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

About human eye sensitivity, visible light 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 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).

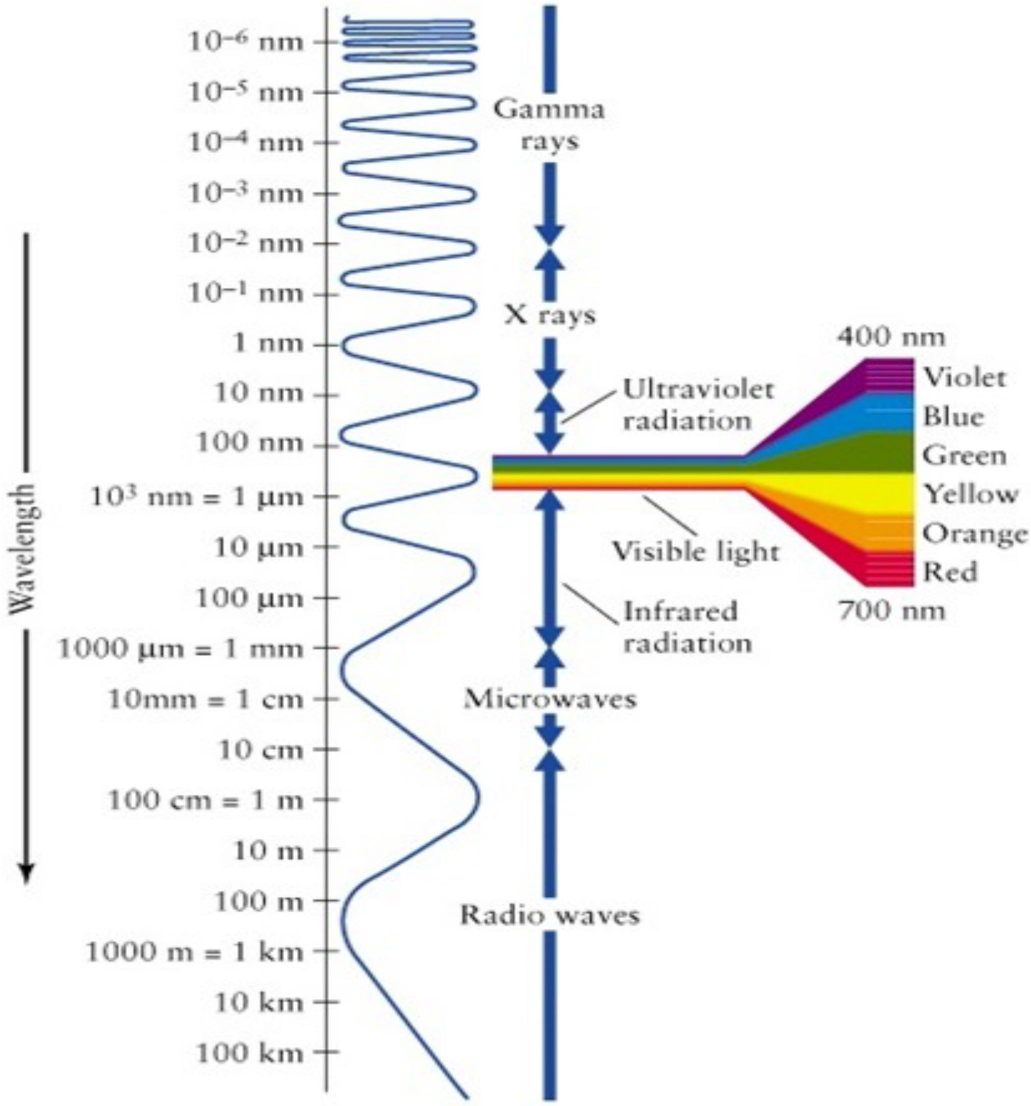

Fig. 1: Wavelength image from Universe by Freedman and Kaufmann

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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. Some typical, specific emission spectrums of different light sources are shown below:

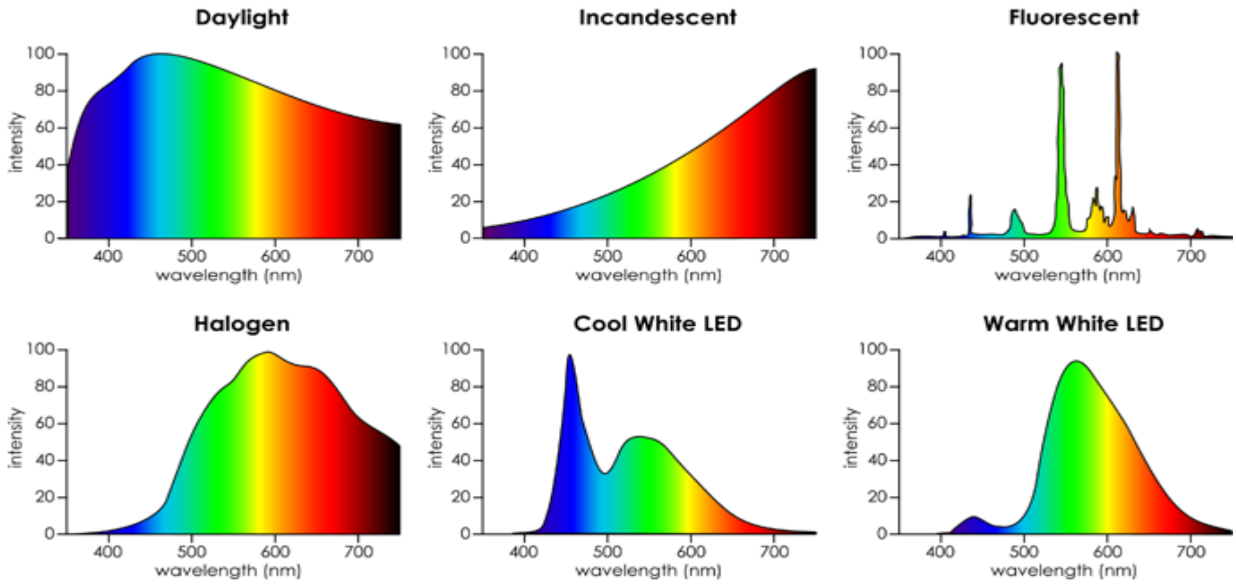

Fig. 2: Comparison of different light sources visible spectral emissions

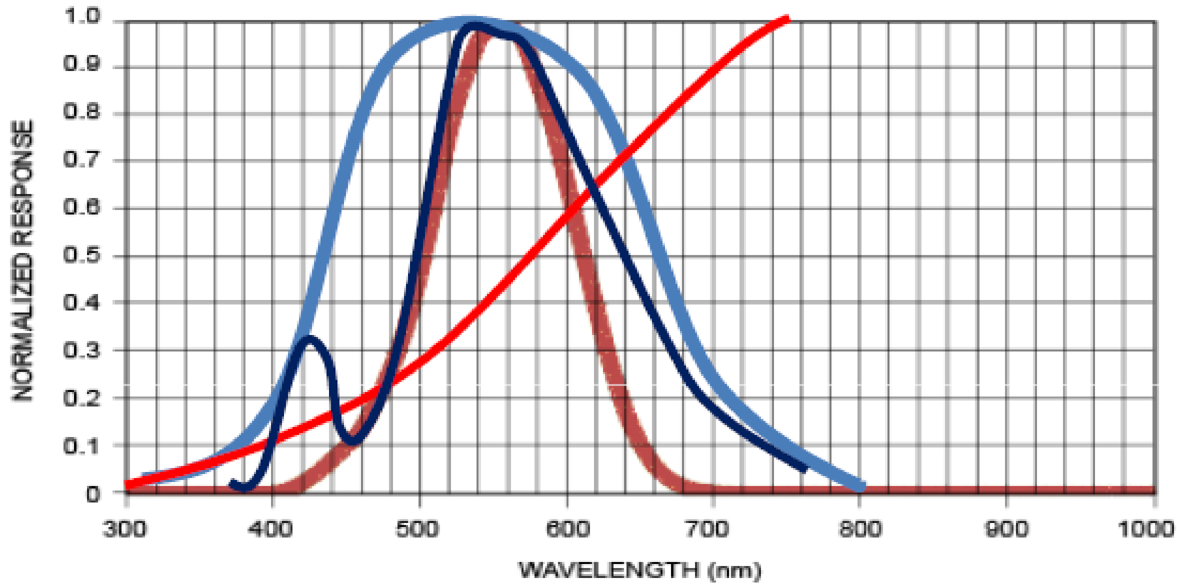

Fig. 3: Comparison between human eye spectral sensitivity (brown line), overlapped a-Si sensitivity (light blue line) vs. incandescent bulb (red line) and white LED (dark blue line) spectral emissions shows actually very good matching for white LED.

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With regard to these new developments and trends, recently especially regarding the rapid market penetration of the new 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 light 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 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 really broad visual spectral emission similar to natural light and incandescent lamps, 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, therefore every light source provided for human use including LED implicit matches very good the a-Si cell sensitivity 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 proven, currently used a-Si technology still offers the optimal overall compromise indoors.

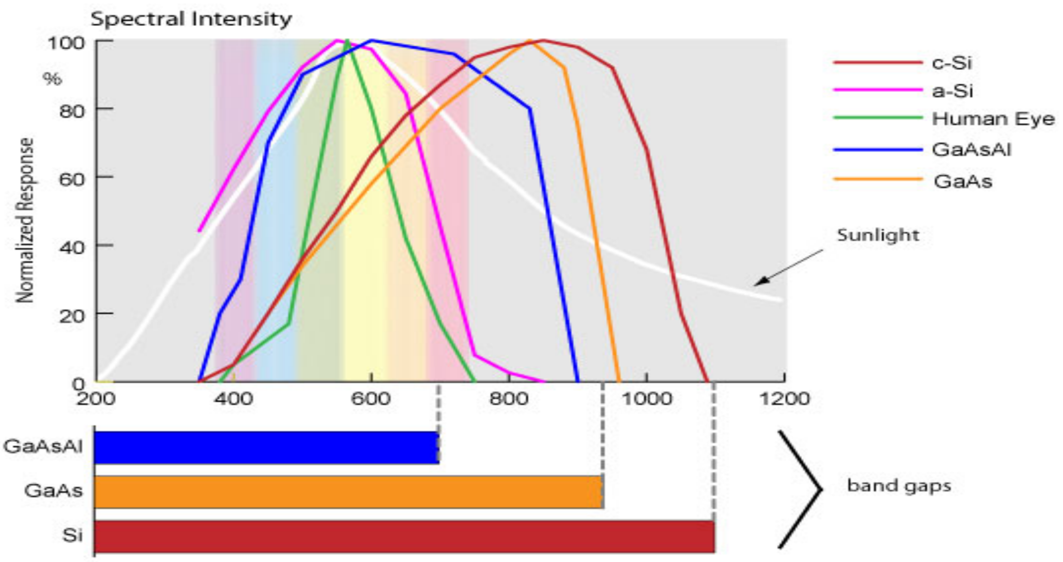

Fig. 4: Different solar cell technologies spectral sensitivities vs. the human eye (green).

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 used 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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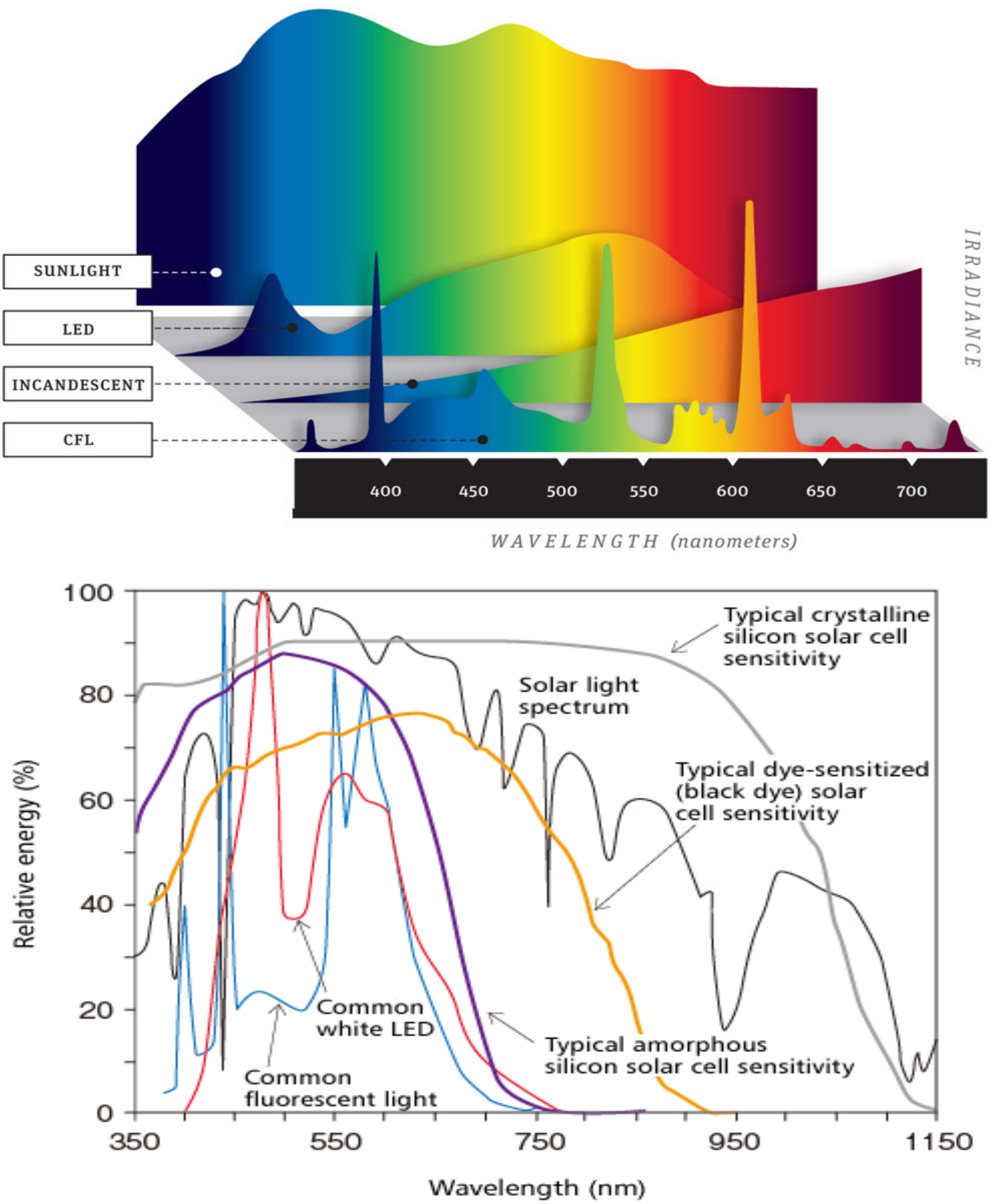

Fig. 5 Comparison between different specific spectral visible light sources vs. spectral sensitivities of different solar cell technologies shows overall best matching for a-Si technology indoors!

Conclusions:

The human eye might perceive different sources of light of the same brightness as similar; however, solar cells conversion efficiency might be quite different depending on manufacturing technology. Indoor solar cells are technological optimized to work under poor specific indoor light conditions (around 0.1% of the outdoor level). While conventional expensive outdoor solar cell is more efficient in optimum conditions (solar light), indoors 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, season and weather. Amount and duration of available natural light is minimal in midwinter (worst case).

High efficient, modern high CRI LED light sources are continuous optimized to radiate as much as possible human centric matched visible, natural daylight like light (highest CRI).

The specific CRI (Color Rendering Index) is determined by the radiated light spectrum. Incandescent lights have notoriously best ability to render colors, CRI for an incandescent bulb with a color temperature of 2700K is 100 (perfect). As color temperature rises, the CRI ratings drop off slightly but typically still remain above 95 (considered an excellent rating). Incandescent lamps have a continuous spectrum while fluorescent lamps have a discrete spectrum; the incandescent lamp has obviously the higher CRI. Typical low cost LEDs have 80+ CRI while some manufacturers claim that their premium LEDs reach 98 CRI.

Fortunately, this for human eye optimized LED spectral emission range also matches with the spectral sensitivity 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” shape of sensitivity curve (see Fig. 5).

Ambient LED lighting is one of the most promising and fast growing technologies today. With their unique design and performance characteristic — such as directional light emission, compact profile, highest efficiency, long life and especially superior optical & color control, see e.g. Human Centric Lighting requirements — LED lamps are best suited to replace / improve most lighting applications including special fields like automotive, outdoor or even LED Grow Lights.

While it is still not possible to define an unique “reference” white LED lamp, accordingly EnOcean evaluations (i.e. using EOSW device placed under incandescent bulb vs. different other light sources, see Appendix) classical amorphous-Si solar panels show quite similar energy harvesting efficiency under all evaluated indoor illumination sources (incandescent, CFL and white LED) under same measured light intensity. Therefore, a-Si technology remains the overall optimal light harvester solution for all typical indoor light conditions.

One last mention regarding LED retrofit: equivalent replacement products should have similar light distributions to the previous ones in order to ensure that their radiated lumens are similar directed in room. Even if the total lumen output of the retrofitted LED lamps is comparable (mostly higher) to the incandescent, not all (but increasingly more) LED lamps types (shape-conditioned) produce similar, omnidirectional light distribution like the classical incandescent glass bulbs. Although a directional “beam” may be of benefit in some applications, by planning it is important to be aware of the environmental light distribution. 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.

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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 radiating defined light intensity levels (@ correspondingly variable distances).

a) DUT light intensity @ the solar panel: 200 lx, 75 k as load (for Vop=3 V)
b) DUT light intensity @ the solar panel: 1 klx, 15 k as load (for same 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), CRI 80+
2. Osram: Superstar Classic A60 Advanced Surround Light LED 10 W=>60 W, E27 220-240 V, 806 lm (dimmable), warm white (2700 K), CRI 80+
3. Karat: AGL LED A60 (180° spot) 10 W=>60 W, E27 230 V, 810 lm (dimmable), warm white (2700 K), CRI 80+
4. Neolux: LED A60 10 W=>60 W, E27, 220-240 V, 806 lm, warm white (2700 K)

CFL (#5 and 6):

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

Incandescent Bulb (#7)

7. Osram: Centra Opal, A60, 60 W, 505 lm (2700 K)

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

Results (A-Si 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%)

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Conclusion:

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