Technical information

LED lighting – from an innovation to the state of the art

The efficiency debate is over. Be it through fashion, EU directives, or even common sense, we have achieved a market where only efficient lights and lighting technologies are available. Now we can finally address other important attributes of light.

Figure 1: Too hot, electricity glutton, dies early – the line voltage incandescent lamp (left). Too bulky (also see Figure 2), hardly focussable – the (theoretically) compatible CFL (right). Now finally the solution: The LED lamp (middle)!

Figure 2: These frequently used to hamper energy savings: The practical and aesthetic problems associated with CFL in the living room – "fitting in" is relative

Directory

1 Review: Lighting techniques and their perception

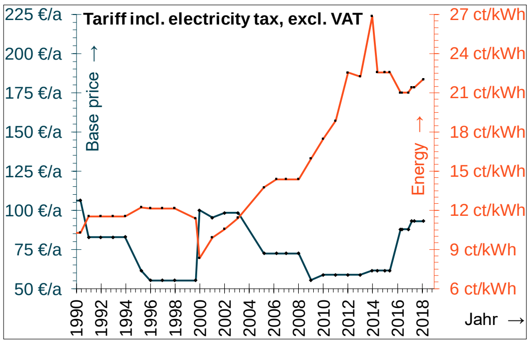


Figure 3: Development of electricity tariffs (municipal utility in a medium-sized town in Northrine-Westfalia, Germany, here without VAT)

Incandescent lamps are inexpensive but do not live long. As thermal light sources, their light is perceived as particularly pleasant, but they are energy gluttons. Although an incandescent lamp prohibition has never been formally implemented in the EU, there do exist minimum lighting efficacy requirements which the incandescent lamp cannot physically comply with. Thus, incandescent lamps have all but disappeared from the European market.

Compact fluorescent lamps (CFLs, Figure 1), although hardly deserving the designation "compact," have become known as "energy saver lamps", and while they do save energy, they don't save space. CFLs may have fit the same socket, but due to their poor aesthetic design, they were only able to replace some of the incandescent bulbs in the market (Figure 2). Because of this, incandescent lamps remained in use, and were responsible for the lion's share of lightbulb energy use, with annual electricity costs of up to 45 € during the peak times of domestic electricity tariffs (approximately 32 ct/kWh including VAT in Germany at the beginning of 2014 – Figure 3). Aesthetic problems aside, dimmable CFLs capable of replacing a 100 W incandescent lamp were still not available on the market.

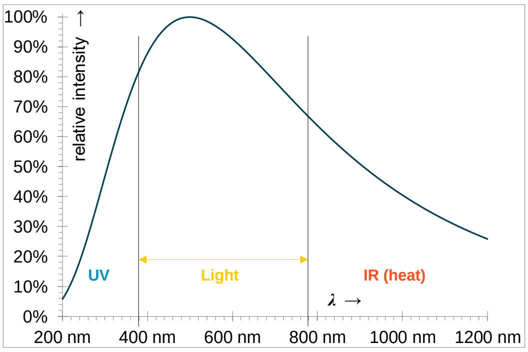


Figure 4: Spectral composition of solar irradiation: The maximum is centred within the visible range (light)

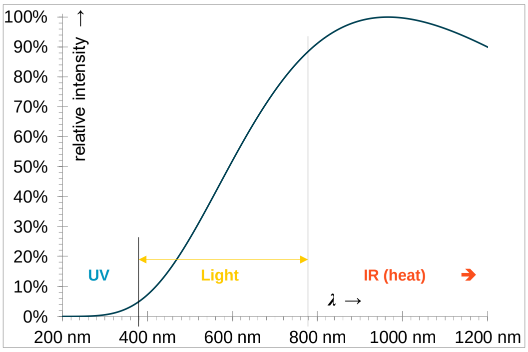


Figure 5: Spectral composition of a general purpose incandescent lamp: The maximum is situated in the infrared range (heat)

Other users complained about the quality of the light that they perceived as "cold," even years after the problem had been tackled, yearning back to the "natural" light of the incandescent lamp, which in fact differs from daylight more than any other artificial light source (Figure 4). Because all metal has a melting point below 6,000°C, incandescent lamps can only be operated up to a maximum of 3,000°C. As such, this system irradiates nearly only heat and hardly any light at all – and this with a very high percentage of red and only small percentages of blue and green light (Figure 5). The one advantage is that a continuous spectrum is obtained, meaning without any abrupt changes of intensity from one wavelength (colour) to the next. Did the incandescent lamp supply “the most natural light?” Once accustomed to LED lighting, a room lit by incandescent lamps will appear dim at first sight (Section 0). The high operating temperature of the filament does provide the advantages that the ambient temperature has practically no influence upon the power, the light quality, and the lifetime expectancy, and that ice and snow will melt away (Figure 25) on such a lamp. These advantages are not enough to justify the continued heating of the outside world by the use of incandescent lights.

Figure 6: With just 45 mW to 170 mW per lamplet not enough heat is generated to melt snow.

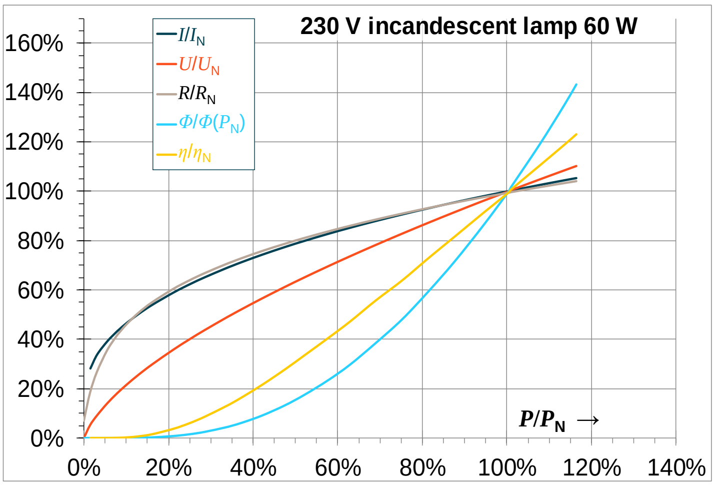


Figure 7: The luminous flux – and hence the lighting efficacy – of incandescent lamps is equal zero below 10% of the rated power input

On the other hand, while the CFL feels cold, its light is often not really bright. CFLs dislike frequent switching. Incandescent lamps allow for the design of flood and spot lights and can be dimmed quite easily. CFLs are dimmable only in exceptional cases and at a price premium. CFL “floodlights” exist only in name, using beam angles – the proper term is “half-peak angle” – above 120°. With either system, incandescent and fluorescent, the efficiency drops rapidly when dimmed down (). What was needed was a lamp which

- could be switched at arbitrary frequencies without compromising its useable lifetime,
- works at full performance immediately after switching on,
- could be dimmed down optimally to 0 level with minor technical investment,
- when at full power has a high lighting efficacy,
- could be designed to shine on the spot or all around,
- could be manufactured with different colours or different tinges of white, respectively,
- has a long life expectancy

- and, above all, is affordable.

Today such a lamp is not only available, but ubiquitous. Whenever new lighting is installed, the question whether fluorescent lamps or LEDs (light emitting diodes) should be used is asked less and less, if at all.

2 Basics of light

The physical properties of light were described in detail in other sections [1, 2, 3]; hence just a quick review. Nowadays there are three different approaches to generating artificial light:

- In thermal light sources, something appropriate is heated up to such a high temperature that it starts to glow very brightly. The first electric lamps used carbon fibres, whereas today the metal tungsten is used for this purpose. The method, however, does not only work electrically; candles, torches, oil lamps and gas lanterns also follow this working principle – albeit in ways even less efficient than the electric incandescent lamp.
- Good efficiencies can be achieved by gas discharge, whereby atoms are shifted into an excited state: One electron is elevated to a higher orbit. When it drops down again it emits a radiation quantum. High temperatures can occur, but they are not directly related to the process of light generation and do not necessarily mean poor lighting efficacy, as these high temperatures occur very locally and are mainly due to poor heat dissipation.
- New is the generation of electromagnetic radiation by means of semiconductors. This is the type of light sources to be dealt with here. High temperatures must be avoided with this method because semiconductors are heat-sensitive. It could be said that this enforces the need for high efficiencies.

With electric light sources the efficiency is called “lighting efficacy” because the human perception depends on the colour (wavelength / frequency) of the radiation. The dependence of the human eye's sensitivity is already integrated into the unit lumens [lm] for the luminous flux (light output). The consequence of this is:

- With monochromatic bright green light at a wavelength of λ = 555 nm (f = 540 THz), where the human eye exhibits its highest sensitivity, a luminous efficacy of 683 lm/W corresponds to an energy efficiency of 100%.
- With “ideal” white light (including equal parts of all visible wavelengths from 384 nm to 789 nm or frequencies from 380 THz to 780 THz, respectively), a luminous efficacy of 182 lm/W corresponds to an energy efficiency of 100%.
- With sunlight (containing **a bit** more green than other colours), a luminous efficacy of 198 lm/W corresponds to an energy efficiency of 100%.

Thus, white lamps promising a luminous efficacy of 200 lm/W or even more

- either cheat with the white colour of the light, containing more green light and less yellow, red and blue light than would be adequate for a “white” lamp,
- or have invented the theoretically impossible “perpetuum lumile”, which becomes ice cold during operation because it sucks up ambient heat and converts it into light.

Physics assigns the latter to the realm of fairy tales; leaving the former the only likely possibility.

3 Optical properties of LEDs

The colour rendering index was introduced to quantify the quality of light. Its definition and measurement are complicated enough to hide a lot behind it. A light source capable of precisely imitating the standardized spectrum achieves the best colour rendering, while one with an even distribution of wavelengths does not. Light sources that successfully imitate natural sunlight also do not provide the best colour rendering. LEDs come quite close to a reference spectrum, and this property is exploited.

Light emitting diodes, by definition, generate a narrow-banded light consisting of only one colour. To generate white light, one initially had to mix it out of two colours, such as from two LEDs (not necessarily three, as is often referenced in older textbooks). For this purpose, two or three LEDs were joined into one. The resulting colour rendering was mediocre, because, for example, a “white” light consisting of only blue and yellow, makes a green object theoretically appear black. In practice, however, some green will be visible. The yellow LED generates a narrow-banded, but not monochromatic light, and will dissipate a bit of green light. This technique has been replaced by the application of a conversion layer on a single blue LED. Hence, today’s white LED is also a fluorescent lamp. Light with longer wavelengths, i.e. lower frequencies and thereby lower energy contents per light quant, can be generated by “slowing down” the blue light quants. In this manner they are converted into green, yellow and red-light quants. After initial difficulties, today it is possible to find the right combination, and thus the desired white colour. Consumer prejudices, however, will likely persist for years, as they did with the CFL. Often the static, unchangeable colour spectrum of incandescent lamps is praised. This light can be influenced only by dimming – and even hereby only in one specific, physically determined manner; otherwise incandescent lamp light does not vary.

3.1 White does not equal white: Advantage or disadvantage?

Figure 8: A demonstration showing…

Figure 9: …how much blue light can be obtained from a small 9 V battery block.

With the LED it is never certain what you will get. This could be seen as a disadvantage or an opportunity. As with fluorescent lamps, warm white, cold white and daylight white LED lamps are available in today’s market. Nevertheless, the light of two lamps with equal values of colour temperature and colour rendering index are really only equal in name. The conversion layer can change the light dramatically. To know what you are getting in a lamp, you have to see the light it produces with your own eyes.

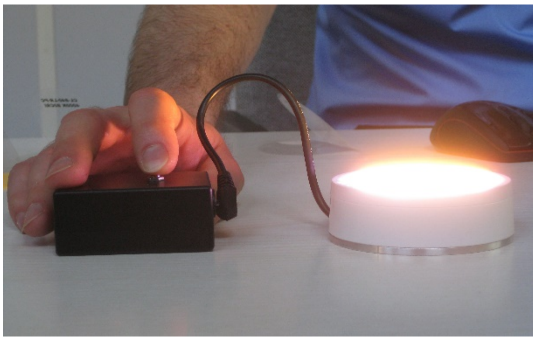


Figure 10: …but prior to all how a fluorescent layer can make white light of any shade out of this …

Figure 11: through a filter

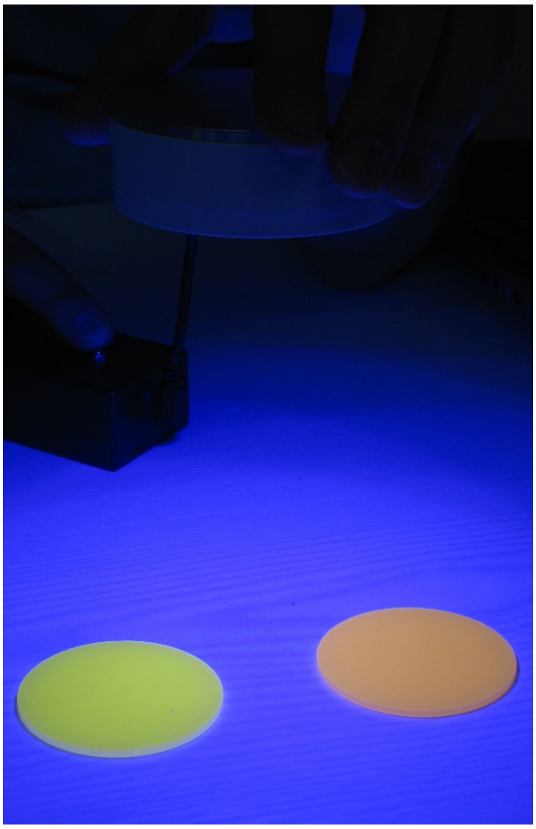


Figure 12: by reflexion

The conversion layer need not necessarily be integrated into the LED, but can also be part of the luminaire [1]. Thereby different colour temperatures can be derived from the same LED element (Figure 8 to Figure 12).

Figure 13: “Colour drift” sometimes (still) leads to differently changing colours of individual LEDs within one luminaire

In this way, also the often observed “colour drift” (Figure 13) can be counteracted. The term implies that individual LEDs, including the same types working together in one lamp, may age in different manners and thereby change their colours divergently. One could also speculate that colour drift is part of the ‘growing pains’ of LED technology, and will be solved in the short rather than in the long term.

3.2 Manifold colours

LED lamps are optimally suited for use in traffic lights, in tail lights and indicators in vehicles, and for other signalling purposes, because here only the desired colour is produced rather than generating a continuous spectrum with an inefficient incandescent light and then filtering all other colours out. It is notable, however, that you also see passenger cars where the 5 W incandescent bulbs in tail lights have been replaced with LED lamps, while the 21 W bulbs in indicators and brake lights have remained. We are still waiting for LED head lights. Yet, it should be noted, that due to the short operating times, the replacement of incandescent bulbs with LED lights will never pay off in terms of energy efficiency. Nor is there an advantage with regard to lower maintenance costs, since incandescent vehicle lamps are typically good for a vehicle's entire life. After all, a privately-owned passenger vehicle is in operation for only some 200 h/a and lights are not always in use during this time. As with many other aspects of a car, it is more a question of aesthetics or image. In contrast, the new, widely introduced daytime running light always consists of LEDs.

3.3 Flash and blinking lights

While LED indicator lamps preliminarily remain a feature of luxury vehicles, LEDs are ideally suited to flashing, emergency vehicle lights. LEDs are the only lamps which would not suffer from the frequent switching and the LED can be highly overloaded for short periods. The crucial point is whether the heat capacity can intermittently store the waste heat. As long as this is the case, only the average heat dissipation over one operating cycle defines the tolerable power load on the LED. This is yet another property where other lighting systems are left wanting. A prime example of this is the photo flash, today already a domain of the LED.

3.4 Increased bicycle safety

The bicycle lamp in particular, with an available electrical power of only 3 W, benefits from the LED by generating more light and suffering fewer failures. The somewhat obtrusive bluish colour, which allows for slightly better efficacies of white LEDs, also provides some additional safety. Along with the hub dynamo, LEDs have become the lighting standard on a bicycle. Contemporary cyclists no longer perceive a change while cycling when turning on the light or when a light automatically switches on in low light. Whereas with the earlier lamps, putting the old tyre dynamo into operation always meant that one had to downshift, and possibly, under wet conditions, suffer tyre damage instead of generating light. Lights that remain on even while the bike is stationary are also now possible (Figure 14) even without the use of an accumulator battery; an integrated capacitor suffices for several minutes of LED light. Even though the capacitors need to be recharged while riding, the thrifty LEDs still have sufficient power to charge up a mobile phone! Neither of which would have been possible with the earlier incandescent bulbs.

Figure 14: The standard nowadays: LED bicycle rear light with park light function

Figure 15: Daytime driving light is a marvellous thing if you avail of a hub dynamo; other than a rating in "lux" without mention of border conditions, which is bare of any sense at all

Unfortunately, as a leftover from the early days of LED lighting, the "performance" of bicycle head lamps is measured in lux. Lux [lx] is the unit for illuminance, indicating how much light hits a certain surface area (1 lx = 1 lm/m²). However, the lux figure does not indicate the distance at which this illuminance was measured, nor the size of the lit surface area (Figure 15). Without these factors taken into consideration, the lux is somewhat meaningless.

3.5 Decorative lighting

The advantages of LEDs become most obvious in decorative lighting. Lighting scenarios with changing colours made up from a multitude of small, dispersed lighting points are an ideal use for LEDs. The lighting efficacy is nearly one order of magnitude greater than the use of small extra-low voltage (ELV) incandescent bulbs, shifting the system into a range where it is no longer worthwhile thinking about further improvements, particularly since decorative lighting does not use great luminous fluxes. Too bright decorative light is not wanted anyway. An old set of Christmas lights with 85 incandescent bulbs (35 * 1 W + 50 * 0.7 W) replaced with a set of 320 LEDs will use10 times less active power and the apparent power (Figure 17) is decreased by a factor of 5 with the new bulbs. Thereby the operating costs dropped from 2.10 € to 21 cents per season. More than anything else, this is brought about by the easy miniaturisation of individual LED lamps. Even if they cannot be made any smaller, the individual lamps could still be operated at substantially reduced power (also sees Section 5.2.4). In this way the LED enables the use of battery-based technologies in areas where this was previously not possible (Figure 18). Replacing the batteries with NiMH accumulator cells adds a triple advantage on top: Not only through cost savings and waste reduction with the batteries, but also the lower cell voltage of the NiMH cells with 1.25 V instead of 1.5 V expands the operating time over-proportionally (Figure 24), while the minimal loss of brightness is negligible.


Figure 16: Adhesive LED strips

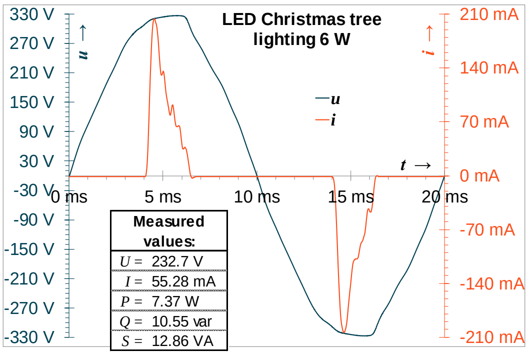


Figure 17: Christmas tree lighting with 320 LEDs, overall power rating 6 W, gross measurement including power supply unit 7.3 W


Figure 18: Decorative lighting designed for battery operation, converted here for use with a power supply unit – however at least three lamplets have already “dimmed down” after only 1,000 hours of operation

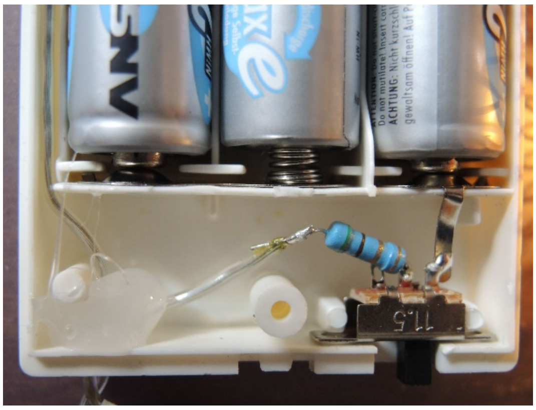


Figure 19: A serial resistor suffices here (Figure 18) as a “current limiter”


Figure 20: The Three Magi…


Figure 21: …backlighted with adhesive LED strips and a net (ELV) connected load of less than 50 mW (also see Section 5.2)

To some extent, the average consumer can also use ELV technology (Section 5.2): adhesive LED strips are available on the retail market (Figure 16), and can be cut by the customer to the desired length at certain marked points. Each package includes a connector power pack for operating these custom-made strips on the 12 V DC output (SELV, short-circuit proof). Any three consecutive LEDs are connected in series and have a serial resistor, forming one "cuttable" unit.

3.6 The LED on stage

Despite the high investment costs, LED spotlights have also made their way into theatres. They are particularly suited for colour change and the combination of LEDs with different colours in one spotlight may reduce the required connection power to one tenth of what was needed with incandescent lamps. The optionally flood or spot shaped characteristic of the LED, the lag-free switching on and off, and the ability to dim up and down offer the most flexibility for the user and is far superior to the old incandescent lamps. Although incandescent lamps are able to match certain properties described above, they do require quite a lot of "thermal management." Replacing mechanically operated colour filters with a separate electrical control for groups of coloured LEDs improves reliability and response times. The possibility of lamps failing in the middle of a performance, and literally going out with a loud bang, is also avoided. LEDs burn out slowly and silently, if at all, and with those few operating hours on stage they are unlikely to reach the end of their useful life. "Ideal" is a frequently abused term, but this type of lamp is in fact nearly ideally suited for this purpose. Because of this ideal fit, the increased costs of LED lighting have not hampered their introduction into theatre. Finally, and a very good argument for the expenditure on LED lighting, is that actors no longer suffer under the extreme heat produced by incandescent lamps.

3.7 Medical technology: 'OP-timal' lighting

The hospital operating theatre, where the light needed for surgeons to operate reaches the intensity close to that of sunlight, has come to prefer the LED for similar reasons as those mentioned in section 3.6. Considering that the radiation of the old halogen lamps contains a significantly higher ratio of heat versus light when compared to the sun's radiation, it is not hard to imagine the effects of the heat on the patients and medical staff beneath them. In fact, incandescent lamps (initially conventional ones and later halogen lamps) are reported to be 1,000 W and up. The famous Berlin Charité Hospital reports that assistants continuously wiped sweat off the surgeons' foreheads. Contemporary LED operating lamps, however, exhibit quite poor lifetimes, some burning out after just six months. This is the result of a "squeezed" design which favoured high power density over other properties, this took priority over other features including the expected lifetime of the lamps. Here too, the composition of LEDs with different colours provides the possibility to customise and optimally tune light.

4 Thermal properties of the LED

Why then, for a lamp that has so little heat loss, is heat so problematic? Why is it so much more difficult for the LED to lose 4 W out of 7 W heat-waste, while a halogen lamp dissipates 32 W out of 35 W without any trouble? There are three reasons for this:

- The LED is very small, and therefore the heat generated is concentrated on a very small surface area.
- As a semiconductor component, it cannot tolerate temperatures as high as an incandescent lamp made of metal and glass can (Figure 22).
- Incandescent lamps lose a large part of their heat, some 50% to 80%, by radiation. In contrast, the LED loses next to none because its surface is very small and the heat radiation increases to the fourth power of the actual temperature.

For these reasons, the LED cooling process was renamed “thermo-management.” The power of the lamps was primarily limited by the uncertainty on how to cool them. Some early consumers had the unfortunate experience that their lamp, with the promise of a 40,000-hour life, burned out after a mere three days. The manufacturers had a problem:

Figure 22: For various reasons it was high time for a conversion here of the ceiling integrated lamps from 35 W halogen to 7 W LED!

- Principally speaking, testing a product with a lifetime rating of 40,000 hours takes 40,000 hours. All attempts to shorten the test period by making the conditions harsher, such as raising the operating voltage and the ambient temperature, will result in less accurate test results. The further the conditions of the tests are from a realistic setting, the less accurate the results. Like all mathematical models, there is an element of hypothesis and assumption.
- Lamps initially were made with as few of the expensive LEDs as possible per lamp. The operating temperatures were accordingly high – and so were the failure rates. However, with even more of the expensive LEDs in the lamp, the price at the time would have been prohibitive.

Today the technology is available and the costs for the components are low: At www.leds.de, for example, you can get individual LEDs and modules (in lots between 1 piece and 150 pieces – no industrial quantities!) for from about 30 cents to 1.25 Euros per watt (corresponding to well over 100 lm). The affordability of LEDs led to more being used per lamp, thus each LED only reaches “lukewarm” temperatures. Now it is possible to reach the expected lifetime of the lamp. In many ways the development of the LED mirrors that of the CFL, history repeats itself.

5 Electrical properties of the LED

“Light emitting diodes” (LEDs) have served as signalling lamps for four decades. Following this period, there were rapid developments in brightness and luminous efficacy. LEDs have thus established themselves as being suitable for lighting purposes. The properties of these lamps are highlighted below.

5.1 General

The LED, as its name implies, is a semiconductor diode. However, for lighting purposes it is operated in forward mode only. The other way around it would emit light as well, but only for one, short moment, and preliminarily one could also “smell” the light. The blocking voltage is comparatively low because this diode is not foreseen for use as a rectifier. Like every diode, it exhibits an exponential characteristic in forward operation. This means that instead of Ohm’s Law with its linear (proportional) coherence between voltage and current, it is exponential. Hence, the diode current I_D is calculated dependent on the voltage U_D across the diode and on the (absolute) temperature T at the junction according to the so-called Shockley equation:

$$I_D = I_S\left(e^{\frac{U_D}{nU_T}} - 1\right) \quad [2]$$

with:

n	the coefficient of emission, a correction factor for the individual diode;
$U_T = \frac{kT}{q}$	the temperature voltage, in which:
$k = 1.38 \cdot 10^{-23}$ J/K	Boltzmann’s Constant (a natural constant);
$q = 1.6 \cdot 10^{-19}$ As	the elementary charge (a natural constant; charge of one electron);
T	the absolute temperature of the junction during measurement [K];
I_S	the saturation reverse current of a diode, which – largely independently on the voltage – flows also in reverse direction, as long as the blocking voltage is not exceeded.

The order of magnitude for germanium diodes is around 100 nA and for silicon diodes around 10 pA. This is no less than a ratio of 1:10,000, although the absolute values are very small in either case. The value is however crucial for calculating the behaviour in forward operation, which is represented by the following formula:

$$I_D = I_S\left(e^{\frac{qU_D}{nkT}} - 1\right)$$

But this, for whatever reason, is not how it is found in literature. This is unfortunate, because as above, it immediately stands out that the temperature is in the denominator of the exponent and dampens the exponential growth of the current as it increases. This surprises a practitioner, who has experienced the destruction of materials, in which the conductivity of semiconductor components increases rapidly with increasing temperature and leads to the avalanche-like destruction of the semiconductors. The reality is this: The reverse saturation current I_S of the diode is also a variable and approximately doubles with each 10 K temperature rise. With its starting value (of e. g. 20°C) and the coefficient of emission n, one can “juggle” until a curve is obtained which, at least to a rough approximation, corresponds to a practical measurement. With n = 4.9 and I_S (20°C) = 10 pA the resulting curves are those shown in Figure 24. For these results, an LED was measured twice in two tests using equal current values:

- The first test was conducted while individually mounted on a large heat sink, which would have been sufficient for 100 LEDs. The temperature measured at the surface only increased from 18°C to 23°C during this run.
- The second test was conducted without any heat sink at all and "cooled" only with a temperature sensor attached (Figure 23). The temperature measured at the surface reached 98°C during this run.

The evaluation reveals the following:

- The curves for current and power are approximately equal in course – which is logical, since the voltage across the diode varies little with current.
- The actual and the predicted values for the warm operating state are close in value.
- The measured values for the cold operating state diverge from these with increasing voltage / increasing current, i. e. the discrepancy between cold and warm is much greater in the measurement than it is in the calculation. It looks as if the calculation already included the temperature rise of the diode: The current and power curves increase steeply both times, cooled and uncooled. In the measurement the increase is much less steep when cooled than when uncooled.

Figure 23: Measuring an LED from 1 µA (it does emit some visible light already at this point – see Figure 48) up to the current rating of 330 mA without cooling

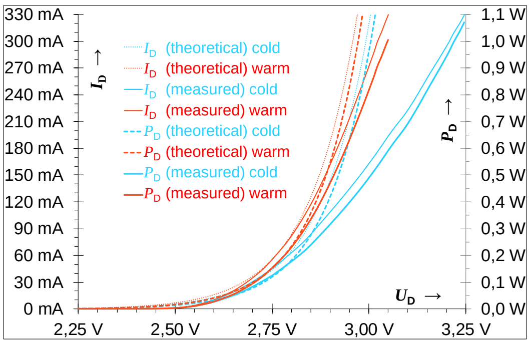


Figure 24: Characteristics of an LED for lighting purposes (Moonstone ASMT-MY06-NMN00) cooled and uncooled, calculated and measured

This last finding is unsatisfactory in principle, but of lesser relevance for the subsequent considerations, since the LED will always heat up during operation and the warm operation represents the critical state. Hence, according to the above theory, the estimated value I_D will always be "on the safe side."

Within the range used in practical operation, very small variations of voltage lead to very great variations of current. This requires some form of current limitation. The LED lamp must include some sort of operating device (ballast or driver) which not only rectifies the alternating current from the line, but also converts the voltage-source characteristic of the mains into a current-source characteristic. Exactly this shall be addressed below.

5.2 LED lamps for extra-low voltage (usually 12 V)

With the abundance of LED lamps on today's market, it is no longer possible to have a comprehensive overview of what is available. With the introduction of LEDs, the use of "halogen spots" is all but eliminated. Since halogen incandescent lamps, as their full name implies, are really just incandescent lamps, their lighting efficacies have never been much better than those of commonplace, all-purpose incandescent lamps. The former trend was to use spotlights anywhere and everywhere to reflect light against white surfaces in an attempt to evenly distribute light, much of which was lost in the practice. (Figure 64). As a result, this style of lighting was even *less* efficient than conventional incandescent lamps normally would have been. The "halogen spot" trend also became prevalent in the commercial sector; such as on office desks, in sales areas and hotels, where incandescent technologies had not previously been in use. Here too, the lighting efficacy was drastically reduced rather than slightly improved. It is not uncommon to find the halogen spots still in use. This trend might have died out sooner had electricity metres the ability to specify time and place of electricity usage, drawing attention to their inefficiency. Interim solutions with LED lamps which made an unpleasant sound [3], did not find success and have meanwhile disappeared again from the market. Attempts to relabel the noisy fans as "active heat sinks" did not save them from extinction (Figure 25, Figure 26).

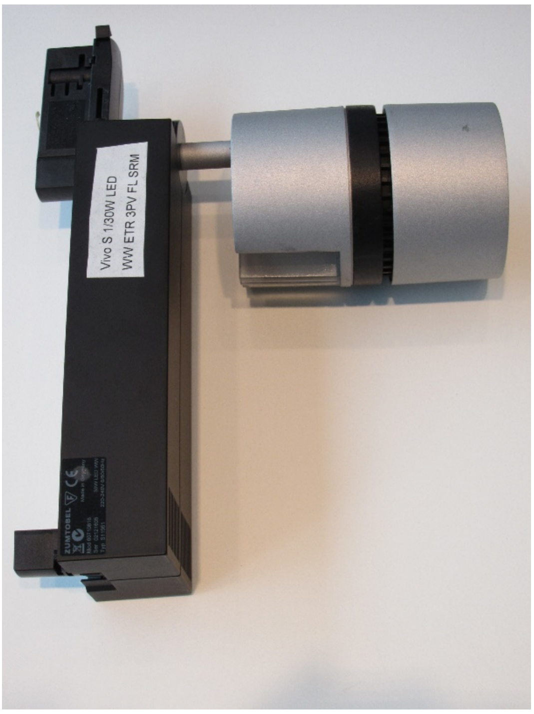


Figure 25: Not visible in an assembled state …

Figure 26: …but in state of operation unfortunately audible: Who would be a fan of LED fan noise?

Today there are lamps available that make it possible to convert the existing systems into very efficient light sources. Both the complete lamps with integrated reflectors as well as the individual bulbs can now be replaced with LED lamps. Sometimes there is really an urgent need for action for various reasons. For instance, the conversion of 17 flood lights from 35 W halogen each to LED lamps of 7 W each (Figure 22) in a basement room elaborated into an office did cost around 50 € but also saves some 50 € a year since. At the same time – without really having any measured values at hand – the room appears significantly brighter than it used to be (cf. Section 9.3).

Figure 27: Usually the pin-base lamps fit into existing fixtures…

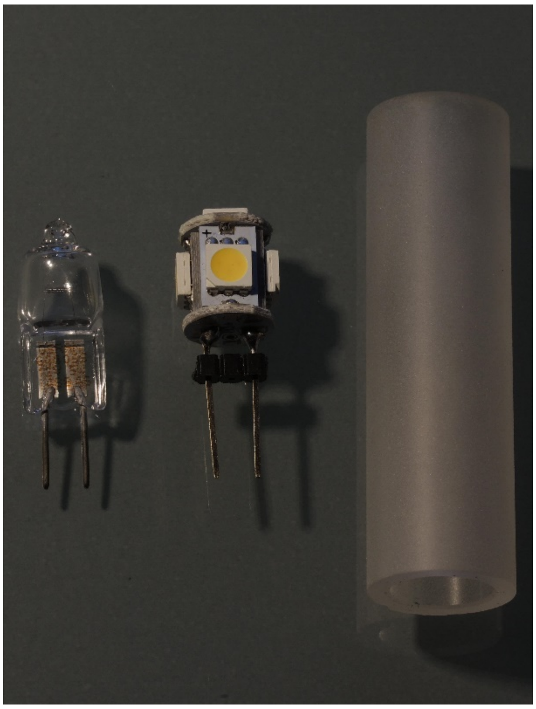


Figure 28: …in this case, however (Figure 27), they do not fit into the decorative glass tube shaped shades

Also the individual little plug-in bulbs can now be replaced with LED lamps (Figure 29). The LED lamps with GU4 or GU5.3 pin sockets are not much larger than the halogen lamps they should replace. Nevertheless, it is important to check the dimensions of the lamp to see if it will fit in the fixture (e. g. in Figure 27). In this case, for instance, the 1 W LED lamp does not fit into the decorative glass tube shaped as a replacement for the 5 W halogen lamp (Figure 28).

These small LED lamps are available as two different versions:

5.2.1 Lamps for DC voltage

Figure 29: Typical LED "driver" 12 V; here with an output power rating of 100 W

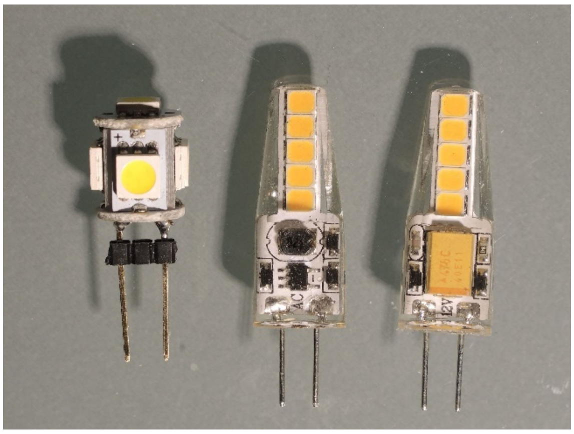


Figure 30: LED lamp 1 W for 12 V DC (left) and 2 W for 12 V DC and AC (right)

5.2.2 Lamps for DC and AC

Here too, the nominal voltage is typically 12 V. A conventional halogen lamp transformer can usually remain in use here. An electronic device, on the other hand, may cause trouble because these devices often cannot cope with low nominal voltage. In such instances, the lamps will either not work at all or start to blink or flicker. As LED lamps use about 80%, or even up to 90% less power, this happens not only when a part of the halogen lamps fails, but when they are replaced with LED lamps. Lamps also suitable for AC voltage may include different network topologies:

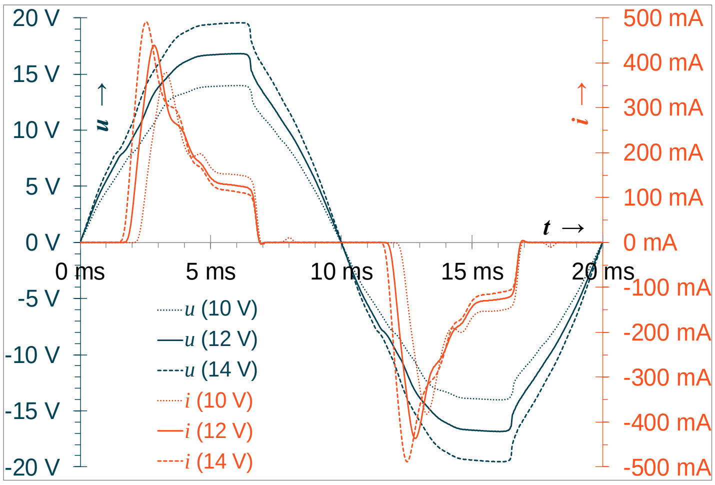


Figure 31: Behaviour of an LED GU4, power rating 2 W, on 10 V, 12 V and 14 V – 50 Hz (for DC see Table 1)

LED lamps 12 V – GU4			
U	**10 V**	**12 V**	**14 V**
U/U_n	83,3%	100,0%	116,3%
2 W AC and DC lamp			
$I\,-$	205 mA	162 mA	143 mA
$I/I(U_n)\,-$	126,4%	100,0%	87,9%
$P\,-$	2,054 W	1,952 W	1,994 W
$P/P(U_n)\,-$	105,3%	100,0%	102,2%
$I\,\sim$	144 mA	163 mA	181 mA
$I/I(U_n)\,\sim$	88,8%	100,0%	111,1%
$P\,\sim$	1,162 W	1,498 W	1,845 W
$P/P(U_n)\,\sim$	77,6%	100,0%	123,2%
$Q\,\sim$	0,858 var	1,256 var	1,725 var
$S\,\sim$	1,445 VA	1,955 VA	2,526 VA
1 W AC lamp			
$I\,-$	40 mA	67 mA	97 mA
$I/I(U_n)\,-$	59,8%	100,0%	143,9%
$P\,-$	0,404 W	0,810 W	1,356 W
$P/P(U_n)\,-$	49,8%	100,0%	167,4%

Table 1: Measured values of the 2 W pin-base lamp for DC and AC operation (Figure 31) and of the 1 W DC lamp (Figure 29)

- Either: There is only a bridge rectifier and, again, a series resistor in place (Figure 24). LEDs are however particularly sensitive to fluctuating voltage, which leads to flickering. The operating device needs to prevent this – and as a rule it does (Figure 32).

- Or: There is some sort of current stabilisation, or better yet, a power stabilisation in place. If present, it may work like a linear regulator (an automatically adapting resistor, a current limiter), or (with a less intensive loss) switched. As stated, however, such profound loss reduction does not make sense with LED lamps of this power range. After all, the electronic circuitry also needs to be accommodated inside the lamp. In the 2 W lamp (Figure 29 centre and right) this has apparently been successful (Figure 33): The current intake increases up to an applied operating voltage of 10 V and drops again above. The effect is imperfect with AC (Table 1), but nearly perfect with DC voltages between 10 V and 14 V (Figure 32). In addition, the lamp has a small smoothing capacitance (Figure 31): The waveform when operating on AC reveals that the capacity is there; the position of the current curve just before the voltage peak reveals that the capacitance is only relatively small. The steps in the falling edge of the current curve display the electronics' efforts to compensate for the fluctuating voltage, but below 10 V its attempts are unsuccessful. If the smoothing capacitances were large, i. e. 10 times the physical volume of the lamp itself, then the latter would behave just as flawlessly on AC as it does on DC, but it is simply not possible to have a small sized lamp with the advantages of a big one. The nominal power is not reached on AC, not even at 14 V.

5.2.3 Operating devices for ELV (extra-low voltage) lamps

In general, good smoothing and a good stability may be expected from the output voltage of external operating devices (Figure 32). It is unclear why the output current here varies by 7%, although the output voltage between idle and full load only varies by 2.2% and has a residual ripple of only 0.5% – while these measurements were not even taken with an LED load, but with incandescent car lamps as a test load.

What is not successful, however, is the attempt to "reuse" old 12 V electronic operating devices for halogen lamps for the operation of 12 V LED lamps. The load with an intermediate bridge rectifier and a large smoothing capacitance inserted between the old electronic transformer and the new load may cause devices not made for this to fail (Figure 34). With a conventional transformer this would just work. Toroidal core transformers, if present, are particularly well suited, since with the very light load remaining after the conversion, they still exhibit good efficiencies. Other transformers are better replaced with adequate new technology.

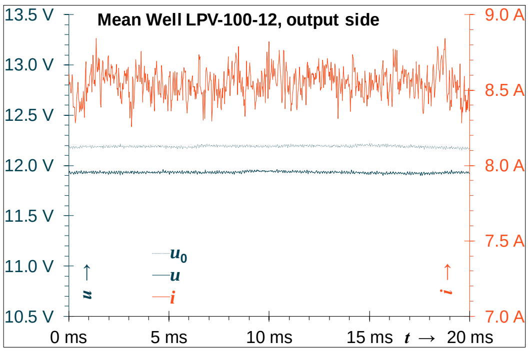


Figure 32: Voltage and current across the output terminals of the device in Figure 29: Good DC voltage stability; hardly any difference between no-load u_0 and full-load voltage u

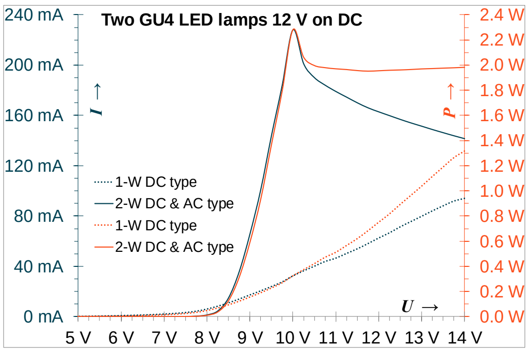
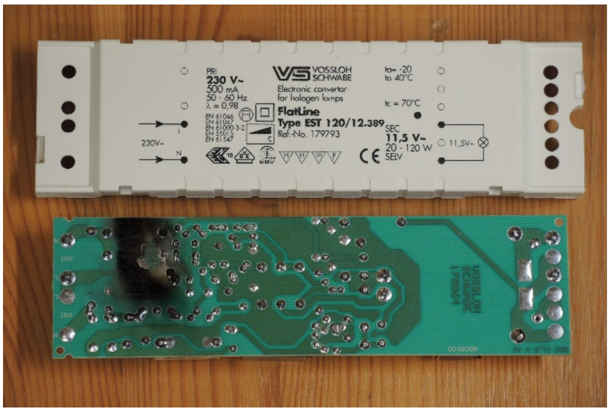


Figure 33: Characteristics of the two 12 V GU4 LED lamps from Figure 29: The 2 W lamp for both DC and AC operation is obviously pro-

Deutsches Kupferinstitut Berufsverband e.V.
Heinrichstr. 24, D-40239 Düsseldorf, Tel.: +49 211 129469-10, www.kupferinstitut.de
Deutsche Bank AG, Düsseldorf, Konto-Nr.: 7 440 720, BLZ: 300 700 24
Amtsgericht Düsseldorf VR 9370, Geschäftsführer: Michael Sander

vided with a current stabilisation, the 1 W DC lamp is not



← Figure 34: Do not imitate: Electronic halogen lamp transformer after an attempt at operating LED lamps on it via rectifier and electrolytic smoothing capacitor

5.2.4 Dimming ELV lamps

By simple variation of voltage or, better still, an adjustable current limitation, lamps with the simple “resistor technology” are always dimmable, even if they should not be explicitly designated as such. Although the dimming function should be integrated into the operating device, the issue rarely arises because there are typically a large number of lamps, each with a very low power that could alternatively be switched as groups. In the case of the scraps of adhesive LED strip used for illuminating the Three Magi (Figure 20, Figure 21), even a series resistor of 1 kΩ was integrated into the connection cable as “dimming.” The net DC power requirement for the brightness depicted in the photo is below 50 mW! Adding to this, however, comes another 300 mW of no-load consumption in the (here only very weakly loaded) power device (Section 6.6).

Low-voltage LED lamps, that are also suitable for operation on AC voltage, tend to employ a more sophisticated technology, aimed at balancing the effects of voltage fluctuations, when possible even within the period of the rectified alternating voltage. This counteracts any attempt at dimming and in such cases, dimmed operation is generally not possible.

5.2.5 Complete ELV systems for lighting technology

At present there is increased reporting about DC networks at all voltage levels. DKE [4] are elaborating a “German Standardisation Roadmap: DC in the low voltage sector” – additionally, “remote power feeding in information and communication technology” [5] is more frequently heard about. Usually the ELV sector is affected. “PoE” (power over ethernet) describes technologies [6] to use the same conductors in a telecommunications cable simultaneously for powering final devices or to employ unused conductors within the same cable for this purpose. Due to the low power requirement of – at least small – LED lamps, complete concepts already exist to feed the complete lighting of offices via data lines. To really understand how and why this is implemented requires the consideration of three specific aspects:

- It is only possible because one dedicated line is used for each and every single luminaire, so that 100 W gets you pretty far with LEDs.

- Installers use pre-fitted cables with standard lengths. They do not shorten them but wind the rests into loops. This makes the installation very quick.
- A further argument forwarded for supporting this technique is that contemporary – or at least future-oriented – lighting installations include individual control of single lamps anyway. With the power and the signals coming in jointly, this will be a lot easier to implement.

5.3 LED lamps for line voltage

In principle, everything that was said regarding ELV also applies to all other LED lamps, but LED lamps for mains operation consist of a pre-fitted interconnection of an operating device – be it external or integrated – and a serial and parallel interconnection of arrays similar to those described above. Only very small lamps consist of only one LED. Experts [7] even emphasize that all lamps and modules named “one LED” and rated more than about 1 W consist of several integrated LEDs. There are no limits to the combination of topologies. The user loses the overview here – but fortunately this does not matter because both lamps and the modules for these are procured pre-fitted off the shelf. However, regarding the lamps, two basic cases need to be distinguished:

5.3.1 Replacement lamps

An even broader variety of sockets and shapes are available for mains voltage lamps than for ELV lamps. From time to time the problems with spatial compatibility still remind us of those with the CFL (Figure 2) because the LED itself may be very small, but in need of a large heat sink. In general, however, the replacement of the old incandescent lamps with LED lamps works better than it did with the CFL, and the replacement of CFL lamps with LED lamps is even easier. Quite generally speaking, in nearly all applications in the home and in the garden, in trade, commerce, industry, and in the public sector, where such lamps are at present still in operation, an LED replacement can be found – and such replacement is indeed recommended.

Only with LED lighting tubes, meant as replacements for fluorescent tubes in existing luminaires, some caution is recommended. Parallels exist with cases from past periods: The promised energy savings are usually achieved by replacing a wide-angle lamp with one delivering directed light – and this in locations where light would be required all around. These “retrofits” represent questionable progress. [8].

5.3.2 Integrated lamps with non-exchangeable LED modules

A trend towards integrated luminaires can be observed in which neither LED modules nor operating devices can be simply exchanged. One may criticize this – or think it over. Thinking may then lead to the conclusion that it is only of limited use to undergo the considerable additional investment to design exchangeability by the user into the luminaires. In a luminaire which is expected to be in operation for about 20 years, it will not be economical to design the lamp itself in such a way that it can be replaced by the user if the lamp also lasts 20 years. We are used to lamps having only a fraction of the lifetime expectancy of the whole luminaire – but if LEDs now start to live up to their promises, then the circumstances are different (also see Section 8 regarding this).

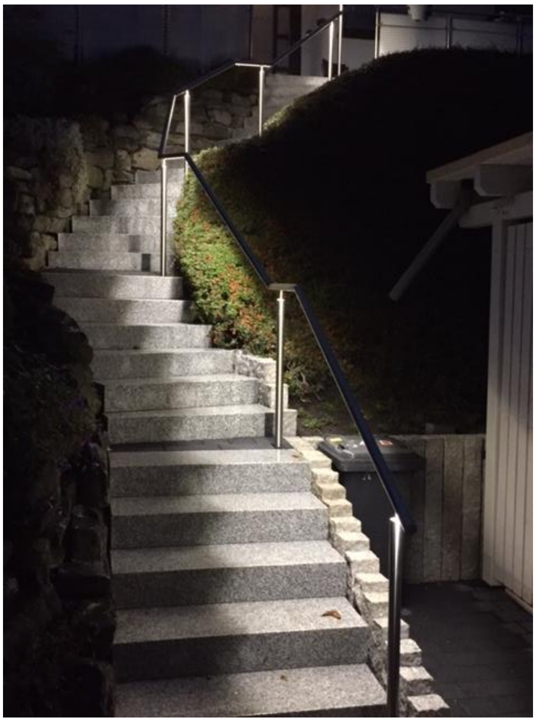


Figure 35: Goodness, how bright it is here! LED outdoor lighting accommodated in a staircase railing

It is somewhat funny indeed to observe even with completely newly designed lamps, luminaires and lighting installations how often the attempt is made to maintain the familiar linear shapes and arrangements known from fluorescent lighting tubes ("strip lights"). This is appropriate or required in only very few applications (e. g. Figure 35). Usually a square, round or elliptic version is more appropriate – and these shapes, of course, are also available to LEDs. The development is reminiscent of the early ages of the railways, as the first railway carriages also consisted of horse coaches which had been converted with railway wheels. Then, when the first "real" railway carriages came up which were designed as such right from the start, the familiar look of horse coaches still dominated the outer shape. Only later was the shape adapted to the purpose and no longer vice versa. History keeps on repeating.

5.3.3 Operating devices for mains voltage lamps

A series of standards that became (more or less) known under the name "Zhaga" [9] is trying – or once tried – to standardize LED modules in such a way that they should become replaceable with each other. However, there is frighteningly little to be heard about this project recently. The individual "books", as they are called here, are available only in English and Chinese – though free of charge. It would certainly be quite attractive for luminaire manufacturers who need to source components to be able to select from several manufacturers. But if – *after* the maturing phase of this market, which was painful for all parties – the lamp exhibits a lifetime expectancy similar to that of the whole luminaire, and the replaceability feature adds quite a bit on top of the price of the complete luminaire, then such a feature is of no interest to the customer.

Without a standard, individual solutions will continue to be most commonly found. In addition to the integrated and the external power supply units, there are also hybrids, where a normally separate operating device lies more or less loosely inside the body of the luminaire (Figure 37, Figure 38). You encounter constant voltage and constant current devices with ratings differing time after time again from one to the next. There is one dedicated operation device for every single application – but which, as a rule, is enclosed in the shipment. If this is not desired, the consumer should select ELV lamps (Section 5.2), which are usually designed for the common voltage levels 5 V, 12 V and 24 V. For these, there is a large selection of operating devices available.

5.3.4 Dimmability of LED lamps for mains voltage

The dimmability of complete integrated lighting installations needs to be carried out in the course of the installation planning; general statements on this are not possible (see however the indications regarding dimmers for building automation systems and the like in Table 2). With reference to the individual luminaires, particularly for the residential sector (Figure 36, Figure 37, Figure 38), individual indications can be provided.

Figure 36: 100 W incandescent lamp finally replaced!

Figure 37: Dimmable ceiling luminaire rated 19 W; 2700 lm; 2900 K

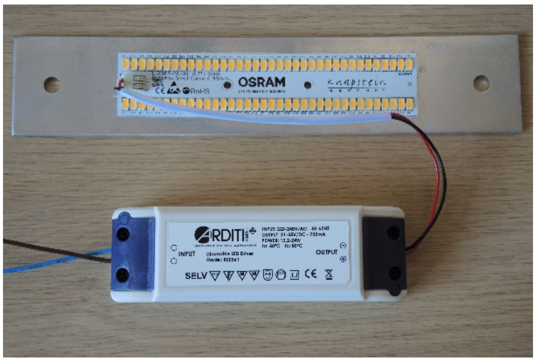


Figure 38: “Guts” of the luminaire in Figure 37

For the luminaire in Figure 2 an adequate LED lamp could still be found, after all (Figure 36): Luminous flux matches, light colour matches more or less (could be better), price matches (≈ 16 €), dimensions (barely) match, and the old leading phase angle control dimmer also matched the new lamp: Flawless function! Although the lamp spent less than one year in operation before the whole luminaire fell victim to the owner's changing taste and was replaced with the one in Figure 37, the expenditure had already paid back via the energy savings.

Nr.	Dimmer (with lamp No.)		Power min.	Power max.	Current min.	Current max.	THD(r) at min.	THD(r) at max.	Notes: Dimmer	Notes: Lamp
1.1	Feller zeptrion 3306.24.S.FMI.61	1	1.3W	8.7W	19mA	52mA	0.79	0.45	Dimmer for zeptrion building automation system. Does not require a neutral conductor – dimmer power loss not included	Stable
1.2		2	1.4W	11.7W	31mA	67mA	0.77	0.60		Stable
1.3		3	1.6W	3.6W	30mA	37mA	0.77	0.67		Range very small, only with SE ZSL-UP additional load
1.4		4	2.6W	5.7W	39mA	31mA	0.41	0.71		Range very small, current increases with dimming
1.5		5	1.6W	5.1W	30mA	37mA	0.77	0.66		Dimming range small
2.1	Feller rotary dimmer 40600.RC.FMI.61	1	1.0W	8.6W	14mA	60mA	0.90	0.64	Does not require a neutral conductor – dimmer power loss not included	Stable
2.2		2	1.8W	11.8W	33mA	86mA	0.95	0.76		Stable
2.3		3	0.7W	3.8W	6mA	25mA	0.61	0.68		Dimming range very wide
2.4		4	3.4W	7.0W	62mA	1mA	0.95	0.85		Dimming range small
2.5		5	0.7W	3.9W	6mA	25mA	0.63	0.69		Dimming range pretty good
3.1	Hager universal remote dimmer 757391	1	0.8W	8.5W	16mA	51mA	0.85	0.46	Requires neutral conductor – Dimmer-dimmer power loss not included. Operation by pushbuttons, dimmer in small distribution box	Stable
3.2		2	1.1W	11.7W	30mA	66mA	0.83	0.60		Stable
3.3		3	0.9W	5.1W	26mA	37mA	0.84	0.67		Stable
3.4		4	3.4W	5.8W	44mA	31mA	0.72	0.41		Dimming range very small
3.5		5	2.1W	3.7W	29mA	25mA	0.83	0.70		Dimming range very small
4.1	Hager universal remote dimmer 757392	1	0.7W	8.0W	12mA	52mA	0.95	0.59	Requires neutral conductor – dimmer power loss not included. With pushbuttons, for small distribution box – special functions	Stable, difficult to handle
4.2		2	1.2W	11.7W	30mA	81mA	0.97	0.75		Stable, dimming range small
4.3		3	0.3W	3.7W	5mA	25mA	0.88	0.70		Stable, dimming range good
4.4		4	2.5W	5.9W	60mA	36mA	0.95	0.56		Dimming range very small
4.5		5	0.3W	3.7W	5mA	25mA	0.89	0.71		Stable
5.1	Hager universal RC remote dimmer 757393	1	0.9W	8.6W	17mA	51mA	0.85	0.46	Requires neutral conductor – dimmer power loss not included. With pushbuttons, for small distribution box	Stable
5.2		2	1.1W	11.6W	30mA	67mA	0.83	0.62		Stable
5.3		3	1.0W	3.7W	19mA	25mA	0.87	0.70		Stable, dimming range very small
5.4		4	2.2W	5.8W	41mA	32mA	0.77	0.41		Stable, dimming range very small
5.5		5	1.1W	3.7W	19mA	25mA	0.88	0.70		Stable, dimming range very small
6.1	Legrand ARTEOR UP-Tasterdimmer Typ 0784 07	1	0.4W	7.3W	10mA	48mA	0.90	0.52	Does not require a neutral conductor – dimmer power loss not included	Flickers during adjustment, stable afterwards
6.2		2	0.7W	11.8W	28mA	84mA	0.93	0.77		Stable
6.3		3	0.1W	3.8W	5mA	26mA	0.95	0.73		Stable, dimming range 0 … 100%!
6.4		4	2.6W	5.7W	39mA	31mA	0.41	0.71		Range very small, current increases with dimming
6.5		5	0.1W	3.8W	5mA	26mA	0.95	0.73		Dimming range very wide
7.1	SE Light Management AG UDK-04-10	1	0.4W	8.9W	13mA	54mA	0.92	0.46	Requires neutral conductor – dimmer power loss not included.Control via 0…10V signal	Stable, dimming range 0 … 100%!
7.2		2	1.1W	11.6W	30mA	67mA	0.83	0.62		Stable
7.3		3	0.1W	3.7W	5mA	25mA	0.92	0.69		Stable, dimming range 0 … 100%!
7.4		4	0.1W	5.9W	11mA	32mA	0.96	0.41		Stable, dimming range 0 … 100%!
7.5		5	0.1W	3.8W	3mA	25mA	0.92	0.69		Stable, dimming range 0 … 100%!

Table 2: Overview over the attempts from Switzerland in 2013 at dimming LED lamps [10], (obtrusive values highlighted by colour)

No.	Lamp	Ratings: Power	Ratings: Luminous flux	Ratings: Colour temp.
1	Philips Master LED BULB MV DimTone	8.0W	470lm	2700K
2	Philips Master LEDbulb MV Dimmable	12.0W	806lm	2700K
3	Philips LEDcandle MV dimmable	4.0W	250lm	2700K
4	Sylvania HI-Spt RefLED ES50	5.5W	350lm	3000K
5	Philips Master LEDcluster	4.0W	250lm	2700K

Table 3: Lamps used in Table 2

Lamp										Dimmer														
Type	Ratings (if indicatec by manufacturer)						Measured values			Universal rotary dimmer Feller 40200.LED			Dimmer for small distribution boxes Eltako EUD61NPN-UC			Pushbutton operated dimmer Legrand ARTEOR			Dimmer for small distribution boxes Theben Dimmax 532 plus			Dimmer for small distribution boxes Hager EVN004		
	P_N	Φ_N	ε_N	I	T	R_a	Dimming	$E_{0°}$	$E_{20°}$	P	S	$E_{0°}$	P	S	$E_{0°}$	P	S	$E_{0°}$	P	S	$E_{0°}$	P	S	$E_{0°}$
Prima Vista Halogen	40,0 W	330 lm	25°	0 cd	2700 K	0	**min.**	0 lx	0 lx	7,7 W	23,2 VA	1 lx	0,0 W	0,00 VA	0 lx	4,0 W	18,3 VA	1 lx	0,0 W	0,00 VA	5 lx	0,0 W	0,0 VA	1 lx
							25% E	0 lx	14 lx	0,0 W	0,0 VA	0 lx	0,0 W	0,00 VA	0 lx	0,0 W	0,0 VA	0 lx	0,0 W	0,00 VA	0 lx	0,0 W	0,0 VA	0 lx
							max.	270 lx	55 lx	39,2 W	40,8 VA	117 lx	0,0 W	0,00 VA	260 lx	37,7 W	39,9 VA	210 lx	0,0 W	0,00 VA	260 lx	0,0 W	0	265 lx
							Range	4,9	0,0	0,0 W	0,0 VA	117,0	0,0 W	0,00 VA	∞	0,0 W	0	210,0	0,0 W	0,00 VA	52,0	0,0 W	0	265,0
XNovum Lucky Light COB	5,0 W	0 lm	38°	0 cd	3200 K	0	**min.**	0 lx	0 lx	0,0 W	0,0 VA	4 lx	0,3 W	4,6 VA	3 lx	0,3 W	2,3 VA	4 lx	0,5 W	5,2 VA	5 lx	1,0 W	5,3 VA	6 lx
							max.	285 lx	126 lx	0,0 W	0,0 VA	290 lx	5,3 W	10,0 VA	295 lx	5,4 W	8,8 VA	295 lx	5,4 W	10,9 VA	295 lx	5,5 W	8,6 VA	285 lx
							Range	2,3	0,0	0,0 W	0,0 VA	72,5	0,0 W	0,00 VA	98,3	0,0 W	0	73,8	0,0 W	0,00 VA	59,0	0,0 W	0	47,5
Megaman NN 27442	7,0 W	500 lm	35°	650 cd	2800 K	0	**min.**	0 lx	0 lx	0,0 W	0,0 VA	2 lx	0,8 W	6,7 VA	21 lx	0,3 W	2,2 VA	3 lx	0,5 W	5,7 VA	5 lx	0,6 W	2,7 VA	16 lx
							max.	179 lx	66 lx	0,0 W	0,0 VA	156 lx	8,2 W	13,8 VA	180 lx	8,3 W	17,7 VA	170 lx	5,4 W	10,9 VA	181 lx	8,3 W	12,8 VA	200 lx
							Range	2,7	0,0	0,0 W	0,0 VA	78,0	0,0 W	0,00 VA	8,6	0,0 W	0	56,7	0,0 W	0,00 VA	36,2	0,0 W	0	12,5
Sylvania RefLed Coolfit ES 50	5,5 W	345 lm	40°	0 cd	3000 K	0	**min.**	0 lx	0 lx	1,7 W	6,0 VA	14 lx	0,8 W	8,6 VA	7 lx	0,6 W	4,9 VA	10 lx	0,3 W	5,8 VA	1 lx	6,4 W	8,8 VA	16 lx
							max.	193 lx	108 lx	6,9 W	9,7 VA	199 lx	6,0 W	9,2 VA	200 lx	6,8 W	12,3 VA	200 lx	6,1 W	12,6 VA	200 lx	6,1 W	12,6 VA	200 lx
							Range	1,8	0,0	0,0 W	0,0 VA	14,2	0,0 W	0,00 VA	28,6	0,0 W	0	20,0	0,0 W	0,00 VA	200,0	0,0 W	0	12,5
Alibaba ULTRALED COB	6,0 W	0 lm	38°	0 cd	2900 K … 3100 K	0	**min.**	0 lx	0 lx	1,1 W	5,2 VA	15 lx	0,0 W	3,1 VA	0 lx	0,2 W	0,2 VA	10 lx	0,3 W	5,8 VA	0 lx	0,8 W	1,7 VA	26 lx
							25% E	0 lx	0 lx	0,0 W	0,0 VA	0 lx	1,2 W	4,6 VA	40 lx	0,0 W	0,0 VA	0 lx	0,0 W	0,0 VA	0 lx	0,0 W	0,0 VA	0 lx
							max.	160 lx	70 lx	7,0 W	8,8 VA	102 lx	6,0 W	9,2 VA	160 lx	3,9 W	5,4 VA	102 lx	6,2 W	8,5 VA	160 lx	6,2 W	6,8 VA	156 lx
							Range	2,3	0,0	0,0 W	0,0 VA	6,8	0,0 W	0,00 VA	∞	0,0 W	0	10,2	0,0 W	0,00 VA	∞	0,0 W	0	6,0
IsoLED 111711	6,0 W	290 lm	60°	0 cd	3200 K	85	**min.**	0 lx	0 lx	1,4 W	3,1 VA	19 lx	0,4 W	5,0 VA	18 lx	0,5 W	2,3 VA	16 lx	0,2 W	4,6 VA	5 lx	1,1 W	3,1 VA	34 lx
							max.	130 lx	54 lx	3,5 W	4,1 VA	95 lx	4,0 W	6,0 VA	132 lx	3,4 W	4,0 VA	107 lx	4,1 W	7,2 VA	134 lx	4,0 W	4,6 VA	127 lx
							Range	2,4	0,0	0,0 W	0,0 VA	5,0	0,0 W	0,00 VA	7,3	0,0 W	0	6,7	0,0 W	0,00 VA	26,8	0,0 W	0	3,7
IsoLED 112035	5,3 W	410 lm	70°	0 cd	2700 K	83	**min.**	0 lx	0 lx	1,5 W	3,1 VA	9 lx	0,4 W	4,8 VA	10 lx	0,4 W	2,0 VA	6 lx	0,2 W	4,7 VA	1 lx	1,1 W	3,1 VA	19 lx
							max.	108 lx	72 lx	5,1 W	5,4 VA	88 lx	5,6 W	6,9 VA	110 lx	4,7 W	5,1 VA	94 lx	5,6 W	8,0 VA	105 lx	5,5 W	5,7 VA	102 lx
							Range	1,5	0,0	0,0 W	0,0 VA	9,8	0,0 W	0,00 VA	11,0	0,0 W	0	15,7	0,0 W	0,00 VA	105,0	0,0 W	0	5,4
IsoLED 110082	5,0 W	340 lm	140°	0 cd	2800 K	85	**min.**	0 lx	0 lx	1,4 W	3,2 VA	6 lx	0,4 W	5,0 VA	7 lx	0,5 W	2,4 VA	6 lx	0,2 W	4,7 VA	3 lx	1,1 W	3,2 VA	12 lx
							max.	47 lx	38 lx	3,9 W	4,5 VA	35 lx	4,2 W	6,1 VA	46 lx	3,7 W	4,3 VA	40 lx	4,4 W	7,4 VA	47 lx	5,8 W	8,9 VA	44 lx
							Range	1,2	0,0	0,0 W	0,0 VA	5,8	0,0 W	0,00 VA	6,6	0,0 W	0	6,7	0,0 W	0,00 VA	15,7	0,0 W	0	3,7
LEDIMAX Spotlight LED	5,5 W	345 lm	36°	700 cd	3000 K	80	**min.**	0 lx	0 lx	0,0 W	0,0 VA	2 lx	0,7 W	6,3 VA	32 lx	0,4 W	3,0 VA	1 lx	0,2 W	5,3 VA	1 lx	1,7 W	6,5 VA	80 lx
							max.	240 lx	106 lx	0,0 W	0,0 VA	245 lx	5,8 W	10,4 VA	245 lx	6,1 W	13,8 VA	245 lx	5,8 W	11,9 VA	245 lx	5,8 W	8,9 VA	245 lx
							Range	2,3	0,0	0,0 W	0,0 VA	122,5	0,0 W	0,00 VA	7,7	0,0 W	0	245,0	0,0 W	0,00 VA	245,0	0,0 W	0	3,1
Philips Master LED Spot MV	5,5 W	350 lm	40°	0 cd	2700 K	0	**min.**	0 lx	0 lx	0,0 W	0,0 VA	1 lx	0,6 W	5,7 VA	30 lx	5,7 W	10,5 VA	1 lx	0,2 W	5,2 VA	0 lx	0,4 W	1,6 VA	1 lx
							max.	245 lx	98 lx	0,0 W	0,0 VA	240 lx	5,4 W	9,6 VA	245 lx	0,2 W	1,3 VA	245 lx	5,6 W	11,2 VA	245 lx	5,6 W	8,2 VA	235 lx
							Range	2,5	0,0	0,0 W	0,0 VA	240,0	0,0 W	0,00 VA	8,2	0,0 W	0	245,0	0,0 W	0,00 VA	∞	0,0 W	0	235,0

Table 4: Overview over the attempts from Switzerland in 2015 at dimming LED lamps [11]

- However, the new luminaire would not put up with the old leading phase angle control dimmer, flickering over a wide part of the dimming range. But fortunately, the manufacturer of the switch series had updated their products and now also offers a lagging phase angle control dimmer for the present models at reasonable prices – problem solved.
- Initially the light was perceived as not particularly satisfactory, since – independently of its colour temperature and colour rendering index ratings – it looked somewhat greenish. Though the LED module (Figure 38) could now be replaced with one of a different colour, so far this has not happened. You get used to quite a lot.

Hence, also in dimming technique a lot of deficiencies are still waiting to be dealt with (also see Section 6.6). In two major tests in Switzerland, a German and a Swiss author tried out the compatibilities and incompatibilities of various (plain and sophisticated) dimmers on various LED lamps specified as “dimmable” (Table 2, Table 4). The details were published in Switzerland [10; 11]. The following was noted as particularly remarkable (and in part listed in the tables):

- One lamp may perform unsatisfactorily on one dimmer but flawlessly on another one.
- Correspondingly, one lamp may function poorly on a specific dimmer, but another lamp may function fine on the same dimmer.
- For instance, in some combinations the lamps tend to flicker over a part of the dimming range.
- In some combinations, the dimming ranges are too narrow, while in others the dimming ranges are quite wide, ranging nearly down to zero.
- The dimming effect may also work unevenly, with negative effects on usability.
- Between the “net” measurements on dimmers without a neutral conductor connection (dimmers wired in series with the lamp) and those measurements on dimmers including a neutral conductor connection (where hence the inherent losses were included in the measurement result) no difference could be noted.
- In the lowest dimming position, the active power intake is generally very low, with systems capable of dimming down to 0 it is nearly equal to 0. In case the active power does not drop substantially, this also applies to the brightness (Table 2, column “Notes – lamp”).
- In extreme cases, however, a dimmed lamp may exhibit a higher input of harmonic reactive power than when undimmed (Table 2).
- In the inverse extreme, a lamp may exhibit lower (relative!) THD values than when not dimmed (Table 2).
- In the top dimming position, the power intake of the lamps more or less equals the rating throughout.
- From the five points last mentioned, it can be concluded that the power loss in the dimmer can generally be regarded as low. Usually it is below 1 W.

In either of the tests, both plain and sophisticated dimmers were included, for flush-mounted boxes or in switchboards, with revolving button or for remote control via analogue (e. g. 1…10 V) or digital (e. g. DALI) signals, as depicted in the tables.

During the second experiment (Table 4), 5 dimmers were tested on 10 lamps with GU10 sockets, including a compatible incandescent line voltage halogen lamp for comparison. Also the illuminances $E_{0°}$ at an altitude of 2.5 m vertically below the lamp and $E_{20°}$ at an angle of 20° off the vertical were measured. These two values yield (no more than) an impression of how precise the lighting angle ratings are – if any.

After all, the entire battery of tests would need to be repeated nearly every year, since the choice of LED lamps and dimmers changes very rapidly. However, a standard is still lacking about how a dimmer has to communicate with a lamp. In 2012 the company Osram tried to do so under the name “Ledotron” [12], but it is worrying how little you hear about it. In the meantime, we remain stuck with trial and error in each individual case. Osram themselves – or their outsourced LED subsidiary “Ledvance” – allege to see this differently [13], but Wikipedia does not know the term Ledotron. Not even the English language pages do. Why does nobody with Osram worldwide write a contribution? On top of this, a suspicious amount of reduced stock is for sale on the internet. This is unfortunate. The world would have needed a standard here that does make its way into practical application. But if you are expected to pay some 40 € for a so-called “energy saver lamp” (i.e. a CFL, not even an LED lamp), and about another 60 € for the dimmer, and the item is not even available, then any potential customer will hesitate. This may be due to the fact that Ledotron – contrary to what the name suggests – was meant more for the dimmability of CFLs, where this is even more difficult. The LED makes it simpler – and then, at some stage, one day it may work without a standard. Integrating the higher degree of sophistication for an obsolete technology into every dimmer is surely not very economical.

Dimming LED lamps for saving electrical energy, however, will hardly ever pay off in the residential sector – and it is rarely ever the real motivation. Rather, it is all about having enough light, but never too much light, depending on the respective situation (watching TV, cosiness). In the public sector, in offices, and industry, the dimmability of the LED is often promoted – but hardly ever utilized. There are good reasons for this, for the LED is already very efficient, and the investment will rarely ever pay off. Either light is needed and you switch it on, or it is not needed and you switch it off. Automating these processes suffices.

6 Energy and cost efficiency of LED lighting

White LEDs have an objective physical advantage over fluorescent lamps, because the discharge process in a fluorescent lamp generates pure UV radiation, which consequently has to be converted into visible radiation in total by the conversion or phosphor layer, and this process implies significant conversion losses (described by the term “conversion efficiency”). In contrast, LEDs start from blue light, so has to be only partially converted and not so far (e. g. only from blue to yellow) and which can, in part, be used directly. There used to be some cheating here initially by using more blue light directly than would have been ideal for a white mixture; hence the earlier often bluish tinge of cheaper (or rather “less expensive”) LED lamps. These initially achieved similar lighting efficacies as fluorescent lamps. Nowadays, LEDs prove superior to CFLs by 50% (Section 6.3). In bigger lamps, such as those used in industry and commerce, the difference levels out a bit.

6.1 EU regulations now…

The “eco-design requirements for non-directional household lamps” were regulated by the EU in 2009 [14], and in the beginning of 2013 “directional lamps, light emitting diode lamps and related equipment" followed [15]. In 2015 a few modifications were carried out [16]. The last tier of [16], which was to take effect on September 1, 2016 was postponed to September 1, 2018 (all other modifications are – in part unfortunately – not relevant for these considerations presented here). The last phase of [15] remained on schedule to go into effect on September 1, 2016. According to this, a requirement applies to household lamps with non-directional light and a rated luminous flux Φ between 60 lm and 12,000 lm, that their power intake P_{max} shall not be any greater than

$P_{max} = 0.8 * (0.88\sqrt{\Phi} + 0.049\ \Phi)$ for clear-glass lamps and

$P_{max} = 0.24\sqrt{\Phi} + 0.0103\ \Phi$ for frosted glass lamps.

Apparently, incandescent lamps have been the godfathers of this distinction; after all, this directive [14] dates back to 2009. Clearly, it was either not desired or not yet possible to close the market completely to clear, incandescent lamps, because alternative lamps with directional light were not sufficiently developed for all standard applications. With CFLs this is practically impossible, and the LED had not progressed so far at that time. The limit values for frosted lamps, however, are so stringent that they cannot be complied with by any incandescent lamp at all.

On September 1, 2018, the above factor 0.8 was reduced to 0.6. Thereby the very lenient values for clear lamps were restricted a bit; those for frosted lamps, being much stricter anyway, remain unaffected by this. A CFL is always considered a frosted lamp. An LED lamp is considered clear when the LED is "clearly visible." Theoretically, there is a loophole in this regulation. By covering an LED with a frosted glass, only the limit values targeting at incandescent lamps would apply, but in practice this is irrelevant because even the values allocated to LEDs in 2009 do not pose a real challenge.

According to directive [15], the maximum power intake P for directional LED lamps is calculated by way of a complicated process using the "useful luminous flux" Φ_{use} of the lamp, which is identical to the total luminous flux within a solid angle of 90°, on a detour via an energy efficiency index (EEI). The EEI should perhaps be called "inefficiency index", since a certain maximum value (of 0.2 for LEDs and fluorescent lamps since 2016) must not be exceeded. In the end, this results in a minimum requirement to the lighting efficacy of LED lamps of:

$P = 0.88\sqrt{\Phi_{use}} + 0.049\Phi_{use}$, if $\Phi_{use} < 1300$ lm, and

$P = 0.07341\Phi_{use}$, if $\Phi_{use} \geq 1300$ lm.

Remarkably, low power lamps (below 4 W) are exempted from the obligatory labelling. Earlier, you might have suspected yet another loophole here, since with LEDs, more than with other technologies, the power is often split across a great number of small lamps. This looks better, glares less, and facilitates heat dissipation. Hence, a substantial share of all household lamps are exempted from the obligatory labelling. On the other hand, such regulation would not really be very reasonable with such small lamps and their efficacies still exceed those of the replaced incandescent lamps by an order of magnitude even without regulation. Even the sensitivity against high temperatures of such small objects forces designers and developers to limit the heat loss. The idea to integrate a fan into the lamp instead has fortunately faded away in the meantime.

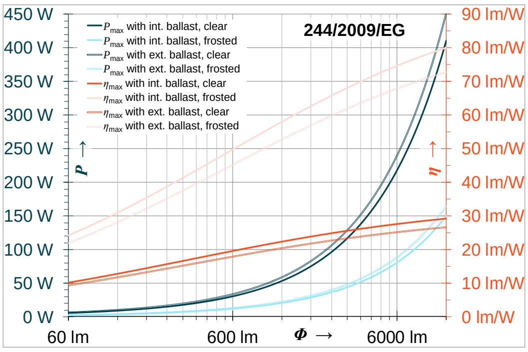


Figure 39: Minimum requirements for the lighting efficacy of non-directional household lamps according to EU Directive 244/2009/EG from September 1, 2018

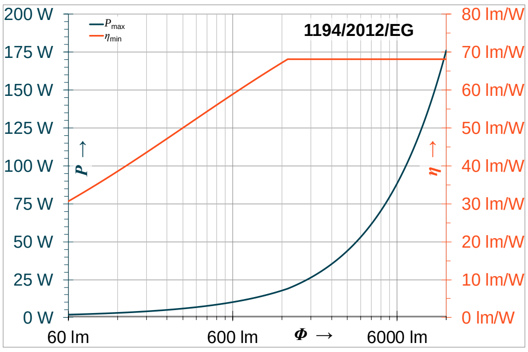


Figure 40: Minimum requirements for the lighting efficacy of directional household lamps according to EU Directive 1194/2012/EG

6.2 …and in the future…

Unfortunately, neither of the two cases has taken into account the fact that the quantity of LED light can always be increased by skimping on quality. The latest efforts of the EU are therefore to incorporate the colour rendering index in the efficiency formula in a way so that a better colour rendering permits a slightly lower light output. This change has been under discussion for several years now.

6.2.1 …on the lamp…

Finally, since July 2018, a suggestion by the EU commission is open for discussion to limit the power input P_{on} of any lamp from September 2021 onwards to

$$P_{\text{onmax}} = C\left(L + \frac{\phi_{\text{use}}}{F\eta}\right)R$$

with:

C	a correction factor (see Table 5),
η [lm/W]	the threshold efficacy,
F	the efficacy factor,
L [W]	the end loss factor,
R [lm/W]	the *CRI* factor,
Φ_{use}	the “useful luminous flux” (see above Section 6.1)

with:

F = 1 for non-directional light sources and

F = 0.85 for directional light sources,

R = 0.65 for $R_a \leq 25$ and

$$R = \frac{R_a + 80}{160}$$ for $R_a > 25$.

So there cannot be any more talk of “equal rights for all” and “the best technology shall win,” as initially planned, since different values are now given for η and L, depending on the light source technology. These range from

η = 70.2 lm/W for CFLs without integrated ballasts and for T8 lamps operated on magnetic ballasts up to

η = 120 lm/W for “other lamps not listed separately here” – including (all!) LED lamps – or from

L = 1.9 W for T5 lamps up to

L = 50 W for high-pressure sodium vapour lamps, respectively.

To LED lamps the following applies:

L = 1.5 W for “simple” lamps,

L = 2 W for IT-supported, i. e. remote controllable lamps (but which are not considered any further hereinafter).

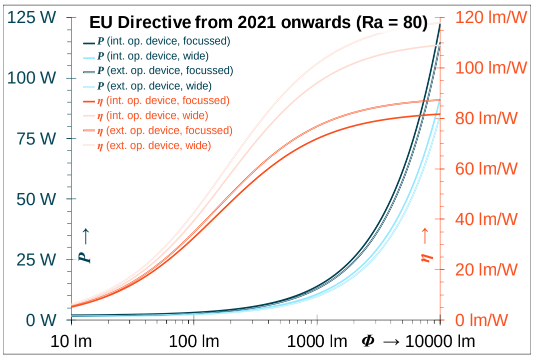


Figure 41: Draft for the planned EU regulation of LED lamp efficacies including the colour rendering index; calculated here for R_a = 80

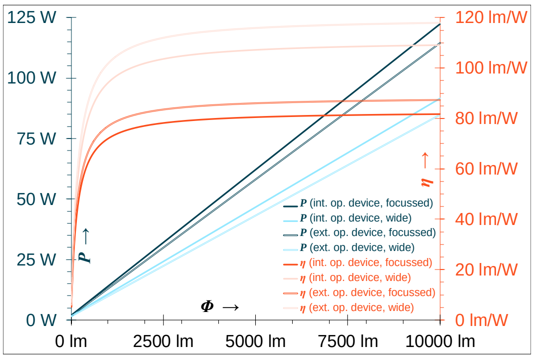


Figure 42: As in Figure 41, however in linear scale

This yields the curves of required lighting efficacies or the maximum permissible power intakes, respectively, against the useful luminous flux Φ_{use} for directional and non-directional LED lamps (Figure 41). Unlike earlier, there has been no talk of restricting the range of application e. g. for lamps between 60 lm and 12,000 lm. But particularly the linear plot provides the evidence that above a magnitude of about 4,000 lm (corresponding to a 58 W fluorescent T8 lamp) hardly any more change becomes noticeable. The maximum permissible power input increases practically linear to the light output here.

Table 5 lists the values to be used for calculating the correction factor C. The magnitude of the influence resulting from the colour rendering index R_a becomes ostensive from a selection of calculated values (Table 6). It also becomes evident here – as well as through another graph (Figure 43) – that what is pursued is anything but LED lobbying: If, for instance, the useful luminous flux Φ_{use} of a T8 fluorescent lamp operated on a magnetic ballast or of a CFL without integrated ballast equals 1,000 lm and the colour rendering index is R_a = 80, then the power consumption of the lamp alone (without the ballast) has to be $P_{onmax} \le 16.55$ W. Hence, the lighting efficacy must not fall below a value of $\eta_{min} = 60.4$ lm/W. The LED lamp, however, is conceded only 9.83 W, this meaning a required lighting efficacy of at least 106.7 lm/W. If it is unable to match this limit, it shall not be placed in operation. Instead, a fluorescent lamp may then be chosen which is still compliant – despite significantly poorer performance.

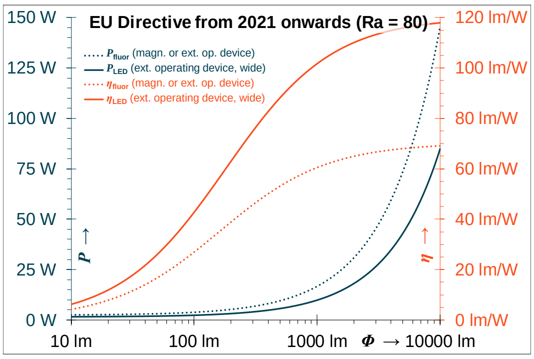


Figure 43: Comparison between planned lighting efficacy requirements of LED and fluorescent lamps, respectively (the requirements for T8 lamps with magnetic ballasts and those for CFLs without integrated ballasts are the same)

Correction factor C for EU Directive 2021		variable colour: no	variable colour: yes
Non-directional light sources	without integrated operating device	1.00	1.10
	with integrated operating device	1.08	1.18
Directional light sources	without integrated operating device	1.15	1.25
	with integrated operating device	1.23	1.33

Table 5: Values for the correction factor C (lamps with variable colour not considered in this article)

Minimum efficacies according to planned EU directive from 2021 onwards

R_a	Φ_{use}	LED lamps, integrated operating device, directional P_{onmax}	η_{min}	LED lamps, integrated operating device, non-directional P_{onmax}	η_{min}	LED lamps, external operating device, directional P_{onmax}	η_{min}	LED lamps, external operating device, non-directional P_{onmax}	η_{min}	Fluorescent lamps & magn. ballast / CFLs w/o int. ballast P_{onmax}	η_{min}
0	10 lm	1.28 W	7.8 lm/W	1.11 W	9.0 lm/W	1.19 W	8.4 lm/W	1.03 W	9.7 lm/W	1.59 W	6.3 lm/W
	100 lm	1.98 W	50.4 lm/W	1.64 W	61.1 lm/W	1.85 W	53.9 lm/W	1.52 W	65.9 lm/W	2.42 W	41.3 lm/W
	1000 lm	9.04 W	110.7 lm/W	6.90 W	144.9 lm/W	8.45 W	118.3 lm/W	6.39 W	156.5 lm/W	10.75 W	93.0 lm/W
	10000 lm	79.58 W	125.7 lm/W	59.55 W	167.9 lm/W	74.41 W	134.4 lm/W	55.14 W	181.4 lm/W	94.09 W	106.3 lm/W
60	10 lm	1.72 W	5.8 lm/W	1.50 W	6.7 lm/W	1.61 W	6.2 lm/W	1.39 W	7.2 lm/W	2.14 W	4.7 lm/W
	100 lm	2.67 W	37.5 lm/W	2.21 W	45.4 lm/W	2.50 W	40.1 lm/W	2.04 W	49.0 lm/W	3.26 W	30.7 lm/W
	1000 lm	12.17 W	82.2 lm/W	9.29 W	107.6 lm/W	11.37 W	87.9 lm/W	8.60 W	116.2 lm/W	14.48 W	69.1 lm/W
	10000 lm	107.13 W	93.3 lm/W	80.17 W	124.7 lm/W	100.16 W	99.8 lm/W	74.23 W	134.7 lm/W	126.66 W	79.0 lm/W
80	10 lm	1.97 W	5.1 lm/W	1.71 W	5.8 lm/W	1.84 W	5.4 lm/W	1.58 W	6.3 lm/W	2.44 W	4.1 lm/W
	100 lm	3.05 W	32.8 lm/W	2.52 W	39.7 lm/W	2.85 W	35.1 lm/W	2.33 W	42.9 lm/W	3.72 W	26.8 lm/W
	1000 lm	13.90 W	71.9 lm/W	10.62 W	94.2 lm/W	13.00 W	76.9 lm/W	9.83 W	101.7 lm/W	16.55 W	60.4 lm/W
	10000 lm	122.43 W	81.7 lm/W	91.62 W	109.1 lm/W	114.47 W	87.4 lm/W	84.83 W	117.9 lm/W	144.75 W	69.1 lm/W
100	10 lm	2.21 W	4.5 lm/W	1.92 W	5.2 lm/W	2.07 W	4.8 lm/W	1.78 W	5.6 lm/W	2.75 W	3.6 lm/W
	100 lm	3.43 W	29.1 lm/W	2.84 W	35.3 lm/W	3.21 W	31.2 lm/W	2.63 W	38.1 lm/W	4.19 W	23.9 lm/W
	1000 lm	15.64 W	63.9 lm/W	11.95 W	83.7 lm/W	14.62 W	68.4 lm/W	11.06 W	90.4 lm/W	18.61 W	53.7 lm/W
	10000 lm	137.74 W	72.6 lm/W	103.07 W	97.0 lm/W	128.78 W	77.7 lm/W	95.44 W	104.8 lm/W	162.84 W	61.4 lm/W

Table 6: A selection of limit values for the maximum power intake and the minimum lighting efficacy according to the planned EU directive from 2021 onwards

6.2.2 …and on the operating device

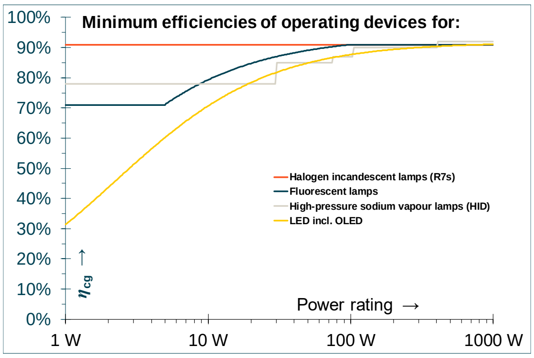


Figure 44: Foreseen minimum efficiencies of operationg devices for lamps

The efficiency η_{cg} of external control gear for LED and OLED lamps shall not exceed a value of

$$\eta_{cg} = \frac{P_{cg}^{0.81}}{1.09 P_{cg}^{0.81} + 2.1}$$

depending on the nominal output power P_{cg}. These limit values are set differently for other lighting systems (Figure 44). It is pleasant to see, however, that for operating fluorescent lamps a distinction between electronic and magnetic ballasts is no longer made. It is displeasing to see that certain types of halogen incandescent lamps will still be in the market after 2021!

6.3 And the winner is: The LED!

A 2012 catalogue data comparison of various lamps by the three leading manufacturers Osram, Philips, and Megaman showed that the CFLs of that time exhibited a mean lighting efficacy of 65 lm/W, the LED lamps in contrast only 61 lm/W (incandescent lamps just a sparse 18 lm/W) [17]. That survey, however, did not calculate the arithmetic mean of all the lighting efficacies, but instead the sum of all light outputs was divided by the sum of all line power ratings, so that the strongest lamp with 100 W (6700 lm) was in fact weighted 50 times as strong as the weakest lamp with 2 W (100 lm). After all, the biggest lamp supplies over 50 times more light than the smallest one and thus provides – so to say – an accordingly greater contribution to the lighting market.

Repeating such a survey today is somewhat cumbersome as finding a representative selection of fluorescent lamps is difficult. A new list (Table 7) will contain some models still found on the internet that are either sold out or are no longer being produced (Figure 61).

Since incandescent lamps were not excluded from the competition, they also appear in the table. They are still available for purchase often as residual stock and at 50% off the original price (Figure 60). With the inclusion of incandescent lamps, the bottom line looks accordingly sad (Table 9). The figures in red are, as far as possible, the weighted average: For instance, the 2,000 W lamp contributed 40,000 lm to the sum of 81,722 lm and is accordingly more strongly represented in the mean of 18 lm/W than the 7 W lamp, which contributed only 42 lm. The red-brown values, however, only represent the arithmetic means of the respective columns.

	Selected example lamps				Price		Rated	Costs (constant duty)		
	Type	*P*	*Φ*	*η*	abs.	rel.	lifetime	Lamp	Energy	total
CFL E27 with integrated ballast (except)	Megaman Candlelight Mini (E14)	3 W	75 lm	25 lm/W	2,25 €	30,00 €/klm	10000 h	1,97 €/a	7,85 €/a	9,82 €/a
	Osram Lumilux (T5, no ballast)	4 W	140 lm	35 lm/W	1,45 €	10,36 €/klm	8000 h	1,59 €/a	10,47 €/a	12,06 €/a
	Megaman HELIX MM28006	5 W	270 lm	54 lm/W	2,89 €	10,70 €/klm	10000 h	2,53 €/a	13,09 €/a	15,62 €/a
	Philips TL Mini (T5, no ballast)	6 W	260 lm	43 lm/W	1,40 €	5,38 €/klm	10000 h	1,23 €/a	15,70 €/a	16,93 €/a
	Osram Dulux Twist	7 W	350 lm	50 lm/W	7,60 €	21,71 €/klm	12000 h	5,55 €/a	18,32 €/a	23,87 €/a
	Sylvania Mini-Lynx	8 W	450 lm	56 lm/W	3,26 €	7,24 €/klm	6000 h	4,76 €/a	20,94 €/a	25,70 €/a
	Osram DSST CL P	9 W	430 lm	48 lm/W	7,00 €	16,28 €/klm	10000 h	6,13 €/a	23,56 €/a	29,69 €/a
	Philips Genie ESaver	11 W	600 lm	55 lm/W	4,99 €	8,32 €/klm	8000 h	5,46 €/a	28,79 €/a	34,26 €/a
	Osram Dulux Twist	12 W	660 lm	55 lm/W	3,19 €	4,83 €/klm	10000 h	2,79 €/a	31,41 €/a	34,20 €/a
	Megaman MM33110	15 W	950 lm	63 lm/W	8,69 €	9,15 €/klm	15000 h	5,07 €/a	39,26 €/a	44,34 €/a
	Megaman MM01612	18 W	1151 lm	64 lm/W	3,90 €	3,39 €/klm	15000 h	2,28 €/a	47,11 €/a	49,39 €/a
	Osram Dulux Twist	20 W	1300 lm	65 lm/W	4,90 €	3,77 €/klm	10000 h	4,29 €/a	52,35 €/a	56,64 €/a
	Osram Dulux Twist	23 W	1600 lm	70 lm/W	12,90 €	8,06 €/klm	10000 h	11,30 €/a	60,20 €/a	71,50 €/a
	Calex Art.-Nr. 576490	24 W	1450 lm	60 lm/W	6,12 €	4,22 €/klm	10000 h	5,36 €/a	62,82 €/a	68,18 €/a
	Megaman MM30304	30 W	1900 lm	63 lm/W	6,65 €	3,50 €/klm	10000 h	5,83 €/a	78,52 €/a	84,35 €/a
	Osram Lumilux (no ballast)	40 W	3325 lm	83 lm/W	8,20 €	2,47 €/klm	12000 h	5,99 €/a	104,70 €/a	110,69 €/a
	Philips Essential	50 W	3100 lm	62 lm/W	29,99 €	9,67 €/klm	8000 h	32,84 €/a	130,87 €/a	163,71 €/a
	Philips Tornado	65 W	4125 lm	63 lm/W	21,37 €	5,18 €/klm	10000 h	18,72 €/a	170,14 €/a	188,86 €/a
	Sum / mean (weighted)	**350 W**	**22136 lm**	**63 lm/W**	**136,75 €**	**6,18 €/klm**	**10222 h**	**6,87 €/a**	**50,90 €/a**	**57,77 €/a**

Table 7: Sample from January 2018 from the market for CFLs with E27 socket and integrated ballast (where available; exemptions marked in colour)

If the survey were repeated today, the fluorescent lamps results would be nearly the same as they were then (Table 7), but it becomes evident that the LEDs have caught up quite a bit (Table 8)! Unlike the earlier overview, the prices and the lifetime expectancies are included. Now these three compilations based on manufacturers' indications do not raise any scientific claim of neutrality, comparability, statistical relevance, let alone completeness, but rather want to instigate readers to carry out their own, more thorough, investigations. Whatever was meant by "lifetime" in the respective cases (Section 44) was not questioned here, and the same items are offered in other places at totally different prices, of course – once including, once excluding VAT. Yet, the compilation provides a rough overview leading to the following insights:

	Selected example lamps				Price		Rated	Costs (constant duty)		
	Type	*P*	*Φ*	*η*	abs.	rel.	lifetime	Lamp	Energy	total
LED lamps E27 with integrated ballast	EGB LED drop-shaped lamp	0,65 W	32 lm	49 lm/W	7,50 €	234,38 €/klm	35000 h	1,88 €/a	1,70 €/a	3,58 €/a
	Eiko EAN 4260420260552	1,00 W	90 lm	90 lm/W	3,98 €	44,22 €/klm	10000 h	3,49 €/a	2,62 €/a	6,10 €/a
	Osram LED RF CLASSIC P 25	2,00 W	230 lm	115 lm/W	2,91 €	12,65 €/klm	15000 h	1,70 €/a	5,23 €/a	6,93 €/a
	Bioledex Tema	3,00 W	250 lm	83 lm/W	1,39 €	5,56 €/klm	50000 h	0,24 €/a	7,85 €/a	8,10 €/a
	Philips LEDclassic	4,00 W	470 lm	118 lm/W	4,99 €	10,62 €/klm	15000 h	2,91 €/a	10,47 €/a	13,38 €/a
	Osram LED Star Classic A 40	5,50 W	470 lm	85 lm/W	2,51 €	5,34 €/klm	15000 h	1,47 €/a	14,40 €/a	15,86 €/a
	Philips LED classic A60	7,00 W	806 lm	115 lm/W	3,05 €	3,78 €/klm	15000 h	1,78 €/a	18,32 €/a	20,10 €/a
	Philips CorePro LEDbulb	8,50 W	806 lm	95 lm/W	4,46 €	5,53 €/klm	15000 h	2,60 €/a	22,25 €/a	24,85 €/a
	Osram LED Star Classic A 75	11,00 W	1060 lm	96 lm/W	4,05 €	3,82 €/klm	15000 h	2,37 €/a	28,79 €/a	31,16 €/a
	Philips LED A60	13,00 W	1521 lm	117 lm/W	4,26 €	2,80 €/klm	15000 h	2,49 €/a	34,03 €/a	36,52 €/a
	Philips LED-TL	15,00 W	1521 lm	101 lm/W	7,45 €	4,90 €/klm	15000 h	4,35 €/a	39,26 €/a	43,61 €/a
	Müller Licht item No. 400346	20,00 W	2450 lm	123 lm/W	9,90 €	4,04 €/klm	15000 h	5,78 €/a	52,35 €/a	58,13 €/a
	Kwazar luminaire LED 4U CORN	23,00 W	1920 lm	83 lm/W	11,00 €	5,73 €/klm	25000 h	3,85 €/a	60,20 €/a	64,06 €/a
	Liqoo LED corn bulb	30,00 W	3000 lm	100 lm/W	21,99 €	7,33 €/klm	30000 h	6,42 €/a	78,52 €/a	84,95 €/a
	MHtech LED corn bulb	35,00 W	3000 lm	86 lm/W	25,99 €	8,66 €/klm	35000 h	6,50 €/a	91,61 €/a	98,12 €/a
	Bonlux LED studio lamp	40,00 W	3650 lm	91 lm/W	18,66 €	5,11 €/klm	35000 h	4,67 €/a	104,70 €/a	109,37 €/a
	Die Glühbirne 5630 SMD corn	50,00 W	4600 lm	92 lm/W	15,74 €	3,42 €/klm	20000 h	6,89 €/a	130,87 €/a	137,77 €/a
	eSavebulbs LED corn bulb	65,00 W	6500 lm	100 lm/W	34,99 €	5,38 €/klm	50000 h	6,13 €/a	170,14 €/a	176,27 €/a
	Sum / mean (weighted)	**333,65 W**	**32376 lm**	**97 lm/W**	**184,82 €**	**5,71 €/klm**	**23611 h**	**3,64 €/a**	**48,52 €/a**	**52,16 €/a**

Table 8: January 2018 sample from the market for LED lamps with E27 socket and integrated operating device (note: Power ratings even come with decimals here!)

- 1,000 lm of fluorescent light cost about 6.20 €.
- 1,000 lm LED light, however, cost only about 5.70 € nowadays!

- 1,000 lm of incandescent light comes in at only about 0.70 €.

This includes the purchase prices of the lamps only. Interestingly, the LEDs surpass their predecessors even in this point! But the calculations appear as following when one includes the electricity costs (household tariff) and the lifetime expectancies of the lamps:

- 1,000 lm of permanent fluorescent light for 1 year costs about 41 € for electricity and 6 € lamp wear. The lamp is nearly used up afterwards.
- 1,000 lm of permanent LED light for 1 year costs about 27 € for electricity and only 2 € lamp wear. The lamp is far from exceeding its expected usable life.
- 1,000 lm of permanent incandescent light for 1 year costs about 142 € for electricity and 5 € for lamp wear. The lamp has to be replaced between 4 and 8 times during this period.

This makes any further comment appear superfluous; the figures speak for themselves. Only commercial applications in trade and industry will be addressed where electricity is available at 20 ct/kWh or 10 ct/kWh, respectively, instead of 30 ct/kWh, as in a private household. The calculated values shift accordingly, but the balance remains:

E27 incandescent lamps (except)	Selected example lamps				Price		Rated	Costs (constant duty)		
	Type	***P***	***Φ***	***η***	**abs.**	**rel.**	**lifetime**	**Lamp**	**Energy**	**total**
	General purpose lamp (E14)	7 W	42 lm	6 lm/W	7,98 €	190,00 €/klm	1000 h	69,90 €/a	18,32 €/a	88,23 €/a
	General purpose lamp	15 W	120 lm	8 lm/W	0,80 €	6,65 €/klm	1000 h	6,99 €/a	39,26 €/a	46,25 €/a
	General purpose lamp clear	20 W	235 lm	12 lm/W	2,90 €	12,34 €/klm	2000 h	12,70 €/a	52,35 €/a	65,05 €/a
	General purpose lamp	25 W	220 lm	9 lm/W	1,10 €	5,00 €/klm	1000 h	9,63 €/a	65,44 €/a	75,06 €/a
	General halogen lamp clear	30 W	405 lm	14 lm/W	2,90 €	7,16 €/klm	2000 h	12,70 €/a	78,52 €/a	91,23 €/a
	General halogen lamp clear	40 W	420 lm	11 lm/W	0,90 €	2,14 €/klm	1000 h	7,88 €/a	104,70 €/a	112,58 €/a
	General halogen lamp clear	46 W	700 lm	15 lm/W	2,90 €	4,14 €/klm	2000 h	12,70 €/a	120,40 €/a	133,11 €/a
	General halogen lamp clear	57 W	915 lm	16 lm/W	2,90 €	3,17 €/klm	2000 h	12,70 €/a	149,20 €/a	161,90 €/a
	Allgebrauchs-Glühlampe klar	60 W	710 lm	12 lm/W	0,90 €	1,27 €/klm	1000 h	7,88 €/a	157,05 €/a	164,93 €/a
	General purpose lamp	75 W	940 lm	13 lm/W	0,90 €	0,96 €/klm	1000 h	7,88 €/a	196,31 €/a	204,20 €/a
	General halogen lamp clear	77 W	1320 lm	17 lm/W	1,90 €	1,44 €/klm	2000 h	8,32 €/a	201,55 €/a	209,87 €/a
	General purpose lamp	100 W	1360 lm	14 lm/W	0,90 €	0,66 €/klm	1000 h	7,88 €/a	261,75 €/a	269,63 €/a
	General halogen lamp clear	116 W	2135 lm	18 lm/W	3,90 €	1,83 €/klm	2000 h	17,08 €/a	303,63 €/a	320,71 €/a
	General purpose lamp	150 W	2160 lm	14 lm/W	5,95 €	2,75 €/klm	1000 h	52,12 €/a	392,62 €/a	444,75 €/a
	General purpose lamp	200 W	3040 lm	15 lm/W	5,90 €	1,94 €/klm	1000 h	51,68 €/a	523,50 €/a	575,18 €/a
	Halogen ceiling floodlight (R7s)	400 W	9000 lm	23 lm/W	4,49 €	0,50 €/klm	2000 h	19,67 €/a	1047,00 €/a	1066,66 €/a
	Halogen ceiling floodlight (R7s)	1000 W	18000 lm	18 lm/W	5,59 €	0,31 €/klm	1000 h	48,97 €/a	2617,49 €/a	2666,46 €/a
	Halogen ceiling floodlight (R7s)	2000 W	40000 lm	20 lm/W	8,32 €	0,21 €/klm	2000 h	36,44 €/a	5234,98 €/a	5271,42 €/a
	Sum / mean (weighted)	**4418 W**	**81722 lm**	**18 lm/W**	**61,13 €**	**0,75 €/klm**	**1444 h**	**22,40 €/a**	**642,45 €/a**	**664,85 €/a**

Table 9: January 2018 sample from the market for incandescent lamps with E27 (as far as could be found; exceptions marked with colour)

- The energy consumption by far dominates the total operating costs. This is why the LED is leading here.
- Cases in which lamp replacement comes with considerable effort, also point in the same direction, because coincidentally the lamps with the highest lighting efficacy are the same as those providing the highest longevity: The LED again.
- The term “fluorescent lamps” was selected deliberately here, since the traditional linear fluorescent lamps could be included. Quite roughly, the power ratings have the same ratio between the lifetime expectancies, luminous fluxes, and prices as the compact lamps.

Summarized prices from a sample of 18 lamps each						
Time	CFL		LED		Incand. lamps	
	abs.	rel.	abs.	rel.	abs.	rel.
Jan. 2018	136,75 €	6,18 €/klm	184,82 €	5,71 €/klm	61,13 €	0,75 €/klm
Jan. 2019	109,09 €	5,10 €/klm	154,52 €	4,77 €/klm	28,38 €	0,35 €/klm

Table 10: Once again the results from Table 7 through Table 9, summarized here in comparison to the results of the same market survey done one year earlier

6.4 Integrated luminaires with non-replaceable LED modules

The LED frequently also exhibits its good energy efficiency in a rather indirect manner. For instance, powerful spot and flood lights used to be equipped with energy-guzzling incandescent halogen lamps. In outdoor applications, these luminaires were often controlled via motion sensors, by which measure the high power intake did not have such a detrimental effect upon the electricity bill. Also, there was a lack of alternatives: Designing spot and flood lights with CFLs was virtually impossible, and in cold environments their light output dropped considerably. Discharge lamps take several minutes to provide a reasonable light output and are hence practically out of the question for such applications. So what to do? Use LEDs! The LED module can be manufactured with the desired lighting angle right from the start. Whether the reflector (Figure 45) is needed at all is doubtful. More likely than not, it serves as a carrier for the heat sink design (Figure 46) – which is indispensable for the longevity of the electronic circuitry and particularly of the LEDs. After all, even such an efficient lamp still needs to get rid of more than half of the 50 W power intake as heat.

Figure 45: LED floodlight for outdoor applications; manufacturer ratings: 50 W, 4,000 lm, colour temperature 4,800 K … 5,500 K, lighting angle 120°, lifetime expectancy 50,000 h, voltage range 100 V … 277 V, 3 years warranty …

Figure 46: … hence has a lighting efficacy of 80 lm/W (like a fluorescent lamp of this power range) and requires rampant use of cooling fins in order to achieve the rated lifetime (which substantially exceeds that of a fluorescent lamp)

6.5 Lamps with external operating devices

On LED lamps with external operating devices the power intake P_{max} measured at the lamp must be 10% lower than on LED lamps with integrated operating devices, whose losses are inevitably included in the measurement. At least this applies when the light switch is located between the luminaire and the operating device [15] (in future the efficiencies of external operating devices shall be measured separately and made dependent on their power ratings – Figure 44). This is particularly reasonable when the lighting installation is designed to be dimmable. This is because, as a tendency, an LED can be dimmed theoretically down to zero without a major loss in its typical inherent efficacy. In practice, it still achieves an efficacy in the same order of magnitude as around the rated point of operation even when operated significantly below 1% of its rated power, as could be shown during measurements on an LED panel (Figure 47). The relative values of voltage, current, luminous flux, luminous efficacy and – informatively – also of the differential resistance (LED characteristics) were recorded there: Obviously this luminaire in fact incorporates only the LEDs and no electronic gear or serial resistors – which should basically be the purpose of the dedicated separate operating device supplied along with the luminaire.

6.6 Efficient dimming

The latter, in its own right, is rated as “not dimmable,” but when operated on an alternative DC source instead (to be taken literally: a laboratory power supply unit with stabilized output current) it is found that the luminaire alone could be dimmed excellently when operated on an adequate power source (Figure 48).

Had the solution for the attenuation of light output by means of a serial resistor, as implemented e. g. with The Three Magi (Figure 20, Figure 21), been transferred to halogen incandescent lamps, then quite a powerful resistor would have become necessary. “Powerful” in this context, again, designates the ability to absorb quite a bit of precious, expensive electrical power as heat. Adding to this is a property of the incandescent lamp; its resistance drops as temperature drops, so that the “heating share”, i. e. the voltage drop across the resistor, increases over-proportionally. With the LED, due to its characteristics (Figure 24, Figure 47), the effect is just the inverse: The voltage drop across the lamp becomes insignificantly smaller, even when the current is reduced to just a fraction; the voltage drop across the resistor is accordingly low. In addition, the current rating of the LED is already very much smaller than that of an incandescent lamp it replaces.

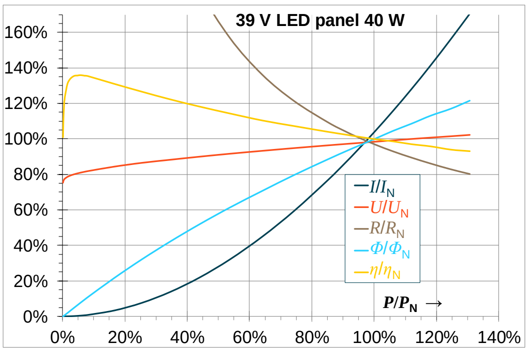


Figure 47: Measurement on an LED panel after the external power supply

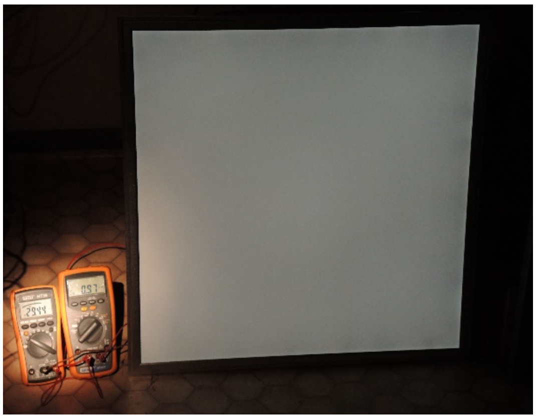


Figure 48: LED panel – not dimmable according to the manufacturer, but when fed with 1 mA instead of 1 A still vislibly lighting!

Similarly, the basement room (Figure 22) was equipped with a commonplace leading phase-angle control dimmer. The lamps were fed via three conventional halogen lamp-transformers – correctly wired after the dimmer than before. Hence, no idle or stand-by consumption arises anywhere when the lights are switched off. This could all be left as it was; the dimmable LED spotlights 12 V 7 W functioned flawlessly. It would have been optimal to have toroidal core transformers in place, but the usually high iron loss of the laminated core transformers is reduced substantially by dimming and becomes negligible compared to the savings achieved, particularly in dimmed mode.

6.7 Rebound-effect?

When any energy efficiency measure has successfully been carried out, the so-called rebound-effect often raises some concern. This means that the improved efficiency instigates an enhancement of use and hence makes the savings void again – if not completely, then at least in part. Indeed, one of the weak points raising complaints about LED retrofit lamps, meant for household purposes, was that they were, literally speaking, too weak. LED lamps rated 1 W to 2 W turned out unable to replace commonplace incandescent lamps of 25 W, 35 W, 50 W or 60 W. Soon, however, the tables turned, and nowadays it is the other way around: Some things are lit so brightly that you may sometimes wonder, “Now is this really necessary?”

Particularly in decorative lighting the beauty to be highlighted is lighted too high. For instance, the purchaser of a Christmas reindeer complained about way too much brightness (Figure 50). The animal was fed with 24 V and 12 W from a DC power supply unit. Good gracious, this would match a former 100 W incandescent light bulb! Earlier this would have lighted a whole living room, not really matching named customer’s intent.

Figure 49: Christmas - decoration with affluent lighting

Again, thanks to “SELV” – Safe Extra-Low Voltage – a “DIY solution” could do the job. The brightness was meant to be lowered considerably. A serial resistor appears as the most straightforward approach. Thanks to the characteristics of the LED (Figure 25), the subsequent additional losses are very limited; this is not the point where the rebound-effect strikes. But what will happen, should the reindeer ever suffer a short-circuit? In the worst case all of the 12 W power would be converted to heat inside the resistor – a precarious situation!

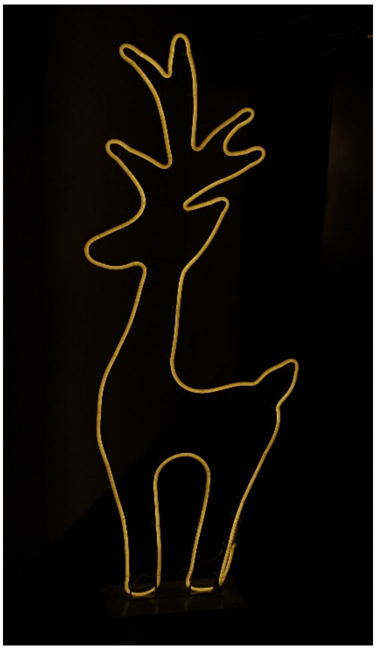


Figure 50: The Die Christmas - decoration from Figure 50 – flood of light attenuated with “DIY means”

Therefore, a small 6 V light bulb was used as a serial resistor. Its positive temperature coefficient is more suitable for this purpose anyway rather than a classical ohmic resistor. In regular operation at the new “reindeer operation point” thus found (at just about 20% of the rated power – Figure 51), the incandescent serial bulb just glows with a voltage drop around 2.5 V; 21.5 V remaining left for the LED. But in the case of a reindeer short-circuit the bulb would blow and thus act as a fuse. Christmas mood saved – and some electrical energy on top of this.

But you may still complain about a rebound-effect in so far as the extremely low energy demand of LEDs, together with their other advantages, facilitate their use particularly in decorative lighting with “throwaway” batteries in places where, so long, this would have been considered only with mains power or not at all. It can only be recommended here to replace the primary cells with accumulator batteries in the corresponding applications (Section 3.5; Figure 19).

7 Network repercussions of LED lamps

It is somewhat confusing that discussions regarding harmonic and inrush currents of LED lamps are cropping up now. Yes, LEDs are new and just about to crowd our low voltage grids, but the front ends of the electronic operating devices – be they external or integrated – are not distinguished from those of CFLs nor from most other electronic appliances. Their network repercussions have been described in detail already [18], for which reason a short summary shall suffice at this point.

7.1 Harmonics

Therefore it is assumed that the reader is familiar with harmonics. As described [18], really meaningful limit values for harmonic currents of lamps start to take effect only at power ratings above 25 W [19], per individual lamp. Let’s have a look at the possible network repercussions.

7.1.1 Single-phase

In the range up to 25 W the limit values for the maximum permissible distortion (deviations from the sine wave given by the line voltage, i. e. current harmonics) are pretty generous, so that the lamp manufacturer will probably not have to integrate any remedial measures. Like most other electronic devices of their power rating range, they are usually equipped with a front end starting with a rectifier bridge and a smoothing capacitor. This leads to the periodic current peaks, always occurring shortly before each voltage peak when the capacitor is being recharged, and to two breaks of the current flow during the rest of the time when the residual voltage amplitude across the capacitor falls below the instantaneous value of the rectified AC line voltage. Typically, the current curves then look like those shown in Figure 49.

Now many grains pile up a heap. Because quite a few of such “grains” are permanently connected to the mains, the line voltage, along with the current, is already distorted as well. A further consequence is that the TRMS input current into a device fed in such a manner is significantly greater than the active current, usually about double the amplitude. Hence, a 3 W lamp has an apparent power intake of about 6 VA. This is only to a lesser extent due to a phase shift of the fundamental current against the applied voltage, i.e. fundamental reactive power, although these lamps do exhibit a slightly capacitive behaviour throughout: You see in

Figure 49, for instance, that the current peak slightly leads the voltage peak. The greater share of the effect, however, is caused by the reactive power Q_v (also designated as D), i. e. by the current harmonics, representing yet another species of reactive power. Table 11 gives an overview of the most significant harmonics h in the input current to the lamp (and of the feeding line voltage at the instance of measurement):

Line voltage	U = 230.0 V,
TRMS current	I = 22.9 mA,
Fundamental current	I_1 = 13.2 mA,
Active power (measured)	P = 2.87 W,
Apparent power	S = 5.17 VA,
Fundamental apparent power	S_1 = 3.04 VA,
Fundamental reactive power	Q_1 = 0.98 VA,
Harmonic reactive power	$Q_v = D$ = 4.19 VA,
Displacement power factor	$cos\varphi$ = 0.947,
Total power factor	λ = 0.556.

Harmonics of an LED lamp Osram 3 W		
h	U	I_L
1	230,0V	13,2mA
3	1,9V	11,6mA
5	1,1V	9,3mA
7	2,8V	6,4mA
9	0,8V	4,2mA
11	0,4V	3,5mA
13	0,1V	3,4mA
15	0,3V	3,3mA
17	0,2V	2,8mA
19	0,1V	2,5mA
21	0,4V	2,2mA
23	0,1V	2,2mA
	230,0V	**22,9mA**

Table 11: Harmonic currents of the lamp in Figure 49

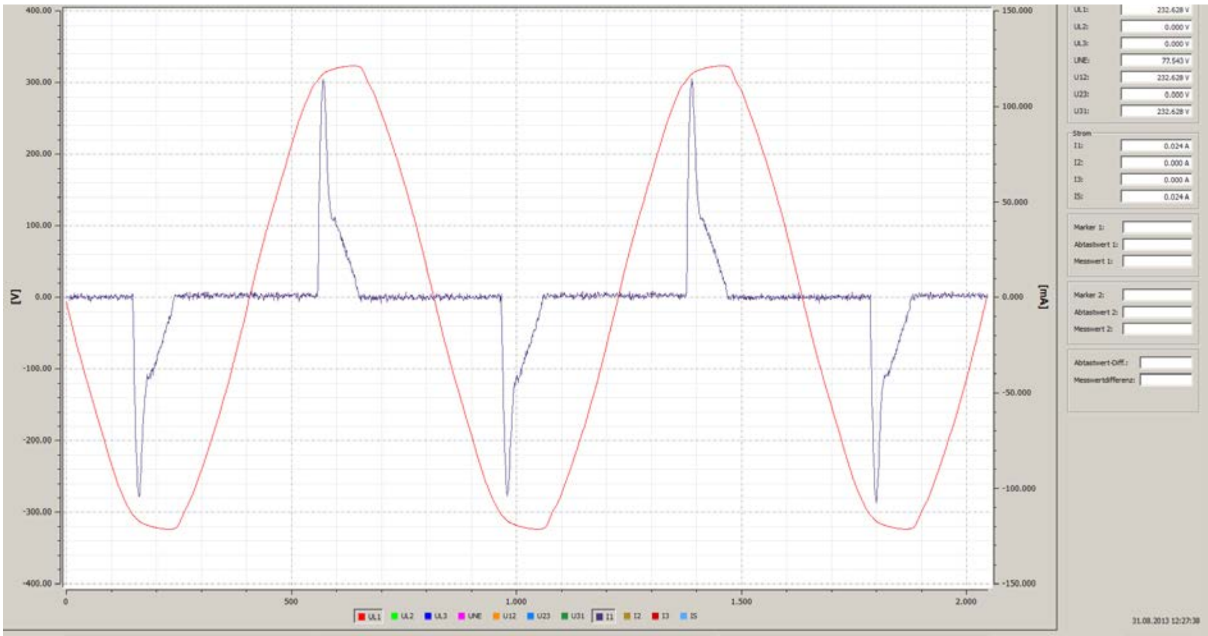


Figure 51: Typical input current into a small LED lamp 3 W

The conductors are loaded accordingly higher, i.e. at 5.17 VA, in order to transfer 2.87 W to the lamp in the above example. Earlier, however, 50 VA had to be transmitted at this point in order to transfer 50 W to the respective incandescent lamp.

7.1.2 Three-phase

But if three such loads (Figure 50, Figure 51) – or rather complete groups of these, respectively – are operated now between each one of the line conductors and the neutral conductor of the three-phase system, then the situation described many times before occurs where, despite a balanced distribution of the loads across the phases, the return currents do not necessarily cancel out in the neutral conductor, but rather the opposite. In the following example the conductive angle of the individual load is less than 60°, so that there is no mutual overlap between any two of the three line currents at all. Consequently, no outgoing and returning currents can cancel each other out, and a neutral conductor current arises, the absolute arithmetic mean value of which may be 3 times as great as each of the phase currents. The TRMS value may still rise up to √3 times that value (Figure 52).

What will happen if you interrupt the neutral conductor, which appears to be more important than any of the phase conductors? After all, we are not dealing with a classical imbalance here. Let's put the system to the test (Figure 53). The "PQ-Box 200" by A. Eberle employed here [20] provides the opportunity to record the voltage between the neutral and protective conductors, which is required to trace EMC problems in today's systems. In this situation this feature could be used to record the voltage between the existing star point of the system and the new one among the three lamps: The newly formed star connection is still somehow located in the middle, however not at all at rest. It leaps around somewhat like a hexagon – and even so in a stochastic manner in an irregular hexagon because we are dealing with electronic loads here which incalculably do just anything. The peaks of the voltage between the two neutral points reach an amplitude of 145 V!

Under such circumstances, voltage and current curves across the loads prove to be very discontinuous (Figure 53). Amazingly, two of the three lamps function properly and one flickers. It is uncertain, however, for how long the lamps will endure this state of operation.

Figure 52: Measurement samples for the test

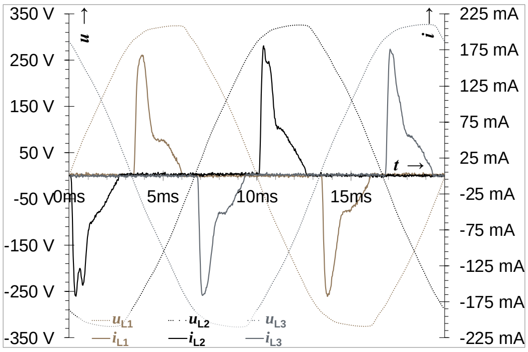


Figure 53: Three LED lamps of plain design (Figure 59) in three-phase operation – displayed here without neutral conductor current for better overview

After switching off one lamp, i.e. interrupting one line conductor, the remaining two lamps also start to flicker – although in theory each of them would still be supplied with a sufficient 200 V. A single-phase test comparison on a variable transformer shows: One lamp alone starts flickering below 36 V, and from 75 V onwards it even burns at full power! So, the malfunction can be traced back solely to the serial operation of two lamps, not to the voltage being 15%

too low on each lamp with two lamps in series on 400 V. That's electronics for you: Sometimes you might think the principles of electrical engineering don't apply as soon as you add some electronics.

The observed behaviour is confirmed when viewing the curves of the *TRMS values* over the duration of the test (Figure 54) instead of the curves of *instantaneous values* over one period or a few periods (Figure 51 to Figure 53):

- As soon as the neutral conductor current is interrupted, the line conductor currents increase. A cross-check calculation reveals only an insignificant increase of active power intake from 5 W to 5.5 W per lamp. The significant increase of current TRMS (of the form factor) traces back to the distortion of current curves having become **even greater** than before.
- The voltage distributes extremely unevenly across the three supposedly equal lamps.
- The TRMS values of the line currents become much more discontinuous as soon as the neutral conductor is missing.
- The voltage between the two star points (of the mains and of the load) is substantial, as noted before.

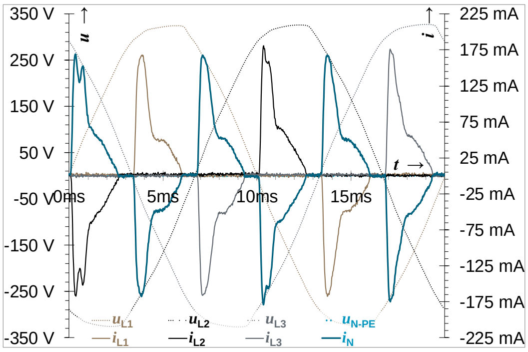


*Figure 54: The same recording as in Figure 51, but here with neutral current included: 3 * 2 peaks per line conductor makes 6 peaks in the neutral conductor, subsequently with a frequency of 150 Hz*

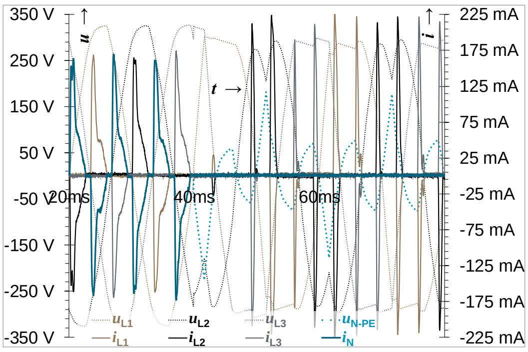


Figure 55: After 40 ms the (relatively) highly loaded neutral conductor was interrupted

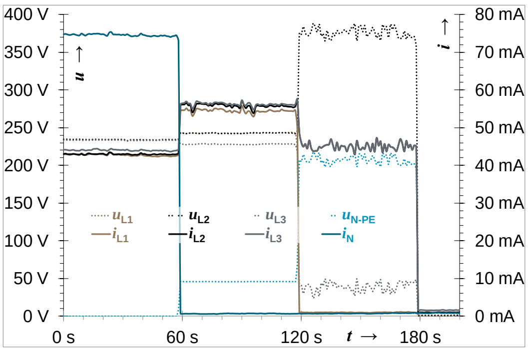


Figure 56: Operation of the lamps according to Figure 50 on three phases – after 60 s interruption of the neutral conductor and after 120 s switching off one lamp (abortion of measurement after 180 s)

7.1.3 Overheated neutral line?

It remains to be considered, however, that e.g. German standards [21] continue to give limit values of current carrying capabilities for maximum three loaded conductors in three-phase cables. The situation that under harmonic loads also four conductors may have to carry load currents simultaneously remains unmentioned. The (no longer quite) new supplement No. 3 [22] tries to close this gap, giving hints and reference values for practically occurring scenarios. One of the difficulties with this is that the standardisation process is quite slow and tends to be overtaken by technological developments. Also LED lamps are not yet mentioned in Supplement 3 – while, as mentioned, the same applies to these as to CFLs, but this at least would have needed mention. This will be added during the next revision.

7.1.4 The risks lurk elsewhere

Replacing incandescent lamps, exhibiting a power factor of 1, first with CFLs and now with LED lamps, both operating at power factors around 0.5, has reduced the active power intake by at least 75% on the other hand. Thereby the TRMS currents in the line conductors have dropped down to half the original values. So, the 150 Hz neutral conductor current is still lower in magnitude than the 50 Hz neutral conductor current arising in a failure case of one line conductor with incandescent lamps. Therefore “smoke signals”, if not present before, are not to be expected after the conversion (described in detail in [18], Table 4). No, the risks and secondary effects are located at a totally different level, i. e. with the earthing configuration of the mains. The neutral currents, still having increased under normal operating conditions, need to be properly returned to the supply, and this means here: Not all across the building! Or in detail:

- It is inevitable and more important than ever that the network configuration shall be a TN-S system, as it is now required by standards for newly erected installations, but a conversion is also recommended for existing installations [23].
- It is equally important to monitor the system – keyword: “differential current monitoring”. Maintenance does not mean to maintain the installation in its present state, no matter how bad this is, or in the best case to wait until the (hopefully installed) residual current protection device cuts the supply off without releasing a preceding warning, but rather to receive a warning message before this happens! Experience has shown that the differential currents in an installation rarely ever increase all of a sudden but more often slowly and gradually. This provides room for action.
- An EMC-compliant installation implies that the active conductors – i.e. including the neutral – are installed as close as possible to each other and as far away as possible from the PE/PA conductor in order to reduce inductive couplings after having avoided the galvanic ones (see above). The higher frequency currents nowadays released into the mains by modern electronic operating devices couple into adjacent conductive parts proportionally to the frequency.

7.1.5 Intermediate summary regarding harmonics

As the designation has it, network repercussions are more a question of the networks than of the devices fed from it. Therefore, one consideration goes into the direction of DC systems – as a supplement to the final circuits of our single-phase and three-phase AC systems or as an alternative for these; this is not yet certain and may vary in each individual case. Also, the voltage level is still under discussion – or shall we introduce two of them right from the start? The reasons are obvious: Most consumer devices nowadays are of an electronic nature and work with integrated or external operating devices which rectify the incoming AC straight away in the first stage before processing it any further; so why not rectify it centrally? Both the purchase costs as well as the efficiencies of big units are more advantageous than with the umpteen small and minute ones all around the place. The problem of the harmonics can also be handled more easily in one central unit than in a multitude of small ones – while these many small "power modification units" would still be required, since hardly any LED module can be operated directly on the given DC voltage, but these could be simplified (DC-DC inverters). A PFC (power factor correction) becomes superfluous or needs to be installed only once on the central rectifier. But it is still a long way to go to the implementation. Meanwhile the harmonic currents will continue to accompany us in the grids – and the latter will need to be designed accordingly; then those many little LED lamps may feel free to behave as they like (Figure 49).

7.2 Inrush currents

Further problems also caused by feeding electronic devices via bridge rectifier and filter capacitor are extremely high inrush currents (Figure 55). An insight that shall be given right here straight away in order to prevent any misfortunes is that also devices with a different architecture, such as PFC, while hardly causing harmonics anymore, may still exhibit high inrush currents. Exceptions (Figure 56) confirm not only the rule, but also the circumstance that this need not necessarily be so.

Now it is not permissible to extrapolate in a linear manner from the inrush current of one lamp to the supposed inrush current of several lamps. The inrush current cannot exceed the short-circuit current of the respective installation. Yet, inrush peaks continue to increase with every single additional lamp being connected to one particular switching device. The effects can be drastic and need to be taken into consideration during the design stage of the installation and the selection of the switching devices. Manufacturers give according indications regarding this, though in a manifold and hence different – this meaning not comparable – manner, since standards for this kind of stress are still lacking.

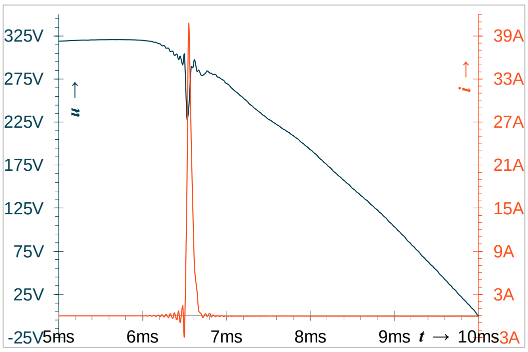


Figure 57: Inrush current of an LED lamp 14 W

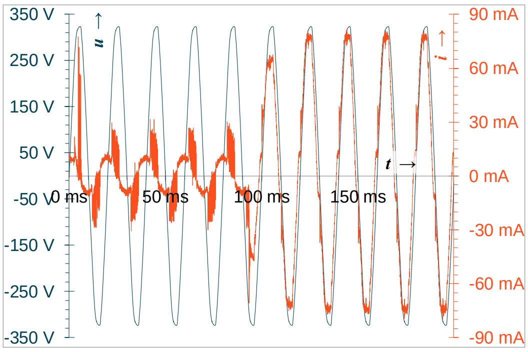


Figure 58: Switching on an LED lamp 10 W, here voluntarily equipped with PFC by the manufacturer (Osram) without any compelling standard – in this case also without any sub-

stantial inrush, but with HF current superimposed upon the "normal" operating current

7.3 HF "supplements"

With any luck you can also get lamps today which, while their input power rating clearly falls below 25 W, still are equipped with a PFC, because the associated electronic circuitry comes at next to no cost nowadays. The harmonic content in the feeding current is then no longer worth any mention, but the smoothing in the "coarse" area comes at the price of superimposed high frequency currents in the "fine" sector. The typical content of fundamental capacitive reactive power also remains (in contrast to the strongly inductive behaviour of old lamps and luminaires with magnetic ballasts). Comparing the waveshapes of the lamps, one finds out that the conventional type is not free of harmonics either (Figure 57), but the curve takes a fairly "calm" course compared to the uneasy change of high-frequency currents continuously superimposed upon the input current into a modern LED street light (Figure 58).

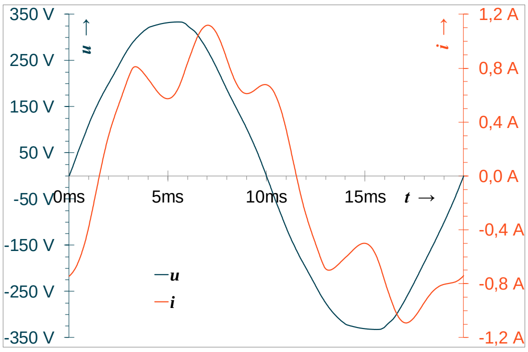


Figure 59: Old street lighting: Sodium vapour lamp with magnetic ballast

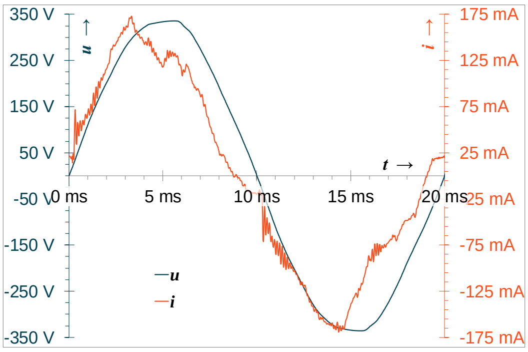


Figure 60: Modern street lighting: LED lamp with electronic ballast

In general, this does not take any effect upon other installations or appliances, but under certain conditions it does (otherwise this would not be a topic, neither here nor elsewhere). The potential for disturbances is particularly great in TN-C systems where the return current, along with its high-frequency "impurifications", can split up everywhere all across the earthing system. Filtering capacitors dimensioned for 230 V and 50 Hz may be overloaded – although the question is justified why one should need a filtering capacitor when there are exclusively voltages and currents of 50 Hz cruising in the system, but then it may strike the compensation capacitors selected by such philosophy. Thought experiment: replace every second sodium vapour lamp in the street lighting installation mentioned above with an LED lamp. Because of the substantial reactive current (Figure 57) the (remaining) sodium vapour lamps are compensated in a decentralized manner inside each luminaire by a parallel capacitor, which is common practice anyhow. This is advantageous for the purification of the mains, since via the capacitors also the high-frequency parts of the currents are shunted. But these high-frequency partial currents will then still be cruising from every single LED luminaire to the respective nearest sodium vapour luminaire – and even more so, since these currents now find a very convenient path with a very low impedance. Hereby, for instance, the capacitors may be overloaded. Neither can it be excluded that an LED lamp disturbs an LED lamp or that similar disturbances pop up:

7.4 Mutual incompatibilities of electrical devices

The dimmer test (Section 35, [10]; [11]) already pointed out how limited the compatibility often is even among devices meant to fulfil a common function. How much more delicate will the situation then be when such components rather meet each other by coincidence? One such case was presented to the public in detail already earlier [24] and therefore needs to be described here in brief only:

In a totally renovated residential building, a complete LED lighting system was installed, including dimmable lamps. The electrical installation had been totally renewed. The lamps worked flawlessly, until the electronically controlled instantaneous water heater went into operation. During these periods all dimmable lamps flickered – including those not actually equipped with a dimmer. All remedial measures carried out brought no help: A capacitor made available by the lamp manufacturer did not, the change to a different type of lamp or dimmer did not, nor did the redistribution of circuits, of course, for the installation had already been diversified in a rampant manner (5-conductor cabling to every room). The only working solution was a provisionally connected UPS serving the lighting circuit, but of course the investment was inadequate as a permanent solution. Obviously the dimmable lamps interpreted any crease in the voltage curve as a signal for dimming. Phase-angle dimming – be it leading phase-angle or lagging phase-angle control – is always characterized by creases which are not contained in an ordinary sine wave. Even if the wave packet control of the electronic instantaneous water heater switches only at zero crossing, which by all means should be the case, every switch-on and every switch-off represents a crease in the current curve, impairing the voltage curve to some degree if currents are that heavy. The inductance of the house’s overhead feeder (go and return conductor are situated much further apart here than in an underground cable) contributed its share to the effect. So a solution could be to find a plain and “simple-minded” lamp that would not draw any conclusions from any creases but dims down solely due to the fact that a part of the voltage-time-area is missing – like with the (not really) good old incandescent lamp and the classical phase-angle control dimmer. The disadvantage is that such a lamp will then also change its light output due to any other variance of voltage. The other solution would go into the opposite direction, namely towards a lamp with even more sophisticated electronics, receiving its signals via a separate channel (data cable or a wireless solution, DALI or the like) and not by way of any creases of the feeding voltage.

8 Lifetime expectancy

Unfortunately, LEDs do age. From the first moment they are in use the luminous flux diminishes, or individual LEDs in a lamp fail [25]. The most crucial factor for the speed of such processes is the operating temperature. Now the internal heating of the diodes could be reduced by not fully loading them, but to operate them below the rated current. Using double as many diodes as necessary and charging them with half the electrical power will expand their lifetime expectancy by several times – and this without compromising efficiency, as would be the case with incandescent lamps. This approach has so long been hampered by the high prices, particularly during the stage of market introduction.

The latter, however, we have now left behind quite suddenly, and the LED has evolved as the standard technique in lighting. It even costs *less* than the preceding technology (Table 7, Table 8)! This does not exclude that lamps dating from 2014 may still experience premature failures (Figure 59). However, this is one of the lamps from Figure 50. Hence, it is possible that this one lamp has suffered damage during the experiment described there (Section 7.1.2) – which would contribute yet another example for the occasionally drastic effects of a star point loss. Quite generally speaking, it may be assumed that the longevity of today's LEDs can be counted on better than those from even a relatively short time ago – with all the care that has to be taken with the term "lifetime expectancy," for there are many different definitions. The respective valid one has to be identified in each individual case before comparing apples to oranges, as excellently described in one source [26]. According to this, the lifetimes have to be measured for at least 6,000 h. After this, a calculation method is allowed up to 6 times this value, i. e. 36,000 h; who measures for more than 6,000 h is also allowed to rate longer lifetimes. What is rated then is a lifetime in hours with a designation like "LM80 B10." This means that after expiry of the lifetime the lumen maintenance is still 80%. This, however, applies only to those lamps which still work at all at that point of time. "B10" points out that up to 10% of all samples may have failed completely by then – with the logical consequences for the luminous flux of the whole installation.

Figure 61: This lamp had been in operation in a bathroom for barely one year and still functions despite the suspicious char, but the fabricator replaced it immediately and free of charge

Apart from that, it goes without saying that the temperature has to be given which this lifetime rating relates to. While the calculation procedure itself is standardized, but it is pointed out that the theoretical, calculated lifetime curves (lumen maintenance of the complete installation including failures) turn out differently depending on the B value towards which you calculate ([26], Figure 7).

A point is also raised that the different LEDs exhibit sensitivities to aggressive gases in industry, such as in public baths (chlorine) or e. g. in agriculture (ammonia). The loss of luminous flux as well as the colour drift may be accelerated by several times due to this. This comes from having to apply the phosphor outside. With fluorescent lamps it is accommodated under glass; with specialized adequate LEDs the glass has to be added (gas tight).

While this is so, the EU Directive tailored to the CFLs is still in existence – to CFLs perhaps more as a sort of corset – that the lifetime rating must be valid for a certain minimum number of switching cycles. Since by principle the switching frequency does not influence LEDs, manufacturers continue to type something like “one million switching cycles” on the package. In analogy, the same applies to the here totally superfluous rating that this lamp reaches 100% of its luminous flux within 0.1 s. Well, of course it does. Why should it not? All that could happen – and is in fact observed on some lamps – is that the electronic circuitry (PFC, inrush current limitation) procrastinates the start-up process of the control gear, e. g. until the smoothing capacitor has been fully charged.

At present a public survey of the EU is ongoing as to which ratings consumers (still) want to see on their products. After all, we also don’t stick a sticker onto each and every car, saying, “This vehicle travels on 4 rubber tyres.” – only because horse drawn coaches used to have wooden wheels and tyres of steel; so do away with the old hat.

9 Outlook

One might allege that the incandescent lamp “prohibition” has removed incandescent lamps from the market, leaving a void for LEDs to fill. One might also allege the LED would have established itself on the market anyway and that the remnants of incandescent lamps now need to be sold off (Figure 60). Which version comes closer to the truth cannot be determined in retrospect.

Figure 62: On sale: In(can)de(s)cent light bulbs

Figure 63: Getting scarce already: The first generation of “enery saver lamps”

9.1 CFLs – at breakneck speed from an innovation to a vintage technique

The CFL had just managed to mature to a sellable product before it was obsolete again (Figure 61). Hardly anybody still wants it. Why should we? After all, the LED household lamp has become the more efficient *as well as* cheaper option and *additionally* overcomes the typical disadvantages of the CFL!

Figure 64: A basement room with incandescent lamp 100 W and …

Hence the question to the German sales manager of Megaman at the Electrotechnical Fair in Dortmund in February 2017: “By the way, how much turnover do you still make with CFLs?” – “Well, some 2% … 3% of the total business.” And this is happening without any CFL phase-out legislation or anything equivalent.

At Light & Building 2018 he confirmed this 2% to 3% share.

Figure 65: … with an LED lamp 14 W, taken with the same exposure data as Figure 62!

9.2 The incandescent lamp had to go

That the LED (Figure 63) outperforms the incandescent lamp is trivial (Figure 62), halogen incandescent lamps included. It is remarkable that – in objective terms, as measured in the lab – you get about the same light from an LED at $^1/_7$ of the power intake of an incandescent lamp! According to subjective perception you get even more light (Figure 64, Figure 65) In part this might be due to the “spotlight fashion” mentioned earlier (Section 15) which has disappeared with the LED’s introduction. There seems not to be any cause and effect relations here, since LEDs are particularly suited to spotlight designs! Nowadays, however, spotlights are limited to the reasonable applications.


*Figure 66: Bathroom lighting with 3*50 W halogen incandescent spotlights*

It has been fairly easy to “put the incandescent lamp on the spot”– with a poor lighting efficacy, though – because its light emitting element, the filament, is very small. The fluorescent lamp cannot catch up with this, although it is a very efficient light source. Assuming an ideal white colour, the fluorescent lamp – including the operating device – achieves a luminous efficacy equal to a physical efficiency in excess of 50%. You can hardly expect anything more than that.


*Figure 67: Bathroom lighting converted to 3*5 W LED lamps, taken with equal exposure settings as in Figure 64*

9.3 LED – from the innovation to state-of-the art

Only the LED is capable of merging these two properties as putting a high luminous efficacy on the spot – and a few more – and it even clearly outperforms the energy efficiency of fluorescent lighting. This alone is not a good reason to convert existing installations. However, in new buildings, or when a complete renovation is due, it should be considered that an LED – with the exception of a few exotic cases –overcomes practically all disadvantages of fluorescent lamps, while also having lower purchase, installation, and operating costs (Table 7, Table 8, Table 9). How can the decision then be anything but in favour of LED lighting? Only out of habit – but habit is not the best consultant.


Figure 68: Working room with 2 CFLs 9 W and 6 W, respectively, in the floor luminaire; desk luminaire (2016) already OEM equipped with LED 3 W


Figure 69: Working room with 2 LED lamps 5.5 W and 4 W, respectively, in the floor luminaire, taken with equal exposure data as Figure 66 (desk luminaire LED 3 W as before)

The everlasting and exclusive argument so far why someone should switch from fluorescent to LED lighting – or should be willing to do so – was: Because of the energy efficiency! This applied for so long as the lighting efficacies of the LEDs were not higher than those of fluorescent lighting (Section 26). Ever since the LED has in fact worked out a certain lead in this respect (Figure 66, Figure 67), you need no longer allege this were so. Now the LED supporters can dedicate themselves to other advantages of the LED.

9.4 Energy efficiency is not everything

The energy efficiency of LEDs is no longer a topic at the annual LED Forum in Lausanne since 2016 [27]. Rather, experts discuss about “human centric lighting” (HCL) there, i. e. adequate lighting for humans, and about circadian lighting, which (with respect to light colour) imitates the rhythm of daylight, and about similar properties. These are much easier to implement by means of LEDs than with all older techniques, or they become viable only thanks to LEDs.

Meanwhile the LED continues to show it can do more than save energy (Figure 68, Figure 69): Never having to dismantle any furniture again because the very much concealed T5 lamp needs replacement; never again break or char one’s fingers when replacing the little GU4 bulbs accommodated in the decorative metal trims!

Figure 70: Decorative lighting in a living room wall unit with T5 lamps 8 W and 13 W as well as halogen incandescent lamps 5 W and 20 W, overall power rating 115 W

Figure 71: Decorative lighting in the living room wall unit from Figure 68, converted to LED adhesive strips (Figure 16; Figure 21) and LED GU4 lamps, overall power rating now only more ≈ 36 W

9.5 Durable products in transitory markets

The balance (Table 9) clearly reveals that it is most economical to dedicate old or even not really so old incandescent lamps to the dustbin, even if they are still functional (Figure 70). But what about the only slightly used or in part even unused CFLs? They were procured recently, driven by the desire to have something better, something “future oriented” – and now (Figure 71)? Dispose of them? In the end this will be the solution. Shortly after the conversion of the luminaire from Figure 2 with a dimmable LED lamp (Figure 36) the complete luminaire was replaced (Figure 37). With its lifetime expectancy of about 50,000 h it will probably be on duty there for another 20 years. Will inhabitants still be willing to operate it in that place, functional though it still may be? Will they be willing to put it back into a functional state (thanks to Zhaga [9])? Its predecessor – though still functioning – ended up at the municipal recycling dump after about 25 years of service life – without the nearly brand-new LED lamp, though. The latter now does its (very sporadic) service in a different luminaire which is rarely ever used and where the incandescent lamp so long present could have remained in place for the next 20 years, but it ended up (first in Figure 70 and then) in the trash can, for the LED was now there, representing the better solution in every respect. In this way practical experience raises doubts about the sense of long service lives on markets intensely characterized by innovation.

Figure 72: The other form of glass recycling?

Figure 73: And now what to do with these? Dispose them as problem waste – never mind whether they have ever been in use or not?

But this trend may also calm down again, for the LED's way from the innovation to the standard solution is practically finalised. Soon nobody will speak of "LED lamps" or "LED luminaires" anymore but only of lamps and luminaires. Neither do we any longer say, "Turn on the electric light, please!", as a colleague's grandma used to say, but just "Turn on the light!". And soon there will be "only" a Light Forum in Lausanne [27].

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Deutsches Kupferinstitut Berufsverband e.V.
Heinrichstr. 24, D-40239 Düsseldorf, Tel.: +49 211 129469-10, www.kupferinstitut.de
Deutsche Bank AG, Düsseldorf, Konto-Nr.: 7 440 720, BLZ: 300 700 24
Amtsgericht Düsseldorf VR 9370, Geschäftsführer: Michael Sander