True energy-efficient lighting: the fundamentals of lighting, lamps and energy-efficient lighting

by Prof Wilhelm Leuschner and Lynette van der Westhuizen

Energy efficiency and saving electrical energy are concepts that are quite generally known. Whether these savings are sustainable or cost-effective for the consumer is another question. After almost 150 years of gas discharge and incandescent light sources for general lighting, we have recently entered the field of semiconductor lighting, generally called solid state lighting (SSL) in the form of light-emitting diodes (LED) and organic LEDs (OLEDs), to use for energy-efficient lighting.

Energy-efficient light can be defined as improved lighting at reduced life cycle cost or pay-back period. To determine the quality of light, one has to cover all the metrics involved: not only the quantity of light, but also the colour appearance and the colour rendering of the lamp. To determine energy saving and energy efficiency, one has to take more than just the electrical input power (Watts), the cost of electricity and the life expectancy of the lamp into account. There are several fundamental metrics involved in evaluating cost-effective, energy-efficient lighting that improves the quality of the light at the same time.

Light and vision

Figure 1 shows six different lamps of more or less the same light output in the on and off conditions. However, a photograph does not accurately portray the colour appearance or actual luminous flux. The eye is a much better instrument for instantaneous comparisons of light and colour.

Vision and visibility relies on luminance ("brightness") contrast and colour contrast only. This applies to light radiated (lamps) and/or reflected (tasks) from surfaces of various shapes and formats. The light or light power radiated from a light source is defined as the luminous flux Φ specified in lumens. This luminous flux can be rated as a density unit of solid angle (steradian) or a surface area (square metres). The first quantity is called the luminous intensity I, where 1 lumen radiated in 1 steradian is called 1 candela. Luminous intensity is measured as a function of direction and these results are usually presented as polar diagrams of luminous intensity, from which the beam angle (full width half maximum value of luminous intensity) can be determined.

Illuminance E is defined as the luminous flux falling on a surface area, where 1 lumen falling on 1 m^2 is called 1 lux. Neither luminous flux nor luminous intensity can actually give an indication of the "brightness" of the source of light. The quantity used for evaluating the visibility of a surface (light source or reflecting surface) is the luminance of the

a. b. c. d. e. f.

Figure 1. Six lamps (off and on) (from left): a. 100 W incandescent b. 15 W warm white CFL c. 15 W cool white CFL d. 8 W 2700 LED e. 8 W 4000K f. 7 W 6000 LED

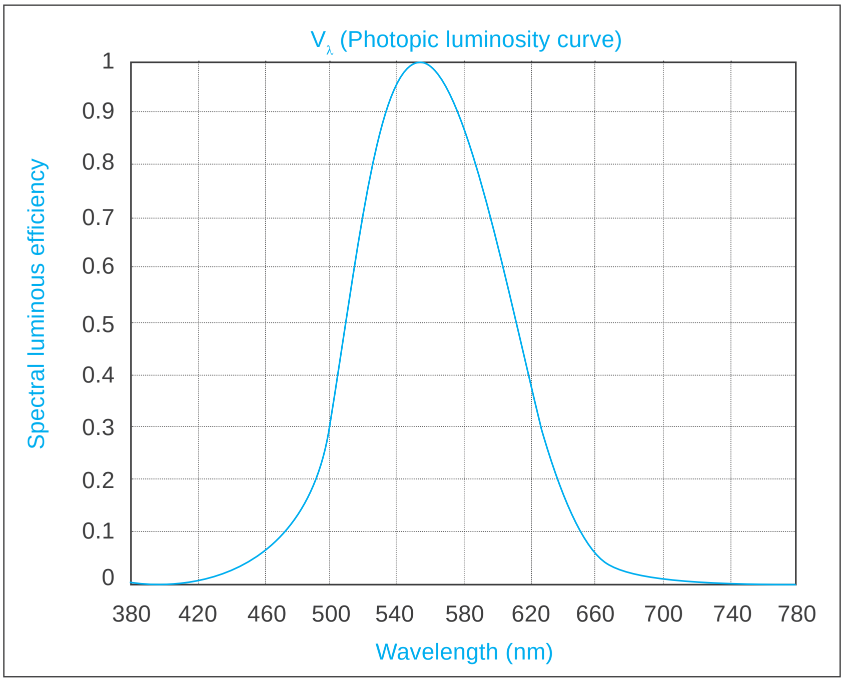
specific "radiator". This is determined by dividing the luminous intensity of the surface (facing the observer or luminance meter) by the specific projected area of the surface. This is determined by the viewing angle of the observer or luminance meter. The unit used is candela per square metre. For example, for a lamp with a luminous intensity of 1 candela in a specific direction and a projected surface area of the lamp (or reflector surface) on 1 m^2, the luminance L of the surface L = 1 cd/1 m^2.

Once these three quantities (Φ, I and L) are matched for two light sources, they produce the same quantity of light, with the same distribution and the same luminance. One will not be able to see the difference. Matches are seldom complete and one has to evaluate the importance of variations that are present.

Colour

Visual colour appreciation of light sources relies on two fundamental metrics, i.e. the colour appearance of the light source and the colour rendering of different colour objects illuminated by the same light source. Over many years, many different scientists have recommended different ways of producing these two metrics for a lamp of a known spectral power distribution (SPD), i.e. radiant or luminous flux as a function of the wavelength in the visible region of approximately 380 to 780 nm. This range of electromagnetic radiation, which is called visible light, peaks at 555 nm for standard photopic vision (luminance levels of above approximately 3 cd/m^2) – see the V_λ curve in Figure 2.

In general, colour appearance is a personal preference and there is no optimal colour. Colour rendering is a metric where (irrespective of which system of evaluation is used) the higher the number, the better; with no personal preference involved. One should not confuse these two metrics, as one can get excellent colour rendering from various lamps of dramatically different colour appearances (for example, warm white, natural white, cool white to daylight).



→ *Figure 2. V_λ curve.*

Colour appearance describes the dominant hue of the light, i.e. red, green, blue, yellow, white, etc. For general lighting, white light has been the dominant colour in use. The colour appearance can be defined uniquely through two numbers or coordinates on the International Commission on Illumination (CIE) chromaticity diagram; known as the x and y or u and v colour coordinates.

In the case of "white light" sources, the use of adjectives such as cool white, warm white, daylight and natural white have been used for many years in linear fluorescent and compact fluorescent lamp (CFL) products.

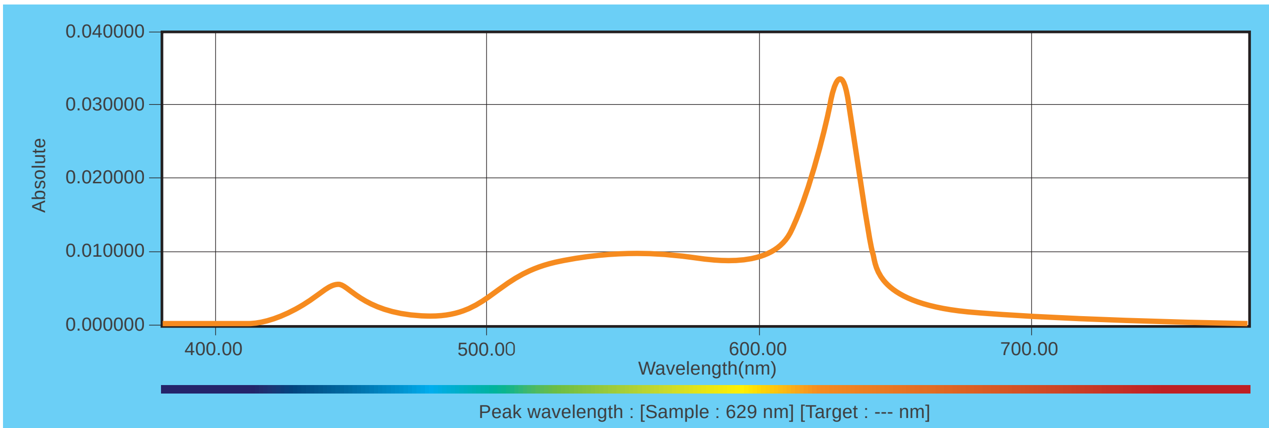
To make these shades of white more quantifiable, measurable and universally acceptable, the metric of colour temperature and correlated colour temperature (CCT) with units of Kelvin (K) was introduced.

These CCT numbers can be summarised as follows:

- Warm white : CCT = 2700 to 3000K
- White : CCT = 3500K
- Cool white : CCT = 4000K
- Daylight : CCT = 6500K

These numbers can, however, be misleading as they represent numerous chromaticity coordinates.

This is due to different SPDs, which have different chromaticity coordinates, having the same best match to a blackbody radiator of that CCT.



Lv	*628.08*
x	*0.4588*
y	*0.4162*
CCT	*2764*
Ra	*90*

R1	*90*
R2	*98*
R3	*81*
R4	*83*
R5	*93*
R6	*99*
R7	*91*
R8	*89*

R9	*90*
R10	*88*
R11	*79*
R12	*86*
R13	*94*
R14	*86*
R15	*92*

Peak Wavelength	*629*
Dominant Wavelength	*583.30*

→ *Figure 3. SPD and colour metrics of a typical warm white LED lamp. (Note: L_v is the relative luminance of the measuring point in the measuring sphere.) LED supplied by Kwalico.*

Radiant flux as a function of spectral radiant flux

$$\Phi_e = \int_{\lambda = 0}^{\infty} \phi_{e\lambda}(\lambda)\, d\lambda$$

Where: Φ_e = total radiant flux in Watt
$\phi_{e\lambda}(\lambda)$ = spectral radiant flux in Watt/nanometre

Luminous flux as a function of special radiant flux

$$\Phi_v = 683 \int_{\lambda = 380}^{760} \phi_{e\lambda}(\lambda)\, V_\lambda(\lambda)\, d\lambda$$

Where: Φ_v = total luminous flux in Lumen
$\phi_{e\lambda}(\lambda)$ = spectral radiant flux in Watt/nanometre
$V_\lambda(\lambda)$ = photopic eye responsivity curve in p.u. with the peak value of 1 at 555 nm

The value 683 is the maximum luminous efficacy of radiant flux in $lm \cdot W^{-1}$.

The second metric in evaluating the quality of the colour of a lamp is the colour rendering characteristic, which can also be described as the colour fidelity of the light source. Currently, a most unsatisfactory way of calculating the colour rendering index (CRI) from the SPD of a lamp's radiation is used. The general CRI (R_a) of a light source has been prescribed by the CIE. The procedure, in essence, entails the use of eight printed colour samples to be illuminated in turn by a reference light source and the lamp under test. The shift in colour appearance is calculated for all eight samples and the average of the eight indices represents the R_a value. One of the main complaints against the use of the CRI is the use of a reference light source, which in most cases is a black body radiator of the same CCT as the lamp under test. There are many other colour rendering evaluation systems under consideration for improving accuracy without using an incandescent lamp as a reference light source.

In the assessment of colour appearance and colour rendering, it is important to evaluate the SPD curves of different light sources and weigh that with the eye responsivity curve (also known as the V_λ curve) in Figure 2.

For evaluating the six different lamps with respect to actual visibility, we present the SPD in $W \cdot nm$, as well as the spectral luminous flux distribution in $lm \cdot nm^{-1}$. Note that the SPD values have been multiplied by 683 to match the peak value of the V_λ curve at 555 nm.

A spectroradiometer (Konica Minolta) is used to measure the SPD of any light source (lamp or reflector). The lamp under test is placed in an integrating sphere to eliminate special variations in the

Figure 4. The spectral luminous flux distribution as compared to the normalised SPD.

light distribution of the lamp. The spectroradiometer (through a close-up lens) is focused on the reflected surface in the small measuring sphere attached to the integrating sphere. From the SPD for a specific lamp, the spectroradiometer software is used to calculate all the different colour metrics of the lamp as shown in Figure 3 for a typical warm white LED lamp.

Figure 4 shows the SPDs (blue curve) of the six different light sources as shown in Figure 1. Once the individual SPDs are multiplied with the V_λ curve, the spectral luminous flux distribution (red curve) is obtained as a function of wavelength (in lumen per nanometre), as normalised to 1 000 lumen output for all six light sources. The integral under the curve will produce the normalised luminous flux for all six lamps (normalised to 1 000 lumen).

It is important to note that the actual spectral luminous flux from the individual lamps (the light we see) drops off very quickly below about 450 nm and above 660 nm. The incandescent lamp is slightly higher at the long wavelengths around 700 nm. It is clear that using the incandescent lamp as the reference light source for obtaining colour rendering characteristics may not be the optimal reference source.

Rated life

Historically, the life expectancy of lamps is determined from cyclic batches of each type of lamp through a switching procedure and then ensuring that at least 50% of the batch of lamps are still burning at the time when rated life is reached. Life expectancy can range from 1 000 hours for general lighting service (GLS) incandescent lamps to over 50 000 hours for LED lamps. To test LED lamps for such long periods of time (five years or more) is impractical and cannot be done for such a dynamic and rapidly improving new technology. New life-testing procedures for LED lamps take place over a test period of a maximum of 6 000 hours. An extrapolation procedure is then followed to determine rated life at a specific lamp lumen depreciation level (for example, when 70% of the initial luminous flux output is reached), called the L_{70} point. Values such as L_{80} or L_{90} can also be used. This number is accompanied by the failure rating (for example, F_{50} will indicate a failure rate of less than 50%).

It is important to realise that with life expectancy or rated life, irrespective of whether it is 1 000, 15 000 or 50 000 hours, there is a large chance of many of the lamps failing anywhere during that time; some even within hours of installing them. To allow for such early and normal early failures of lamps, some lamp manufacturers now include guarantee inserts in the packaging to replace such lamps within one to three years of purchase.

Electrical characteristics

By moving from simple incandescent lamps (non-linear resistance filament) to electronic-driven fluorescent lamps (including CFLs) and semiconductor (including LED and OLED) lamps, the resulting electrical current and power characteristics have changed dramatically. The electronic components in the lamp power supply for these lamps create current harmonics, which can be measured as current harmonic distortion (total harmonic distortion or THD), which also results in a distortion power factor, which means that the apparent power (measured in volt ampere or VA) and the active power (measured in Watt or W) can be dramatically different. Power factor, as defined by active power divided by apparent power, can be as low as 40% for some CFL and LED lamps. Most users of electricity (except for single residential) pay for electrical energy usage in kilowatt-hours (kW·h), as well as electrical apparent power measured as half hourly maximum demand in kVA. So, a high power factor is essential in searching for cost-effective energy-efficient lighting.

Energy-efficient lighting

By selecting a replacement lamp for a failed or inefficient light source appears to be simple: pick an "energy saver" with the same luminous flux output (in lumens) as that of the lamp to be replaced, but use one with lower rated active power in Watts. Reducing the electrical power consumed to produce the same light reduces the CO_2 and other toxic gas emissions from coal-fired power stations, as well as water consumption and other ecological benefits. This approach does not, however, automatically result in cost-effective energy-efficient lighting of the same quality of light or better.

In the competition between CFL and LED as the only general light source for the future, the outstanding good and bad characteristics of each can be listed and weighted fairly easily, as shown in Table 1.

Cost of energy efficiency (pay-back period)

Some of the most important factors that influence the pay-back period when replacing legacy lamps with energy-efficient lighting of the same or better light output (quantity and quality) include the cost of the lamp, the cost of electricity (kWh and kVA), lamp replacement costs and the number of operating hours a day.

Lamp type/criteria	CFL	LED
Cost	Low	High but dropping
Life	Fair	Very long
Lumen/W	Fair	Better and improving fast
Supply	Limited voltage range	Wide voltage range
Robustness	Bad	Good
Colour characteristics	Average	Good to excellent
Disposal	Restricted	No restriction
Light source	Area (linear or spiral, etc.)	Point or area
Controllability	Limited to some dimming	Excellent: smart lighting
Environmental effect	Mercury content	Sapphire chips: no danger

→ *Table 1. Comparison between CFL and LED lamps.*

Future predictions

Historically, with the GLS incandescent lamp, the wattage rating was the most important factor to consider, as it defined luminous flux output, luminous intensity distribution, luminance, colour appearance and colour rendering, power factor, current distortion, life expectancy, etc. With the CFL and LED electronic-driven lamps from many suppliers all over the world, minimum quality specifications have to be set and certified by individual manufacturers.

The lamp packaging should clearly specify and guarantee the most important metrics, such as the following:

- Power supply details (voltage and frequency)
- Luminous flux output in lumens
- Luminous intensity distribution (polar diagram and/or beam angle)
- Luminous efficacy in lumen/Watt
- Colour appearance (chromaticity coordinates or CCT)
- Colour rendering (CRI or better index)
- Rated life (L_{70} F_{50} or better)
- Approximate pay-back period (not more than three years)

Conclusion

It is the opinion of the authors that the introduction of semiconductor lighting is opening up a new era of quality aesthetic and functional lighting of outstanding quality, with reduced concerns relating to lighting maintenance and lamp replacement. This can be achieved with excellent energy efficiency and high affordability.

Source

Commission International de l'Eclairage, Division 1. 1995. *Vision and colour: Method of measuring and specifying colour rendering properties of light sources. Technical Report CIE 13.3-1995.* Kegelgasse, Vienna: CIE.

***Prof Wilhelm Leuschner** and **Lynette van der Westhuizen** are associated with the Light and Visibility Laboratory in the Department of Electrical, Electronic and Computer Engineering.*

→ *Prof Wilhelm Leuschner*

→ *Lynette van der Westhuizen*