The Appropriateness of Organic Solar Cells for Indoor Lighting Conditions

B. Minnaert*[a], P. Veelaert[a]
[a]University College Ghent, Schoonmeersstraat 52, B-9000 Gent, Belgium

ABSTRACT

Most commercially available photovoltaic solar cells are crystalline silicon cells. However, in indoor environments, the efficiency of silicon solar cells is poor. Typically, the light intensity under artificial lighting conditions is less than 10 W/m² as compared to 100-1000 W/m² under outdoor conditions. Moreover, the spectrum is different from the outdoor solar spectrum and there is more diffuse than direct light. Taken into account the predicted cheaper costs for the production of organic solar cells, a possible niche market for organic PV can be indoor applications. In this article, we study the influence of the narrow absorption window, characteristic for organic solar cells, for different indoor conditions. This comparison is made for typical artificial light sources, i.e. a common incandescent lamp, an LED lamp and a "warm" and a "cool" fluorescent tube, which are compared to the outdoor AM 1.5 spectrum as reference. The comparisons are done by simulation based on the quantum efficiencies of the solar cells and the light spectra of the different light sources. A classical silicon solar cell is used as reference. In this way we determine the appropriateness for indoor use of organic solar cells.

Keywords: photovoltaic energy, organic PV, indoor PV, absorption window, spectral distribution

1. INTRODUCTION

1.1 Indoor Photovoltaic Solar Cells

Nowadays, wireless communication networks (cameras, router nodes, sensor networks,…), focused towards indoor applications, use batteries as their source of energy. However, batteries have a limited lifetime and have to be replaced in due time. The lifetime of the battery is often the limiting factor for the lifetime of the device. Often, the cost of replacing the battery outweighs the cost of the device itself. Also from an environmental perspective, battery waste should be minimized if possible. Moreover, the progress of the battery technology has not improved significantly in terms of energy density and size in the last decade, especially for low power applications such as e.g. sensor networks.

The lifetime of the device can be extended many times if the device itself would be able to harvest energy from renewable resources in the environment. The energy from heat, motion or light in the environment can be extracted to supply electronic devices. We speak of thermal, vibration or solar based energy harvesting, which can be accomplished respectively by e.g. a piezoelectric generator, a thermoelectric generator and a photovoltaic solar cell.

Photovoltaic (PV) solar energy is an efficient natural energy source for outdoor applications. However, for indoor applications, it is important to note that the efficiency of classical crystalline silicon photovoltaic cells is much lower. This results in too big surface areas for the photovoltaic cells compared with the size of the wireless network device.

Indoor photovoltaic applications have been prominent on the market since the first half of the 1970s[1]. The electrical energy spent for lighting purposes can partly be recycled by powering devices with photovoltaic solar cells. Indeed, the radiation (visible and non-visible) emitted from artificial light sources can be used for the production of electricity. Mainly amorphous silicon is used, in watches and calculators. The latter has been the most successful indoor PV application to date, reaching annual sales of 10 million pieces by 1990, thus avoiding millions of alkaline batteries. This volume of solar cell sales represented at the time approximately 10% of the global photovoltaic shipments[1]. Since then, the solar calculator market has saturated while the outdoor PV market boomed. Therefore, in order for the indoor PV market to grow, it is necessary that they become applied in other devices such as cameras, router nodes and sensor networks.

*Ben.Minnaert@HoGent.be; phone ++32-9-243 2589

Silicon solar cells are expensive and are therefore not always economically feasible for powering cheap devices. A possible way to decrease the cost of photovoltaics, is the use of plastic solar cells, based on organic compounds. Nowadays, efficiencies up to 7.9 % are reached for single junction organic cells[2]. There are several reasons why organic materials are suitable for photovoltaic applications. The main advantages are:

- the low cost of the active materials.
- the small amount of necessary active material. Because of the high absorption coefficients[3] (usually $\geq 10^5$ cm^{-1}), a thin layer (≈ 100 nm) of organic materials is sufficient. This could lead to lightweight applications. By comparison, in a crystalline silicon solar cell, the active layer is about 200 to 300 µm thick.
- organic solar cells can be applied on flexible substrates, allowing for use on e.g. clothes.
- the low cost of the substrate (e.g. plastic foil).
- a large cost reduction potential compared to inorganic cells is expected by the quantum leap achievable in terms of manufacturing by the prospect of a reel-to-reel production technology.
- the production of an organic solar cell would require less energy input, making the payback energy time of the cell only a few months. In comparison, the energy payback time of a conventional Si solar cell is two to four years.
- organic materials are abundant and non-toxic.

There is no short-term ambition to replace silicon solar cells by organic counterparts. Indeed, the efficiency and stability of organic PV is still not sufficient to compete with Si cells. However, in small niche markets, organics can break through, e.g. in small consumer applications such as watches, calculators, portable electronic devices,…

In this paper, we investigate whether or not organic solar cells can be appropriate for indoor low-power applications. As well the lack of long-term stability as the inferior power conversion efficiency can hinder the use of organic PV for indoor applications. We will limit ourselves to one important aspect of organic cells: the narrow absorption window. Indeed, compared to the absorption band of inorganic semiconductors, a characteristic of organic solar cells is their narrow absorption window[4]. The cause of this narrow window can be found in the lack of sufficient discrete energy levels at higher energies, unlike inorganic materials, which have a quasi-continuous band.

Different photovoltaic cells for applications on earth are usually rated by their power output under standard test conditions, i.e. an illumination intensity of 1000 W/m^2 under the global AM 1.5G spectrum, at a cell temperature of 25 °C. Although these conditions seldom appear at the same time (except in the lab), this characterization give a reasonable guideline for comparing different solar cell types for outdoor conditions. However, the standard test conditions are not relevant for indoor applications. Typically, the light intensity under artificial lighting conditions found in offices and factories is less than 10 W/m^2 as compared to 100-1000 W/m^2 under outdoor conditions, depending on the type of and the distance from the light source. Moreover, the spectrum can be totally different from the outdoor solar spectrum. The spectrum depends not only on the type of light source, but also on the presence of reflected and diffused light. Unfortunately, there are no international norms which determine the way of characterizing solar cells for indoor applications. The inferior efficiency of organic PV to inorganics is determined under these standard test conditions. It is worth investigating whether or not the same conclusions can be drawn for indoor conditions.

To study the appropriateness of organics for indoor applications, we compare different organic solar cells under typical artificial light sources, i.e. a common incandescent lamp, an LED lamp and a “warm” and a “cool” fluorescent tube, which are compared to the outdoor AM 1.5 spectrum as reference. The comparisons are done by simulation based on the quantum efficiencies of the solar cells and the light spectra of the different light sources.

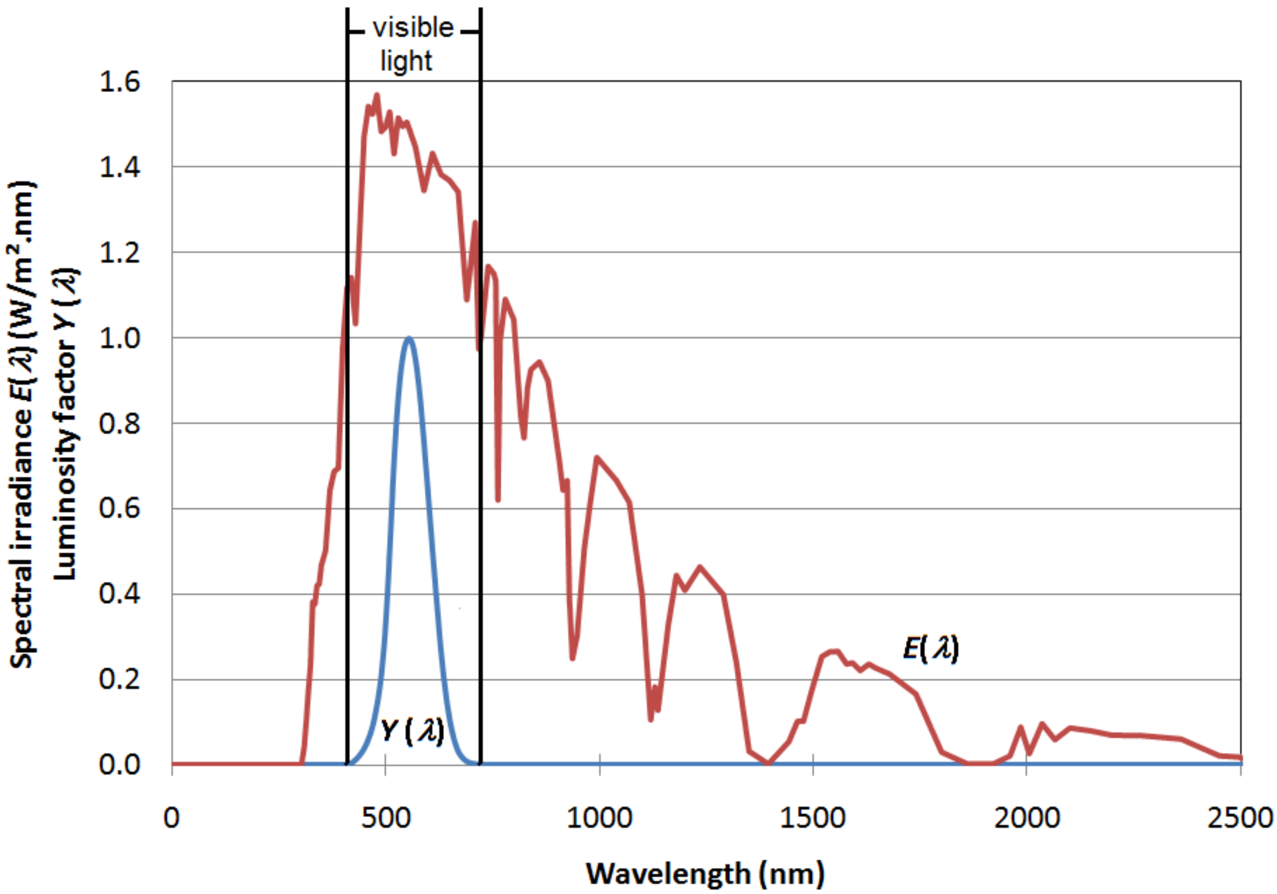

Figure 1. The spectral irradiance $E(\lambda)$ of the solar spectrum and the luminosity factor $Y(\lambda)$. The region of the visible light is indicated.

1.2 From Irradiance to Illuminance

Figure 1 shows the spectral irradiance of the solar spectrum AM 1.5: it plots the power density of the solar radiation on the earth's surface as a function of the wavelength λ. The total power density E of the radiation can easily be determined by summing the contributions at each wavelength of the spectral irradiance E_λ:

$$E = \int_0^\infty E_\lambda(\lambda) d\lambda \tag{1}$$

However, the total power density E for the radiation of an artificial light source does not indicate how weak or strong we perceive the light source. Indeed, the human eye is only capable of detecting light within a narrow wavelength region: from 380 (violet) to 780 nm (red). Moreover, the sensitivity of the human eye is not constant within this range: it peaks around 555 nm. Although the sensitivity of the eye differs from person to person, one has premised an empirical, international accepted, standard curve as a function of the wavelength. This standard sensitivity curve is called the luminosity factor $Y(\lambda)$ (figure 1). With this factor, the irradiance (in W/m²) can be converted to the corresponding quantity illuminance E_v, which takes into account the sensitivity of the human eye:

$$E_v = K_m \int_0^\infty E_\lambda(\lambda)\, Y(\lambda) d\lambda \tag{2}$$

The illuminance E_v is expressed in lumen (lm) per m² or lux. The coefficient K_m is equal to 683 lm/W and is part of the empirical definition of the lumen. This coefficient K_m is called the maximum spectral efficacy and is chosen such that an irradiance of 1 kW/m² of the global solar spectrum AM 1.5 corresponds[5] to 100 klux according to equation (2).

2. METHODOLOGY

2.1 Artificial Indoor Light Sources

The radiation in an indoor environment is of course dependent on the type of light source present. Nowadays, fluorescent lamps are the most commonly used artificial light sources. But the radiation is influenced by many other factors. Direct and diffuse daylight can enter the indoor room through a window. The glass properties and glass coating can alter the spectrum of the outdoor light. Indoor lit objects will absorb radiant energy, which they can re-emit at different wavelengths. Radiation in the room is reflected. The performance of an indoor PV cell is also influenced by its location in the room, its orientation, indoor obstacles…

In this paper, we make abstraction of all those influences: we only study the influence of different types of artificial light sources. Specifically, we consider the following light sources: an LED lamp, a "warm" and a "cool" fluorescent tube and a common incandescent lamp. The spectra of the light sources are given in figure 2.

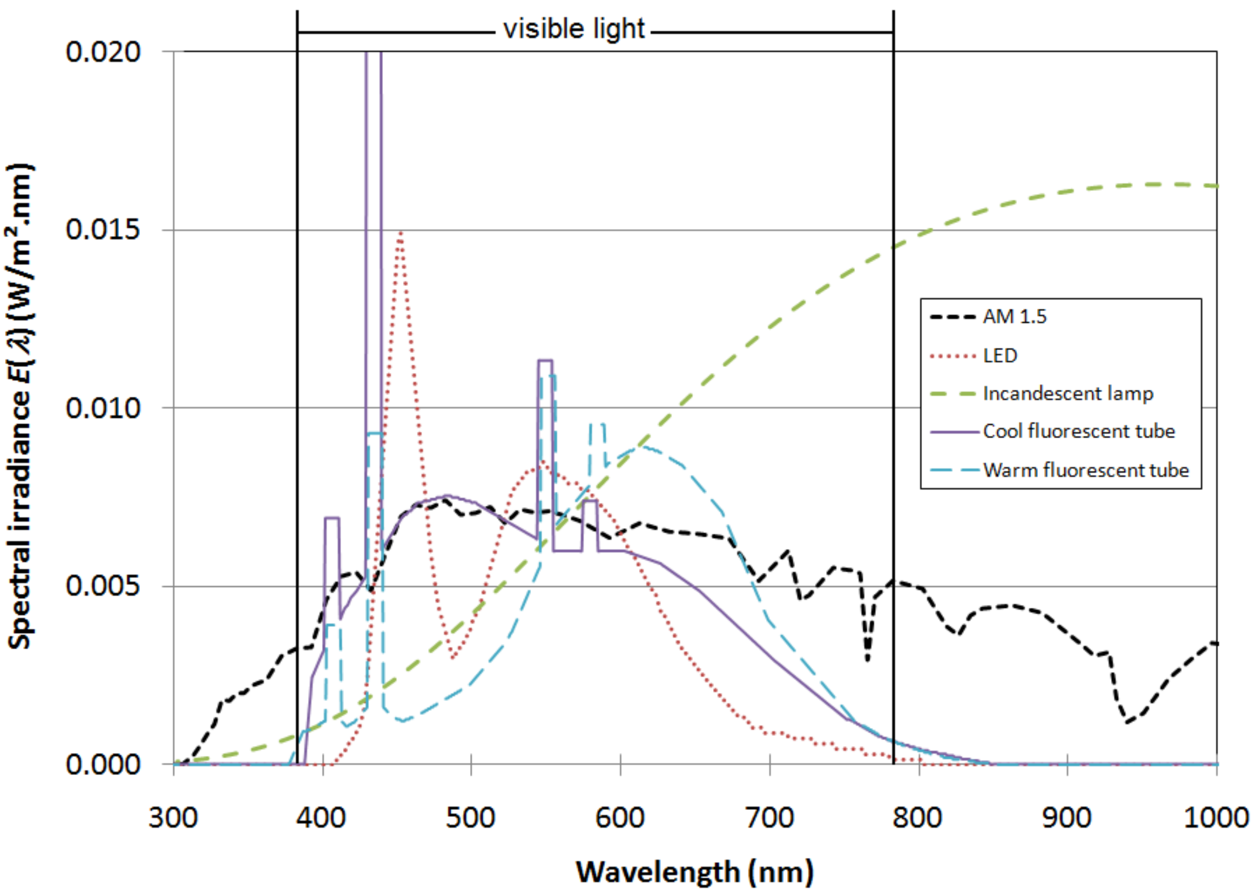

Figure 2. The spectral irradiance of some typical artificial light sources and the solar spectrum AM 1.5 as reference. All light sources, including the solar spectrum AM 1.5, are scaled to 500 lux. The region of the visible light in the spectrum is indicated.

As LED lamp, we consider a typically cool white emitter ("LZ4-00CW10") manufactured by LedEngin Inc.[6]. We consider two distinct fluorescent tubes: a "warm" and a "cool" light (respectively "Deluxe Warm White" and "Chroma 75")[7]. The intensity of a warm fluorescent tube is higher in the red region of the visible light, whereas a cool lamp peaks in the blue region. We approximate the common incandescent lamp by the spectral distribution of a black body at temperature 3000 K, which also turns out to be a good approximation for the spectral distribution of a normal halogen lamp[5]. Figure 2 clearly shows that the larger part of the spectrum of the fluorescent tubes and the LED lamp falls within the range of the visible light. The largest portion of the common incandescent lamp however is not contained within this range. This indicates the inefficiency of incandescent lamps for lightning purposes: a lot of the energy is lost as heat (infrared region).

We want to compare the same lightning conditions. Therefore, we scale all the light sources to an illumination of 500 lux to obtain a correct comparison. We use the value of 500 lux because it is recommended for general offices[8]. Where the main task is less demanding, e.g. a corridor, a lower level (e.g. 100 lux) is sufficient. The required illumination can also be higher (1000 lux) in e.g. production rooms in industry where detailed work is necessary (e.g. circuit boards inspection) and in operation theatres in hospitals. We compare the different light sources to the outdoor AM 1.5 spectrum as reference, which we also scale to an illumination of 500 lux. All spectra, scaled to 500 lux, can be found in figure 2.

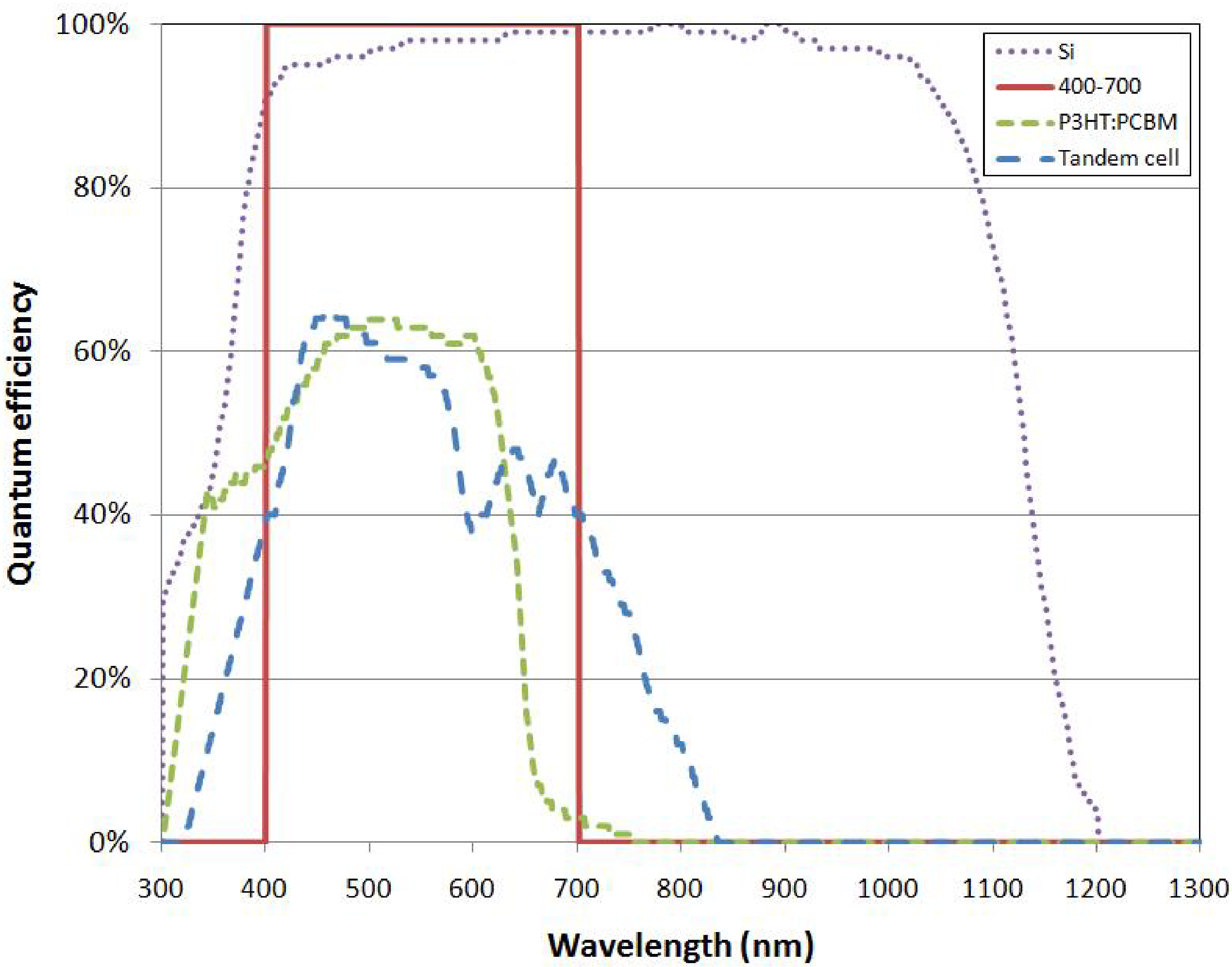

Figure 3. The external quantum efficiency of a silicon solar cell, an ideal organic cell with an absorption window from 400 nm to 800 nm, a P3HT:PCBM bulk heterojunction solar cell and an organic tandem cell.

2.2 Organic Solar Cells with Different Absorption Windows

The active material in an organic bulk heterojunction solar cell consists of an interpenetrating network of an *n*-type and a *p*-type (semi)conductor. From the quantum efficiency data of more than 20 different material combinations (*p*- and *n*-type)[9], we can conclude that most single junction organic cells have an absorption window which starts between 300 and 400 nm, and ends at 600 to 700 nm. Because we only want to study the influence of the absorption window, we will first simulate the performance of theoretical organic cells, only differing in absorption window width. Because we will compare relatively, we first consider ideal solar cells. We consider ideal cells whose absorption window starts at 300 or 400 nm, and reaches to 600, 700, 800 and 900 nm. Although single junction cells with absorption windows to 800 or 900 nm are rare, these broad windows can be reached by using tandem configurations. We name the cells by their absorption range, e.g. the cell "400-700" has an absorption window from 400 to 700 nm (figure 3).

The power conversion efficiency η of the solar cell is given by

$$\eta = \frac{FF \cdot J_{sc} \cdot V_{oc}}{P_{in}} \tag{3}$$

with FF the fill factor, J_{sc} the short-circuit current density, V_{oc} the open circuit voltage and P_{in} the total power density of the incoming radiation. We first consider ideal cells where the fill factor FF equals unity. The short-circuit current density J_{sc} is given by:

$$J_{sc} = q \int_0^\infty \Phi_\lambda(\lambda) \cdot QE(\lambda) \cdot d\lambda \tag{4}$$

with q the elementary charge and $\Phi_\lambda(\lambda)$ the spectral flux density of the light source (in 1/m².s.nm), indicating how many photons are incident on the solar cell per unit of area, per unit of time and per wavelength. We consider the (external) quantum efficiency QE to be unity within the absorption window and zero outside the window (e.g. "400-700" in figure 3). The open circuit voltage V_{oc} of an *inorganic* cell can ideally be taken equally to the bandgap of the absorber: $V_{OC}=E_g/q$. However, in *organic* solar cells, there is an extra voltage loss, caused by the energy difference between the LUMO-levels of the *n*-and the *p*-type, necessary for exciton dissociation. We assume for the organic solar cell a voltage loss of 0.2 V. This value was put forward as an empirical threshold necessary for exciton dissociation[9]. We assume for our ideal organic cells that

$$V_{oc} = \frac{E_g}{q} - 0.2\,V \tag{5}$$

We compare these ideal QE's with the QE of a record silicon solar cell[10] as reference (figure 3).

After considering ideal solar cells, we consider realistic organic solar cells. We consider a classical organic bulk heterojunction solar cell with P3HT as *p*-type and PCBM as *n*-type[11]. Its absorption window ranges from 300 nm to about 650 nm. We also consider an organic tandem solar cell, combining a solid state dye-sensitized cell with a ZnPc/C_{60}-based bulk heterojunction cell[12]. Because of the use of a tandem configuration, the absorption range extends further to 850 nm. Both QE's are plotted in figure 3.

3. RESULTS AND DISCUSSION

3.1 Ideal Organic Solar Cells with Different Absorption Windows

Figure 4 shows the electrical power density output of the different ideal organic solar cells for the artificial light sources. The silicon solar cell and the AM 1.5 spectrum are added as comparison. We want to stress that this is the maximum obtainable power in the theoretical situation described above. Because we have idealized all cells in the same way, and only changed one parameter (the absorption window), it is justified to compare the results qualitatively. The highest output is obtained by illumination with an incandescent lamp, certainly at broad absorption windows. This was to be expected. Indeed, figure 2 clearly shows that the incandescent lamp has his highest intensity within the visible region. An

important conclusion is that, depending on the light source, broadening the absorption window is not always beneficial. Indeed, a wider absorption window will lead to more absorbed photons (and thus a higher current), but will lower the useful energy of each photon (lower voltage). Broadening the absorption window is beneficial in an outdoor AM 1.5 environment and for an incandescent lamp. For an environment with LED lamps or cool fluorescent tubes, a too broad absorption window deteriorates the power output. For a warm fluorescent tube, one notices the big improvement if the absorption window extends to 700 nm or further. This was to be expected because of the peak of this spectrum between 600 and 700 nm (figure 2).

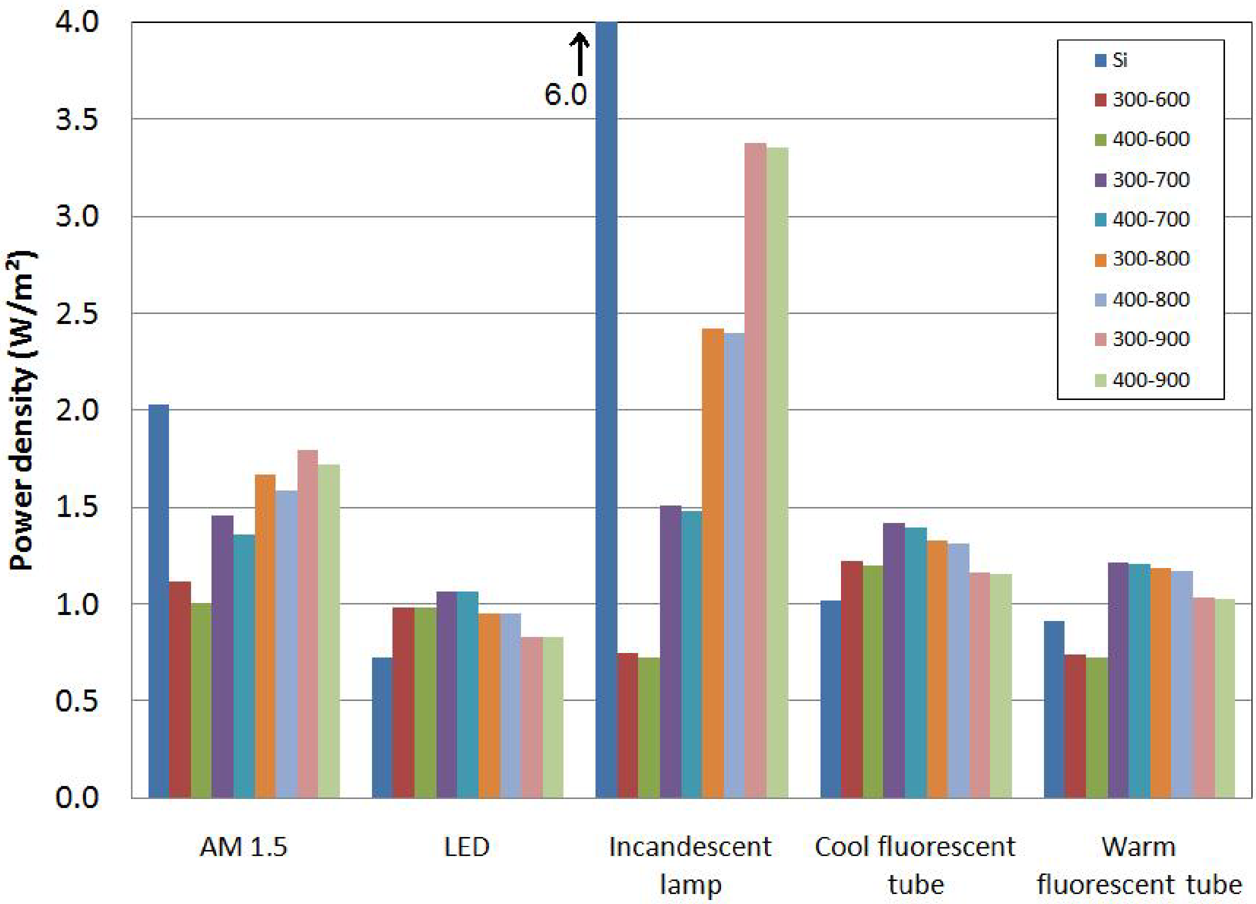

Figure 4. The electrical power density output of the different ideal organic solar cells for the artificial light sources. The silicon solar cell and the AM 1.5-spectrum are added as comparison.

We now compare the different organic cells to the idealized silicon cell (figure 5). The silicon cell is characterized by the *QE* given in figure 3, a fill factor of one and an open circuit voltage which equals the bandgap. One notices that indeed the silicon solar cell is superior in an outdoor environment. Also in an indoor room with incandescent light, the silicon cell performs best. However, in an environment with LED or cool fluorescent lamps, the organic cells perform better, even at narrow absorption windows. Also under warm fluorescent light, the organic PV cells perform better if the absorption window extends to 700 nm or further. This indicates that –only taken into account the characteristic narrow absorption window of organics– organic solar cells can compete with classical solar cells in certain indoor environments. In other words, if an organic cell performs less under e.g. LED light than a classical Si solar cell, the narrow absorption window is not to blame.

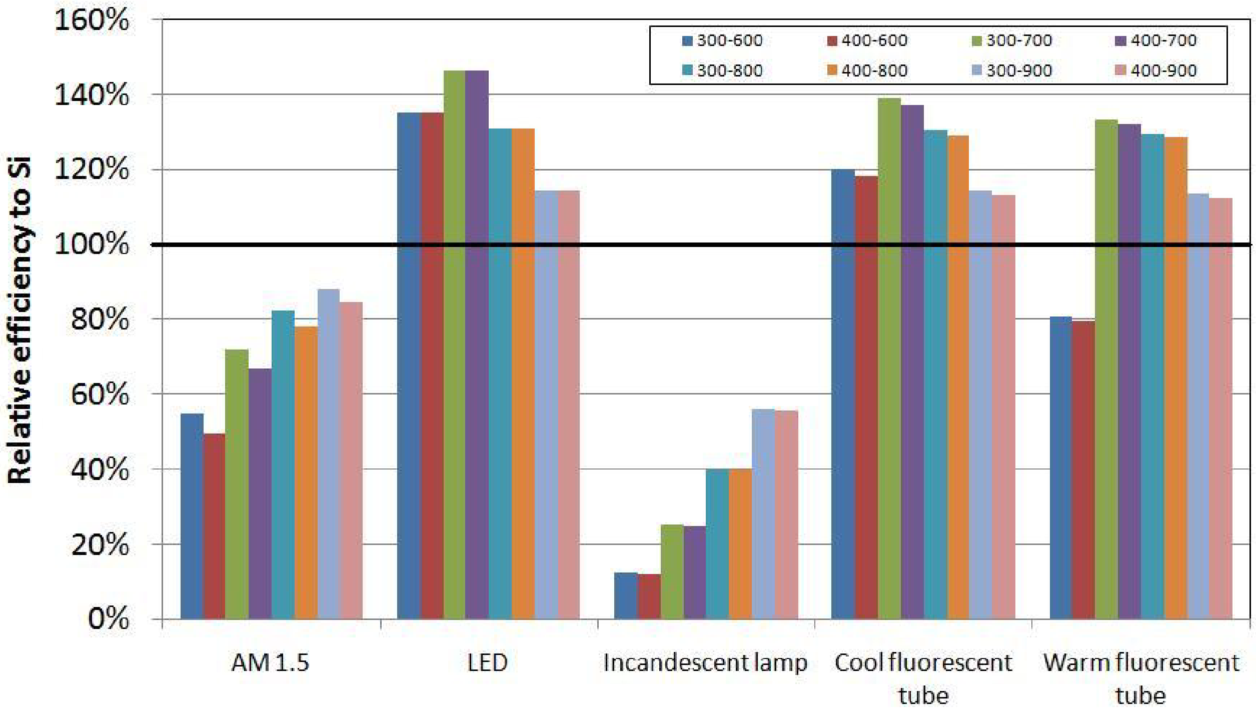

Figure 5. The performance of ideal organic solar cells with different absorption windows, relative to a silicon solar cell.

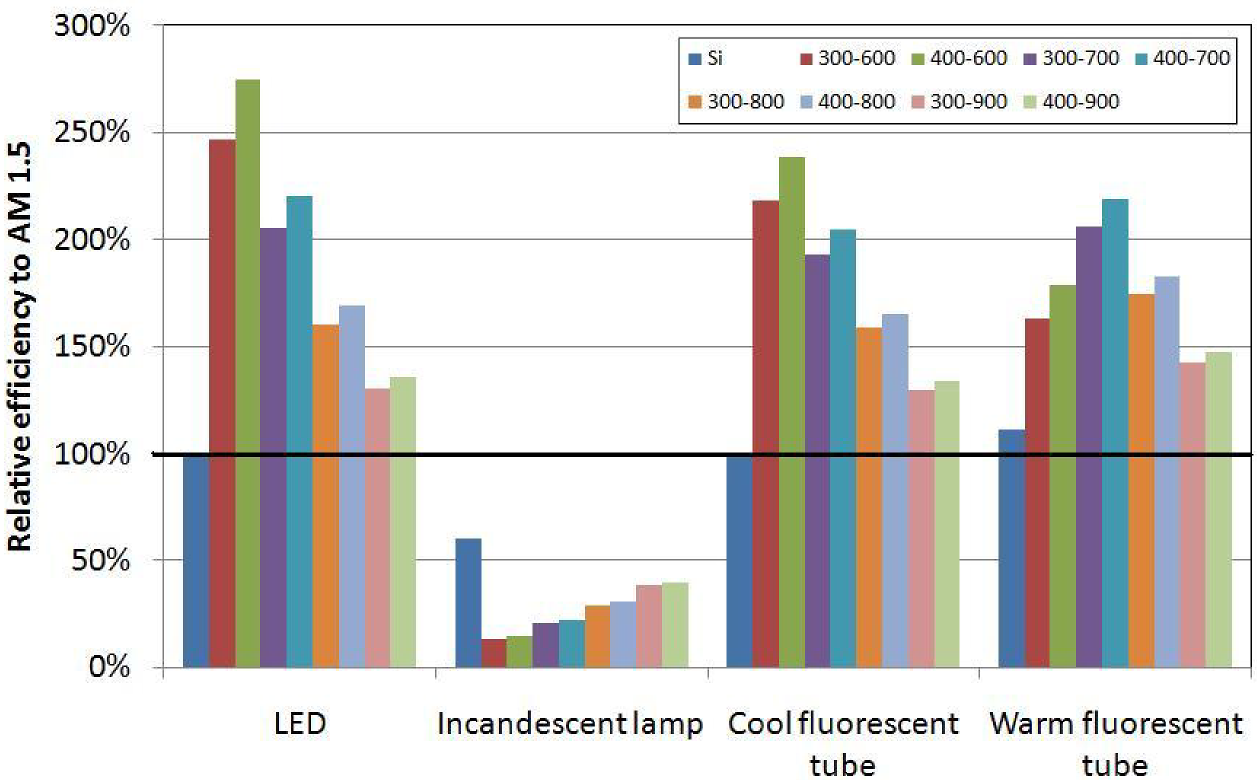

Figure 6. The performance of ideal solar cells in different environments, relative to the outdoor spectrum AM 1.5.

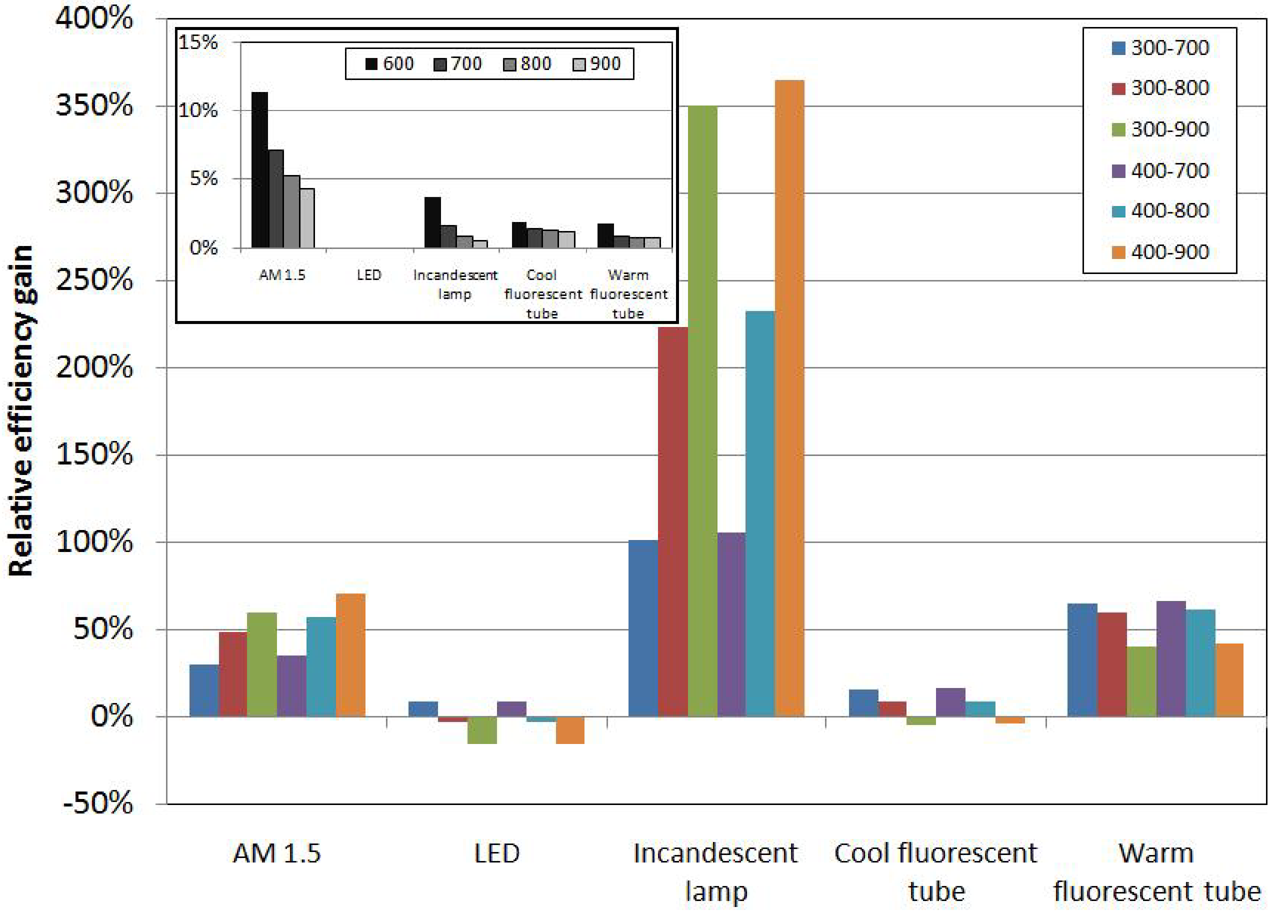

Figure 7. The relative efficiency gain by broadening the absorption window to 700, 800 and 900 nm, compared to the cell with an absorption window to 600 nm. The inset shows the relative efficiency gain by extending the absorption window from 400 to 300 nm.

We now compare the different artificial light sources, compared to the outdoor spectrum AM 1.5 (figure 6). We notice the bad performance of incandescent lamp compared to the outdoor spectrum. Even with a broad absorption window, the efficiency hardly reaches 40 % of the efficiency in an outdoor environment. However, in the other artificial lightning environments, the cells perform better indoor than outdoor. A cell with only a very narrow absorption window from 400 to 600 nm performs 2.5 times better in an LED environment than outdoors. One notices again that this efficiency gain for LED and fluorescent tubes is reduced for broader absorption windows.

Next, we investigate in detail whether or not it is useful to broaden the narrow absorption window of an organic cell for indoor use. Figure 7 plots the efficiency gain if we would extend the absorption from 600 nm to 700, 800 or 900 nm. First, we see the huge improvement (factor 2 to 3.5) of broadening the absorption window for incandescent light. This is logical, considering the intensity of incandescent light in the range 600-900 nm (figure 2). However, remember the relative underperformance of incandescent light compared to other environments. An important conclusion from figure 7 is that is not useful to extend the absorption window for an LED or cool fluorescent tube environment. On the contrary, in certain cases, the performance deteriorates. The reason is the limited presence of these spectra in the 600-900 nm range (figure 2). Again, for a warm fluorescent tube, it is important that the solar cell absorbs the 600-700 nm range. Absorption above 700 nm however contributes little to the performance.

We also investigate whether or not it is useful to extend the narrow absorption window of an organic cell for indoor use from 400 nm to 300 nm. The inset of figure 7 shows the performance gain which can be attained by extending to the ultraviolet region. One notices that the efficiency gain is negligible for indoor use. For LED, there is even no difference

because LED does not emit light in the 300-400 nm range. For indoor solar cells, absorption in the ultraviolet region is not a requisite.

3.2 Realistic Organic Solar Cells

After considering ideal solar cells, we consider realistic organic solar cells. As described above, we consider a classical organic P3HT:PCBM solar cell and an organic tandem solar cell (figure 3). We take into account their measured *QE* (respectively based on ref. 11 and 12), their V_{oc} (respectively 0.57 and 1.36 V) and their *FF* (respectively 50 % and 54 %). We compare these organic cells to the silicon cell. We now however stop idealizing the silicon solar cell and take into account its V_{oc} (696 mV) and its *FF* (83.6%). The performance compared to the (record) silicon cell shows that the Si cell is better in all environments. The single junction P3HT:PCBM cell reaches maximum 27 % of the efficiency of the silicon cell in an LED environment. The tandem cell however, mainly because of the higher open circuit voltage, reaches 60 to almost 70 % of the efficiency of a silicon cell. Taken into account the expected low cost of organic photovoltaics, it can be economically feasible for organic PV to compete with silicon solar cells in indoor environments.

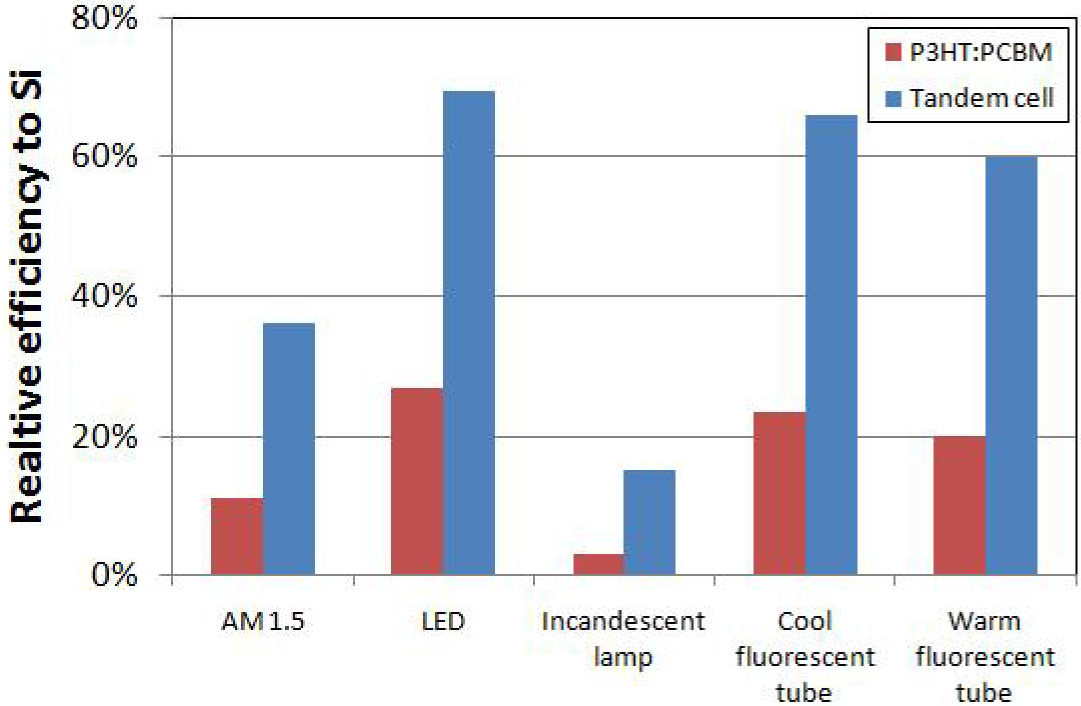

Figure 8. The performance of realistic organic solar cells, relative to a silicon solar cell, for different environments.

4. CONCLUSIONS

The highest power output at an illumination level of 500 lux is obtained by illumination with an incandescent lamp, certainly at broad absorption windows. Broadening the absorption window is beneficial in an outdoor AM 1.5 environment and for an incandescent lamp environment. However, for an environment with LED lamps or cool fluorescent tubes, a too broad absorption window deteriorates the power output. For a warm fluorescent tube, a big performance gain can be achieved if the solar cell absorbs the 600-700 nm range. Absorption above 700 nm however contributes little to the performance. Finally, broadening the absorption window from 400 to 300 nm into the ultraviolet region is not a requisite for indoor solar cells.

The performance of real organic cells compared to the (record) silicon cell shows that the Si cell is better in all environments. However, certainly of tandem configurations, organic solar cells have the potential to compete with the expensive crystalline silicon solar cell in indoor environment, illuminated by LED of fluorescent lamps.

REFERENCES

1. Randal, J.F.,[Designing Indoor Solar Products], John Wiley & Sons, 56-59 (2005).
2. Green, M.A., Emery, K., Hishikawa, Y. and Warta, W. , "Solar cell efficiency tables (version 35)," Progress in Photovoltaics: Research and Applications 18(2), 144-150 (2010).
3. Hoppe, H. and Sariciftci, N.S. , "Organic solar cells: an overview," J. Mater. Res. 19(7), 1924-1945 (2004).
4. Winder, C. and Sariciftci, N.S. ,"Low bandgap polymers for photon harvesting in bulk heterojunction solar cells," J. Mater. Chem. 14(7), 1077-1086 (2004).
5. Virtuani, A., Lotter, E. and Powalla, M. ,"Influence of the light source on the low-irradiance performance of $Cu(In,Ga)Se_2$ solar cells" Solar Energy Materials and Solar Cells 90, 2141-2149 (2006).
6. LedEngin Inc., Datasheet "LZ4-00CW10 High Luminous Efficacy Cool White LED Emitter," (2008).
7. www.salsburg.com/lightcolor/lightcolor.html
8. CIBSE, [Code for Lighting], Butterworth-Heinemann (2002).
9. Minnaert, B. and Burgelman, M. ,"Empirical study of the characteristics of current-state organic bulk heterojunction solar cells," European Physical Journal - Applied Physics 38(2) 111-114 (2007).
10. Zhao, J., Wang, A. and Green, M.A. ,"19.8% efficient "honeycomb" textured multicrystalline and 24.4% monocrystalline silicon solar cells," Applied Physics Letters 73(14) 1991-1993 (1998).
11. Kim, Y., Cook, S., Tuladhar, S.M., Choulis, S.A., Nelson, J., Durrant, J.R., Bradley, D.D.C., Giles, M., McCulloch, I., Ha, C. and Ree, M. ,"A strong regioregularity effect in self-organizing conjugated polymer films and high-efficiency polythiophene:fullerene solar cells," Nature Materials 5(3), 197-203 (2006).
12. Bruder, I., Karlsson, M., Eickemeyer, F., Hwang, J., Erk, P., Hagfeldt, A., Weis, J. and Pschirer, N. ,"Efficient organic tandem cell combining a solid state dye-sensitized and a vacuum deposited bulk heterojunction solar cell," Solar Energy Materials and Solar Cells 93(10), 1896-1899 (2009).