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Construction of a Laboratory Solar Cell Testing Equipment and Evaluation of Some Practical Construction Parameters on a Silicon Solar Cell Photo Conversion

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Abstract: *In this work, a solar cell test equipment was built with low-cost components. The equipment was evaluated by analyzing I-V curves of a monocrystalline silicon solar cell including the measurement of the short circuit current (Isc), open-circuit voltage (Voc), maximum power (Pmax), form factor (FF), and power conversion efficiency (PCE). Practical parameters for the construction equipment were investigated, namely the luminous intensity, the type of illumination, and the distance between the cell and the light source. The heating caused by the lamps was investigated on the short circuit current. The equipment proved to be robust and efficient to compare solar cells properties. However, it was observed that all the studied factors can change the measured photovoltaic parameters, and they must be fixed to obtain measurements capable of being compared.*

Keywords: Solar Cell; I-V Curves; Irradiance; Photo conversion; Characterization.

1. INTRODUCTION

The use of photovoltaic energy has been growing strongly in recent years due to the various advantages of these systems that convert light energy into electricity. In addition to obtaining energy from an unlimited source which is the sun, photovoltaic systems can be installed connected to the electricity grid, where the excess energy produced can be sold or installed in an isolated manner in regions with difficult access. Therefore, there are many reasons for the development of increasingly efficient and cheaper solar cells [1, 2]. The performance of these devices in terms of photo conversion capability is often analyzed using the I-V (current-voltage) curve. The I-V curve shows the current and voltage values generated by a solar cell in a circuit with a variable resistive load. The I-V curves reveal important properties of the solar cells such as short circuit current (Isc), open-circuit voltage (Voc), maximum power (Pmax), fill-factor (FF), and the conversion power efficiency (PCE). The latter is a relationship between the light power received and the electrical power generated by the cell. To obtain an I-V curve it can be used specialized systems capable of obtaining a massive set of points in a few seconds, or a manual data collection can be carried out with a circuit with only 4 components. In this case, a solar cell, a potentiometer, an ammeter, and a voltmeter are used. In any situation, a light source must be used. However, for the calculation of the PCE, the power supplied by the light in a certain area must be known. Standard Testing Conditions (STC) are the standards that the solar industry uses to test a solar panel. These conditions are 25°C for the cell temperature, 1000W/m2 of solar irradiation, and 1.5 of an air mass. STC conditions are difficult to obtain as lamps do not have an electromagnetic spectrum identical to that of the sun, and lamps with filters capable of simulating the solar spectrum are very expensive. In Figure 1 we can see the difference between the electromagnetic spectra of different types of lamps compared to the spectrum of sunlight AM 1.5G.

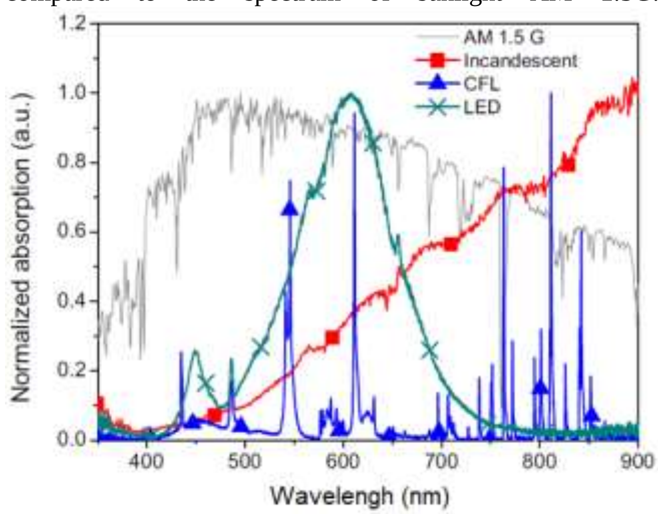

Fig. 1: Normalized power spectra of the different light sources studied: 1-sun AM 1.5 G (line), incandescent light bulb 2800 K (red squares), CFL 6500 K (blue triangles), and LED 3000 K (green crosses). Reproduced with permission from Nano Energy 26, 631 (2016). Copyright 2016 Elsevier Ltd [3].

In addition to the radiation spectrum, other important factors for the conversion of light energy into electrical energy are the amount of light that reaches the solar cell defined by the irradiance value (Irr) and temperature.

Irradiance, temperature, and light spectrum can affect all the properties obtained with the I-V curves [4]. When using artificial sources for illumination, the irradiance captured by the solar cell may vary depending on the constructive aspects of the test equipment. Power and type of lamps, distance from the cell to the light source, dimensions and reflectivity of the walls, are characteristics of the equipment that necessarily need to be fixed to correctly measure the solar cell properties.

In this work, therefore, we sought to build a low-cost and reliable equipment, capable of generating I-V curves under controlled conditions.

2. EXPERIMENTAL

For current and voltage measurements, a wooden box measuring 30 x 30 x 40 cm was built with a square base. A square opening of 15 x 15 cm was made in its front to access the interior. Figure 2 shows the box in operation. In the opening, a black rubber was glued to better closure and to not lose light by crevices.

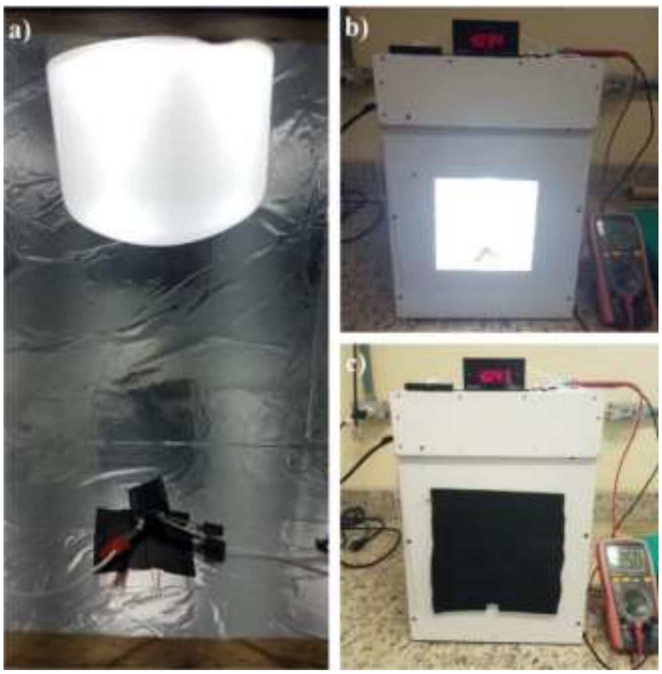

Fig. 2: Photovoltaic test box. A) Interior of the box showing the solar cell connected to the electrical circuit. B) The box opened and operating with a 30W LED lamp. C) The box closed and operating with the voltmeter positioned above the box and a multimeter on the side operating in ammeter mode.

Inside the box, 3 lamp holders were installed allowing to choose the use of one to three lamps. In this work, a 30 Watts LED lamp and two 10.5 Watts LED lamps were used, all with a color temperature of 6500 K. For comparison, an incandescent lamp of 100 Watts power (light temperature unknown) and three CFL lamps (5500 K color temperature) of 20 Watts each were also tested. The inside of the box was covered with aluminum foil to enhance the illumination and minimize the effects of poor positioning of the solar cell in relation to the light source(s). The temperature inside the box was measured using a digital thermometer with an accuracy of 0.1°C placed near the solar cell. A measurement performed with solar lighting was also carried out by placing the solar cell outside the box on a clear day at 11:30 am.

The measurement of illuminance was performed with a digital luxmeter brand ICEL model LD-500. Illuminance is a measure commonly used indoors and indicates the luminous flux per unit area, its SI unit is lm/m^2, called Lux (lx). The illuminance measure, however, is the measure of the visible luminous flux density, and therefore it is necessary to convert the illuminance value into irradiance that also takes into account the wavelengths outside the visible spectrum. This conversion depends on the electromagnetic spectrum of the light source. In the work of [3], a relationship between illuminance and irradiance for different types of lamps is presented. Considering linearity in this relationship between illuminance and irradiance (Irr) for each type of lamp, it is possible to deduce the equations 1, 2, 3, and 4 that relate these two quantities.

$$1 \text{ lx} = 9.12 \times 10^{-3} \text{ W/m}^2 \text{ for the sun} \quad (1)$$

$$1 \text{ lx} = 3.47 \times 10^{-3} \text{ W/m}^2 \text{ for LED lamps} \quad (2)$$

$$1 \text{ lx} = 6.00 \times 10^{-3} \text{ W/m}^2 \text{ for CFL lamps} \quad (3)$$

$$1 \text{ lx} = 21.1 \times 10^{-3} \text{ W/m}^2 \text{ for incandescent lamps} \quad (4)$$

The electrical scheme, shown in the diagram in Figure 3, was assembled to take the photoconversion measurements and is composed of an ammeter, a voltmeter, a potentiometer, and a commercial monocrystalline silicon solar cell of approximately 4.7775 cm^2 in area.

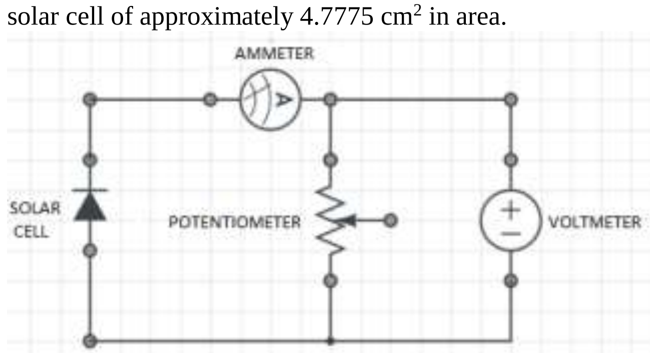

Fig. 3: Circuit scheme of the photovoltaic Laboratory Solar Cell Testing Equipment.

As the ammeter, the digital multimeter MD-1301 Icel was used, with precision in µA (Figure 4-a). The potentiometer used was a Phillips brand, model 505, linear 1k

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resistance (Figure 4-b). Dawer DPM-100 digital voltmeter was also used, with an accuracy of 1mV (Figure 4-c).

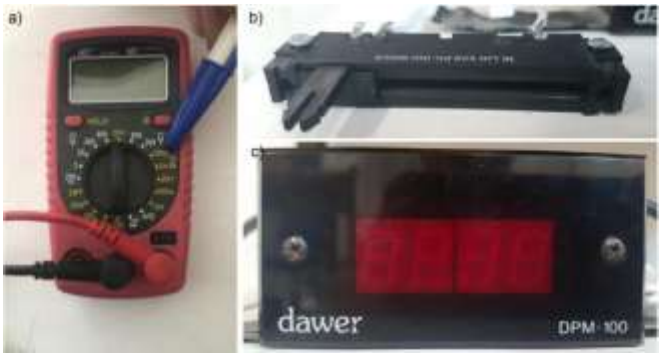

Fig. 4: Equipment used in the electrical circuit: a) Digital multimeter; b) potentiometer and c) voltmeter.

With the testing box assembled, a series of tests were carried out under conditions that varied from the type of lighting (LED lamps, CFL lamps, incandescent lamps, and solar lighting) and luminosity (varied by the proximity to the light source and the number of lamps of the same type). The I-V curves were obtained by varying the resistance of the potentiometer minutely and transcribing the current and voltage generated by the solar cell point by point. When the potentiometer has its resistance null, we have the value of maximum current and minimum voltage. At this point, the current value is called short-circuit current (Isc). When potentiometer resistance is maximum, we have maximum voltage and minimum current. This voltage value is called the open-circuit voltage (Voc). In addition to the values of Isc and Voc, the values of maximum power (Pmax), fill factor (FF), and power conversion efficiency (PCE) were also analyzed. Pmax is obtained by the largest value of the multiplication of current by voltage and is given in Watts (equation 5). The FF is obtained by equation 6. This factor is related to cell performance where high-quality cells have FF greater than 0.7 (grade A), while second-row cells have a FF of 0.4 to 0, 7 (grade B). The conversion efficiency (PCE) is calculated by equation 7, where Irr is the irradiance value in W/m2 and A is the area of the solar cell in m^2 [5].

$$P = V\,I \qquad (5)$$

$$FF = \frac{P_{max}}{V_{OC}\,I_{SC}} \qquad (6)$$

$$PCE = \frac{P_{max}}{I_{rr}\,A} \qquad (7)$$

For each curve, about 50 current and voltage points were recorded and later plotted in the form of the I-V curve.

3. RESULTS AND DISCUSSION

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3.1 Influence of luminosity

The first tests were to verify the influence of luminosity intensity on the photo conversion results. For this, tests with LED lamps and CFL lamps were carried out using three configurations of lamps for each type of lamp. In Figure 5, we see the I-V curves obtained with LED lamps and in Figure 6 we see the I-V curves obtained with CFL lamps. Tables 1 and 2 show the main data obtained by the I-V curves of LED and CFL lamps respectively.

With increasing illumination, there is an increase in the density of semiconductor charge carriers. These charge carriers can then cover a certain distance before recombining. This distance is called diffusion length and depends on the diffusion coefficient of the material and the lifetime of the charge carrier [6, 7]. With the greater density of charge carriers, the recombination processes become more significant, thus decreasing the form factor of the I-V curves. Keogh et al. [8] describes that the dominant recombination mechanism varies according to the luminous intensity in the solar cell and high luminous intensity has a great impact on the series resistance and little impact on the shunt resistance, on the other hand, a low luminous intensity occurs the opposite.

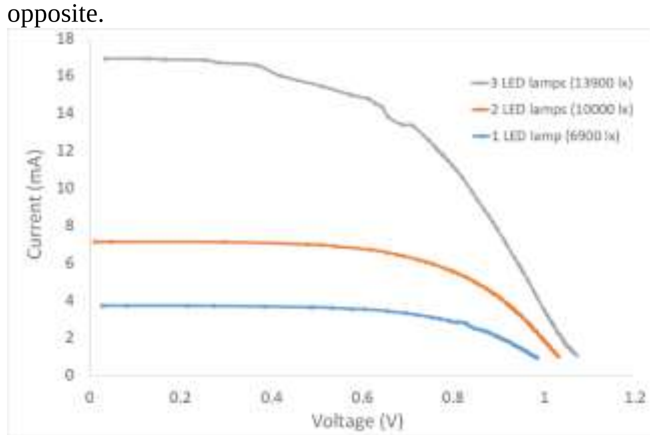

Fig. 5: I-V curves for three LED lamps configurations showing the photovoltaic conversion response to the lightning intensity.

Table 1: Photovoltaic parameters of three configurations of led lamps.

parameters	*1 lamp*	*2 lamps*	*3 lamps*
Isc (mA)	3.72	7.14	16.93
Vop (V)	0.98	1.03	1.07

Pmax (mW)	2.34	4.49	9.48
PCE	0,20	0,27	0,41
Fill Factor	0,64	0,61	0,52
Iluminance (lx)	6900	10000	13900
Irradiance (mW/m²)	23943	34700	48233

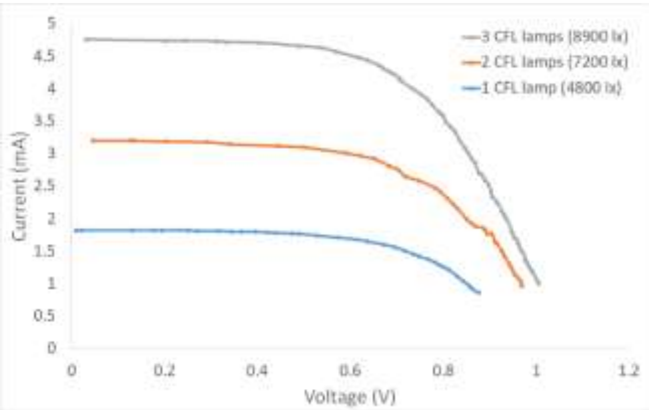

Fig. 6: I-V curves for three CFL lamps configurations showing the photovoltaic conversion response to the lightning intensity.

Table II: Photovoltaic parameters of three configurations of CFL lamps.

parameters	*1 lamp*	*2 lamp*	*3 lamps*
Isc (mA)	1.82	3.2	4.76
Vop (V)	0.88	0.97	1.01
Pmax (mW)	1.08	1.94	2.94
PCE	0.08	0.09	0.20
Fill Factor	0.68	0.62	0.61
Iluminance (lx)	4800	7200	8900
Irradiance (mW/m²)	28800	43200	30883

3.2 Influence of the type of lighting

The comparison between different types of lighting revealed large differences in the parameters of photovoltaic energy generation. The graph in Figure 7 compares measurements made with solar lighting, LED lighting, CFL lighting and incandescent lighting. It is clear that solar lighting brings much higher values of voltage, current, and power. This was already expected since solar lighting is the one with the highest illuminance (28500 lx) and irradiance (259920 mW/m^2).

A proportional increase in the Pmax of the solar cell can be observed as a function of the illuminance since the lighting conditions with lower illuminances (CFL lamps and incandescent lamp) presented the lowest values of Pmax. However, as the relationship between illuminance and irradiance depends on the type of lamp and its electromagnetic spectrum, we find situations such as the incandescent lamp, even with high irradiance, is not capable of producing a high Pmax in the cell because its spectrum emits a large part of the luminous power in the infrared range whose photons do not have enough energy to excite the silicon electrons to its conduction band.

Table 3 shows the values for the main photovoltaic parameters measured with the different light sources.

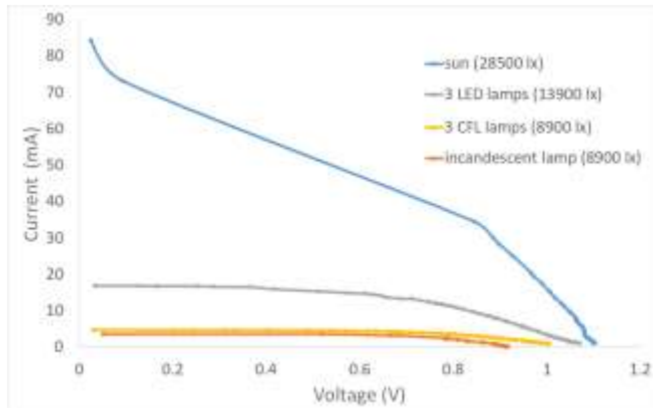

Fig. 7: I-V curves comparing the photovoltaic conversion with 4 different light sources. Sun, LED lamps, CFL lamps and Incandescent lamp.

Table III: Photovoltaic parameters of three led lamps configuration with different intensities

parameters	*sun light*	*3 LED lamps*	*3 CFL lamps*	*incande scent*
Isc (mA)	84.40	16.93	4.76	3.64
Vop (V)	1.10	1.07	1.01	0.92
Pmax (mW)	29.24	9.48	2.94	2.19
PCE	0.24	0.41	0.12	0.02
Fill Factor	0.31	0.52	0.61	0.66
Iluminance (lx)	28500	13900	8900	8900
Irradiance (mW/m²)	259920	48233	53400	187790

Analyzing the PCE values, it can be seen that LED lighting provides the highest efficiency in converting light power into solar cell power. Again, this is justified due to the spectrum of LED lamps concentrating photons in the region of approximately 450 nm to 750 nm. Considering the silicon bandgap as 1.17, wavelengths greater than approximately 1050 nm do not promote the photoelectric effect, not being

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able to generate energy in the solar cell. These infrared photons are more abundant in solar radiation and incandescent lamps, which leads these illuminations to low conversion efficiency. Another mechanism that leads to low conversion efficiencies is the thermalization of charge carriers generated by the absorption of high energy photon [9]. Thus, the spectrum that provides greater efficiency in converting crystalline silicon cells is the spectrum generated by LED lamps.

The fill factor again proved to be a luminosity-dependent parameter, and for higher illuminances, the lower the fill factor.

3.3 Influence of proximity to the light source

Although the assembled test box is internally capped with aluminum foil and does not contain cracks where luminosity would be lost, the tests in different proximities to the lamps showed differences in illuminance (measured by the luxmeter) and in power generated by the solar cell. Figure 8 shows the I-V curves obtained with two distances from the light source, one at a distance of 7 cm and the other at a distance of 15 cm from the light sources. As shown in Table 4, the closer proximity of the lamp (distance of 7 cm) causes greater luminosity to reach the cell, increasing the generated current, but without a significant gain in voltage compared to when the cell is positioned 15 cm from the lamp. As previously observed, the FF and PCE were dependent on the luminosity, suffering a reduction in their values when approaching the cell to the light source.

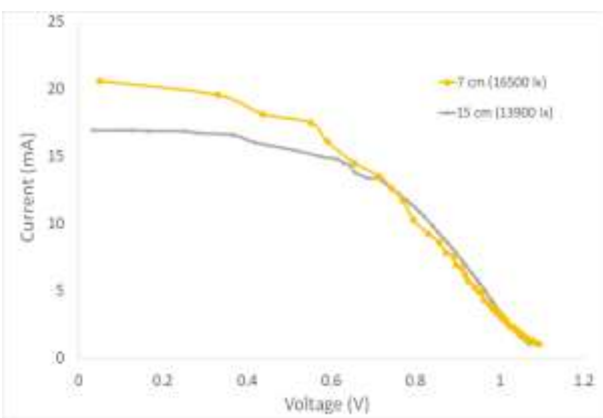

Fig. 8: I-V curves comparing the photovoltaic conversion in two distances from de solar cell to the light source. The gray line is 15 cm of distance, and the yellow line is 7 cm of distance.

Table IV: Photovoltaic parameters of led lamps configuration with different distances.

parameters	*15 cm (3 LED lamps)*	*7 cm (3 LED lamps)*
Isc (mA)	16.93	20.60
Vop (V)	1.07	1.09
Pmax (mW)	9.48	9.66
PCE	0.41	0.35
Fill Factor	0.52	0.43
Iluminance (lx)	13900	16500
irradiance (mW/m^2)	48233	57255

3.4 Influence of temperature

The temperature at which measurements are taken can influence the results [10, 11]. When the lamps are turned on, there is a gradual increase in temperature inside the test box. This fact is even more accentuated when using incandescent lamp. The effect of temperature is more easily observed in the short-circuit current value. Figure 9 (a) and (b) show the short-circuit photocurrent as a function of temperature when using incandescent lighting and LED lamps, respectively.

It can be noticed that increasing the temperature, it reduces the short-circuit current value. Also, is observed that for the same time of measure, the temperature of the equipment raises 25C° for the incandescent lamp and only 6C° when using the LED lamps.

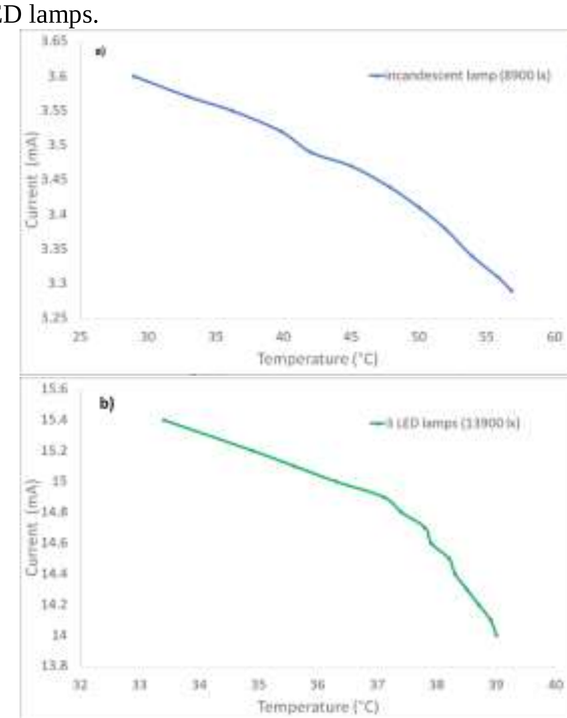

Fig. 9: Short-circuit Current in function of the temperature increase for the (a) incandescent lamp and (b) 3 LED lamps.

4. CONCLUSIONS

The low-cost laboratory-mounted equipment proved to be versatile for the use of different lighting and capable of taking measurements of the main parameters of solar cells. Furthermore, it could be observed that the main photovoltaic parameters are strongly altered according to the type of lighting, luminous intensity, and distance from the light source. Comparative measures of different cells can be taken by fixing these variables.

The study of different lighting sources revealed that the silicon solar cell has better efficiency in converting light originated from LED lamps than from other lighting sources due to the irradiance spectrum of the LED lamps that have more suitable photons energies for the formation of electron-hole pairs in the band structure of the material.

As expected, the illuminance has a direct influence on the photovoltaic responses of the silicon cell, and the greater the illuminance for the same type and light source, the greater the values of short-circuit current, voltage and power generated.

The fill factor of the curves was dependent on both the type of light source and the light intensity of the source. It could be clearly observed that by reducing the number of LED or CFL lamps, the fill factor increases. The sun, with high illuminance (28500 lx) had the smallest fill factor, despite the higher short circuit current, voltage and power generated.

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