ABSTRACT
This paper presents the performance of solar cells under different electric lighting sources in indoor environments. Experiments are conducted for different solar technologies like polycrystalline Silicon, Amorphous Silicon and Dye-Sensitized. Measurements are done under illumination from incandescent, fluorescent and LED light sources in this paper. Also, simulations are done to find out the maximum power points of different solar cells under different electrical light sources. And, the output power densities of four types of solar cells have been investigated under three illumination sources encountered in buildings. The results confirm aforementioned significant difference between incandescent, fluorescent and LED light sources.

Keywords: indoors, solar cells, output power densities, energy harvesting, lighting sources.

1. INTRODUCTION
Energy harvesting powered devices has the potential for widespread use in buildings as sensors in indoor systems. For mains powered devices, harvesters offer an alternative which avoids the installation and material costs of power supply cables. For battery powered installations, harvesters offer more environmentally friendly solutions and do not need periodic replacement since long lifetimes can be achieved. Maintenance costs associated with the replacement of batteries and service interruptions due to depletion of batteries can be avoided by employing self-powered devices. A harvester-based approach also improves the flexibility of a building management system; for example a sensor node can be easily relocated with minimal effort as there is no fixed wiring to alter and the location information of the corresponding sensor can be easily updated in the control software with no need to change the fixed infrastructure. However, clearly the operation of self-powered devices is limited by the amount of ambient energy that they can harvest from their local environment.

The most prevalent ambient energy source available in buildings is light, which can be harvested using photovoltaic devices. The light can be from both natural and electrical sources and a range of different types of solar cell are available to suit differing light sources and intensities. These must be selected to suit the type of light and its intensity. Inside buildings, there is limited or no natural light in some locations or at some times. When natural solar energy is not available, photovoltaic devices must rely on electrical light sources and therefore the solar cell must operate efficiently under electrical lighting. The nature of electrical light sources is changing over time from incandescent sources, through fluorescent lights, with LED lights currently attracting significant interest due to energy savings. This impacts on the selection of the solar cell to achieve an optimum solution since the spectrum and intensity of the light source depends on its type.

For illumination systems in buildings, the light level should be constant irrespective of the type of source used, but the amount of energy harvested by a photovoltaic device will change depending on the light source type, even for an identical light intensity. Of major importance to energy harvesting powered devices is that the solar harvester selected will harvest sufficient energy when deployed irrespective of the light source providing the illumination. A danger is that a solar cell based energy harvester will work perfectly with a specific light source, upon installation, but, when the building occupant changes the type of light source, for example when the bulb expires, the harvester produces insufficient energy for operation. This paper provides general guidelines in harvester design to mitigate this risk.

An investigation of the difference in the energy harvested, caused by changing the electrical lighting source is presented in detail in this paper. This work investigates the output power achievable from four types of solar cell under three different electrical illumination sources: incandescent (halogen), compact fluorescent lamp (CFL) and LED (white light LED and colour-controllable LED), typically encountered within buildings, for various illumination levels. Within the LED lighting category both a standard white light LED device and an RGB colour controllable LED have been utilised. The use of the RGB source permits the analysis of the effect of varying the illumination spectra from a nominally white spectrum.
In buildings the illumination system accounts for approximately 9% of residential electricity use and 40% of commercial electricity use. Incandescent light bulbs waste over 90% of their input energy as heat. By upgrading incandescent lamps to CFL or white light LED, on average 70% or 85%, respectively of the previous energy consumption, can be saved. Therefore in many situations lighting installations are being upgraded from incandescent lamps to save both energy and money.

Examples of the typical illumination sources used in this work are shown in Figure-1.

Because the different lamp types used utilize different emission methods to produce their illumination, the spectral content of the emitted light varies between the lamp types. The 20 W incandescent dichroic reflector lamps has a color temperature (CCT) of 2800 K, the 11 W CFL lamp has a CCT of 6400 K, and the 1 W white light LED lamp has a CCT of 3500 K. For comparison purposes in this paper the natural solar light is measured indoors in an open plan space with the light passing through double glazed windows with glass that is treated to reduce solar heating effects.

![Figure-1. Typical illumination sources, from left to right: 20 W incandescent lamp, 11W CFL lamp, 1W white light LED lamp, 6W RGB colour controllable LED lamp.](image)

Color-controllable LEDs in a directly interchangeable format are a recent addition to the lighting market. In addition to the basic lighting function they can also be used to change the color of an environment for entertainment or recreational purposes such as changing the illumination color to fit a particular mood or activity. These lamps are usually remotely controlled, either using a specific wireless remote controller or from a Wi-Fi or Bluetooth enabled device such as a smart phone or tablet.

### Table-1. Details of the selected solar cells including the use for which each one is optimised.

<table>
<thead>
<tr>
<th>Model</th>
<th>Material</th>
<th>Use</th>
<th>Manufacturer</th>
<th>Appearance</th>
<th>Active area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC-SP0.8</td>
<td>Polycrystalline silicon</td>
<td>Outdoor</td>
<td>Multicomp</td>
<td></td>
<td>68.64</td>
</tr>
<tr>
<td>AM-5608</td>
<td>Amorphous silicon</td>
<td>Outdoor</td>
<td>Panasonic</td>
<td></td>
<td>20.28</td>
</tr>
<tr>
<td>AM-1815</td>
<td>Amorphous silicon</td>
<td>Indoor</td>
<td>Panasonic</td>
<td></td>
<td>25.2</td>
</tr>
<tr>
<td>Indy4050</td>
<td>Dye-sensitized (flexible)</td>
<td>Indoor and outdoor</td>
<td>G2Ni</td>
<td></td>
<td>30.5</td>
</tr>
</tbody>
</table>

B. Solar cells utilised

Many different solar cell technologies have been developed and optimized for energy harvesting from either natural or electrical light. One of the parameters influencing the output power density of a solar cell is the spectral composition of the incident light. Therefore, for example, the output power density of an outdoor type solar cell can decrease dramatically when the light source is changed from natural to electrical due to the differing spectra. Energy harvesting powered devices will not operate if the solar cell cannot harvest sufficient energy, which may occur if the solar cell is optimized for a different light source. The four different types of solar cells used in this work were selected because they represent a range of the types used in smaller devices; they are made from different materials optimized for use either outdoors or indoors. The key details of the selected four solar cells are shown in Table-1.

The MC-SP0.8 solar cell from Multicomp is made from poly-crystalline silicon which is widely used in the production of solar cells and has a spectral sensitivity designed to match the wavelengths present in sunlight. It is therefore suited to providing power in outdoor applications where the typical illumination levels are in the range of 1000–100,000 lx. This mature technology has a best achievable efficiency of 14% under standard Air Mass (AM)-1.5 test conditions.

The AM-5608 solar cell from Panasonic, made from amorphous silicon, is used for outdoor applications under illumination levels in the range of 1200 to 100,000 lx. Amorphous silicon is defined as a non-crystalline silicon material; the best efficiency it can achieve under standard AM-1.5 test conditions is 13.4%. The highest
efficiency is achieved when it is operating under specific illumination levels, for which it is optimized.

The AM-1815 solar cell from Panasonic is also made from amorphous silicon but is designed for indoor applications under lower illumination levels in the range of 20–1000 lx. The best achievable efficiency for the material is 13.4%, as for the AM-5608.

The Indy4050 is a flexible solar cell from G24i utilising dye-sensitized solar cell (DSSC) technology. The DSSC has a best achievable efficiency of 11.4% under standard AM-1.5 test conditions. It has high flexibility of up to 10,000 flexures around a 25 mm radius with no measurable drop in performance. Since no glass components are used, the panel has high durability to impact and its working conditions range from 200 lx to 1000 lx. It is also thin, lightweight and water resistant.

The different types of solar cells have differing spectral sensitivities. A comparison between those of the amorphous silicon, poly-crystalline silicon, and dye-sensitized types is presented in Figure-2.

3. EXPERIMENTAL PROCEDURE

Measurements were performed in an opaque enclosure to shield the solar cell from ambient light. The light source was mounted inside the enclosure, and the solar cells situated at the center point of the illumination as shown in Figure 3(a) & (b).

The measurements were performed as follows:

a) Mount the solar cell and light source into the opaque enclosure and allow the output from the light source to stabilize.

b) Adjust the illumination level on the solar cell to the desired lux level by changing the distance or filters between the solar cell and the lamp placed at the location the solar cell is to be located at to measure the illumination level. Once the desired illumination level is obtained the light meter is replaced by the solar cell under test.

c) Vary the load on the output of the solar cell and record the output voltage from the solar cell and the resistance of the load.

d) Use the load resistance and output voltage values to calculate the output power density of solar cell.

e) Plot the output power density of the solar cell against its operating current.

f) From the output power density plot, locate the maximum power density point of the solar cell and the range of output currents at which solar cell can provide at least 90% of the maximum power density.

A multilayer filter was used in conjunction with varying the separation between the source and solar cell to enable the desired illumination levels to be achieved. The filter material was used to add additional attenuation in the case of sources which provided a higher illumination level than was required at the target with the source and solar cell at maximum separation. The filter material used shows a uniform spectral response over the spectral range of 400–900 nm.

The solar cell power output is loaded using a resistance box to allow adjustment of the load current. The voltage across the load is measured with an A/D convertor, and the output power density of each solar cell is then calculated using Eq. (1).

\[
E_d = \frac{V_{Cell}^2}{A_{Active}} \cdot \frac{R_{Load}}{A_{Active}}
\]  

Figure-2. Spectral sensitivity of poly-crystalline silicon, amorphous silicon and dye-sensitized solar cell types.
In this paper, the three white light sources (incandescent, CFL and white light LED) are investigated at three lux levels: 1000 lx representing well illuminated conditions; 500 lx as the normal lighting condition on a desk surface and 200 lx representing ambient lighting. The three primary colours of the colour-controllable LEDs are also investigated but only at 200 lx because of the limited output power of the lamps currently commercially available.

![Figure-3](a) Deployment of the experiment (a) opaque enclosure and lamp holder and (b) filters to adjust the luminance level.

![Figure-4](MC-SP0.8)

![Figure-5](AM-5608)

![Figure-6](AM-1815)

![Figure-7](Indy4050)

4. OUTPUT POWER DENSITIES UNDER DIFFERENT ILLUMINATION SOURCES

A. White light from different sources

The output power density of each solar cell is measured in the first test under the three white light sources, incandescent, CFL and LED. The output power density versus the output current as the load resistance is...
varied of the MC-SP0.8, AM-5608, AM-1815 and Indy4050 under three different illumination sources at 500 lx are shown in Figures 4-7, respectively.

To summarize the results from the tests of the solar cell types under the three white-light illumination sources: the devices exhibit their highest power density under illumination from an incandescent source, with the exception of the AM-1815 which exhibits its optimum performance under fluorescent lighting. These results indicate that the wavelengths at which the different solar cells are sensitive are most prevalent in incandescent light. This is as expected since incandescent light covers a wider spectral range than CFL or LED sources which emit over narrower ranges.

Comparing the results for each solar cell under the different illumination sources shows that the output power density of the MC-SP0.8 falls significantly when the illumination is changed from incandescent to CFL (95% reduction) and white light LED (96% reduction). This indicates that the key wavelengths from which the MC-SP0.8 converts the most energy lie outside of the range of emission of the CFL and LED sources. The AM5608 solar cell also shows a drop in power when changing to CFL or LED sources, but with less marked reductions of 10% and 47% respectively. Likewise for the AM1815 the reductions are less than for the MC-SP0.8, however the highest output density if achieved for the CFL illumination; this is attributable to the spectral sensitivity of the AM1815 being optimised for operation under electrical lighting such as CFLs. Changing from CFL to incandescent and LED lighting causes reductions in maximum output power densities of 22% and 44% respectively.

Finally the Indy 4050 flexible solar cell has lower output power densities for each light source than all the other types tested, with an average of 60% lower power densities, although the difference in maximum output density is less than was experienced with the other types of solar cell. Changing to CFL and LED lighting sources causes corresponding reductions in level of 11% and 22% from that seen with the incandescent source. 60% lower power densities, although the difference in maximum output density is less than was experienced with the other types of solar cell. Changing to CFL and LED lighting sources causes corresponding reductions in level of 11% and 22% from that seen with the indcandescent source.

B. Operational output current range

Energy harvesting devices do not operate at the MPP all the time. Circuits are available to operate solar modules at close to the MPP by actively modifying the load, but these require power to operate and so reduce the overall efficiency of an energy harvesting system. In cases, such as use indoors under low levels of illumination, the available energy may be constrained to the extent that it is not acceptable or practicable to accommodate the additional energy overhead associated with an MPP tracking circuit.

Instead it may be necessary to fix the operational point such that the device is operating close to the MPP under the most commonly encountered operational conditions. In this case it is necessary to use a measure of how well the energy harvester performs when it is not at the ideal load. In this paper the range of output currents at which the harvester provides at least 90% of the maximum power density, under the light source of interest, is used to gauge how robust a device is when deployed in different conditions. The output current from each solar module was measured from zero (open circuit) to the maximum current (low load resistance) at which the output power density of solar cell is less than 10% of that at the MPP. Table-2 shows the range of output currents at which the solar cells can generate at least 90% of the power density at the MPP for the illumination source being tested at an illumination level of 500 lx.

All the solar cells tested can provide a range of more than 20% of the available output currents in which they harvest solar energy with an output power density of at least 90% of the power density at the MPP, except for the Indy4050 which only achieves 15.2% of the output currents under white light LED lighting. This shows that if the harvester is to operate under LED lighting sources, and it is not practicable to use a MPP tracking circuit, that the other types of solar cells tested should be chosen in preference to the dye-sensitized Indy4050 as they have a wider operating range around their MPP and would perform better in a fixed operating point situation. The power densities of the solar cells at their MPP are shown in Table 3 for the incandescent light source, the fluorescent light source, and the white LED light source. We have identified the following uncertainties in the measurement process:

- The light meter has a specified accuracy of ±3% of the reading plus ±0.5% of the full scale of the range in use.
- The sensor is calibrated for a specific colour temperature source, with a bias error for other colour temperatures.
- The sensor is temperature sensitive with an error of ±0.1% C⁻¹. Therefore temperature variations during measurements were minimised.
- The A/D convertor is specified to have an absolute accuracy of 14.7 mV over a full measurement range of ±10 V (0.074% of full scale).
- The resistance box has an accuracy of ±1%.
measurements. Under the incandescent light source, the MC-SP0.8 performs best at all illumination levels, with an output power density 8-23 times greater than the other three solar cells. The output power densities of the MC-SP0.8, AM-5608 and AM-1815 are similar under fluorescent and white light LED light sources. However the Indy4050 can only generate 35% of the output power density of the AM-5608 and AM-1815 under fluorescent lighting at 1000 lx, and 66% of the AM-1815’s output power density under the white light LED at 1000 lx.

C. Three primary colours from the colour-controllable LED

To assess the effects of the changing source spectra provided by the colour controllable LED, the performance of the solar cells under illumination with a selection of different spectral ranges has been measured. These tests measured the output power densities from the solar cells under only the red, green or blue primary colours from the colour-controllable LED. As this new kind of light is designed to change the colour of an environment for entertainment or recreational purposes, it has limited power. Only 200 lx can be achieved by any one of the three primary colours in the lamp tested. To achieve illumination levels of 500 and 1000 lx, it would be necessary to use more than one such colour-controllable LED unit. Of course this will not change the spectral distribution of the LED

<table>
<thead>
<tr>
<th>Power density (µW cm⁻²)</th>
<th>Incandescent source</th>
<th>Fluorescent source</th>
<th>White LED source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200 lx</td>
<td>500 lx</td>
<td>1000 lx</td>
</tr>
<tr>
<td>MC-SP0.8</td>
<td>5.0</td>
<td>10.0</td>
<td>15.0</td>
</tr>
<tr>
<td>AM-5608</td>
<td>4.5</td>
<td>9.0</td>
<td>13.5</td>
</tr>
<tr>
<td>AM-1815</td>
<td>4.0</td>
<td>8.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Indy4050</td>
<td>3.5</td>
<td>7.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Table-3. Maximum output power densities of solar cells under various light sources.

Figure-8. Harvested power density at 200 lx for MC-SP0.8.

Figure-9. Harvested power density at 200 lx for AM-5608.

Figure-10. Harvested power density at 200 lx for AM-1815.

Figure-11. Harvested power density at 200 lx for Indy4050.
Table 4 summarizes the output power densities of the solar cells at their MPP under the three primary colours from the colour-controllable LED compared with the same illumination level from the white light LED.

Table 4. Maximum output power densities (µW cm⁻²) of solar cells under 3 colours of LED at 200 lx.

<table>
<thead>
<tr>
<th>Solar cell module</th>
<th>Maximum output power densities (µW cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Red</td>
</tr>
<tr>
<td>MC-SP0.8</td>
<td>8</td>
</tr>
<tr>
<td>AM-5608</td>
<td>9</td>
</tr>
<tr>
<td>AM-1815</td>
<td>6</td>
</tr>
<tr>
<td>Indy4050</td>
<td>2</td>
</tr>
</tbody>
</table>

Under the blue illumination, all the solar cells provide a higher output power density than green and red (7–38 times) at 200 lx. This is attributable to the lux levels used being referenced to the human eye’s wavelength sensitivity and the corresponding lower sensitivity exhibited by the eye to wavelengths in the blue region. Therefore to give the same perceived illumination and lux level a greater level of optical energy is needed.

5. CONCLUSIONS

Ambient light energy in buildings is a more consistently available energy source for self-powered devices than other ambient energy sources such as vibration or thermal energy, as the majority of daytime activities require the presence of suitable illumination levels. The solar cell selected to be used as the power supply for energy harvesting devices should harvest sufficient energy to operate robustly when deployed, irrespective of the type of light source providing the illumination. The investigation in this paper is therefore based on typical levels of illumination in buildings, and has shown the practical effects of changing the type of illumination sources used on the output power densities of selected types of solar cells. A change in the type of illumination source used causes a change in the radiant spectra of the ambient light. A solar cell can harvest more power when its spectral sensitivity, which is defined by its active materials, fits the radiant spectra of ambient light sources.

The output power densities of four types of solar cells have been investigated under three typical illumination sources encountered in buildings. 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 cells under incandescent illumination sources followed by CFL and then LED. The amorphous-Si solar cells tested (AM-5608 and AM-1815) show a similar power output under all three tested illumination sources encountered in buildings, therefore, for general use from both natural and electrical lighting sources, a solar cell based on amorphous silicon will perform satisfactorily under all lighting sources.

The large difference in output power of the polycrystalline silicon solar cell (MC-SP0.8) between incandescent and CFL/white light LED sources could restrict operation to just incandescent lighting. Indoor energy harvesting devices based on this type of solar cell will perform poorly if the lighting source is upgraded to CFL or white light LED.

All the solar cells examined have a region larger than 20% of their operation current area in which their power density is at least 90% of the output power density of that at their MPP with the exception of the DSSC flexible solar cell under the LED light source. The DSSC flexible solar cell harvests least solar energy in all situations but is required in any application needing flexibility, such as mounting onto curved-surfaces.

REFERENCES


