Supplementary information

Calculation scheme of Shockley-Queisser limit

The SQ calculation scheme for indoor lights is shown in Figure S1. The ultimate efficiency η_{u}, the detailed-balance efficiency η_{d} and the fill factor η_{FF} in Eq. (1) are the three factors limiting the efficiency. The model calculation in this study is for a single p-n junction cell under unconcentrated illumination, where one incoming photon with energy above bandgap energy E_{g} (in eV) excites one and only one electron-hole (e-h) pair. Any e-h pair energy in excess of E_{g} undergoes thermal relaxation, resulting in a population of e-h pairs of the same energy E_{g}. Radiative recombination in the form of blackbody radiation is regarded as the only unavoidable recombination in this ideal device. In brief, the ultimate efficiency is defined as the ratio of the power intensity of all generated e-h pairs P_{eh} to the incident power intensity P_{in} (in unit of W cm^{-2}), given by

$$\eta_{\mathrm{u}} = E_{\mathrm{g}} \int_{E_{\mathrm{g}}}^{\infty} S_{\mathrm{norm}}(\epsilon) \cdot \frac{1}{\epsilon} \mathrm{d}\epsilon \tag{S1}$$

where

$$S_{\mathrm{norm}}(\epsilon) = \frac{S(\epsilon)}{\int_0^{\infty} S(\epsilon)\,\mathrm{d}\epsilon}, \tag{S2}$$

in unit of eV^{-1}, is the emission spectral power distribution (SPD) of the light source $S(\epsilon)$ under the normalization of total power, i.e. $\int_0^{\infty} S_{\mathrm{norm}}(\epsilon)\,\mathrm{d}\epsilon = 1$ and $\int_0^{\infty} S(\epsilon)\,\mathrm{d}\epsilon = P_{\mathrm{in}}$, and ϵ is the photon energy. The device is modeled as a perfect absorber, having complete absorption above the bandgap and complete transmission otherwise. The detailed-balance treatment considers the thermal equilibrium with steady rates of incoming and outgoing radiations. Radiative loss as blackbody radiation is modeled as the dark current, leading to a decrease in V_{oc}. The detailed-balance efficiency is defined as the ratio of the potential energy at V_{oc} condition under the detailed-balance treatment to the bandgap energy, expressed as

$$\eta_{\mathrm{d}} = \frac{qV_{\mathrm{oc}}^{\mathrm{SQ}}}{E_{\mathrm{g}}} = \frac{k_{\mathrm{B}}T}{E_{\mathrm{g}}} \ln\left(\frac{F_{\mathrm{eh}}}{F_{0,\mathrm{rad}}} + 1\right) \tag{S3}$$

where $V_{\mathrm{oc}}^{\mathrm{SQ}}$ is the SQ-limited V_{oc} under the detailed-balance treatment, T is the temperature of the device under test, q is the carrier charge, and k_{B} is the Boltzmann's constant. F_{eh} is the photon incident rate, given by

$$F_{\mathrm{eh}} = \frac{P_{\mathrm{eh}}}{E_{\mathrm{g}}} = P_{\mathrm{in}} \int_{E_{\mathrm{g}}}^{\infty} S_{\mathrm{norm}}(\epsilon) \cdot \frac{1}{\epsilon} \mathrm{d}\epsilon, \tag{S4}$$

and $F_{0,\mathrm{rad}}$ is the rate of emitted photon expressed in the form of blackbody radiation:

$$F_{0,\mathrm{rad}} = \frac{4\pi}{h^3 c^2} \int_{E_{\mathrm{g}}}^{\infty} \frac{\epsilon^2 \mathrm{d}\epsilon}{\exp\left(\epsilon / k_{\mathrm{B}} T\right) - 1} \tag{S5}$$

where h is the Planck's constant and c is the speed of light. In ideal devices, neglecting shunt and series resistances, FF can be written using the Green's empirical form [1]:

$$\eta_{\mathrm{FF}} = 1 - \frac{1 + \ln\left(v_{\mathrm{oc}}^{\mathrm{SQ}} + 0.72\right)}{1 + v_{\mathrm{oc}}^{\mathrm{SQ}}} \tag{S6}$$

where $v_{\mathrm{oc}}^{\mathrm{SQ}} = qV_{\mathrm{oc}}^{\mathrm{SQ}} / k_{\mathrm{B}} T = \eta_{\mathrm{d}} E_{\mathrm{g}} / k_{\mathrm{B}} T$ is the normalized open-circuit voltage. Using Eqs. (1), (2) and (S1)–(S6), SQ efficiency at different illuminances can be computed, with prior knowledge of $S(\epsilon)$ and T. Occasionally, the emission SPD is acquired in the wavelength domain instead of the energy domain. It can be inter-converted using the relation

$$S\left(\epsilon = \frac{hc}{\lambda}\right) = S(\lambda) \cdot \frac{\lambda^2}{hc}. \tag{S7}$$

Under sunlight illumination, the AM1.5G spectrum is taken as the incident SPD, with $P_{\mathrm{in}} = 100\ \mathrm{mW\ cm^{-2}}$. The device temperature is assumed 300 K. SQ limit calculation for IPV has more variables because $S_{\mathrm{norm}}(\epsilon)$ and P_{in} are not unique, but depends on the employed light source, correlated color temperature (CCT) and illuminance level.

As indoor lighting is artificially designed for human vision, the concept of brightness is subjective to visual perception of human eyes. Photometric quantities which are weighed by the spectral sensitivity of human vision instead of radiometric quantities are then used. Illuminance L (in the of lux or lx), also known as luminous flux intensity, is specified as the degree of brightness during performance evaluation of IPV devices. Therefore, unlike the AM1.5G evaluation, PCE calculation under room light requires the conversion to the corresponding radiometric quantity, irradiance (also called incident power intensity), in W cm^{-2}, given by Eqs. (2) and (3). $V(\lambda)$ in Eq. (2) is applicable for human photopic vision ($>$ 5 lux), and adapted from the color-matching function of the CIE 1931 2° standard colorimeteric observer of 1°–4° field of view. The range of the integrals from 360 nm to 830 nm is set according to the definition of $V(\lambda)$. The CIE 1931 standard is the one employed in commercially available photometric instruments [2–5]. Increasing the color temperature generally gives more blue emission and thus cooler color tune, as illustrated by the more dominant blue peak in the spectra in Tables S1(a)–(b). The blueshifted spectra for higher color temperatures result in a decrease in ϕ, and a greater P_{in} at the same L.

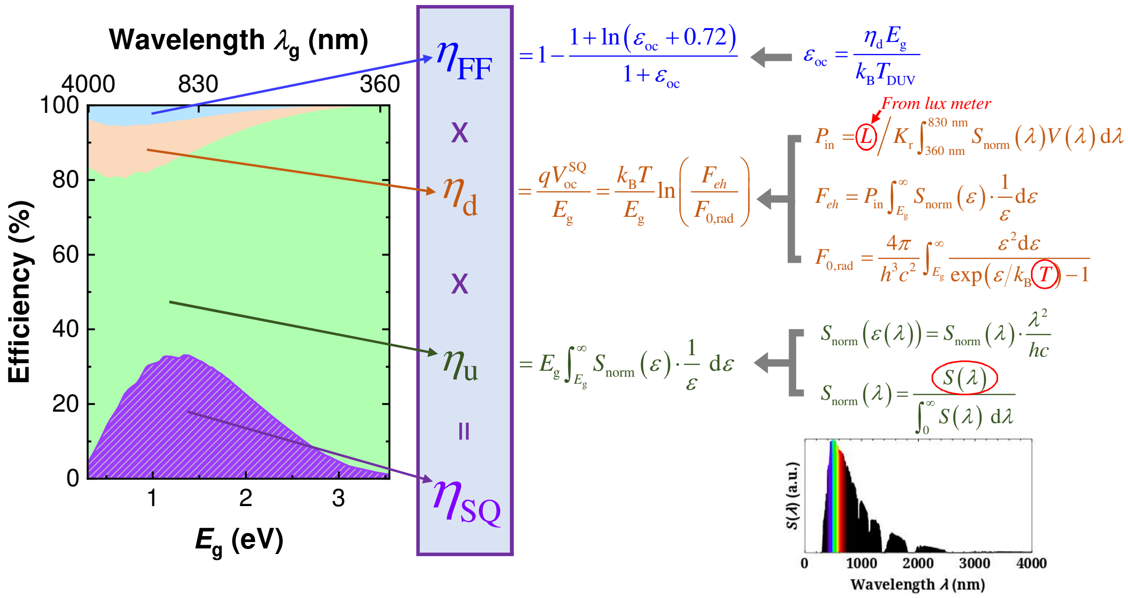


Figure S1. Schematic calculation flow chart of Shockley-Queisser (SQ) limited efficiency for indoor light sources. The plot on the left shows the ultimate efficiency (η_u) loss (green), the detailed-balance efficiency (η_d) loss (orange) and the fill factor (η_{FF}) loss (blue). The remaining is the SQ efficiency. The flow chart on the right depicts the process of the calculation. Variables in red are those required to be specified in the calculation. For details of variable definitions and calculation explanation, please refer to Section 2 and "Calculation scheme of Shockley-Queisser limit" in the Supplementary Information.

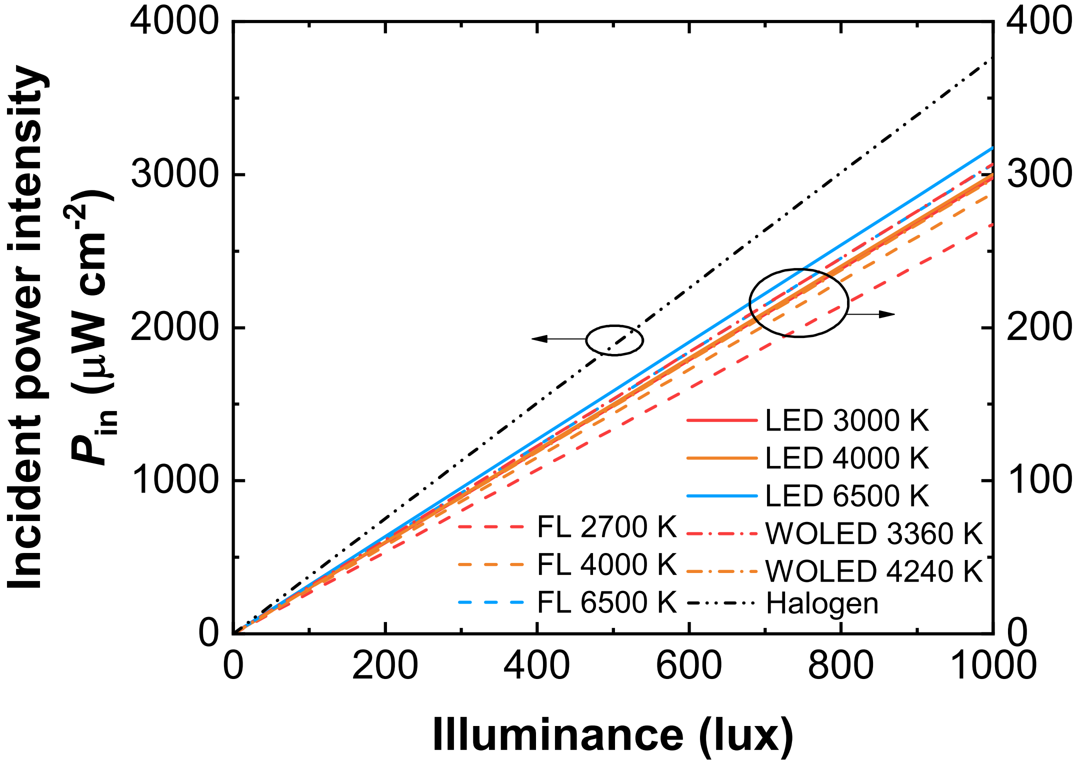


Figure S2. The incident power intensity P_{in} vs illuminance as given in Figure 1 but of all light sources. These values are tabulated in Table S1.

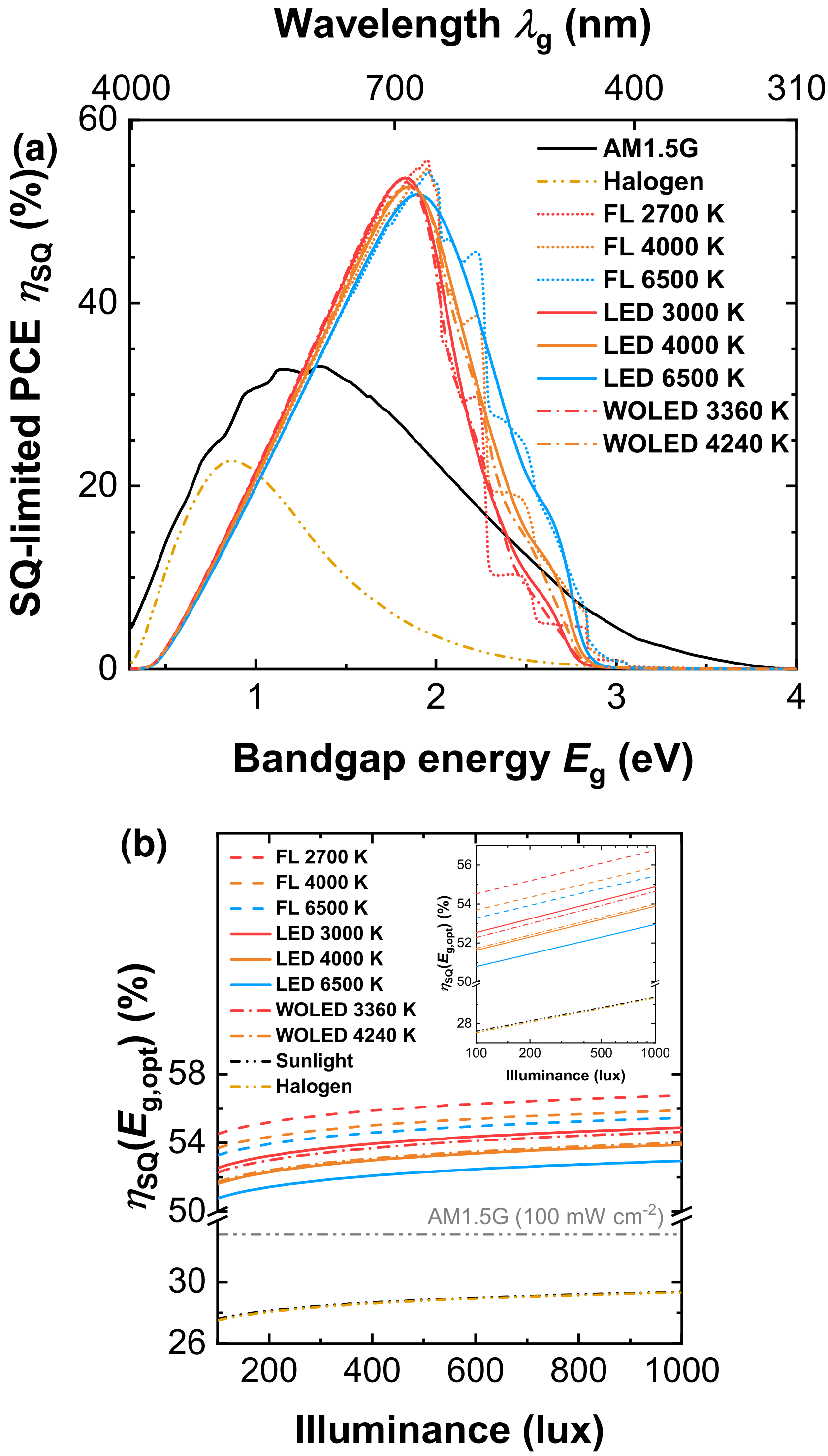


Figure S3. (a) The Shockley-Queisser (SQ) limited power conversion efficiency (PCE) vs bandgap energy E_g and (b) the SQ-limited PCE at the optimal bandgap energy as given in Figure 2 but of all light sources. The inset in (b) shows its linear relation in semilog plot. These values are tabulated in Table S1.

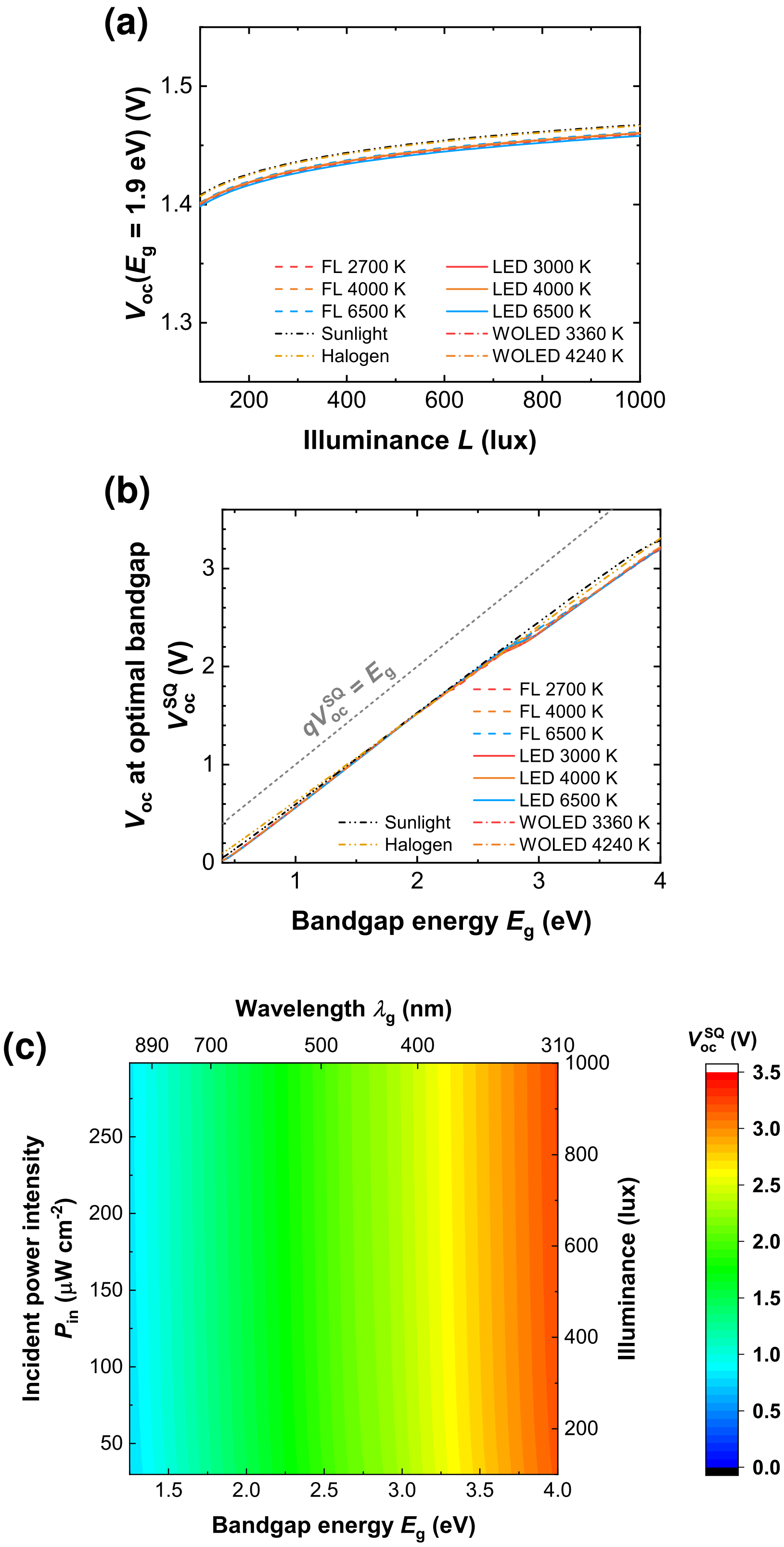


Figure S4. Shockley-Queisser limited open-circuit voltage V_{oc}^{SQ} vs (a) illuminance at bandgap energy of $E_g = 1.9$ eV and (b) E_g at 300 lux. V_{oc}^{SQ} shows little variation with illuminance and light sources. (c) Contour plot of V_{oc}^{SQ} vs incident power intensity (left axis) with the corresponding illuminance (right axis) and bandgap energy E_g (bottom axis) with the corresponding wavelength (top axis) for the 3000 K LED lamp as a typical example of the dependence on illuminance and bandgap. The little gradient across illuminance suggests E_g as the dominant factor affecting the values of V_{oc}^{SQ}.

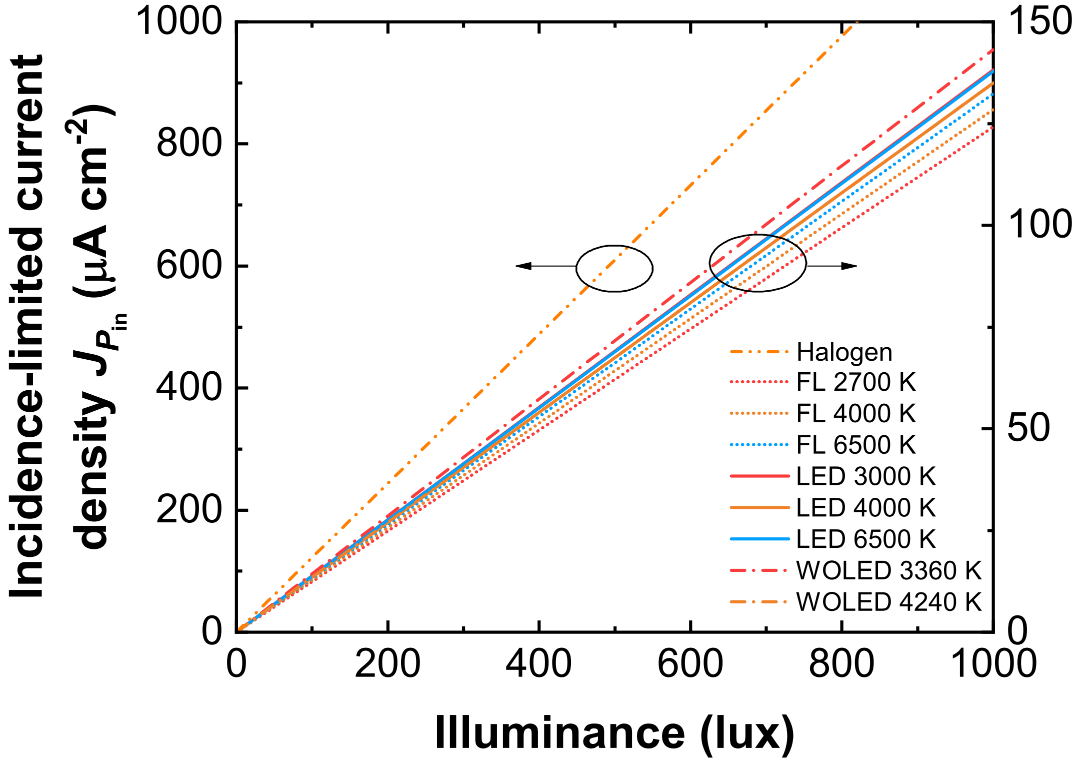
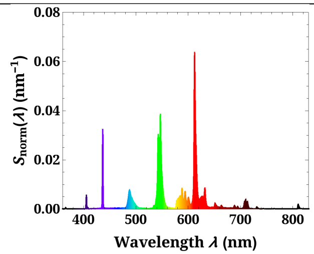
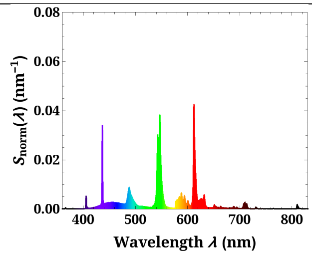


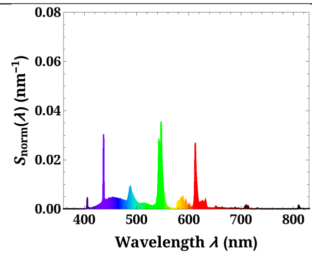
Figure S5. The incidence-limited current density $J_{P_{\text{in}}}$ vs illuminance as given in Figure 4 but of all light sources. These values are tabulated in Table S1.

Table S1. Computed values of incident power intensity P_{in}, open-circuit voltage at the optimal bandgap $V_{\text{oc}}(E_{\text{g,opt}})$, incidence-limited current density $J_{P_{\text{in}}}$ and SQ-limited efficiency at various illuminance levels for different light sources of different color temperatures. The model number (after the "#" symbol), color temperature and normalized emission spectrum of each light source are shown. The color temperatures are depicted in the format of "nominal/calculated form emission spectrum". The photopic matching index ϕ for the light sources is included, defined as $\phi = \int_{360\text{ nm}}^{830\text{ nm}} S_{\text{norm}}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda$. The values serve as an example; they may vary according to the light source model and thus are for reference only.

(a) Fluorescent lamps, in conjunction with electronic ballasts (PAK, PAK300408).

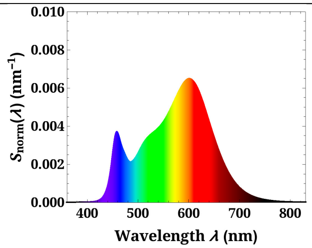
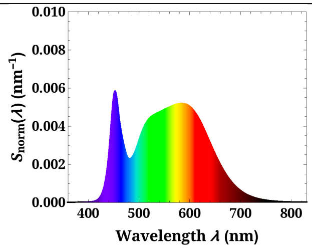
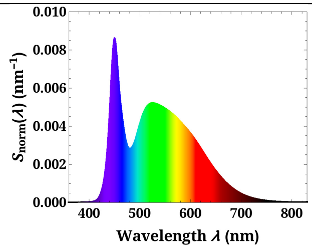




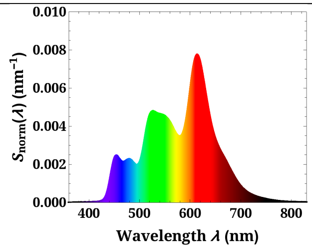


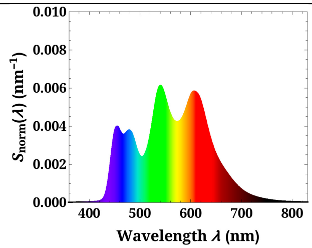
	Warm white (2700/2928 K) #PAK090481 $\phi = 0.5478$, $E_{\text{g,opt}} = 1.95$ eV				Natural white (4000/4265 K) #PAK090491 $\phi = 0.5090$, $E_{\text{g,opt}} = 1.95$ eV				Cool white (6500/6400 K) #PAK-PAK090501 $\phi = 0.4781$, $E_{\text{g,opt}} = 1.96$ eV			
Illuminance (lux)	P_{in} (μW cm^{-2})	$V_{\text{oc}}(E_{\text{g,opt}})$ (V)	$J_{P_{\text{in}}}$ (μA cm^{-2})	Max. PCE (%)	P_{in} (μW cm^{-2})	$V_{\text{oc}}(E_{\text{g,opt}})$ (V)	$J_{P_{\text{in}}}$ (μA cm^{-2})	Max. PCE (%)	P_{in} (μW cm^{-2})	$V_{\text{oc}}(E_{\text{g,opt}})$ (V)	$J_{P_{\text{in}}}$ (μA cm^{-2})	Max. PCE (%)
100	26.8	1.45	12.4	54.52	28.8	1.45	12.8	53.69	30.7	1.46	13.2	53.27
200	53.5	1.47	24.8	55.20	57.6	1.47	25.7	54.35	61.3	1.47	26.5	53.93
300	80.3	1.48	37.3	55.59	86.4	1.48	38.5	54.74	92.0	1.48	39.7	54.31
400	107.1	1.48	49.7	55.87	115.2	1.49	51.4	55.01	122.7	1.49	52.9	54.58
500	133.8	1.49	62.1	56.09	144.0	1.49	64.2	55.23	153.3	1.50	66.2	54.79
600	160.6	1.49	74.5	56.27	172.8	1.50	77.1	55.40	184.0	1.50	79.4	54.97
700	187.4	1.50	86.9	56.42	201.6	1.50	89.9	55.55	214.7	1.51	92.7	55.11
800	214.1	1.50	99.4	56.55	230.4	1.51	102.8	55.68	245.4	1.51	105.9	55.24
900	240.9	1.50	111.8	56.66	259.2	1.51	115.6	55.79	276.0	1.51	119.1	55.35
1000	267.7	1.51	124.2	56.76	288.0	1.51	128.5	55.89	306.7	1.52	132.4	55.45

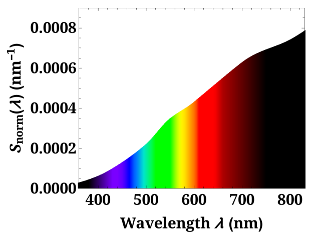
(b) LED lamps.

	 Warm white (3000/3328 K) #PAK-LED-T5-4WF-830 $\phi = 0.4920,\ E_{\mathrm{g,opt}} = 1.83$ eV				 Natural white (4000/4624 K) #PAK-LED-T5-4WF-840 $\phi = 0.4883,\ E_{\mathrm{g,opt}} = 1.85$ eV				 Cool white (6500/6994 K) #PAK-LED-T5-4WF-865 $\phi = 0.4618,\ E_{\mathrm{g,opt}} = 1.90$ eV			
Illuminance (lux)	P_{in} (μW cm^{-2})	$V_{\mathrm{oc}}(E_{\mathrm{g,opt}})$ (V)	$J_{P_{\mathrm{in}}}$ (μA cm^{-2})	Max. PCE (%)	P_{in} (μW cm^{-2})	$V_{\mathrm{oc}}(E_{\mathrm{g,opt}})$ (V)	$J_{P_{\mathrm{in}}}$ (μA cm^{-2})	Max. PCE (%)	P_{in} (μW cm^{-2})	$V_{\mathrm{oc}}(E_{\mathrm{g,opt}})$ (V)	$J_{P_{\mathrm{in}}}$ (μA cm^{-2})	Max. PCE (%)
100	29.8	1.33	13.8	52.53	30.0	1.36	13.5	51.62	31.8	1.40	13.8	50.78
200	59.6	1.35	27.6	53.24	60.1	1.37	27.0	52.30	63.5	1.42	27.6	51.44
300	89.4	1.36	41.4	53.65	90.1	1.38	40.5	52.70	95.3	1.43	41.4	51.82
400	119.2	1.37	55.3	53.95	120.1	1.39	54.0	52.99	127.0	1.43	55.1	52.09
500	149.0	1.37	69.1	54.17	150.1	1.40	67.5	53.21	158.8	1.44	68.9	52.30
600	178.8	1.38	82.9	54.36	180.2	1.40	81.0	53.39	190.5	1.44	82.7	52.47
700	208.6	1.38	96.7	54.52	210.2	1.41	94.5	53.54	222.3	1.45	96.5	52.61
800	238.4	1.38	110.5	54.65	240.2	1.41	108.0	53.67	254.0	1.45	110.3	52.74
900	268.2	1.39	124.3	54.77	270.2	1.41	121.5	53.79	285.8	1.45	124.1	52.85
1000	298.0	1.39	138.2	54.88	300.3	1.41	135.0	53.89	317.5	1.46	137.8	52.95

(c) WOLEDs and halogen lamp. Only calculated color temperatures is available. The values of $J_{P_{\rm in}}$ for the halogen lamp takes into account of photons of energies greater than 1.1 eV.







	Warm white (3363 K) #WOW OLT-HANDY-WH $\phi = 0.4778,\ E_{\rm g,opt} = 1.82$ eV				Natural white (4237 K) #Inlion I1C $\phi = 0.4883,\ E_{\rm g,opt} = 1.85$ eV				Halogen lamp (3100 K) #Oriel 63358 $\phi = 0.0389,\ E_{\rm g,opt} = 0.87$ eV			
Illuminance (lux)	$P_{\rm in}$ (µW cm^{-2})	$V_{\rm oc}(E_{\rm g,opt})$ (V)	$J_{P_{\rm in}}$ (µA cm^{-2})	Max. PCE (%)	$P_{\rm in}$ (µW cm^{-2})	$V_{\rm oc}(E_{\rm g,opt})$ (V)	$J_{P_{\rm in}}$ (µA cm^{-2})	Max. PCE (%)	$P_{\rm in}$ (µW cm^{-2})	$V_{\rm oc}(E_{\rm g,opt})$ (V)	$J_{P_{\rm in}}$ (µA cm^{-2})	Max. PCE (%)
100	30.7	1.32	14.3	52.28	29.7	1.35	13.5	51.72	376.6	0.47	122.1	20.84
200	61.4	1.34	28.6	52.99	59.4	1.37	27.0	52.41	753.3	0.49	244.1	21.63
300	92.1	1.35	43.0	53.40	89.1	1.38	40.5	52.81	1129.9	0.50	366.2	22.09
400	122.7	1.36	57.3	53.70	118.8	1.39	54.0	53.09	1506.6	0.51	488.2	22.42
500	153.4	1.36	71.6	53.93	148.6	1.39	67.5	53.31	1883.2	0.51	610.3	22.67
600	184.1	1.37	85.9	54.12	178.3	1.40	81.0	53.49	2259.9	0.52	732.3	22.88
700	214.8	1.37	100.3	54.27	208.0	1.40	94.5	53.65	2636.5	0.52	854.4	23.06
800	245.5	1.37	114.6	54.41	237.7	1.41	108.0	53.78	3013.1	0.53	976.4	23.21
900	276.2	1.38	128.9	54.53	267.4	1.41	121.5	53.90	3389.8	0.53	1098.5	23.35
1000	306.9	1.38	143.2	54.64	297.1	1.41	135.0	54.00	3766.4	0.53	1220.5	23.47

References

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