New indoor light source trends and their impact on classical photovoltaic harvester (indoor a-Si solar cells) yield

About human eye sensitivity, visible spectrum, indoor light and solar cells

What a human being percepts as light (also called visible spectrum) is only a very tight part of the very broad electromagnetic waves spectrum existing around us. The range between violet color (down to 400 nm) and the deep red (up to 700 nm) is localized between (both already invisible) U.V. (ultra violet) range lefts and I.R. (infrared) range rights, with a sensitivity peak at mid (around 550 nm).

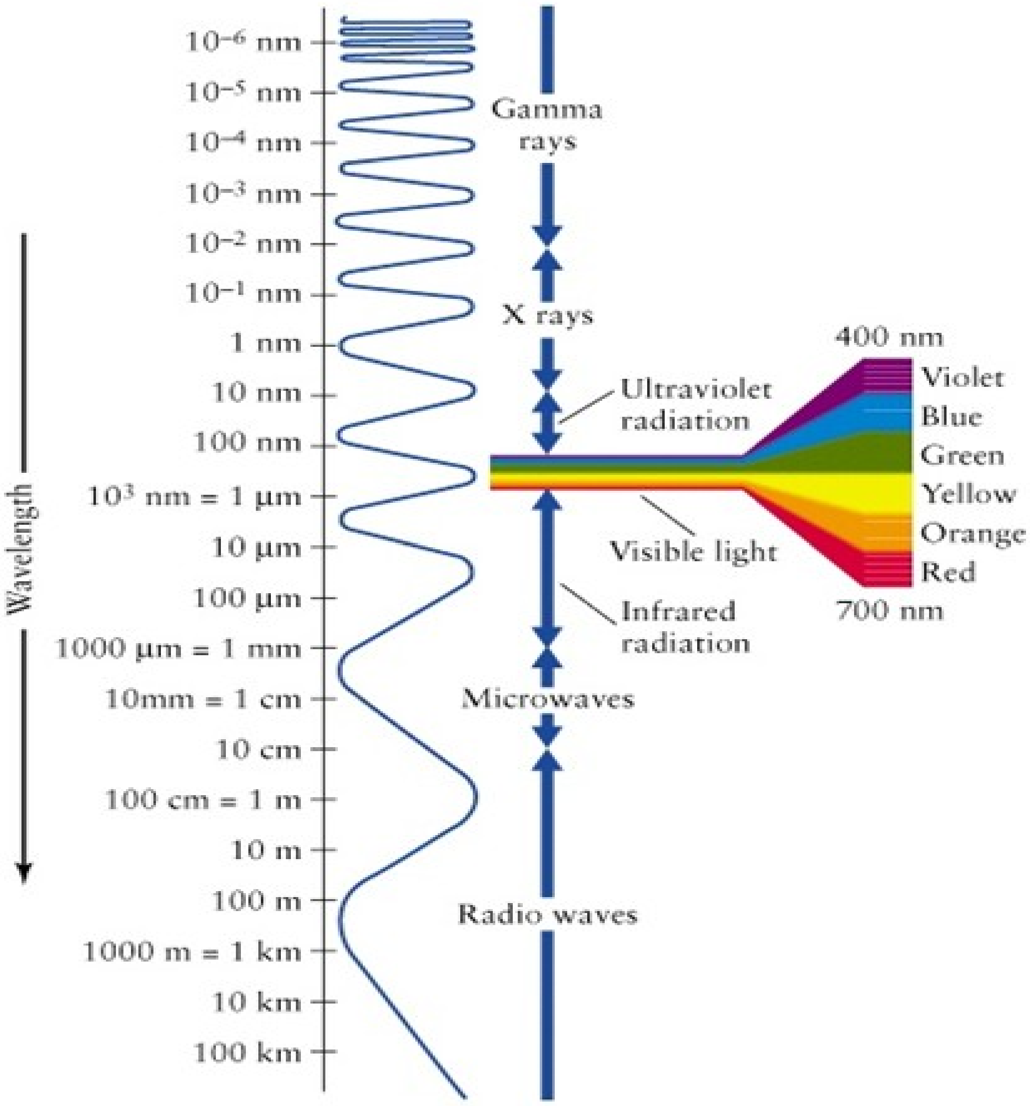

Fig. 1: Wavelength image from Universe by Freedman and Kaufmann

Typical environmental light sources

Environmental daylight consists indoors generally in average of a mix of natural environmental light and artificial light. The first artificial light sources were candelas later followed by incandescent, CFL and recently LED bulbs. Their typical specific visible emission spectrum is illustrated below:

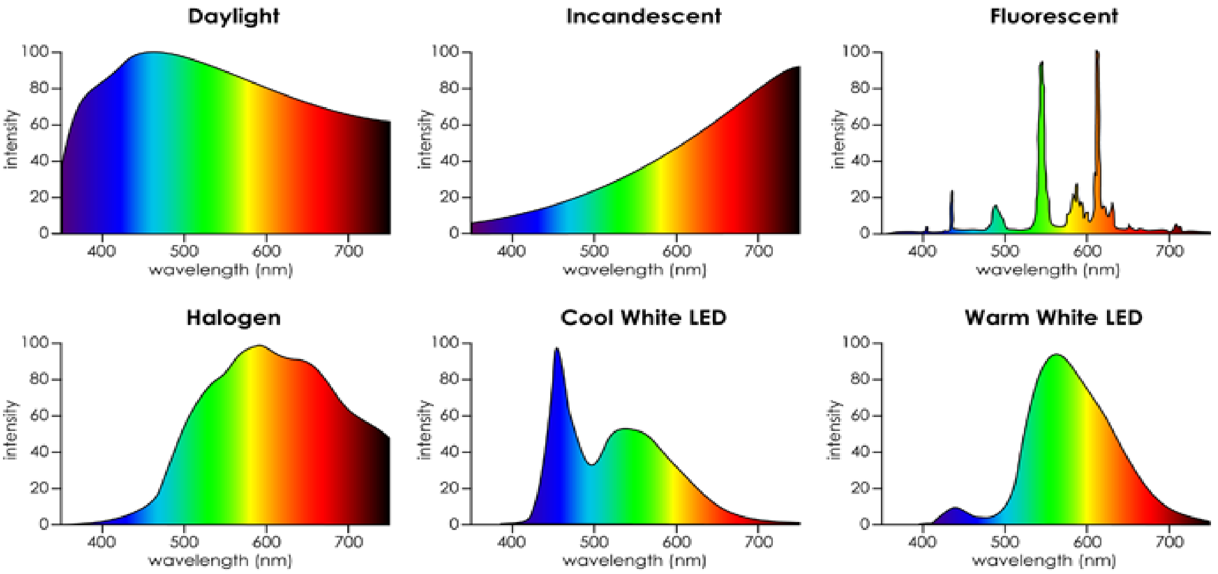

Fig. 2: Comparison of different light sources visible spectral emissions

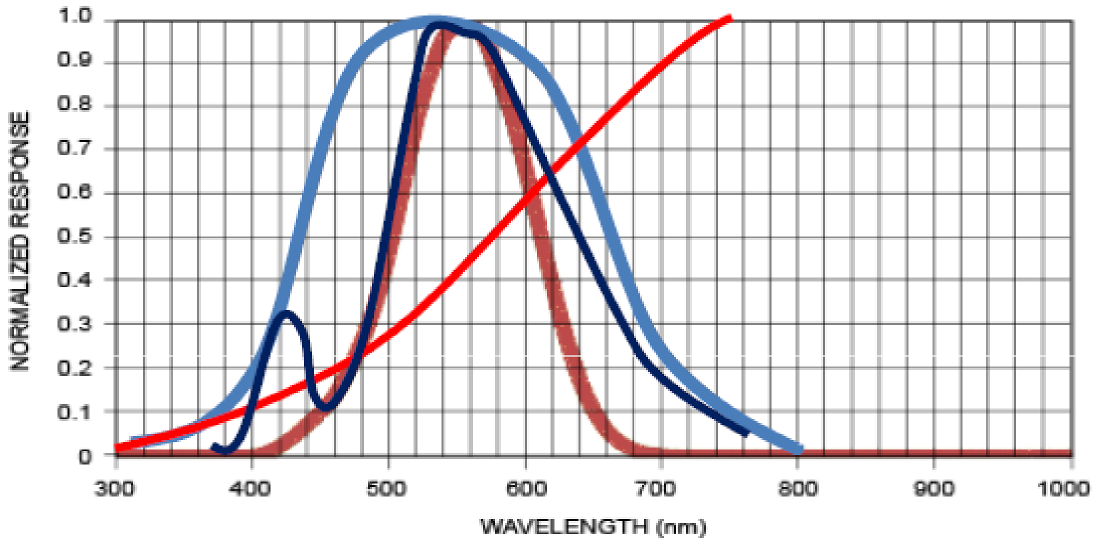

Fig. 3: Comparison between human eye spectral sensitivity (brown line), overlapped a-Si sensitivity (blue line) vs. incandescent bulb (red line) and white LED (dark blue line) spectral emissions shows actually very good matching for white LED.

With regard to these new developments and trends, recently especially regarding the rapid market penetration of the new (and as always first unknown) LED light technology, the first question was about a potentially impact of the new technology on the existing indoor solar cell harvester regarding its yield. Nowadays not the watt number of the light sources is important for the perceived light level but its lumens and color (spectral emission).

The reason for this question was actually the supposition that, contrary to the classical indoor artificial light sources like incandescent and CFL, LED light would have a very tight, color specific spectral emission which in worst case could have negative influence on the solar panel conversion efficiency and therefore for the energy balance.

Now there is a mix of facts which actually contradict this assumption:

1. White LEDs have, in opposite to single RGB colors ones but also to CFL, similar to natural daylight) a really broad visual spectral emission, also see pictures above
2. The spectral sensitivity of the classical indoor solar cell (also called a-Si, amorphous, thin film solar cell) overlaps totally the human eye one, so every light source provided for human use including LED implicit matches very good the a-Si cell one too, see below violet shape (a-Si) vs. green shape (human eye). Its spectral sensitivity range reaches from <350 nm to > 750 nm having a maximum peak around 550 nm too, similar to the human eye, in other words the current a-Si technology still offers the optimal overall compromise indoors:

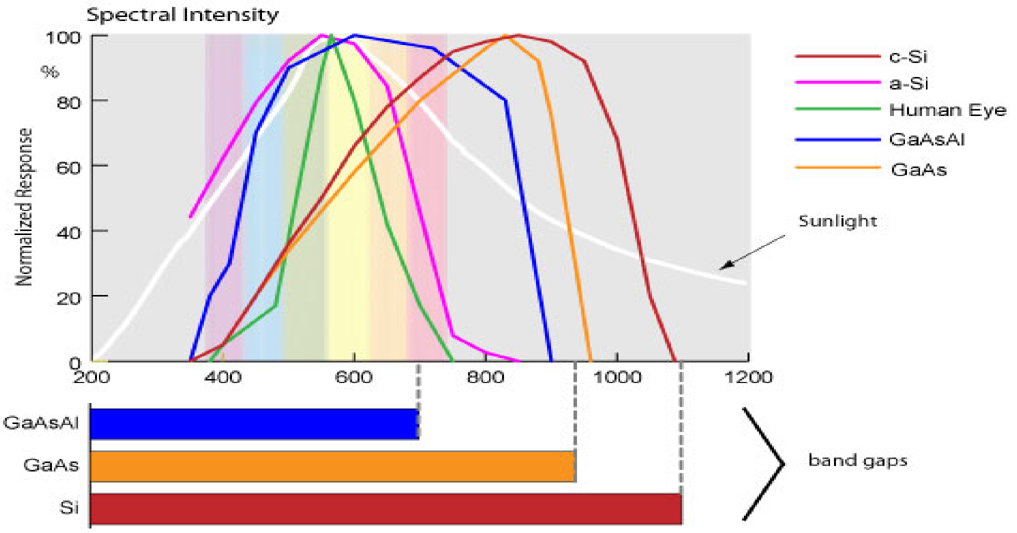

Fig. 4: Different solar cell technologies spectral sensitivities vs. the human eye (green).

3. Artificial indoor light sources can be roughly divided into four different categories:

   Group 1: black body (incandescent bulbs, “warm” white light);
   Group 2: Fluorescent (CFL)
   Group 3: LED (obvious “warm” white LED slightly more efficient as “cold” white LED)
   Group 4: HP (high pressure, i.e. phosphor, sodium, mercury, actually for outdoors only)

4. Indoor light is actually as good as always result of an averaged mix of natural and (different) artificial light sources, so practical there is a continuously varying weighted sum of different spectral sources.

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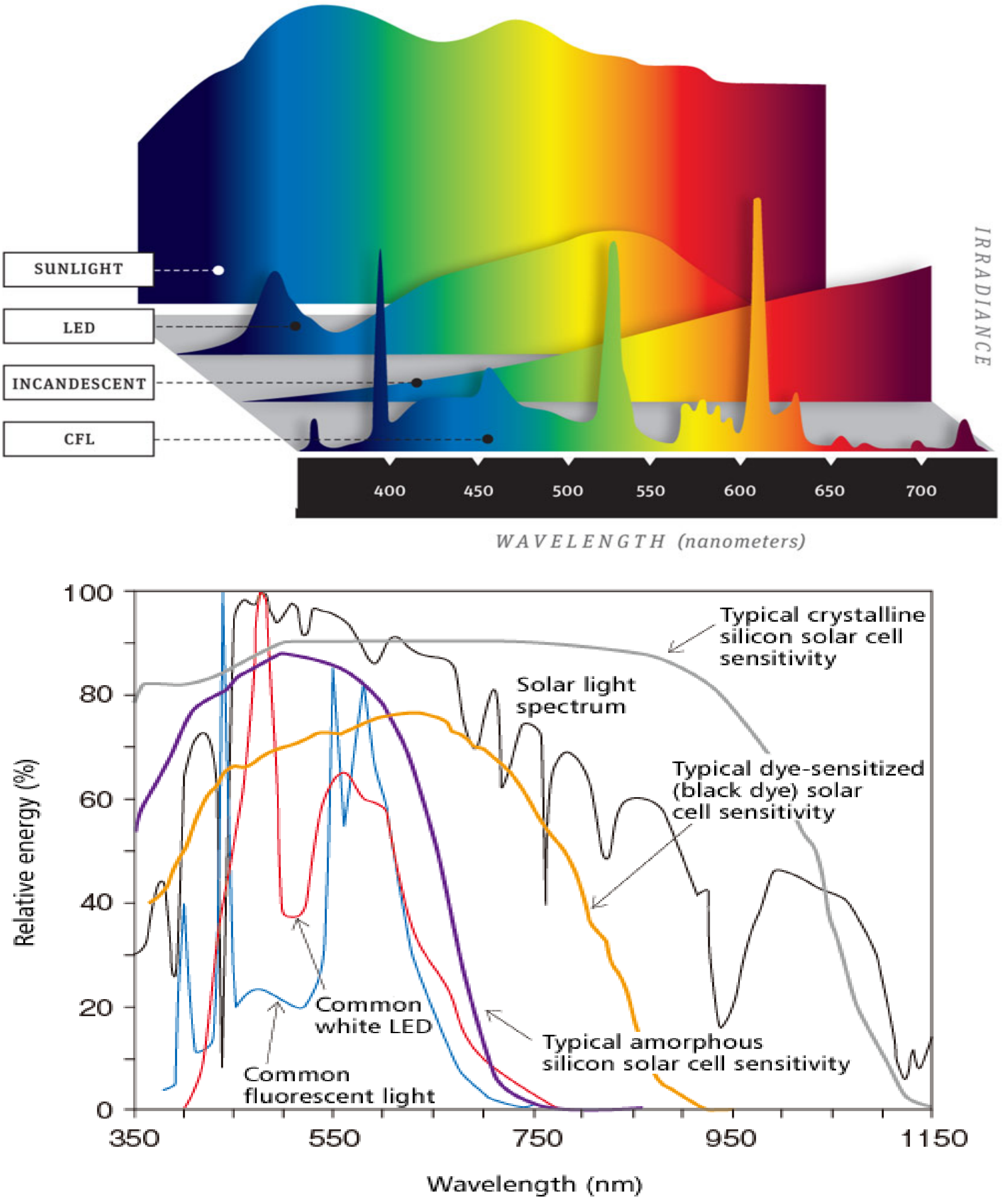

Fig. 5 Comparison between different specific spectral visible light sources vs. spectral sensitivities of different solar cell technologies shows overall best matching for a-Si technology indoors!

Conclusions:

The human eye might perceive different sources of light of the same brightness as “equal”; however, solar cells conversion efficiency might be quite different depending on manufacturing technology and specific light spectrum. Indoor solar cells however are optimized rather for poor indoor light conditions (levels of just few pm compared to outdoor levels!). While conventional expensive outdoor solar cells are more efficient in optimum conditions (solar daylight) indoor cells win indoors on the 24-hour energy cycle because they can use also the very poor early morning and evening light.

During daytime, the light indoors will be actually a mixture of daylight and artificial lamplight varying throughout the day, latitude, room destination/occupation, season and weather. The amount of available natural light is minimal in midwinter (worst case).

White LED light sources are actually optimized to radiate as much as possible visible, daylight like light. Their spectral emissions area matches with the spectral sensitivity area of the classical a-Si indoor solar cells offering maximum conversion efficiency at around 550 nm (maximum human eye sensitivity). This can be visualized very simple by comparing (overlapping) the spectral emission area of every specific mentioned light source vs. the a-Si relative symmetrical “bell” sensitivity curve (see Fig. 5).

Ambient LED lighting is one of the most promising and fast-growing technologies of today. Through careful selection of phosphor compound and other dopant ion changes long life phosphor coated LED lamps could potentially “clone” quite every individual, user specific desired, quasi “designer” light temperature spectrum, including classical tungsten-halogen bulb. With their unique design and performance characteristics — such as directional light emission, compact profile, superior optical & color control, energy efficiency, reduced maintenance and long life — LEDs are best suited to a variety of lighting applications.

Even if it is still not possible to define an unique “reference” white LED lamp, accordingly different previous and current internal measurements (i.e. lastly EOSWU, wall mounted wireless occupancy sensor under incandescent bulb vs. white LED light too, see Appendix) classical amorphous-Si solar panels show quite similar energy harvesting efficiency under all evaluated typical indoor illumination sources (incandescent, CFL and white LED) under same light intensity. Therefore amorphous-Si technology still remains the overall optimal light harvester solution for typical indoor light conditions.

One last mention regarding LED retrofit: equivalent replacement products should have similar light distributions to ensure the lumens produced are directed where they are needed. Even if the total lumen output of the replacement LED lamps is comparable (mostly higher) to the incandescent, not all (but increasingly more) LED lamps types (shape-conditioned) produces also similar omnidirectional light distribution like the classical incandescent ones. Although a directional “beam” may be of benefit in some applications, by planning it is important to be aware of these differences. As consequence, by lamp retrofitting eventually previous correct indoor placed solar powered sensors could be thereafter correspondingly disadvantaged (i.e. out of LED “beam”). A sensor repositioning might be eventually required.

Additional references, resources and useful links:

http://www.enocean.com/fileadmin/redaktion/pdf/app_notes/AN207_ECS310_ECS320_SOLAR_PANEL_Jan11.pdf
https://www.enocean.com/en/enocean_modules/ecs-300/
http://www.enocean.com/fileadmin/redaktion/pdf/app_notes/AN201_SOLAR_UNIT_MOUNTING_Oct10.pdf
https://www.enocean.com/en/enocean_modules_902mhz/wall-mounted-occupancy-sensor-eosw-oem/

Appendix

Following distinct typical indoor artificial light sources (LED and CFL, brands and no names) were compared vs. “classical” incandescent bulb with regard to their energy harvesting potential on typical EnOcean WLP (EOSW) indoor a-Si solar panel, always under constant illumination intensity conditions and constant (resistive) load correspondingly specified solar panel operational voltage Vop (3 V):

Settings: dark room, illumination only DUT light source (#) upright over the solar panel at defined levels of

a) Light intensity: 200 lx, 75 k as solar panel load (Vop=3 V)
b) Light intensity: 1000 lx, 15 k as solar panel load (Vop=3 V)

Digital measurement instruments used: Lux-meter (light intensity), DVM (voltage, current)

LED (#1 to 4):

1. Philips: A60 LED 9.5 W=>60 W, E27 220-240 V, 806 lm (dimmable), warm white (2700 K), Ra>80, (10 €)
2. Osram: Superstar Classic A60 Advanced Surround Light LED 10 W=>60 W, E27 220-240 V, 806 lm (dimmable), warm white (2700 K), Ra=80, (13 €)
3. Karat: AGL LED A60 (180° spot) 10 W=>60 W, E27 230 V, 810 lm (dimmable), warm white (2700 K), Ra>80, (11 €)
4. Neolux: LED A60 10 W=>60 W, E27, 220-240 V, 806 lm, warm white (2700 K), (8 €)

CFL (#5-6):

5. Osram: Energy aver Superstar 14 W=>60 W, E27, 740 lm, warm comfort (2500 K), Ra>80, (4.5 €)
6. GO/ON: A60 11 W=>48 W E27 220-240 V, 550 lm warm white (2700 K), (3 €)

Incandescent Bulb (#7)

7. Osram: Centra Opal, A60, 60 W, 505 lm, (3.8 €)

In following above listed light sources brand names will be simply associated with their numbers, i.e. **#1** stays for Philips LED 9.5 W, **#7** for Osram A60 incandescent 60 W bulb.

Results (solar panel generated current µA@3 V):

#	**µA@200lx**	**µA@1000lx**
1	40	199
2	39	202
3	39	198
4	40	201
5	41	202
6	40	203
7	38	197 (Reference Incandescent A60 Bulb = 100%)

Final conclusion:

1. Results above show that all evaluated light sources types (LED, CFL and Incandescent) respectively all 7 evaluated products generated in the same indoor solar panel under same light intensity the same current (within setup overall measurement tolerances).
2. With regard to the energy harvesting all evaluated light sources are absolutely equivalent. Also there is no difference between expensive brands and “no name” products.