

## WHICH TYPE of solar cell is best for low power indoor devices?

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### ABSTRACT:

Low power devices such as sensors and wireless communication nodes, focused towards indoor applications, face serious challenges in terms of harvesting nearby natural sources of energy for power. Nowadays, these wireless systems use batteries as source of energy. These batteries need to be replaced in due time and this factor plays a major role in determining the life of the device. Often, the cost of replacing the battery outweighs the cost of the device itself. Also from an environmental perspective, reducing battery waste is laudable. In order to obtain an “infinite” lifetime of the system, the device should be able to harvest energy from renewable resources in the device’s environment. Photovoltaic (PV) energy is an efficient natural energy source for outdoor applications. However, for indoor applications, the efficiency of classical crystalline silicon PV cells is much lower. Typically, the light intensity under artificial lighting conditions found in offices and homes is less than 10 W/m<sup>2</sup> as compared to 100-1000 W/m<sup>2</sup> under outdoor conditions. Moreover, the spectrum is different from the outdoor solar spectrum. Although the crystalline Si cell is still dominating the PV market, second generation solar cells, i.e. thin film technologies, are rapidly entering the market. The different PV cells are rated by their power output under standard test conditions (AM1.5 global spectrum and light intensity of 1000 W/m<sup>2</sup>) but those conditions are not relevant for indoor applications. The question therefore arises: which type of solar cell is best for indoor devices? This paper contributes to answering that question by comparing the power output of different thin film solar cells (CdTe, CIGS, amorphous Si, GaAs and an organic cell with active layer P3HT:PCBM) with the classical crystalline silicon solar cell as reference. This comparison is made for typical artificial light sources, i.e. an LED lamp, a “warm” and a “cool” fluorescent tube and a common incandescent and halogen lamp, which are compared to the outdoor AM1.5 spectrum as reference. All light sources (including the outdoor spectrum) are scaled to an illumination of 500 lux to obtain a correct comparison. The best artificial light source for all cell types is the incandescent lamp which, for Si and CIGS, improves the performance of the cell with a factor of 3 compared with AM 1.5. The LED lamp is the worst light source for indoor PV with a decrease in performance of a quarter for amorphous silicon to two thirds for crystalline silicon cells. The best solar cells for indoor use depend heavily on the light source. For an incandescent lamp, crystalline silicon remains the best. However, for an LED lamp or “warm” fluorescent tube, amorphous silicon is significantly better. For “cold” fluorescent tubes as light sources, CdTe solar cells perform the best.

### 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. 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.

Although the crystalline Si cell is still dominating the PV market, second generation solar cells, i.e. thin film technologies, are rapidly entering the market. The different PV cells for applications on earth are rated by their power output under standard test conditions i.e. an illumination intensity of 1000 W/m<sup>2</sup> 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<sup>2</sup> as compared to 100-1000 W/m<sup>2</sup> 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 question therefore arises: which type of solar cell is best for indoor devices? This paper contributes to answering that question by comparing the power output of different thin film solar cells (amorphous Si [Meier], CdTe

[Wu], CIGS [Bhattacharya], GaAs [Bauhuis] and an organic cell with active layer P3HT:PCBM [Kim] with the classical crystalline silicon solar cell as reference [Zhao]. This comparison is made for typical artificial light sources, i.e. an LED lamp, a “warm” and a “cool” fluorescent tube and a common incandescent and halogen lamp, 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. Because we want to focus on the influence of the quantum efficiencies in different indoor environments, we idealize the cells and make abstraction of other cell properties. We refer to reference [Virtuani] for previous work on CIGS solar cells in different artificial lighting conditions.

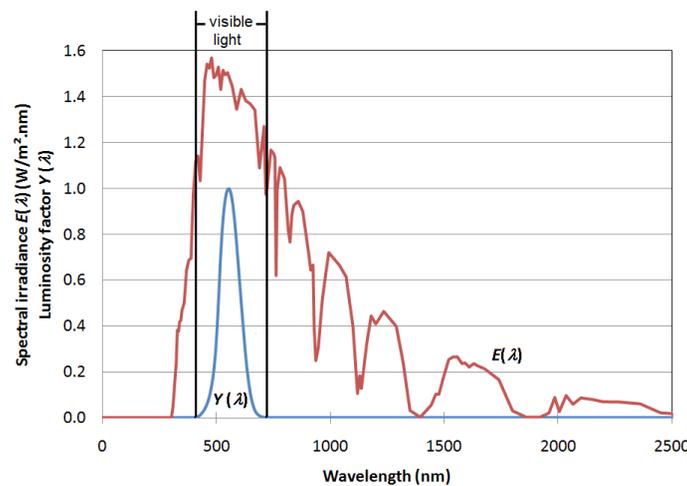


Figure 1. The spectral irradiance  $E(\lambda)$  of the solar spectrum and the luminosity factor  $Y(\lambda)$ . The region of the visible light is indicated

## Methodology

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  $\lambda$ . The total power density  $E$  of the radiation can easily be determined by summing the contributions at each wavelength of the spectral irradiance  $E\lambda$ :

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

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  $W/m^2$ ) can be converted to the corresponding quantity illuminance  $E_v$ , which takes into account the sensitivity of the human eye:

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

The illuminance  $E_v$  is expressed in lumen (lm) per  $m^2$  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  $kW/m^2$  of the global solar spectrum AM 1.5 corresponds to 100 klux [Virtuani].

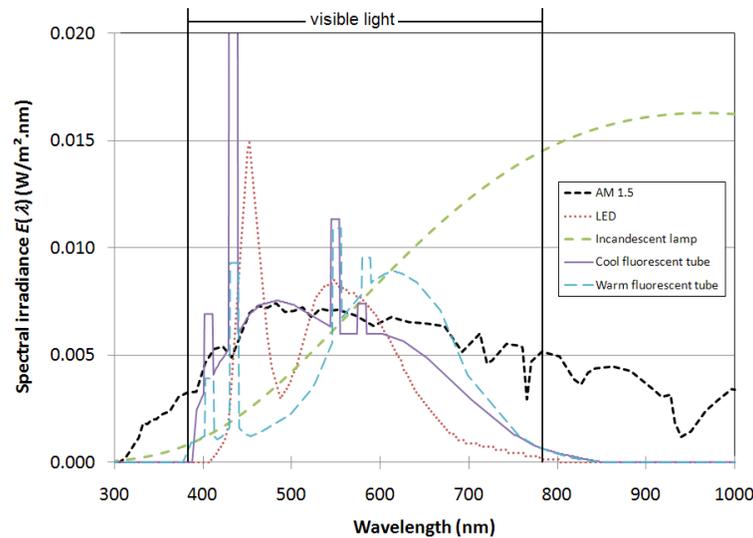


Figure 2. The spectral irradiance of some typical artificial light sources and the solar spectrum AM 1.5 as reference. All light sources, including the solar spectrum AM 1.5, are scaled to 500 lux. The region of the visible light in the spectrum is indicated.

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. As LED lamp, we consider a typically cool white emitter (“LZ4-00CW10”) manufactured by LedEngin Inc.. 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 [Virtuani]. 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. 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. The power conversion efficiency  $\eta$  of the solar cell is given by

$$\eta = \frac{F \cdot J_{sc} \cdot V_{oc}}{P_{in}}$$

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:

$$J_{sc} = q \int_0^{\infty} \Phi_{\lambda}(\lambda) \cdot \mathcal{Q}(\lambda) \cdot d\lambda$$

with  $q$  the elementary charge and  $\Phi_{\lambda}(\lambda)$  the spectral flux density of the light source (in  $1/m^2 \cdot s \cdot nm$ ), indicating how many photons are incident on the solar cell per unit of area, per unit of time and per wavelength. The quantum efficiencies

QE of each cell are given in figure 3 and are based on the reference mentioned above. Because we want to focus on the influence of the QE in different indoor environments, we idealize the cells: we impose a fill factor  $FF$  of unity and approximate the open circuit voltage  $V_{oc}$  to the bandgap of the absorber:  $V_{oc} = E_g/q$ . This idealization allows us to compare the results qualitatively and thus study the influence of one parameter: the quantum efficiency  $QE$ .

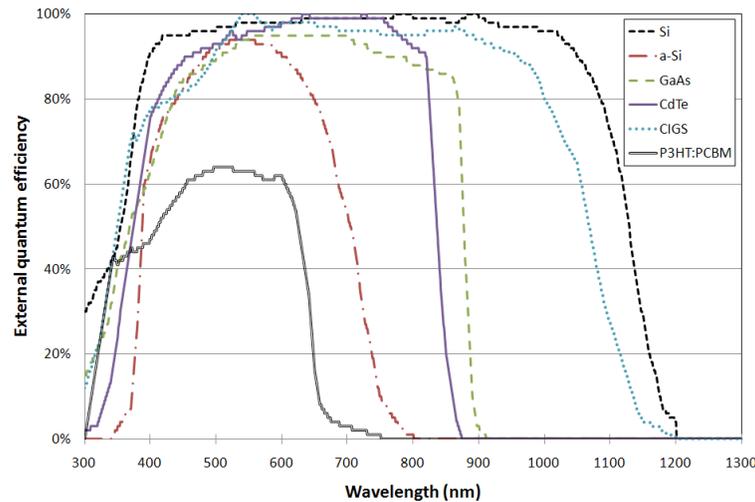


Figure 3. The external quantum efficiency of different types of photovoltaic solar cells.

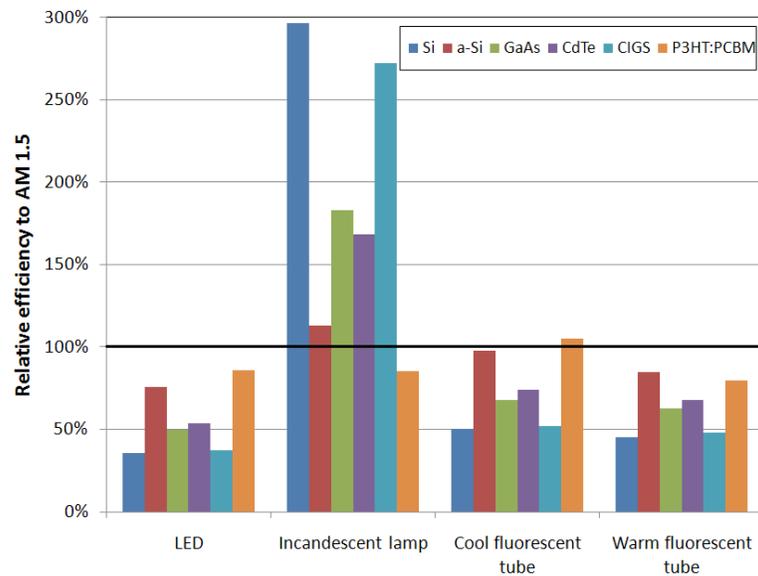


Figure 4. The relative efficiency of different types of photovoltaic solar cells in different lighting conditions, compared to the AM 1.5 spectrum as reference.

## RESULTS

We compare the indoor environments to the outdoor spectrum AM 1.5 (figure 4). We notice that the incandescent lamp is the best artificial light source. For a Si and CIGS cell, the performance of the solar cell improves with a factor of almost 3 compared to AM 1.5. This was to be expected. Indeed, figure 2 clearly shows that the incandescent lamp has the highest intensity within the visible region. The LED lamp is the worst light source for indoor PV with a decrease in performance of a quarter for amorphous silicon to two thirds for crystalline silicon cells. The reason is that an LED lamp is a very efficient light source: it emits only light within the visible region, from 400 to 800 nm (figure 2). This makes an LED lamp very energy efficient; emitting light within the visible spectrum is the primary goal of light sources. However, a silicon cell can absorb light to 1200 nm (figure 3). This explains the worse performance for e.g. silicon cells in LED environment compared to AM 1.5: in an LED environment, there are no photons with a wavelength between 800 and 1200 nm, unlike in an AM 1.5 environment. The best solar cells for indoor use depend heavily on the light source. Figure 5 shows the relative efficiency of each cell to the silicon cell as reference, for each lighting condition. For an incandescent lamp and in an outdoor environment, crystalline silicon remains the best. However, for an LED lamp or “warm” fluores-

cent tube, amorphous silicon is significantly better. For cool fluorescent tubes as light sources, CdTe solar cells perform the best. Figure 5 shows that, by illumination with a warm fluorescent tube, an organic cell performs better than a silicon cell. However, one has to take into account our assumptions. We only considered the  $QE$  as parameter. We neglected the difference in  $FF$  between silicon (83.6 % [Zhao]) and the organic P3HT:PCBM cell (49.7 % [Kim]). Furthermore, we assumed a  $V_{oc}$  equal to the absorbing bandgap, which is, certainly for organics, a rough approximation because it neglects the voltage loss, necessary for exciton dissociation. A more accurate approximation can be found in reference [Minnaert].

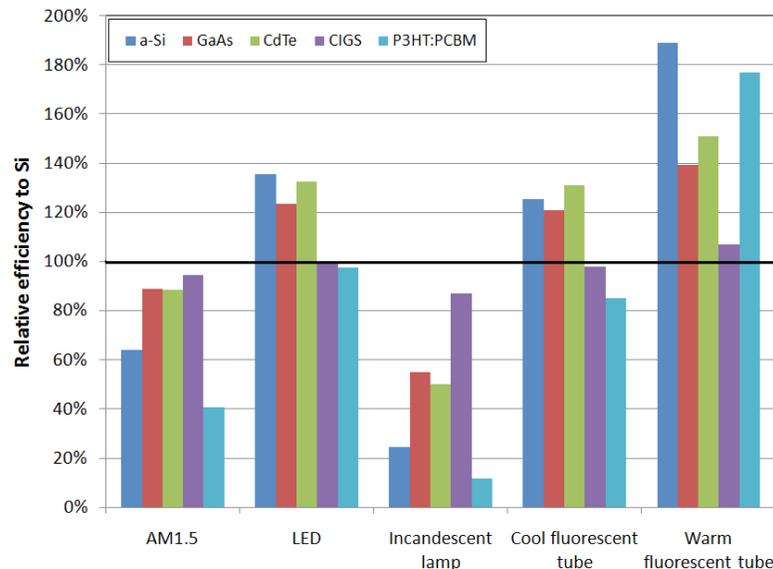


Figure 5. The relative efficiency of different types of photovoltaic solar cells in different lighting conditions, compared to the crystalline silicon solar cell as reference.

## REFERENCES

- Bauhuis, G.J., Mulder, P., Schermer, J.J., Haverkamp, E.J., van Deelen, J., Larsen, P.K. 2005. High efficiency thin film GaAs solar cells with improved radiation hardness. Proc. of the 20<sup>th</sup> European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona (Spain), 468.
- Bhattacharya, R.N., Contreras, M.A., Egaas, B., Noufi, R.N., Kanevce, A., Sites, J.R. 2006. High efficiency thin-film  $CuIn_{1-x}Ga_xSe_2$  photovoltaic cells using a  $Cd_{1-x}Zn_xS$  buffer layer. Appl. Phys. Lett., 89:253503.
- Kim, Y., Cook, S., Tuladhar S.M. et al. 2006. A strong regioregularity effect in self-organizing conjugated polymer films and high-efficiency polythiophene:fullerene solar cells. Nature Materials, 5:197–203.
- LedEngin Inc. 2008. Datasheet LZ4-00CW10 High Luminous Efficacy Cool White LED Emitter.
- Meier, J., Spitznagel, J., Kroll, U., Bucher, C., Fay, S., Moriarty, T. Shah., A. 2004. Potential of amorphous and microcrystalline silicon solar cells. Thin Solid Films, 451:518-524.
- Minnaert, B., Veelaert, P. 2010. The appropriateness of organic solar cells for indoor lighting conditions. Proc. of SPIE Photonics Europe, 12-16 April 2010, Brussels (Belgium).
- Randal, J.F. 2005. Designing Indoor Solar Products, John Wiley & Sons, 56-59.
- Virtuani, A., Lotter, E., Powalla, M. Influence of the light source on the low-irradiance performance of  $Cu(In,Ga)Se_2$  solar cells. Sol. En. Mat. & Sol. Cells, 90:2141-2149.
- Wu, X. 2004. High-efficiency polycrystalline CdTe thin-film solar cells. Solar Energy, 77:803-814.
- Zhao, J., Wang, A., Green, M.A., Ferrazza, F. 1998. 19.8% efficient honeycomb textured multicrystalline and 24.4% monocrystalline silicon solar cells. Appl. Phys. Lett., 73:1991-1993.