



Photovoltaic Modules for Indoor Energy Harvesting

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ABSTRACT

This paper presents the performance of indoor energy harvesting systems based on different photovoltaic modules (monocrystalline silicon, polycrystalline silicon, amorphous silicon and polymer) and artificial electric lighting sources (spot, incandescent, fluorescent and cool white flood LED). In this concern, it is clearly proved that, maximum output power densities to be harvested from the photovoltaic module depends mainly on the spectral responses of both the light source and the module material. Herein, and from the study, experimental work, results and analysis, it is clear that monocrystalline silicon is the optimum solution for all light sources, followed by polycrystalline silicon, whenever used with spot-and incandescent - lamps. On the other hand, amorphous samples were proved to be lightly sensitive to fluorescent light and cool white flood LED. Finally, polymer samples were weakly responded whenever exposed to any of the investigated light sources.

Keywords

Energy harvesting, solar modules, artificial lights, output power densities, emission spectra.

INTRODUCTION

Energy-harvesting systems that convert ambient energy to usable electrical power have emerged as a potential alternative to wired and battery power [1]. Indoor photovoltaic harvesters will soon be playing a major function in supplying energy to low operation power sensors and wireless devices, especially if photovoltaic technology can be advanced and customized for these applications. This is due to the widespread accessibility of light as an energy source inside residential and commercial buildings [2]. Thus, we concluded that by placing the solar cells behind (covered part) the tube light, we can absorb all the photons emitted from the backside of tube light and some amount of electricity can be generated with the help of those emitted photons. Furthermore, that generated electrical energy can be stowed in rechargeable batteries or a power bank. This energy can then be used to power the tube light in the absence of a power supply. Hence, energy can be successfully harvested and recycled using artificial lights [3]. The growth of a light harvesting technology that transports remarkable output power in indoor and low-level light conditions has tremendous potential for application in the area of domotics and building management systems [4].

Of major significance to energy harvesting powered devices is that the solar harvester selected will harvest sufficient energy when deployed irrespective of the light source producing the illumination [5]. Many different solar cell technologies have been progressing and optimized for energy harvesting from either natural or artificial light; the output power of a solar cell is influenced by the spectral composition of the incident light. Energy harvesting powered devices will not operate if the solar cell cannot harvest adequate energy, which may happen if the solar cell is optimized for a different light source

[6]. Thus this paper studies the difference in output power of solar modules under different artificial lighting sources and aims to aid the selection of devices deployed in buildings. The four different types of solar module (monocrystalline silicon, polycrystalline silicon, amorphous silicon and polymer) were selected because they represent the main types available. Four important artificial light sources were tested: spot lamp, incandescent lamp, fluorescent lamp and white flood LED, typically encountered within buildings, for various illumination levels.

1 TYPES OF ARTIFICIAL LIGHT SOURCES AND SOLAR MODULES USED

1.1 Artificial light sources

Artificial sunlight is using the light sources to simulate sunlight which is naturally produced, where the unique characteristics of sunlight are needed. The artificial light sources could be included spot bulbs, incandescent bulbs, fluorescent tubes and light-emitting diodes (Fig. 1). They cannot reproduce the exact sunlight spectrum (300-1000 nm), however, there are available commercial bulbs that approximate this spectrum to a very satisfactory degree. Feature of the proposed artificial light sources could be summarized as follows:

- **Spot lamps** (incandescent light bulbs with reflector), which has a reflection surface that allows light to be focused as a flood or spot.
- **Incandescent lamp**, represented by a 75 Watt on a color temperature (CT) of 2856 K.
- **Fluorescent lamp** with a correlated color temperature of 4230 K. They make up the majority of office illumination.
- **Cool white flood LED lamp**, a light source that nowadays is gaining ground is the Light Emitting Diode (LED) light. A LED lamp is a solid-state lamp that uses the electroluminescence of a band gap material to emit light. LEDs only emit light within a very small band of wavelengths (i.e., one color) [7].

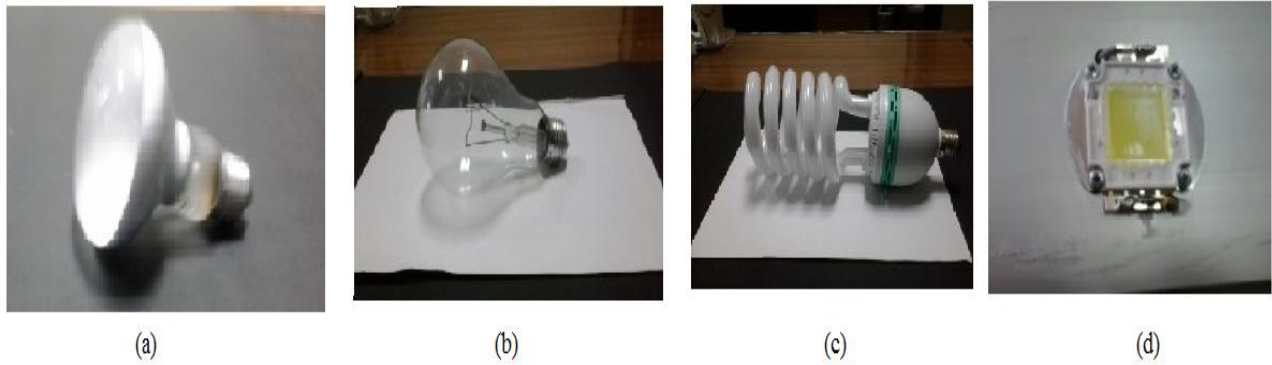


Fig. 1: Artificial light sources including (a) spot-, (b) incandescent-, (c) fluorescent-bulbs and (d) cool white flood LEDs

1.2 Utilized solar modules

Many different solar cell technologies have been developed and optimized for energy harvesting from either natural or electrical light sources. The spectral composition of the incident light mainly affects the output power density of solar cells [8]. The four different types of solar modules used in this work were selected owing to a range of the types used in supplying energy to low operation power sensors and wireless devices; they are made from different materials optimized for use either indoors or outdoors. The key details of the selected four solar modules are shown in Table (1) and Fig. (2).

Table 1. Details of the selected solar modules.

Model No.	Material	Use	Dimensions	Open Circuit Voltage	Short Circuit Current
E-19	Monocrystalline Silicon	Indoor and outdoor	80x60x2.7 mm	6.0 V	130 mA
15870	Polycrystalline Silicon	Indoor and outdoor	112x84x3.0 mm	6.0 V	200 mA
E-28	Amorphous Silicon	Indoor	27x27x1.1 mm	4.0V	9.1 μ A
Power Plastic Type 20	Polymer	Indoor and outdoor	155x90x0.5 mm	11.30 V	106 mA

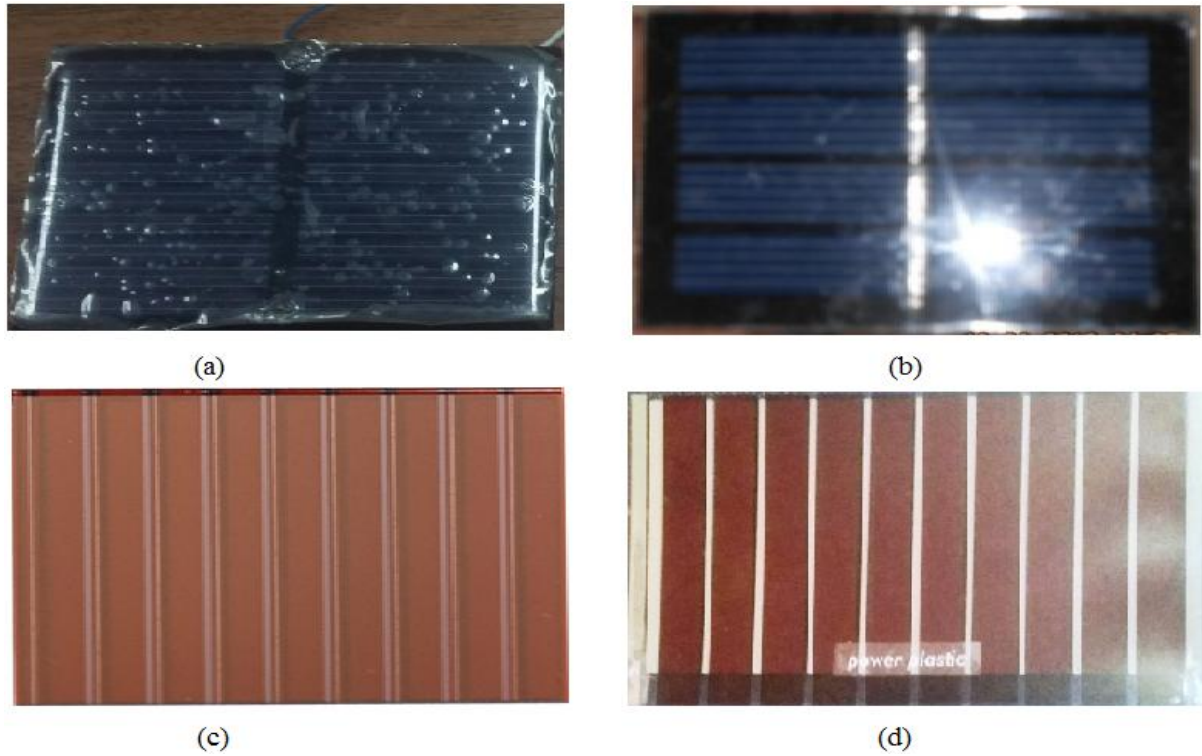


Fig. 2: E-19 (mono-crystalline) Si- solar module (a), 15870 (polycrystalline) Si-solar module (b), E-28 (amorphous) Si- solar module (c) and Power Plastic Type 20 (Konarka polymer) solar modules (d)

2 EXPERIMENTAL PROCEDURES

There are four categories of indoor lighting bulbs: spot, incandescent, fluorescent and white flood LED. The solar modules are placed in a horizontal position (parallel to the light source). Fig. (3) shows the schematic of the experiment, where digital luxmeter was used for precise measurements of illumination levels. Finally, output power density of the solar modules was plotted against its operating current applying the different artificial light sources.

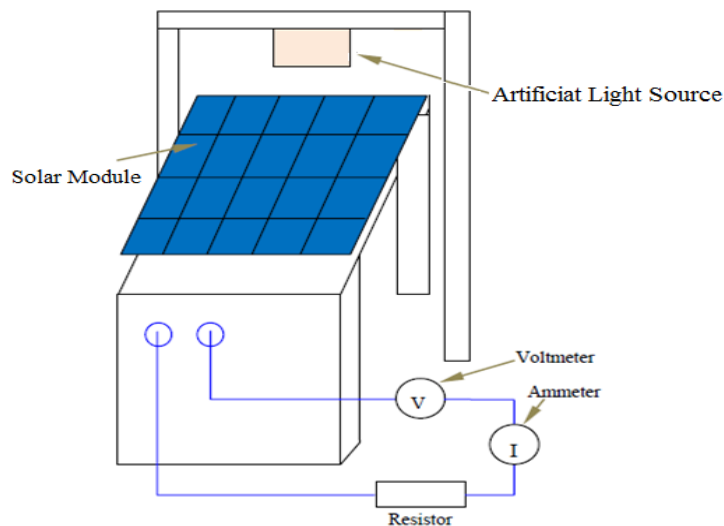


Fig. 3: Setup up used for studying the characteristics of the different solar modules

3 RESULTS AND DISCUSSIONS

3.1 Output power densities under different illumination sources

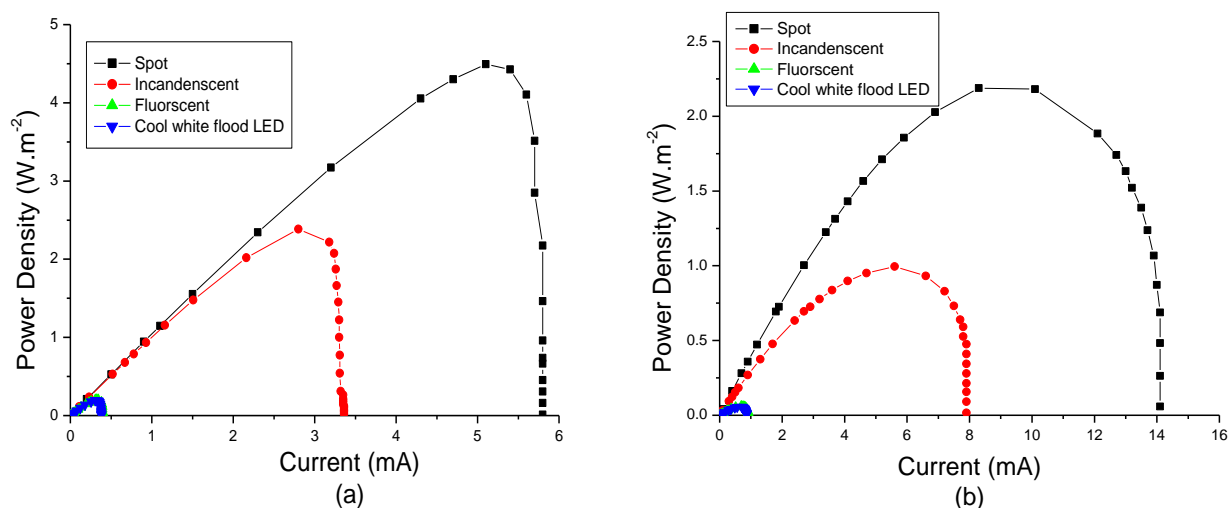
The output power density of each solar module is measured under the four different artificial light sources; spot, incandescent, fluorescent and cool white flood LED. The output power density versus the output current as the load resistance is varied of the monocrystalline silicon, polycrystalline silicon, amorphous silicon and polymer solar modules under four different illumination sources at 700 lux are shown in Fig. (4). Table (2) illustrates the maximum output power density of the proposed solar modules under the proposed artificial light sources at 700 lux. From which, it is clear that monocrystalline silicon is the optimum solution for all light sources, followed by polycrystalline, whenever used with spot- and incandescent - lamps. On the other hand, amorphous samples were proved to be lightly sensitive to fluorescent light and cool white flood LED. Finally, polymer samples were weakly respond whenever exposed to any of the investigated light sources.

To summarize the results from the tests of the solar module types under the four artificial light illumination sources: the devices exhibit their highest power density under illumination from spot and incandescent sources. These results indicate that the wavelengths at which the different solar modules are sensitive are most prevalent in spot light and incandescent light. This is as expected as spot light and incandescent light emission covers a wider spectral range than fluorescent or LED sources which emit over narrower ranges.

Comparing the results for each solar module under the different illumination sources shows that the output power density of the E-19 (monocrystalline silicon) solar module falls significantly when the illumination is changed from spot to incandescent (47% reduction), fluorescent (95% reduction) and white light LED (95.6% reduction) as shown in Fig. (4a). This indicates that the key wavelengths from which the E-19 converts the most energy lie outside of the range of emission of the fluorescent and LED sources. Likewise for 15870 (polycrystalline silicon) solar module also shows a drop in power when changing to incandescent- (55% reduction), fluorescent- (97% reduction) and cool white flood LED- (97.4% reduction) sources (Fig. 4b).

Amorphous silicon is so common, the terms 'thin film' and 'amorphous' are often used interchangeably. As amorphous silicon is less efficient than monocrystalline and poly-crystalline, amorphous modules need to have a large surface area in order to generate the same power output [9]. The E-28 (amorphous silicon) solar module shows a drop in power when changing to incandescent, fluorescent and cool white flood LED sources, but with less marked reductions of 4.5%, 27% and 32%, respectively (Fig. 4c). As well, for the E-28 the reductions are less than for the E-19 and 15870 solar modules. However the output density from the tested E-28 is nearly similar under all four tested illumination sources encountered in buildings.

Finally the Power Plastic Type 20 (polymer) solar module has lower output power densities for each light source than all the other types tested. Changing to incandescent, fluorescent and cool white flood LED lighting sources causes corresponding reductions in level of 21%, 63% and 65% from that seen with the spot source as shown in Fig. (4d).



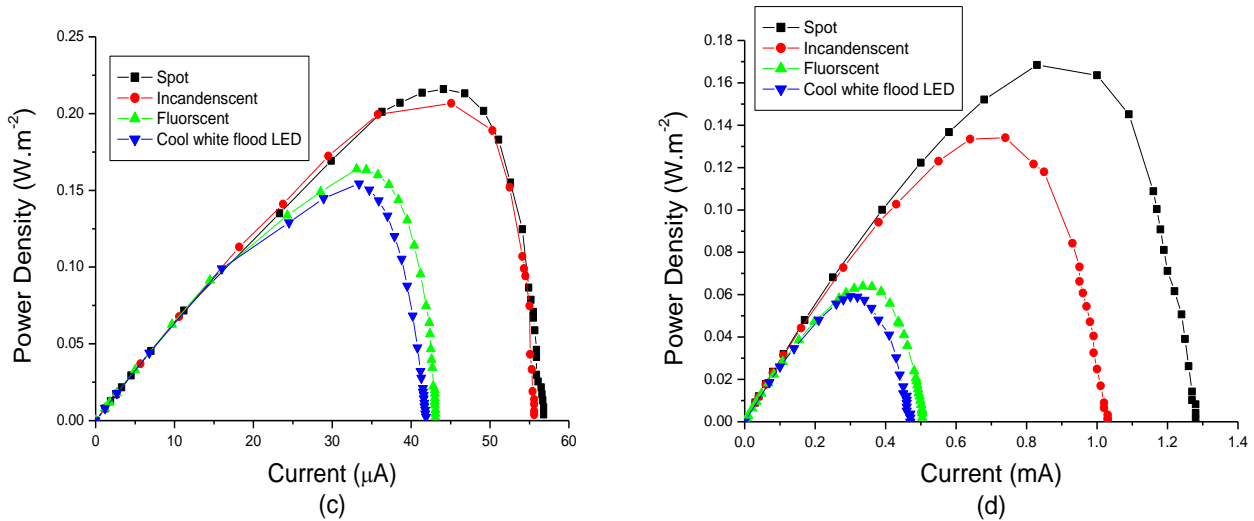


Fig. 4: Harvested power density at 700 lux for (a) E-19 (monocrystalline silicon) solar module, (b) 15870 (polycrystalline silicon) solar module, (c) E-28 (amorphous silicon) solar module and (d) Power Plastic Type 20 (polymer) solar module

Table 2. Maximum output power density of the proposed solar modules Under the proposed artificial light sources at 700 lux.

Materials Artificial light sources	Spot	Incandescent	Fluorescent	Cool white flood LED
	Monocrystalline	4.5 W.m ⁻²	2.4 W.m ⁻²	0.21 W.m ⁻²
Polycrystalline	2.2 W.m ⁻²	0.99 W.m ⁻²	0.06 W.m ⁻²	0.056 W.m ⁻²
Amorphous	0.22 W.m ⁻²	0.21 W.m ⁻²	0.16 W.m ⁻²	0.15 W.m ⁻²
Polymer	0.17 W.m ⁻²	0.134 W.m ⁻²	0.063 W.m ⁻²	0.059 W.m ⁻²

From the given results, the histograms shown in Figs. (5, 6) illustrate the calculated electrical parameters, fill-factor (FF) and efficiency (η) using Eqs. (1 and 2) [10, 11] of the four solar modules, plotted at 700 lux, under the influence of the different artificial light sources. For the E-19 silicon solar module the fill factor value varies within the range from 0.61 up to 0.73, for the 15870 silicon solar module the fill factor varies from 0.38 up to 0.48, for the E-28 silicon solar module the fill factor varies from 0.46 up to 0.49 and, finally, for the Power Plastic Type 20 solar module the fill factor varies from 0.42 to 0.43 with varying artificial light sources from spot lamp to cool white flood LED.

$$FF = \frac{V_{MP} * I_{MP}}{V_{oc} * I_{SC}} \dots\dots\dots (1)$$

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{oc} * I_{SC} * FF}{P_{in}} \dots\dots\dots (2)$$

Where:

V_{oc} : open-circuit voltage,

I_{sc} : short-circuit current,

V_{MP} : maximum voltage,

I_{MP} : maximum current

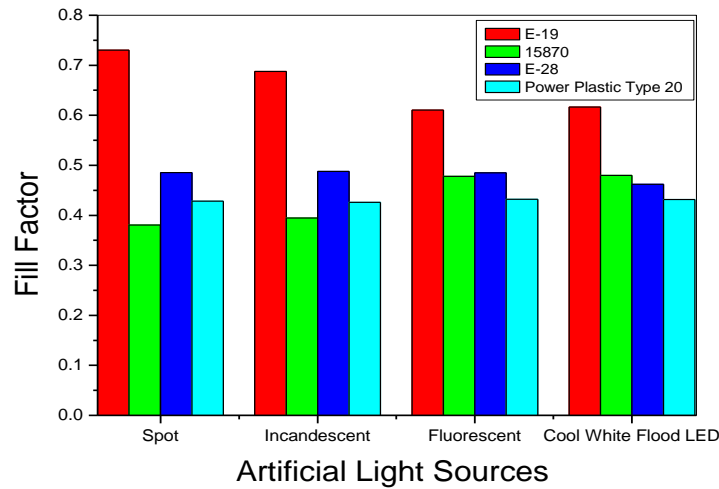
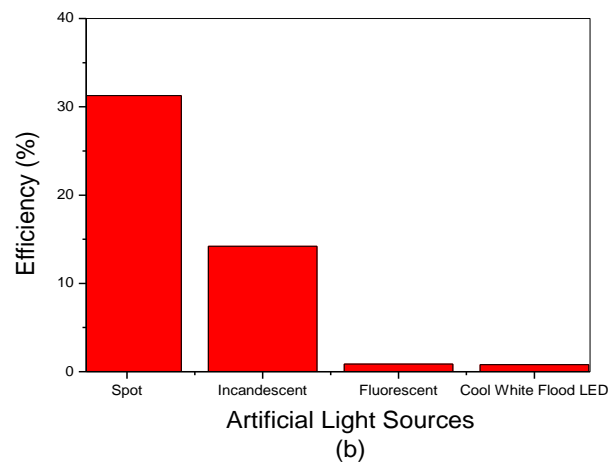
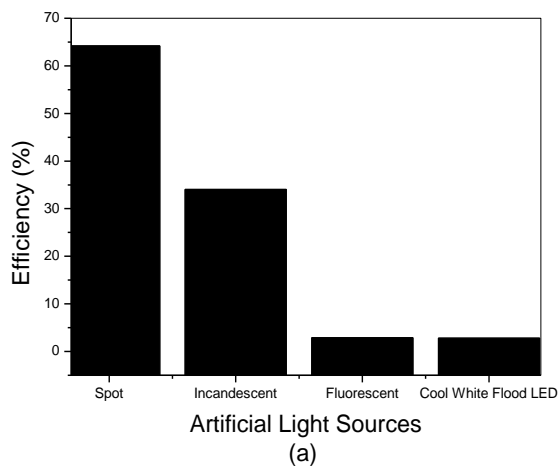


Fig. 5: Histograms showing the fill-factor parameter of monocrystalline Si-module, polycrystalline Si-module, amorphous Si-module, and polymer module, plotted at 700 lux for different artificial light sources

As each solar module has a different size, so the conversion efficiency was used as comparison factor throughout the present part of the work. Herein, it is clearly shown that, the conversion efficiency of the investigated samples is a direct function of the construction of the module and its material as well the type of the artificial light sources. Figure (6) shows the efficiency of the proposed solar modules based on artificial light sources. The E-28 silicon solar module was shown to be the most efficient of the four modules and nearly unaffected by varying artificial light sources. The E-19 silicon solar module, the 15870 silicon solar module and Power Plastic Type 20 solar module have high efficiency with spot lamp and low efficiency with cool white flood LED lamp.



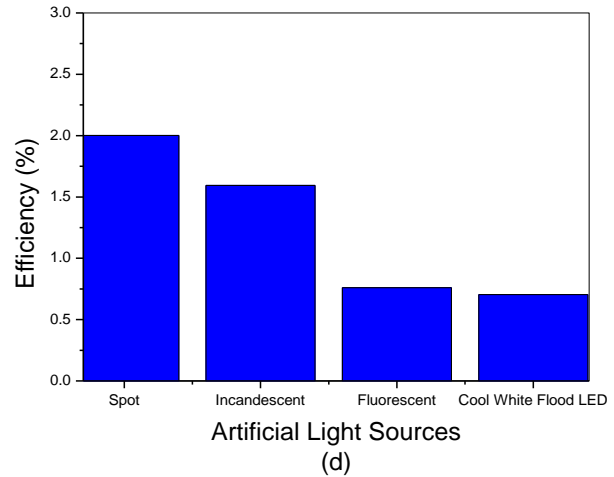
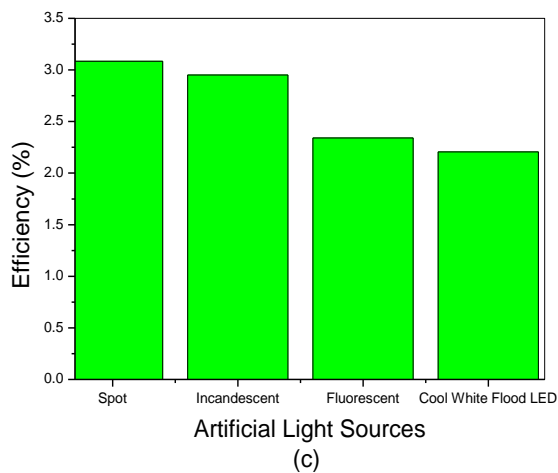


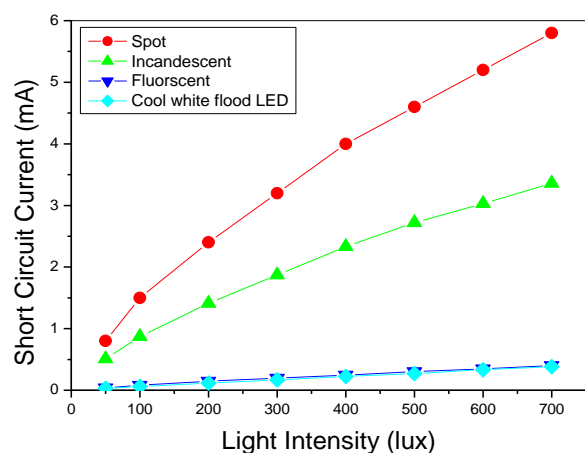
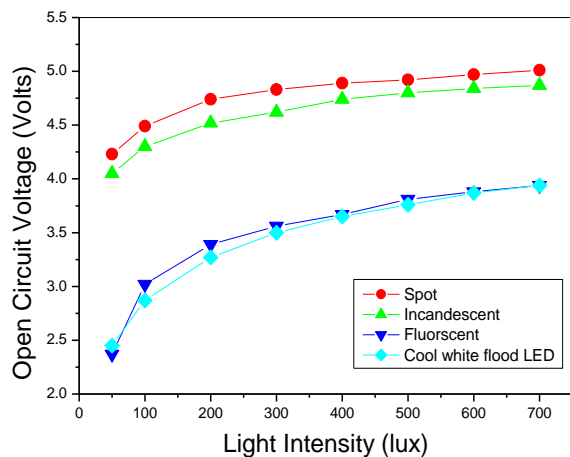
Fig. 6: Dependence of efficiency for the E-19 silicon solar module (a), the 15870 silicon solar module (b), the E-28 silicon solar module (c) and Power Plastic Type 20 solar module (d), plotted at 700 lux for different artificial light sources

3.2 Effects of illumination levels

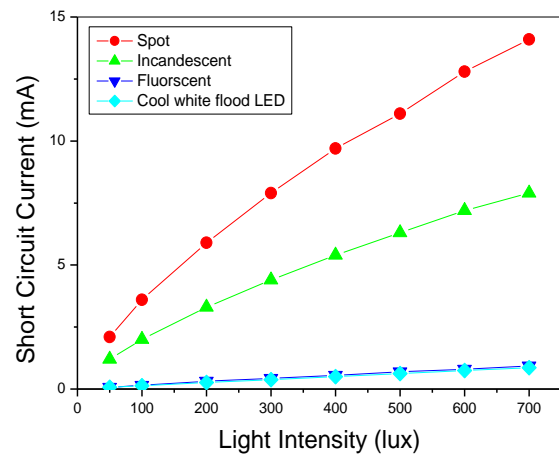
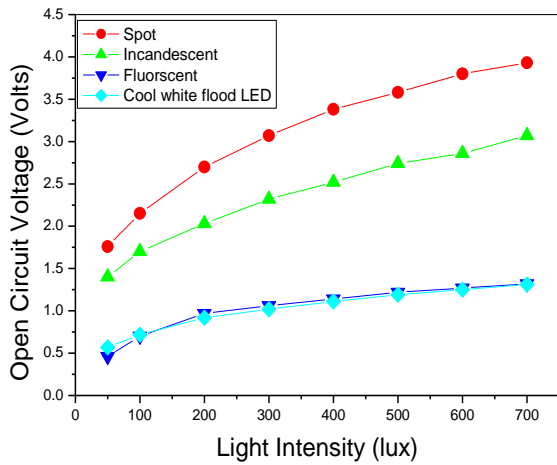
Figures (7 and 8) show the lighting intensity dependences of both the open circuit voltage and short circuit currents, for the proposed solar modules, plotted for different artificial light sources. From which, it is clearly shown that:

- For the E-19 and the 15870 silicon solar modules, their open circuit voltage, irradiated under the influence of the proposed four artificial light sources, reach its saturation levels at light intensity of around 200-300 lux. On the other hand, for the E-28 and Power Plastic Type 20 modules, their voltage saturation levels extended up to more than 700 lux.
- Considering the short circuit current of modules, its values go up proportionally with increasing the incident light intensity.

Finally, it is clear that monocrystalline silicon-, polycrystalline silicon- and polymer-modules are sensitive to spot- followed by incandescent lighting and finally with fluorescent- and cool white flood LED -lightings. On the other hand, amorphous silicon module was shown to be approximately sensitive at the same degree, within few deviations, to all lighting sources.

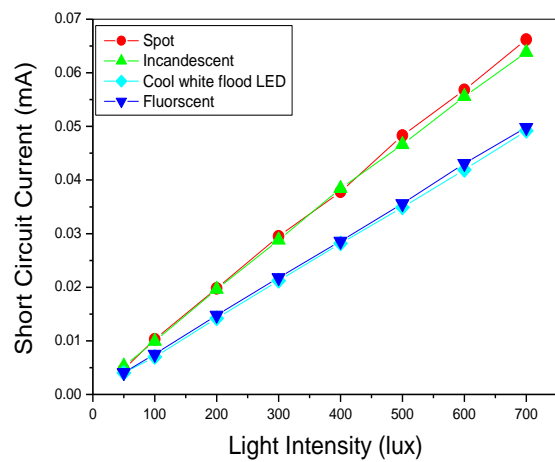
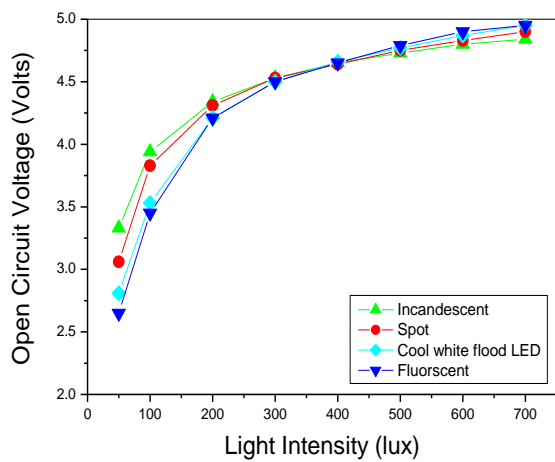


(a)



(b)

Fig. 7: Light intensity dependence of open circuit voltage and short circuit current of E-19 silicon solar module (a) and 15870 silicon solar module (b), plotted for different artificial light sources



(a)

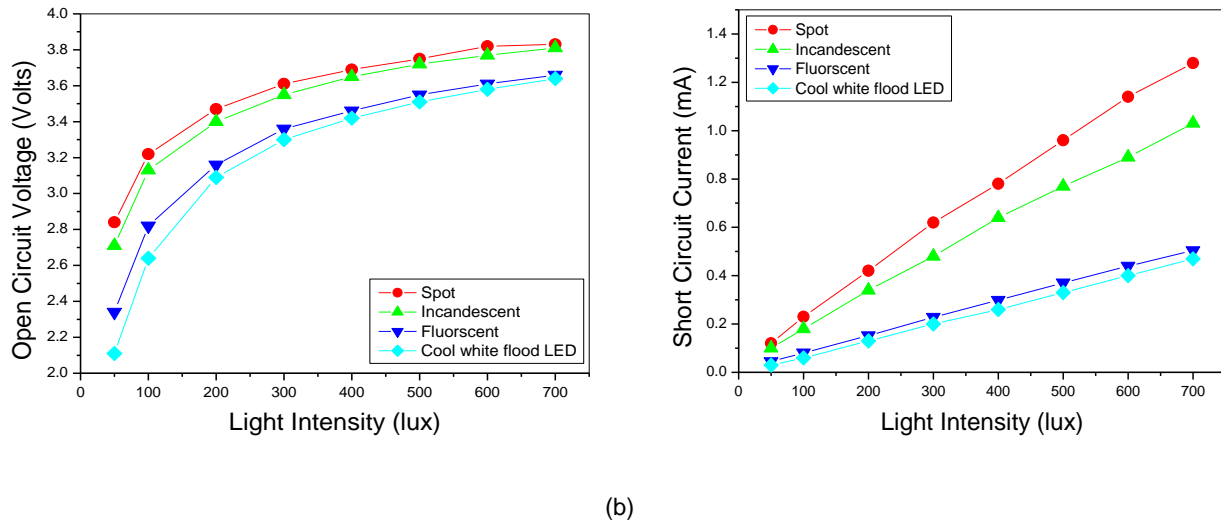


Fig. 8: Light intensity dependence of open circuit voltage and short circuit current of E-28 silicon solar module (a) and Power Plastic Type 20 solar module (b), plotted for different artificial light sources

4 CONCLUSIONS

In conclusion, the solar modules generally harvest less power under fluorescent and cool white flood LED than spot, incandescent artificial light sources. The detrimental effect of upgrading to higher efficiency illumination sources on the performance of solar energy harvesting devices has been evaluated. In general cases, most power is harvested by solar modules under spot illumination sources followed by incandescent illumination sources and then fluorescent and cool white flood LED. The large difference in output power density of the monocrystalline silicon, polycrystalline silicon solar modules and polymer module between spot, incandescent and fluorescent /cool white flood light LED sources could restrict operation to just spot lighting and incandescent lighting. Indoor energy harvesting devices based on this type of solar module will perform poorly if the lighting source is upgraded to fluorescent or cool white flood light LED. The amorphous-Si solar module tested (E-28) shows a nearly similar power density output under all four tested illumination sources encountered in buildings, therefore, for general use electrical lighting sources, a solar module based on amorphous silicon will perform satisfactorily under all lighting sources.

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