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A MODEL DESCRIBING THE SUITABILITY OF DIFFERENT SOLAR CELLS FOR AN INDOOR WIRELESS NETWORK

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ABSTRACT: Wireless communication networks, 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. In order to obtain an "infinite" lifetime of the system, it should be able to harvest energy from renewable resources in the device's environment. Photovoltaic solar energy is an efficient natural energy sources available for wireless networks for outdoor applications. However, for indoor applications, the efficiency of photovoltaic cells is much lower. 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 solar cells with the classical crystalline silicon solar cell as reference. This comparison is made for typical artificial light sources, 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. Using these results, we can determine the appropriateness of different solar cells for an indoor wireless network.

Keywords: modelling, simulation, spectral response.

1 INTRODUCTION

Wireless communication networks (router nodes, sensor networks, camera network,…), 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 have of course a fixed energy rating and therefore a limited lifetime. They have to be replaced in due time and this factor plays a major role in determining the life of a wireless node in the network. Often, the cost of replacing the battery outweighs the cost of the device itself. Also from an environmental perspective, reducing battery waste is laudable. Moreover, 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 sensor networks. In order to obtain an "infinite" lifetime of the system, it should be able to harvest energy from renewable resources in the device's environment. 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 solar energy is an efficient natural energy sources available for wireless networks for outdoor applications. However, for indoor applications, it is important to note that the efficiency of classical crystalline silicon photovoltaic cells is lower than outdoors. In this paper, we study the efficiency of different solar cells for different indoor environments. The results can be applied on a device with varying power requirements and duty cycles. In this way, an answer can be given on the minimum required surface area of the solar cell in each case, and thus on its appropriateness for wireless networks.

A solar-powered application consists of the following components: the external environment, the solar module, energy storage and the device (figure 1). The solar energy from the environment is collected by the solar cell and (whether or not with a regulating circuit) made available for the operation of the device. Because of the unpredictable and variable illumination of the photovoltaic cells, an energy storage system is used to buffer the energy from the cells and distribute it to the device.

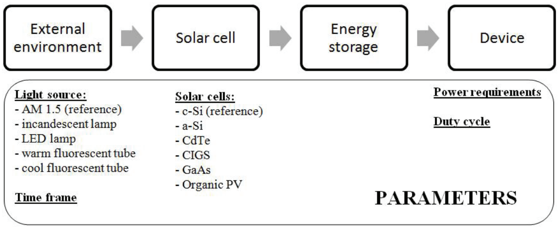

Figure 1: Simplified schematic overview for powering a device with solar cells. The varying parameters in the model are indicated.

Although the crystalline Si cell is still dominating the PV market, second generation solar cells 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/m² 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 is different from the outdoor solar spectrum. It depends not only on the type of light source, but also on the presence of reflected and diffused light. Unfortunately, there are no internationals 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 solar cells (amorphous Si [1], CdTe [2], CIGS [3], GaAs [4] and an organic cell with active layer P3HT:PCBM [5]) with the classical crystalline silicon solar cell as reference [6]. 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. We refer to Virtuani [7] for previous work on CIGS solar cells in different artificial lighting conditions.

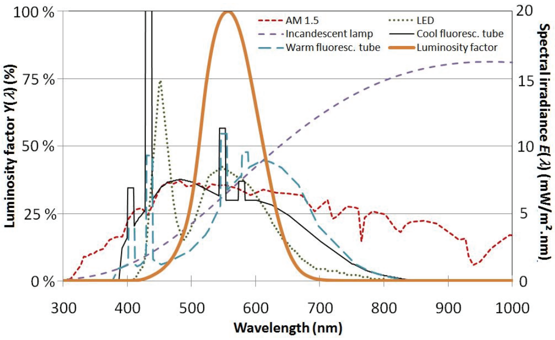

Figure 2: The luminosity factor $Y(\lambda)$; the spectral irradiance of some typical artificial light sources and the solar spectrum AM 1.5 a reference. All light sources, including the solar spectrum AM 1.5, are scaled to 500 lux.

2 THE MODEL

Figure 2 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. 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 2). 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:

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

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 to 100 klux [7].

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 [7]. 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 η of the solar cell is given by

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

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:

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

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 quantum efficiencies QE of each cell are given in figure 3 and are based on references [1-6].

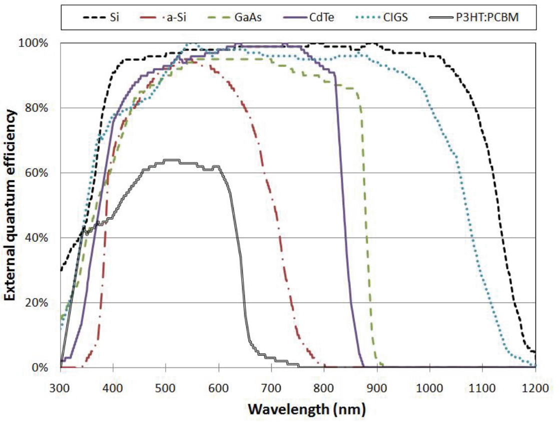

Figure 3: The external quantum efficiencies *QE* of different types of photovoltaic solar cells.

We approximate the open circuit voltage V_{oc} to the bandgap of the absorber: $V_{OC}=E_g/q$ and ignore the influence of parasitic resistances. This idealization allows us to compare the results qualitatively and study the influence of the quantum efficiency *QE*. Using our results, one can obtain guidelines to investigate whether it is realistic to power a certain wireless low power device.

3 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 absorption window of the solar cells. 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 an 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, in the other environments, GaAs and CdTe are significantly better.

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. For an environment with LED lamps or fluorescent tubes, a too broad absorption window deteriorates the power output.

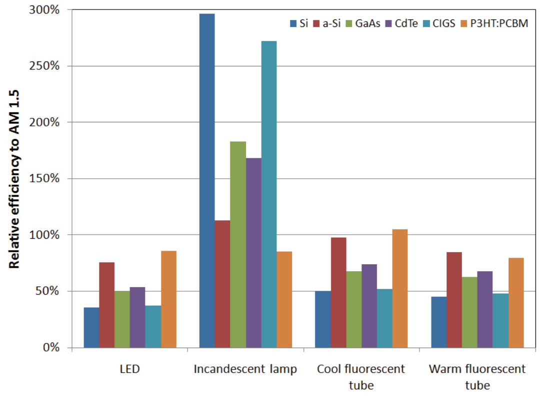

Figure 4: The relative efficiency of different types of photovoltaic solar cells in different lighting conditions, compared to the AM 1.5 spectrum as reference.

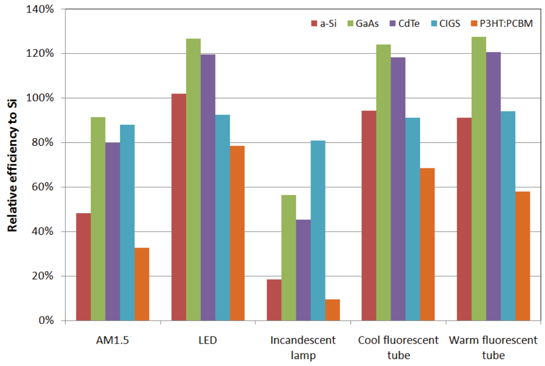

Figure 5: The relative efficiency of different types of photovoltaic solar cells in different lighting conditions, compared to the crystalline silicon solar cell as reference.

Figure 6 shows the electrical power density output of the different 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. Using these results, one can easily obtain guidelines for the necessary surface area of the solar cell for a certain device. For example, a silicon solar cell of 1 dm² can power a device with a power consumption of 50 mW on average under illumination of an incandescent lamp. In an LED environment however, the silicon cell of 1 dm² can only deliver one fifth: 10 mW on average. On the other hand, for the organic solar cell, there is no difference in power generation of the solar cell between illumination by an LED or an incandescent lamp. One dm² delivers 5 mW. Of course, one has to take into account the time frame the light sources are on, e.g. in a hospital the indoor light can be constant on. In an office, it can be dark at night. One has also to consider the duty cycle of the device, typical for low power wireless networks. Indeed, a node (camera, router node, sensor node,...) in a wireless communication network is usually not always active. For example, a surveillance camera can only be recording images when a person is detected by a sensor. Or a communication node is only active when it has to transmit data to another node. The difference in power consumption between the active state and the sleep state can be quite large [8]. The power consumption of the device can be estimated with the formula

$$P = f \, . \, P_{active} + (1 - f) \, . \, P_{sleep}$$

with respectively P_{active} and P_{sleep} the power consumption in the active and the sleep state and f the fraction of the time that the device is active (i.e. the duty cycle) [8]. If one considers a device with a certain minimum power requirement and duty cycle, one can –with our results- easily calculate the minimum surface area for the different types of solar cells in the different indoor environments.

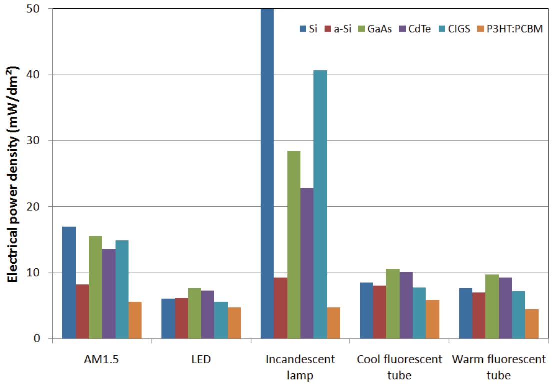

Figure 6: The electrical power density output of the different solar cells for the artificial light sources. The silicon solar cell and the AM 1.5-spectrum are added as comparison.

4 CONCLUSION

We compared different types of 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. These calculations lead to guidelines for the required surface area of the different types of solar cells, depending on the indoor environment and the device.

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