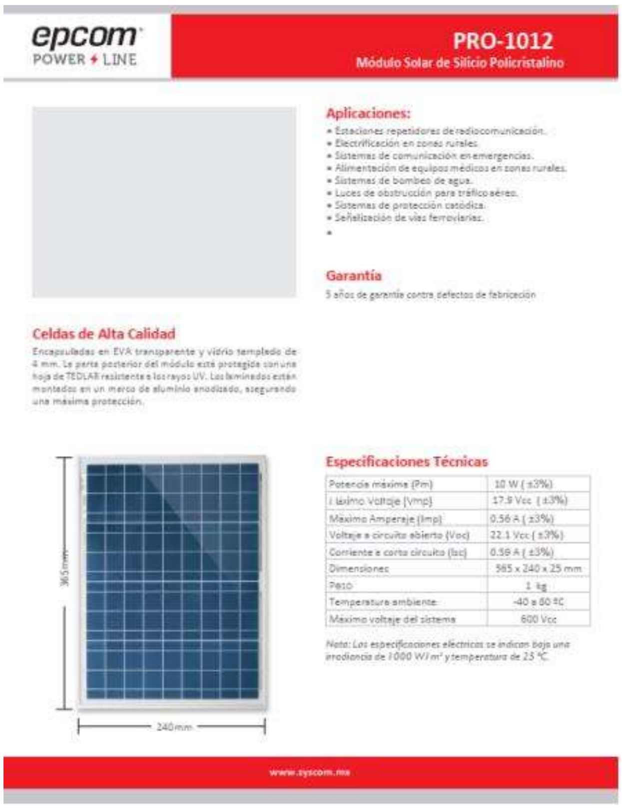
Annexes

Annex A. Measurements taken on the test prototype.

Cuadrante/Altura	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm
1	360.60	139.26	94.50	85.79	83.31	79.58
2	441.43	364.33	272.32	216.36	172.84	106.93
3	222.58	82.06	103.20	80.82	78.33	72.12
4	62.17	145.48	118.12	87.04	74.60	68.39
5	18.65	92.01	135.53	140.51	141.75	113.15
6	308.38	185.27	123.10	94.50	85.79	77.09
7	264.85	92.01	105.69	80.82	78.33	69.63
8	584.43	322.05	252.42	182.79	128.07	116.88
9	299.67	187.76	110.66	83.31	75.85	73.36
Promedio	284.75	178.92	146.17	116.88	102.10	86.32

Nota: Valores registrados en W/m^2.

Annex B. EPCOM PRO-1012 photovoltaic module datasheet



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POWER LINE

PRO-1012
Módulo Solar de Silicio Policristalino

Aplicaciones:

- Estaciones repetidoras de radiocomunicación.
- Electrificación en zonas rurales.
- Sistemas de comunicación en emergencias.
- Alimentación de equipos médicos en zonas rurales.
- Sistemas de bombeo de agua.
- Luces de obstrucción para tráfico aéreo.
- Sistemas de protección catódica.
- Señalización de vías ferroviarias.
-

Garantía

5 años de garantía contra defectos de fabricación

Celdas de Alta Calidad

Encapsuladas en EVA transparente y vidrio templado de 4 mm. La parte posterior del módulo está protegida con una hoja de TEDLAR resistente a los rayos UV. Los laminados están montados en un marco de aluminio anodizado, asegurando una máxima protección.

Especificaciones Técnicas

Potencia máxima (Pm)	10 W (±3%)
Máximo Voltaje (Vmp)	17.9 Vcc (±3%)
Máximo Amperaje (Imp)	0.56 A (±3%)
Voltaje a circuito abierto (Voc)	22.1 Vcc (±3%)
Corriente a corto circuito (Isc)	0.59 A (±3%)
Dimensiones	365 x 240 x 25 mm
Peso	1 kg
Temperatura ambiente	-40 a 80 ºC
Máximo voltaje del sistema	600 Vcc

Nota: Los especificaciones eléctricas se indican bajo una irradiancia de 1000 W/m² y temperatura de 25 ºC.

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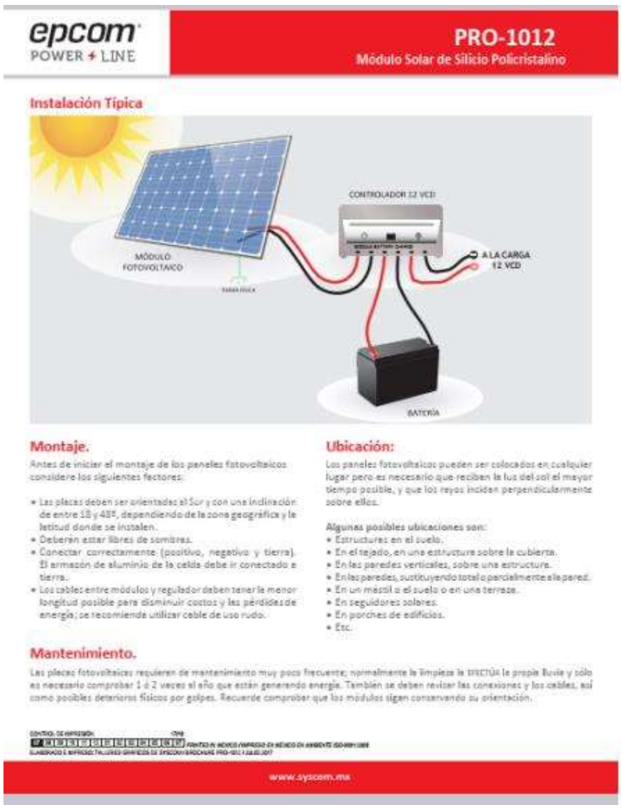

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Instalación Típica

Montaje.

Antes de iniciar el montaje de los paneles fotovoltaicos considere los siguientes factores:

- Las placas deben ser orientadas al Sur y con una inclinación de entre 18 y 48º, dependiendo de la zona geográfica y la latitud donde se instalen.
- Deberán estar libres de sombras.
- Conectar correctamente (positivo, negativo y tierra). El armazón de aluminio de la celda debe ir conectado a tierra.
- Los cables entre módulos y regulador deben tener la menor longitud posible para disminuir costos y las pérdidas de energía; se recomienda utilizar cable de uso rudo.

Ubicación:

Los paneles fotovoltaicos pueden ser colocados en cualquier lugar pero es necesario que reciban la luz del sol el mayor tiempo posible, y que los rayos incidan perpendicularmente sobre ellos.

Algunas posibles ubicaciones son:

- Estructuras en el suelo.
- En el tejado, en una estructura sobre la cubierta.
- En las paredes verticales, sobre una estructura.
- En las paredes, sustituyendo total o parcialmente a la pared.
- En un mástil o el suelo o en una terraza.
- En seguidores solares.
- En porches de edificios.
- Etc.

Mantenimiento.

Las placas fotovoltaicas requieren de mantenimiento muy poco frecuente; normalmente la limpieza la EFECTÚA la propia lluvia y sólo es necesario comprobar 1 ó 2 veces al año que están generando energía. También se deben revisar las conexiones y los cables, así como posibles deterioros físicos por golpes. Recuerde comprobar que los módulos sigan conservando su orientación.

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Acknowledgment

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Conclusions

In this work, a solar simulator prototype was designed and built, which was characterized and used to obtain an electrical properties curve in a photovoltaic module. The analysis determines that the prototype built can be comparable to a solar simulator type CB, because it is close in the spectral conformity in simulator type C and in the spatial inequality in the AM0 spectrum of type B.

The height of 30 cm above the lamps was the optimum in the system to achieve the best radiation uniformity of magnitude 98.6 W/m2 within the area covered by the light from the lamps. Inside it was observed that the temperature rises 1.4 degrees per minute when the prototype is in operation, which presents a weakness of the simulator, a temperature control system is recommended to counteract the rise in temperature.

It was determined that the LED lamps of the prototype differ 46.23% with respect to the sun in terms of spectral conformity, and 7.43% in terms of spatial inequality, these results indicate that the prototype solar simulator class CB is suitable for experimental use, since it can approximate the sun in spectral and spatial terms.

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