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# Efficiency simulations of thin film chalcogenide photovoltaic cells for different indoor lighting conditions

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## Abstract

Photovoltaic (PV) energy is an efficient natural energy source for outdoor applications. However, for indoor applications, the efficiency of PV cells is much lower. 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. In this context, the question arises whether thin film chalcogenide photovoltaic cells are suitable for indoor use. This paper contributes to answering that question by comparing the power output of different thin film chalcogenide solar cells with the classical crystalline silicon cell as reference. The comparisons are done by efficiency simulation based on the quantum efficiencies of the solar cells and the light spectra of 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.

Keywords: chalcogens; cadmium telluride; computer simulation; solar cells.

## 1. 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. 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, in an indoor environment, the efficiency of classical crystalline silicon photovoltaic cells is lower than outdoors.

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. This is especially true for chalcogenide cells as CdTe and CIGS cells. 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 $W/m^2$ 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 gives 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 question therefore arises: are thin film chalcogenide photovoltaic cells appropriate for indoor devices? This paper contributes to answering that question by comparing the power output of different chalcogenide solar cells 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 AM 1.5 spectrum as reference. The comparisons are done by efficiency 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. This paper is inspired by the excellent work of Virtuani [1] on CIGS solar cells in different artificial lighting conditions.

## 2. Methodology

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 $\lambda$ of the spectral irradiance $E_\lambda$:

$$E = \int_0^\infty E_\lambda(\lambda)\,d\lambda \,. \qquad (1)$$

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 [1] to 100 klux according to equation (2).

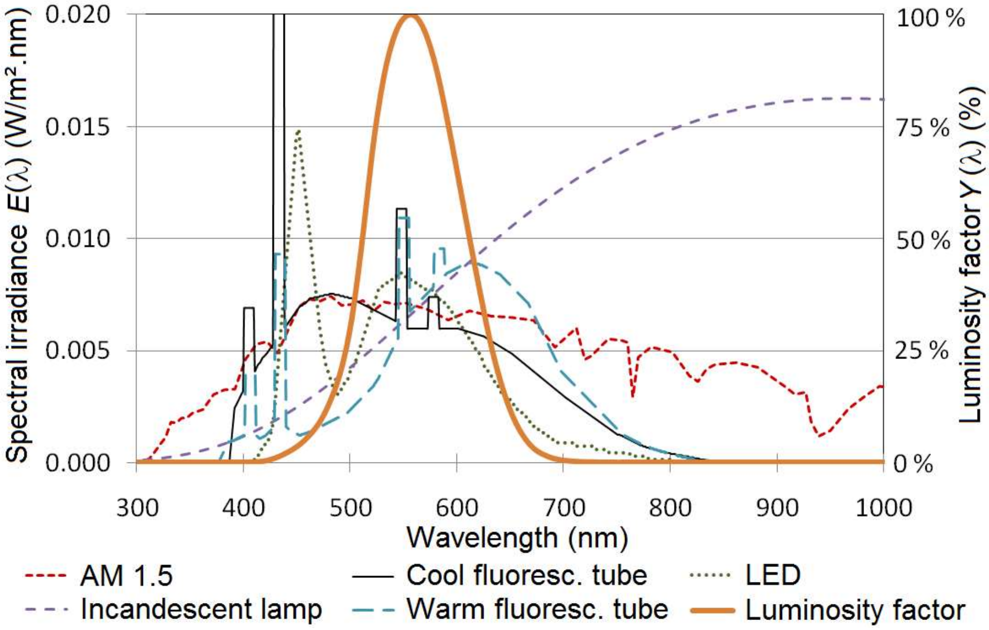


*Fig. 1: The luminosity factor Y(λ); the spectral irradiance of some typical artificial light sources and the solar spectrum AM 1.5 as reference. All light sources, including the solar spectrum AM 1.5, are scaled to 500 lux.*

The 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. [2]. 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 [1]. 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).

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.

The power conversion efficiency $\eta$ of the solar cell is determined from the current-voltage characteristic and 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), indicating how many photons are incident on the solar cell per unit of area, per unit of time and per wavelength.

The aim of this study is to investigate the influence of the quantum efficiency *QE* (in particular the spectral location of the absorption window) in different indoor environments. Indeed, the spectral location and the width of the absorption window are an important parameter influencing the efficiency of the solar cell, depending on the type of (artificial) light source in the indoor environment. Because we want to focus on the influence of one parameter only, the *QE*, we idealize the cells and make abstraction of other cell properties. First, we ignore the influence of the parasitic resistances. Under the low light intensities, present in indoor environments, the efficiency of chalcogenide solar cells drops significantly compared to standard test conditions. The reason is the reduction of $V_{oc}$ and *FF*, mainly due to the shunt resistance [3].Second, we ignore the possible red kink effect [4] which can occur at low illumination intensities, lowering the *FF*. Because we only want to study 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: $V_{OC}=E_g/q$. Of course, this is an idealized, non-realistic situation, but it allows us to make abstraction of the other influences and thus study the influence of one parameter only: the quantum efficiency *QE*.

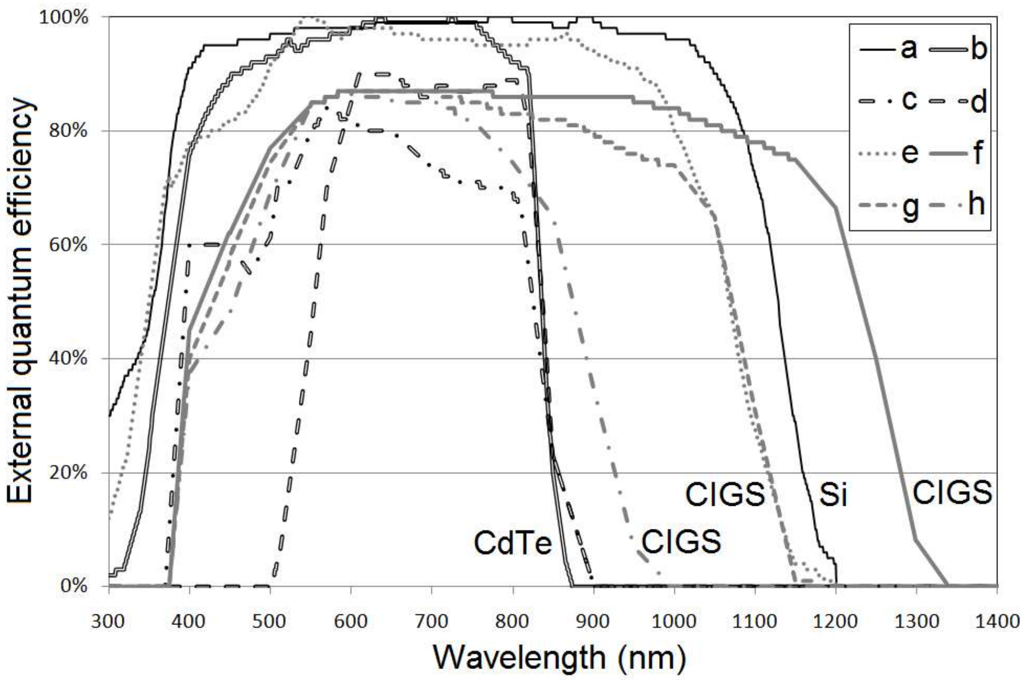


*Fig. 2: The external quantum efficiency QE of different types of photovoltaic solar cells. We refer to the text for the explanation of the different types.*

We consider the following solar cells (the quantum efficiencies *QE* of each cell are given in Fig. 2): a Si cell (a) with high efficiency as reference [5]; a CdTe cell (b) with high efficiency [6] and two CdTe cells (c,d) with respectively a layer of

CdS of 150 nm and 1000 nm CdS, influencing the absorption at lower wavelengths [7]. Furthermore, we consider a CIGS cell (e) with high efficiency [8] and three $Cu(In,Ga)Se_2$ cells with different Ga/(Ga+In) ratios (and thus different bandgaps, or absorption edges at higher wavelengths) [9]. The above ratio for cells (f), (g) and (h) is 0 (no Ga), 0.24 and 0.61, respectively.

### 3. Results

We compare the indoor environments to the outdoor spectrum AM 1.5 (Fig. 3). We notice that the incandescent lamp is by far the best artificial light source. For a Si and most CIGS cells, the performance of the solar cell improves with a factor of about 3 compared to AM 1.5. This was to be expected. Indeed, Fig. 1 shows that the incandescent lamp has the highest intensity within the absorption windows of the solar cells (Fig. 2). The CdTe cells perform about 1.5 to 2 times better than in an outdoor AM 1.5 environment.

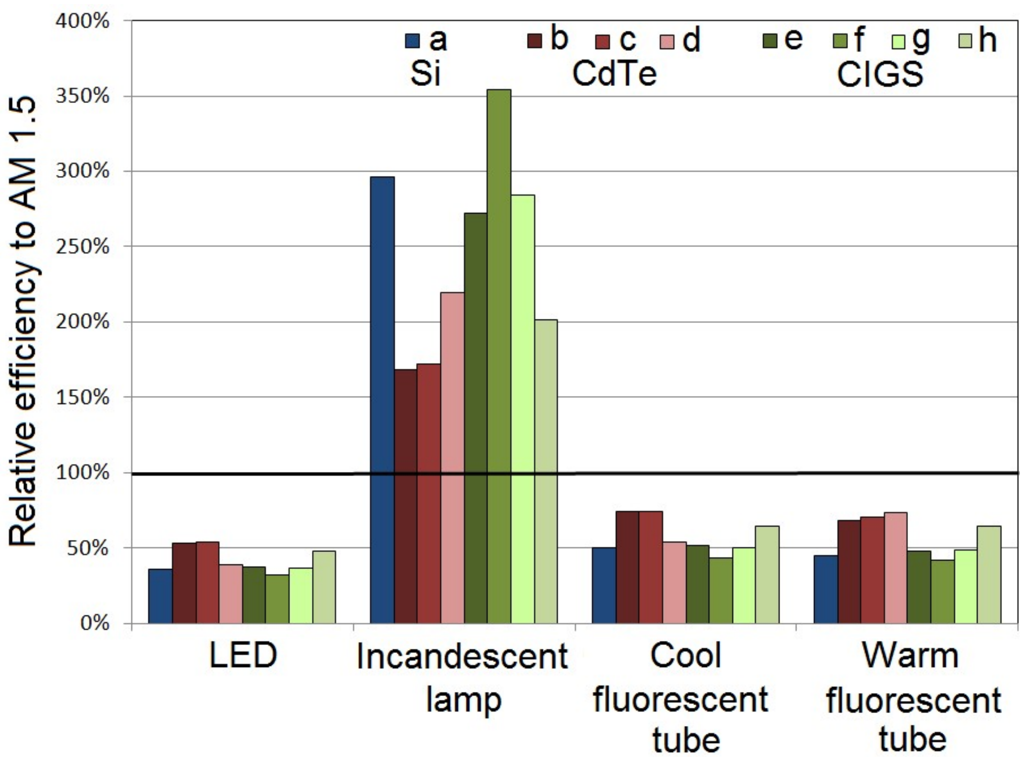


*Fig. 3. The relative efficiency of different types of photovoltaic solar cells in different lighting conditions, compared to the AM 1.5 spectrum as reference. We refer to the text for the explanation of the different types.*

The LED lamp is the worst light source for indoor PV with a decrease in performance of a half to two thirds. 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 (Fig. 1). This makes an LED lamp very energy efficient; emitting light within the visible spectrum is the primary goal of light sources. However, a CIGS cell can absorb light to e.g. 1100 nm (Fig. 2). This explains the worse performance for the CIGS cells with a broad absorption window in an LED environment compared to AM 1.5: in an LED environment, there are no photons with a wavelength between 800 and 1100 nm, unlike in an AM 1.5 environment. Therefore, a CdTe cell, with an absorption window to 850 nm, is to be preferred in an LED environment.

An important conclusion is that, depending on the light source, broadening the absorption window is not always beneficial. The CIGS cell with a wider absorption window than the CdTe cell performs worse in an LED environment. 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, which explains the better performances for the CIGS cells with a broad absorption window. For an environment with LED lamps or fluorescent tubes, a too broad absorption window deteriorates the power output. This is best seen by the results of the cells f, g and h (which mainly differ in bandgap) for the different artificial light sources.

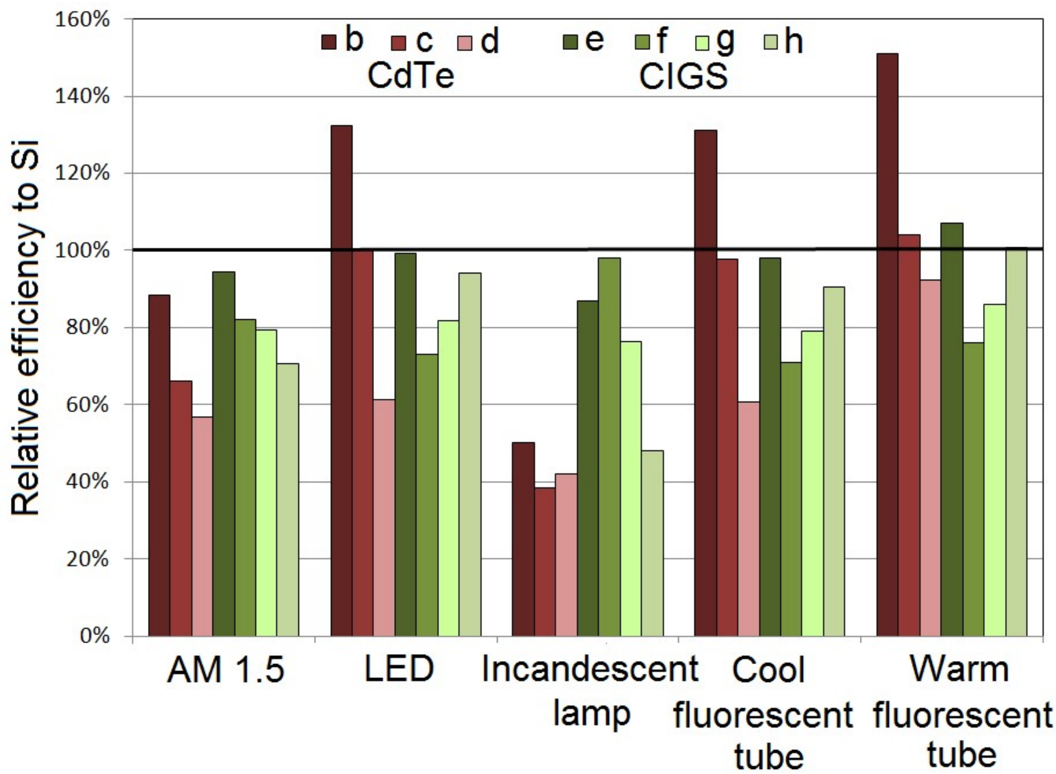


*Fig. 4: The relative efficiency of different types of photovoltaic solar cells in different lighting conditions, compared to the crystalline silicon solar cell as reference. We refer to the text for the explanation of the different types.*

The best solar cells for indoor use depend heavily on the light source. Fig. 4 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 the other environments, the CdTe cell with high efficiency (b) performs better: one third in an LED and cool fluorescent environment, and even 50 % better in an environment with warm fluorescent tubes. The explanation is again the more coincident absorption window of CdTe with the visible light region. It is interesting to note that quite some CdTe and CIGS cells perform nearly as well as the Si cell with high efficiency, indicating the appropriateness of chalcogenide cells for indoor applications. Although we only considered the *QE* (and thus also the bandgap) of the cells, the main conclusions will qualitatively remain valid because of the similar values of the *FF* of the different cell types.

## 4. Conclusions

We compared different chalcogenide solar cells in different indoor environments. This was done by efficiency simulation based on the quantum efficiencies of the solar cells and the light spectra of typical artificial light sources. The performances of the cells were compared relatively to a silicon solar cell and to the outdoor spectrum AM 1.5 (Fig. 3 and 4). The main conclusion is that chalcogenide cells can compete with silicon cells, depending on the indoor environment.

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