B. Minnaert, P. Veelaert, "The Suitability of Organic Solar Cells for Different Indoor Conditions", Advances in Science and Technology, Vol. 74, pp. 170-175, 2010, doi: 10.4028/www.scientific.net/AST.74.170, http://www.scientific.net/AST.74.170

The suitability of organic solar cells for different indoor conditions

Ben Minnaert[1,a] and Peter Veelaert[1,b]

[1]University College Ghent, Schoonmeersstraat 52, B-9000 Gent, Belgium

[a]Ben.Minnaert@HoGent.be, [b]Peter.Veelaert@HoGent.be

Keywords: photovoltaic energy, organic solar cells, indoor PV.

Abstract. Most commercially available photovoltaic solar cells are crystalline silicon cells. However, in indoor environments, the efficiency of Si-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 properties and suitability of several bulk heterojunction organic solar cells (with distinct different absorption spectra) for different indoor conditions. We simulate different light environments and use a silicon solar cell as reference. Depending on the required power for the indoor device, we determine minimum requirements for the environment (light intensity and indoor spectrum) and for the organic solar cell (absorption spectrum and surface area). In this way we determine the appropriateness and conditions for a competitive indoor use of organic solar cells.

Introduction

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. Energy from heat, motion or light in the environment can be extracted to supply electronic devices.

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. 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 [1]. 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 [2]. 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. 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.

Methodology

From Irradiance to Illuminance. Fig. 1 shows the spectral irradiance of the solar spectrum AM 1.5. The total power density E of the radiation can easily be determined by summing the contributions at each wavelength λ 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 $Y(\lambda)$ (Fig. 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 [3] to 100 klux according to equation (2).

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 Fig. 1.

As LED lamp, we consider a typically cool white emitter (“LZ4-00CW10”) manufactured by LedEngin Inc. [4]. We consider two distinct fluorescent tubes: a “warm” and a “cool” light (respectively “Deluxe Warm White” and “Chroma 75”). 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 [3]. Fig. 1 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).

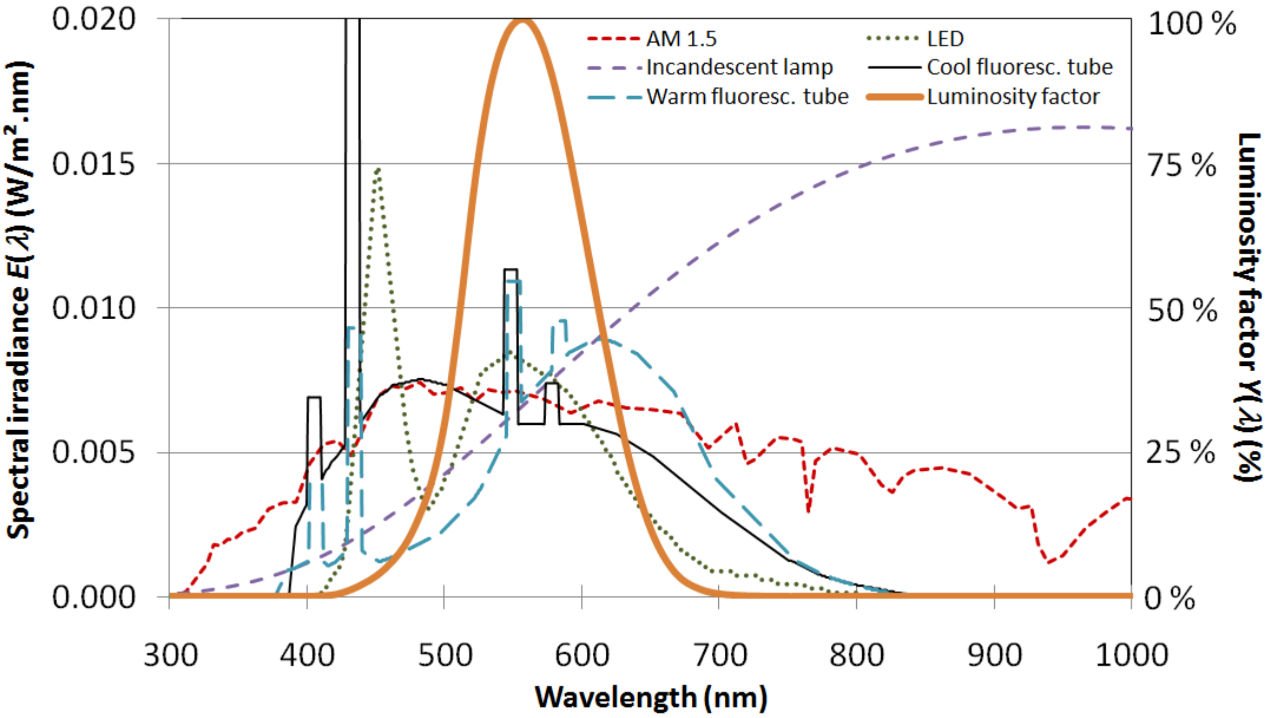

Fig. 1: The luminosity factor $Y(\lambda)$; the spectral irradiance of some typical artificial light sources and the solar spectrum AM 1.5 as reference. All light sources, including the solar spectrum AM 1.5, are scaled to 500 lux.

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. 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 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 Fig. 1.

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) [5], 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. We suppose a *FF* of 65 % and a *QE* of 70 % within the absorption window (Fig. 2), which are realistic values [5]. We consider 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 (Fig. 2).

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. 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). 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 [5]. We assume for our organic cells that

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

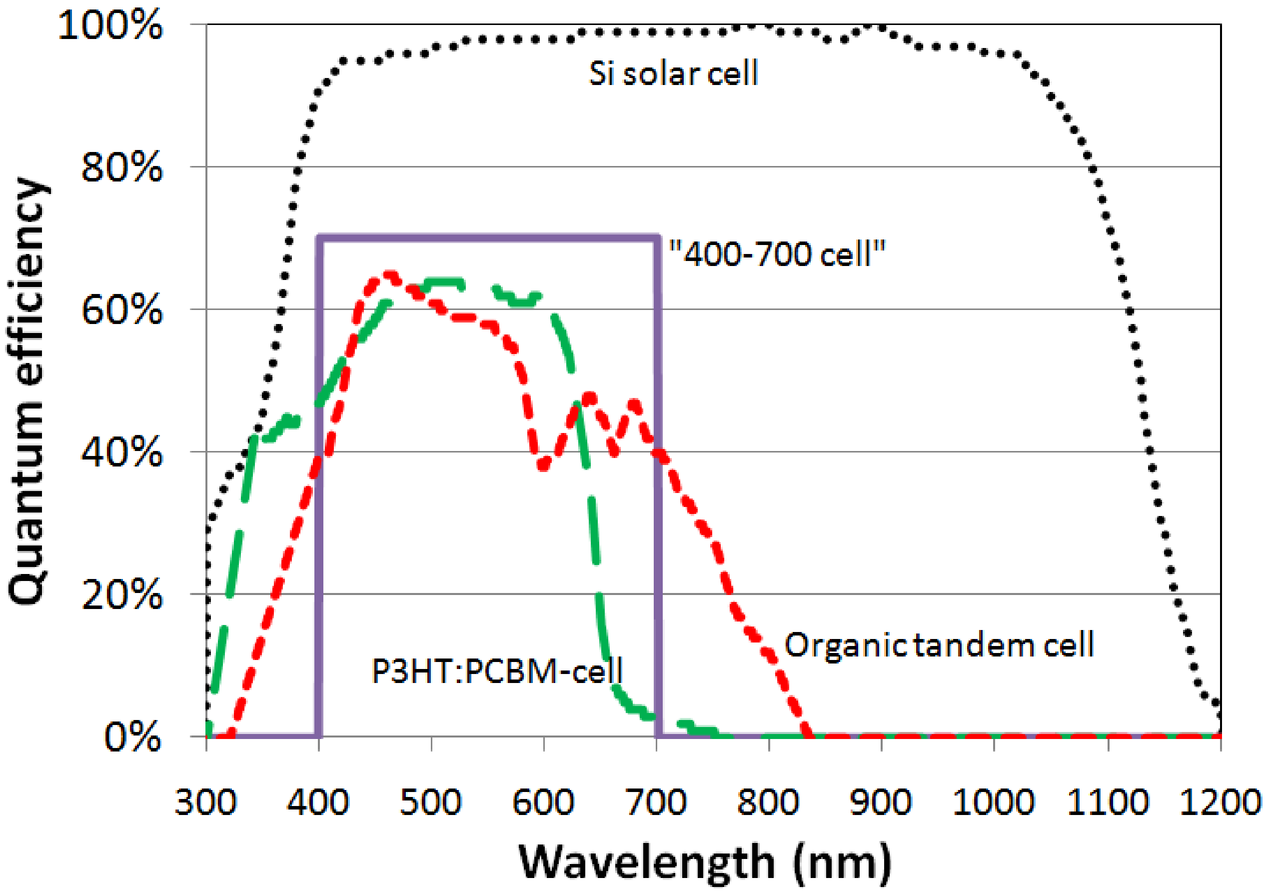

Fig. 2: The external quantum efficiency of a silicon solar cell, a theoretical organic cell with an absorption window from 400 nm to 700 nm, a P3HT:PCBM bulk heterojunction solar cell and an organic tandem cell.

We also consider realistic organic solar cells: (i) a classical organic bulk heterojunction solar cell with P3HT as p-type and PCBM as n-type [6]. Its absorption window ranges from 300 nm to about 650 nm. (ii) an organic tandem solar cell, combining a solid state dye-sensitized cell with a ZnPc/C60-based bulk heterojunction cell [7]. Because of the use of a tandem configuration, the absorption range extends further to 850 nm. Both *QE*'s are plotted in Fig. 2. Their V_{oc} are 0.57 and 1.36 V and their *FF* 50 % and 54 %, respectively.

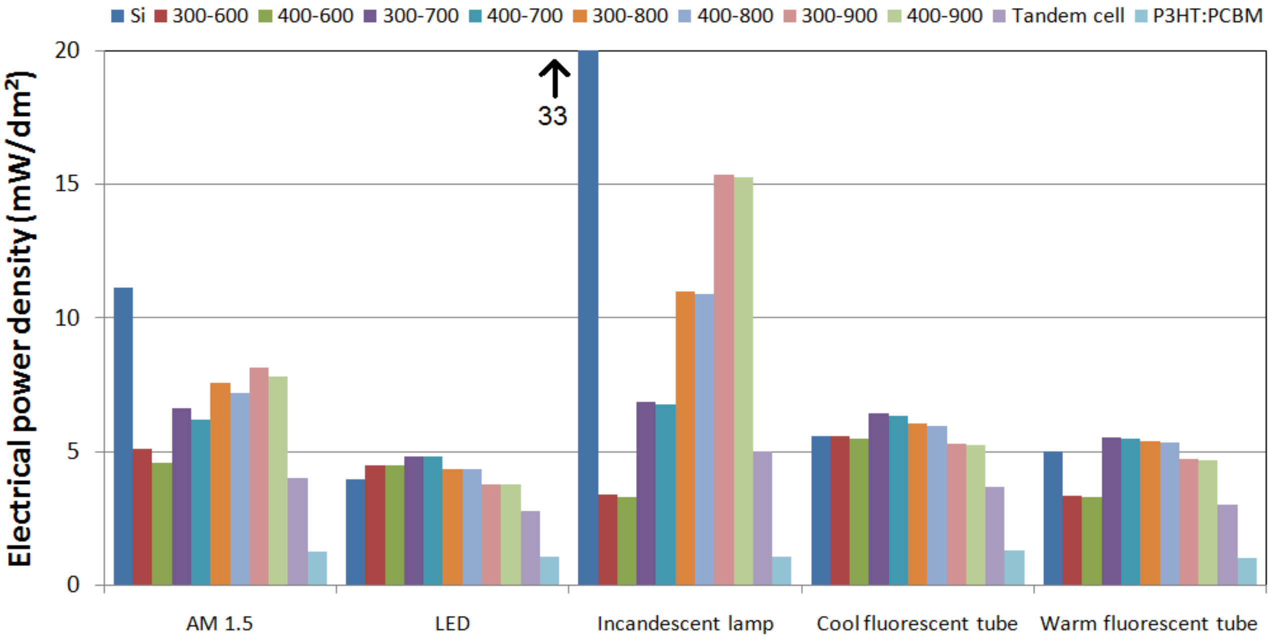

Fig. 3: The electrical power density output of the different organic solar cells with a surface area of 1 dm² for different artificial light sources. The silicon solar cell and the AM 1.5-spectrum are added as comparison.

Results

We consider cells with a surface area of 1 dm², which can be a realistic surface area for indoor applications. Fig. 3 shows the electrical power density output of the different solar cells for the artificial light sources. The silicon solar cell [1] and the AM 1.5 spectrum are added as comparison. The highest output is obtained by illumination with an incandescent lamp, certainly at broad absorption windows. This was to be expected. Indeed, Fig. 1 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 (Fig. 1).

One notices that the silicon solar cell, with a V_{oc} of 696 mV and a *FF* of 83.6%, is superior in an outdoor environment. Also in an indoor room with incandescent light, the silicon cell performs best. However, in the other environments, the Si cell obtains comparable results than the (theoretical but realistic) organic solar cells. This indicates that, 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 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.

A wireless sensor network node (and other low power indoor devices) consumes power in the order of several mW (e.g. 5 mW). From Fig. 3, one can determine the required surface area in each (500 lux) environment for a specific indoor device. One notices that an organic cell of 1 dm² can often be sufficient to power an indoor device. Whereas a 1 dm² P3HT:PCBM cell can only power a device of about 1 mW consumption, the organic tandem cell is able to provide power for a device of 2.75 mW in an LED environment and 5.0 mW with incandescent lights. The above calculations were done for light intensities of 500 lux. One can however easily adapt the results to an environment of e.g. 100 or 1000 lux. Indeed, for the spectra listed here, the results scale (almost) proportionally with the light intensity in lux (the proportionality is not perfect, but it is a very good approximation for these spectra and for realistic light intensities).

Conclusions

The suitability of several organic solar cells (with distinct different absorption spectra) for different indoor conditions was studied in this article. Among others, we found that the highest electrical output is obtained by illumination with an incandescent lamp, certainly at broad absorption windows. Furthermore, depending on the light source, broadening the absorption window is not always beneficial. We determined the necessary requirements regarding surface area of the solar cell, power consumption of the device for the different indoor spectra (Fig. 3), and for different illumination intensities. In conclusion, 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 certain indoor environments.

References

[1] Green, M.A., Emery, K., Hishikawa, Y. and Warta, W.: Progress in Photovoltaics: Research and Applications Vol. 18 (2010), p. 144

[2] Winder, C. and Sariciftci, N.S.: J. Mater. Chem. Vol. 14 (2004), p. 1077

[3] Virtuani, A., Lotter, E. and Powalla, M.: Solar Energy Materials and Solar Cells Vol. 90 (2006), p. 2141

[4] LedEngin Inc., Datasheet LZ4-00CW10 (2008)

[5] Minnaert, B. and Burgelman, M.: European Physical Journal - Applied Physics Vol. 38 (2007), p. 111

[6] 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.: , Nature Materials Vol. 5 (2006), p. 197

[7] Bruder, I., Karlsson, M., Eickemeyer, F., Hwang, J., Erk, P., Hagfeldt, A., Weis, J. and Pschirer, N. : Solar Energy Materials and Solar Cells Vol 93 (2009), p. 1896