# A STUDY OF DYE SENSITIZED SOLAR CELLS UNDER INDOOR AND LOW LEVEL OUTDOOR LIGHTING: COMPARISON TO ORGANIC AND INORGANIC THIN FILM SOLAR CELLS AND METHODS TO ADDRESS MAXIMUM POWER POINT TRACKING

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ABSTRACT: With increasing applications in consumer electronics such as smart phones, laptops and tablet PCs, the need for pervasive computing with a requirement of lower power consumption is increasing every day, This opens the door for energy harvesting that could charge the batteries in these devices to keep them continually functioning in some useful state. There has been a lot of attention on flexible thin film solar cells, such as dye sensitized (DSSC), organic and inorganic, given their low cost and improving efficiency. Such cells are suitable for these applications both under outdoor and indoor conditions due to their larger spectral response. Understanding the behavior of solar cells such as DSSC under indoor light conditions along with power management algorithms to extract maximize the collected energy is vital for consumer electronics applications. This analysis is compared to organic and inorganic thin film solar cells.
Keywords: Dye-sensitized, Spectral response, Shading, Power Conditioning.

## 1 WHY ENERGY HARVESTING?

With the advent of ubiquitous computing and information exchange through consumer applications using smart phones and laptops to name a few, power consumption requirements are expected to become stringent. Furthermore, the usage of conventional batteries is becoming a concern as it requires constant replacement or maintenance. Energy harvesting has gained a lot of attention to address this challenge. Energy harvesting is defined as the process of utilizing ambient energy to perform functionalities of mobile/small electronic devices. Typical such sources are light, mechanical (vibration), and thermal. Table I summarizes these sources with respect to performance and harvesting techniques to extract each of these energy sources [1]. In addition to performance, other factors such as integration of energy harvesting methods to a self-rechargeable battery, size, shape, weight, mechanical flexibility, water resistance and operating temperature ranges strongly dictate the choice of the energy harvesting methods. While it is clear that all these techniques have the potential and hurdles to climb, solar cells appear to be a preferred choice in many of these applications. Mobile applications are used in locations where there is always some availability of light, thereby making solar cells as a convenient solution. It is important to note that there is a lot of ongoing work on embedding multiple energy harvesting methods into the same system [2, 3], which would ideally be the best solution. The challenge of such systems however is enormous as they involve optimization of power electronics topologies and intelligence to ensure maximum energy extraction and power conditioning. The discussion in this paper is limited to light energy harvesting using solar cells.

## 2 SOLAR CELLS FOR INDOOR APPLICATIONS

Since majority of the mobile devices are primarily used in indoor applications, it is important to understand the behavior of solar cells in indoor lighting.

Currently, crystalline silicon solar cells dominate the solar cell market. However, this technology is targeted for high power outdoor applications due to their coverage of the solar spectrum. On the other hand, the light spectrum is quite different when it comes to indoor applications. Therefore it is vital to look at other cell types that may have a stronger spectral response which in turn has an impact on cell efficiency. The cell efficiency which is defined as the ratio of the solar cell peak output power divided by the incident power on the solar cell is dependent on the lighting source. A significant portion of the spectrum under outdoor light conditions falls in the red region of visible light. It turns out that crystalline silicon has a much stronger spectral response in this region in comparison to lower wavelengths. Whereas, indoor conditions which is primarily fluorescent lighting have a significant portion of the spectrum in the 600 nm range and below. The other indoor lighting source is incandescent. Solar cell technologies based on amorphous silicon (a-Si), organic solar materials (OPV), and dye sensitized materials (DSSC) [4, 5] fit this regime very well. They are therefore thought to be more suitable for indoor applications. DSSC technologies in particular, even though are lagging in conversion efficiencies compared to inorganic cell technologies such as crystalline Si and a-Si, they have the advantages of low cost processing, flexibility, conformabilities to different shapes – a key enabler for consumer applications, light weight and display of different colors.

The goal of this paper is to discuss a quantitative feasibility analysis of DSSC in response to indoor and low light outdoor conditions, while also addressing power management algorithms that help maximize the collected energy. This analysis is compared to organic and inorganic thin film solar cells. Finally, the paper will discuss single and multi-cell topologies and the effect of shading on the robustness of these algorithms.

## 3 MEASUREMENT SETUP

There are three categories of indoor lighting: fluorescent, incandescent, and daylight. Even though a brief comparison will be made across all the three these lighting conditions, predominant focus will on fluorescent lighting, due to its popular use in home, business, and warehouses.

The cell performance measurements are made inside a Pantone color viewing light box that has three sources: fluorescent, incandescent and daylight. This box allows experiments to be conducted in a controlled manner. Care is taken to ensure that there is no stray light affecting the measurements. The solar cells are placed in a horizontal position (parallel to the light source).

Illuminance values are measured used a lux meter. Combinations of neutral density filters are used to obtain different illuminance values. Lux is a typical unit for measuring indoor lighting. For outdoors, irradiance is measured in Watts/m$^2$.

Fundamental difference between illuminance and irradiance is the weighting of the spectral response. Irradiance includes the power from all wavelengths weighted equally, whereas illuminance weights the power from each wavelength in proportion to the sensitivity of the human eye, which in turn is most sensitive to green light.

Majority of the solar cell characterization studies are reported under outdoor or sunlight conditions. The peak output is reported at standard test conditions (STC) conditions with intensities of 1000W/m$^2$. On the other hand, indoor lighting conditions are significantly different. Table II shows these values that were measured in this study in various zones of an office environment.

The lower limit of the office environment could be extended down that may include a conference room where lighting was turned down during projected presentations, that is 50 – 100 lux. On the other hand, the higher limit was extended in a bright indoor lighting such as a studio, assembly areas and warehouse lighting to 3000 lux. Based on the empirical relationship between lux and W/m$^2$, it turns out that the average indoor lighting is approximately 1 to 2 W/m$^2$, less than 500 times lower than outdoor conditions. As a result, all of our measurements and analysis are done using lux values.

IV measurements are done using a Keithley 2400 source meter to measure the solar cell open and short circuit values, as well as the maximum power parameters of the solar cell. Normalization is done for current and power to one square centimeter to perform comparative studies among the various solar cells.

Cell and maximum power point parameter correlations are done as part of maximum power point (MPP) algorithm determination.

## 4 SOLAR CELL BEHAVIOUR UNDER VARIOUS INDOOR LIGHTING CONDITIONS

Fig. 1 illustrates the various solar cell maximum power density (mW/cm$^2$) values that were determined from the IV scan for different illuminance conditions at room temperature for fluorescent lighting. Further demarcation is highlighted in Fig. 2 using the light level measurements done for realistic indoor office lighting environment as shown in Table II. This demarcation method helps the understanding of the applicability for a given solar cell for a given light condition.

This analysis indicates that among the various cells measured, DSSC shows higher power density across indoor conditions relative to a-Si and (OPV) solar cells.

On the other hand, similar drill down analysis done under incandescent lighting conditions indicates that poly Si solar cells show a superior performance over others as shown in Fig. 3. These results, in general is consistent with the spectral response curves that therefore results in poly Si showing the best performance relative to other cells considered in our study for incandescent conditions. While it is known that the wide band-gap for DSSC [5] would explain the higher performance for fluorescent conditions, it is relatively better than other wide band-gap materials in incandescent conditions as well as indicated in Fig. 3. A slightly lower performance for DSSC for a given lux value under fluorescent condition compared to daylight condition (Fig. 4) can be explained by the additional infrared component in the daylight spectral response.

For indoor conditions, since fluorescent light is more popular, it is vital to understand the amount of power that can be generated for realistic lighting conditions of around 250 – 500 lux is in the order of 25 uW/cm$^2$. This number is key for the end product manufacturers to wrap an energy harvesting solution to their application. The other challenge is to ensure that the system extracts MPP from the solar cell and the method of extraction.

## 5 MPP ALGORITHMS

It is well known that cell parameters and the maximum power parameters strongly predict the efficiency of the solar cell. Most studies focused on STC conditions or primarily outdoor conditions. However, a quantitative understanding the behavior under low-light (indoor) conditions is vital. Reason is that this enables the system to maintain or work towards staying at the MPP location under varying conditions such as lighting change due to source distance or light source, angle of incidence, or temperature change. This is done through the implementation of an appropriate MPP algorithm. Several MPP algorithms have been developed [6 - 8], some of which are used very commonly in high power applications such as the P&O, incremental conductance etc. However, the implementation of such algorithms requires high performance controllers which could be costly as well as high in power consumption. It turns out that for energy harvesting systems, the MPP algorithm developed is the one that needs the least amount of resources or circuits as these systems are embedded in consumer applications which need to be low cost and ones that need to consume very low power.

Detailed investigation for all three cells reveals that the short circuit and maximum current are strongly linear with illuminance. Similarly, the open-circuit voltage and the maximum voltage show linearity on a logarithmic scale of illuminance, all with extremely high correlations. Figure 5 and 6 shows the correlation plots between $V_{max}$ versus $V_{oc}$ and $I_{max}$ versus $I_{sc}$ respectively for the DSSC cell.

These strong correlations open the door to design simple cost-effective MPP algorithms for controllers associated with these solar cells for indoor applications where cost is a priority for commercial feasibility. Equation 1 is called the fractional voltage method that can be used to estimate the maximum power point voltage ($V_{max}$) after finding the open circuit voltage ($V_{oc}$). Similarly, Equation 2 is called the fractional current method that estimates the maximum power point current ($I_{max}$) based on the short circuit current ($I_{sc}$). Figure 2 shows a simple algorithm that corrects the maximum power point voltage for changes in illumination. The following relationships are simple MPP algorithms for indoor applications of a DSSC cell.

**Fractional voltage method**

$$V_{max} = 0.74*V_{oc} \quad \textbf{(1)}$$

**Fractional current method**

$$I_{max} = 0.93*I_{sc} \quad \textbf{(2)}$$

Equations 1 and 2 are simple algorithms that are adapted as most suitable choices considering their spectral response and their ability to conform to the application.

It turns out that the values of the constants in the fractional methods are very close for the various cells considered in this study. Besides, the same is true across fluorescent and incandescent light sources for a given cell type, suggesting these fractional methods could be used with little loss of MP for a system independent of the type of solar cell used.

However, these techniques are presented with some challenges due to non-optimal conditions such as shading that will be discussed in the next section.

## 6 SINGLE VERSUS MULTI CELLS AND THE EFFECT OF SHADING

The effect of implementing multi- versus single-cell solar panels in low-power energy harvesting systems is considered to understand the impact on non-optimal conditions such as shading. Multi-cell systems produce higher output voltages, whereas single-cell systems produce a low voltage. However, this is well below what is the usability by the majority of electronics produced today. Ten single-cells connected in series generate approximately 10 x $V_{oc}$ of a single cell which is usually around 5.0 V. This can be used directly by today's electronics or regulated down to a lower voltage to support the current micro-controllers that run at 3.3V or 1.8 V. The easy use of this voltage has contributed to multi-cell popularity. However, multi-cell topologies are more expensive relative to the system cost for these applications. Moreover, multi-cell topologies suffer from the shading problem that could hamper the effectiveness of the simple fractional MPP algorithms.

In more recent history, single-cell panels are receiving a stronger focus. This is most likely the result of the convergence of several factors. The cost of a single-cell panel is lower than a multi-cell. Construction of single-cell panels is simpler and maximizes the cell area since there is less wiring for inner-connecting the cells. Also, the area available on today's electronic products is smaller and the overhead of the inner-connection of a multi-cell takes up precious area that could be used to generate current. Lastly, the single-cell does not have the same weakest cell problem like the multi-cell when shadowing occurs. However, a single-cell generates approximately 0.5V, which is a relatively low voltage and difficult to use to directly power existing electronics.

Shading is a known non-optimal condition that could occur often in indoor applications. For example, consumer applications like cell phones or remote controls could have some unavoidable temporary one or more cell shading issue by a person or an object while the device is in use. Shading can severely distort the IV and PV curve. End result is that the system would no longer be able to extract maximum power under such conditions. Fig. 7 shows a set of PV curves for a 4 cell DSSC connected in series with and without shading (simulated using opaque strips of various thicknesses) under realistic indoor office condition. The multiple MPP peaks and the shift of the single peak cases due to shading changes the value of the constant in the fractional MPP algorithms.

This explains why the MPP algorithm might need to be sophisticated besides simply using fractional methods that are applicable under optimal conditions. However as explained before, sophisticated methods involve the use of a more complex power conditioning electronics that might make the solution more expensive for a given application while consuming a lot more power than the ones using simple fractional methods.

An alternative solution is to use a single-cell topology that can avoid multiple peaks in the PV curve. The tradeoff is low-cell voltage and lower efficiency compared to a multi-cell with a same area and cell type. On the other hand, implementation of MPP method in a single-cell is much simpler since there is only one peak on the PV curve and also the power required to implement the MPPT function would be significantly smaller than in the multi-cell system.

## 7 CONCLUSIONS

Our study shows that DSSC under indoor conditions for energy harvesting applications is a better candidate than a-Si and OPV in terms of maximum power density. Derivation of the constants in the fractional MPP algorithms indicate that they could be implemented with little loss of maximum power across various solar cell types as well as across fluorescent and incandescent conditions. However, shading could render the method ineffective for the popular multi cell solutions. One solution to this problem is to implement a single cell topology.

## 8 ADDITIONAL COMPONENTS

### 8.1 Illustrations

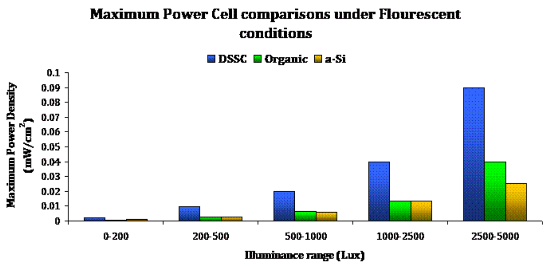


**Figure 1:** Cell comparison under fluorescent lighting condition.

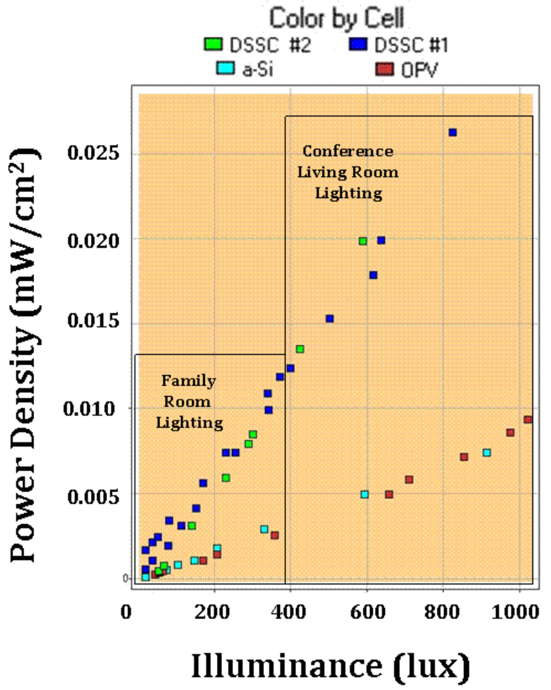


**Figure 2:** Windowing cell comparison for realistic indoor conditions.

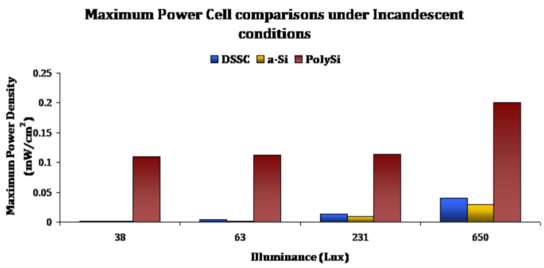


**Figure 3:** Cell comparison under incandescent lighting condition.

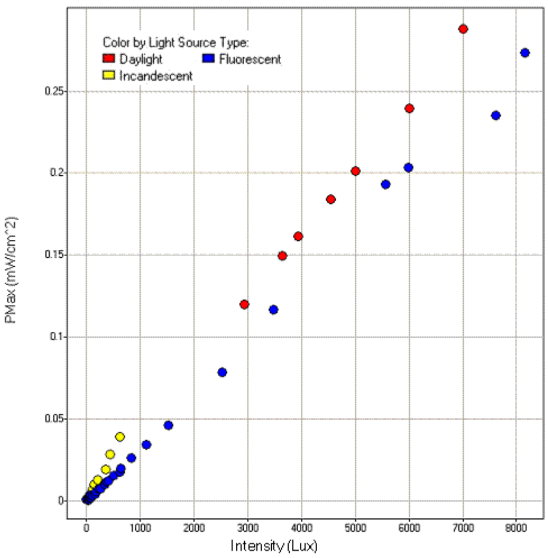


**Figure 4:** DSSC cells under different lighting conditions

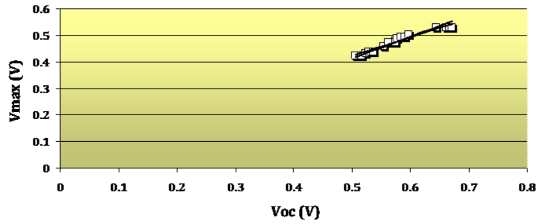


**Figure 5:** $V_{max}$ plotted as a function of $V_{oc}$ for a fractional voltage algorithm for DSSC.

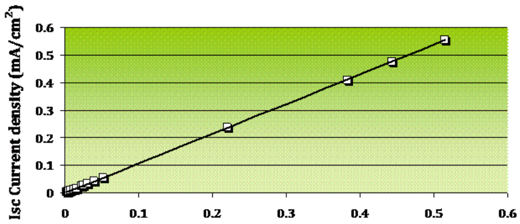


**Figure 6:** $I_{max}$ plotted as a function of $I_{sc}$ for a fractional current method algorithm for DSSC.

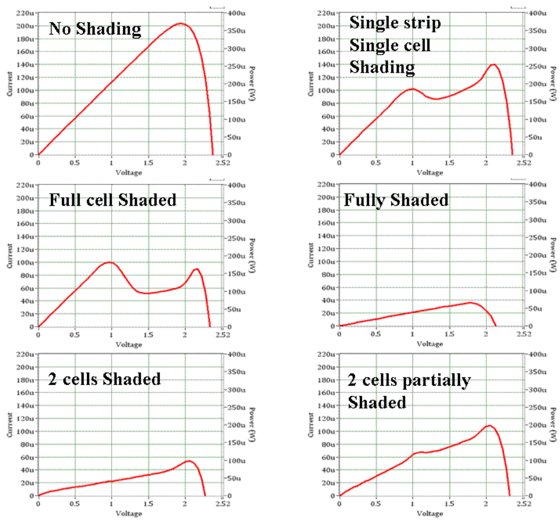


**Figure 7:** Effect of shading in a multi-cell topology.

## 8.2 Tables

**Table I:** Performance and harvesting techniques by energy source [1]

| Energy harvesting source | Performance ($mW/cm^3$) |
|---|---|
| Solar Cells | 15 |
| Piezoelectric | 0.33 |
| Vibrational | 0.116 |
| Thermoelectric | 0.04 |

**Table II:** Measurement of lighting in indoor conditions

| Zone type | Illuminance (Lux) | | | |
|---|---|---|---|---|
| | Minimum | Maximum | Range | Mean |
| **Conference rooms** | 251 | 338 | 87 | 295 |
| **Lab area** | 347 | 614 | 267 | 481 |
| **Desk** | 369 | 668 | 299 | 519 |
| **Window area** | 455 | 550 | 95 | 503 |
| **Lunch area** | 364 | 517 | 153 | 441 |
| **Hallway** | 327 | 498 | 171 | 413 |

8.3 References


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