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Technologies

Energy

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Contents

Executive Summary

This document covers MEErP Task 4 and related Parts of Task 5. It deals with technology aspects of light sources. It consists of three main parts:

- A description of recent lighting technologies (chapters 2 to 4). The focus is on LED lighting, but OLED-lighting, laser-diode lighting, and smart lamps are also addressed. The LED technology description clarifies the backgrounds for the progress made in recent years and indicates where further improvements are expected. This leads to a proposal for a LED timeline, i.e. a projection for LED efficacy and LED prices.
- A description of classic lighting technologies (chapter 5). For each type of lamp the current average EU-characteristics (base case) are summarized, and the best available technology is discussed. In particular it is identified if LED retrofit lamps are available for the existing non-LED light sources, and what their characteristics are.
- Production, distribution and end-of-life (chapter 6). This part focuses on the input for the EcoReports that will be used in Task 5 for the analysis of environmental impacts, i.e. bill-of-materials, packaging volume and weight, and recycling possibilities.

LED technology

The vast majority of white-light LEDs manufactured today are based on a blue-emitting gallium nitride (GaN) or indium gallium nitride (InGaN) LED source used in combination with a yellow-emitting cerium-doped yttrium aluminium garnet (Ce3+ YAG) phosphor. The combination of the original blue light with the converted yellow light yields the desired white light. This type of LED is called a phosphor-conversion or pc-LED.

There are two other types of LEDs: the colour-mixing or cm-LED and the hybrid LED. The colour-mixing LED uses a combination of blue-, green- and red- (and amber-) emitting LEDs together with a colour mixing optic. This is also referred to as an RGB(A)-LED. This technique can be applied e.g. for LED light sources with (user-controllable) colour-change ability.

The hybrid solution combines a pc-LED with discrete-coloured LEDs to create the desired light output. Typically, a red- and/or amber-emitting LED is added to the basic pc-LED to make the white light warmer, to create (user-controllable) light sources that can produce a range of white tones, from cool-white to warm-white, or to implement the dim-to-warm feature.

One of the main reasons that pc-LEDs are the majority is that blue-emitting LEDs currently have the highest efficiency. According to the US DoE [1], in 2013 the power conversion efficiency (optical power output divided by electrical power input) was 55% for the blue LED, 44% for the red LED, 22% for the green LED and only 8% for the amber LED. It is therefore convenient to create in particular the green and amber light by means of down-conversion of blue light by means of phosphors [2], even if this conversion also entails losses: for green light the phosphor conversion efficiency is around 80%.

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[1] Solid-State Lighting Research and Development, Multi-Year Program Plan, US DoE, May 2014, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf

[2] This technique is similar to the one used in fluorescent lamps

Colour-mixing LEDs have less phosphor losses, but they now suffer the low power conversion efficiency of red, green and amber LEDs. However, what counts in the end are the lumens produced, and these do not only depend on the power conversion efficiency, i.e. $W_{optical}/W_{electrial}$, but also on the spectral distribution of the light, that determines the lumen/$W_{optical}$. Colour-mixing LEDs potentially deliver more lumens for the same optical power output than pc-LEDs. Due to the combination of advantages, potentially this solution offers the highest efficacies for the future.

The overall blue-LED power conversion efficiency can be subdivided in [1]:

- Electrical efficiency, currently reported around 92%: depends on the voltage losses between the injection point of electrons (the electrical contacts) and the active layer of the LED die.
- Internal Quantum Efficiency, currently reported around 88%: this is the ratio of the photons (light) emitted from the active layer of the LED die to the number of electrons injected into the active layer.
- Extraction efficiency, currently reported around 85%: due to the differences in refraction index between the semiconductor materials and the air, the emitted photons can remained trapped inside the LED die.
- Packaging efficiency, currently reported around 80%: additional losses due to the integration of the LED die into a package.

The product of these four efficiencies leads to the 55% power conversion efficiency for blue LEDs. The other 45% of input power, in one way or the other, becomes heat generated in the LED package. This makes the LED junction temperature rise, and higher temperatures imply lower efficacy (temperature droop) and lower lifetime. As regards temperature, the decrease in efficacy is approximately -0.2%/K. As regards lifetime, the useful life is nearly halved for each 10˚C increase in junction temperature. To avoid this, a good thermal design is necessary and/or the operating current can be decreased (which generates less heat, but also less light). Relatively low operating currents are also used because efficacy (and lifetime) decreases when current density increases (current droop).

Efficacy improvements have a double positive effect: they also reduce the amount of heat produced. Some years ago, relatively low lumen LED bulbs (500-800 lm) had efficacies of 60-80 lm/W and a heavy and bulky heat sink, while recent LED filament lamps reach efficacies of 100-120 lm/W and are without heat sink [3]. Anyway, LED lamps are still not suitable for high-temperature applications (ovens), and they may have reduced efficacy and reduced lifetime when mounted in existing luminaires that have not been thermally optimized for such lamps. This is true in particular for the higher-lumen LED lamps.

In general a lower CCT and a higher CRI imply lower efficacies.

Looking at LED cost reductions, one contribution derives from the shift to larger wafer sizes [4]. In 2010 59% of the wafers was 2” diameter, in 2012/2013 53% of the wafers was 3”, while for 2015 it is expected that 55% of the wafers will have a diameter of 6” (150 mm). The increase in wafer size enables a cost reduction, and a production capacity increase. The choice of the wafer substrate material may also offer opportunities for

[3] This is not only due to efficacy improvements but also to other dissipation methods, i.e. gas filling of the lamps.

[4] LED dies are grown using a process called epitaxy, not individually, but a certain quantity together on a larger wafer. Large wafers reduce the per-die processing costs.

cost reduction. More than 80 percent of today's LEDs are built on a sapphire substrate. Alternatives are: e.g. silicon carbide, bulk GaN, silicon, germanium.

Another large contribution to cost (and resources) reduction derives from improved package designs. A 2006 package had in-plane dimensions of 7 x 7 mm (not counting the electrical leads) and a height around 6 mm. The same manufacturer now produces chip-scale flip-chip packages with approximate in-plane dimensions of 1 x 1 mm and a height (thickness) around 0.25 mm. The package level cost reduction is reported to be 80%. The new package design also offers thermal advantages.

Encapsulation materials are another opportunity for efficiency increase and cost reduction. They do not only protect the LED die, optionally act as a host for the phosphors, and optionally function as lenses to regulate the light distribution, but also play an important role in the light extraction efficiency. Standard-LEDs use an epoxy resin as encapsulation and lens material, but higher quality LEDs usually apply a silicone-based material. Silicone has a better resistance against heat and against high-intensity blue light. In 2014 the market shares by weight were approximately 20% silicone and 80% epoxy, but modern high-power LEDs typically use silicone. However, premium-grade silicone materials are very expensive and a significant cost factor in LED manufacturing.

Huge progress has been made in recent years in LED lighting technology, and it can be derived from the above that much more can be done. Examples of research topics are (not exhaustive):

- New semiconductor materials. US DoE indicates this as a core technology research priority task.
- Improvement of the power conversion efficiency of in particular green, amber and red LEDs.
- Reducing the sensitivity of the internal quantum efficiency to the current density (i.e. current droop) is a significant opportunity for improved efficacy and cost reduction.
- Reducing the thermal sensitivity of LED packages (i.e. temperature droop) would allow the LEDs to be driven harder (higher operating current) and thus emit more light without compromising efficacy. Lowering the operating temperature would also have beneficial effects on LED lifetime.
- Improved phosphor materials, in particular narrowing the emission bandwidth for green and red phosphors. Also the use of nanoparticles ('QLED') may play a role here.
- Improved and cheaper encapsulation materials, with textured surfaces to improve light extraction efficiency.
- Improved and cheaper substrate material.
- Further optimization in package design.

As regards LED control gears, their main function is to convert the AC mains voltage input in a direct current output of the desired amplitude. Technically, a LED control gear can be made with nearly any desired characteristics. However, the demand for additional functions (dimming, colour control) or for more severe requirements (power factor, EMI, flicker) will usually increase the cost of the driver, consume more material resources, and can also have an impact on the required space, on the energy efficiency, and on the standby power consumption.

During the 2009 preparatory studies, LED control gear efficiencies around 90% were found. Today, so called 'offline LED drivers' with AC input voltage, power factor correction, safe isolation and dimming, can be found with efficiencies up to 95 %, depending on the wattage. Current-control LED drivers operated from a DC voltage (12/24 V) can be found on the market with efficiencies up to 97%.

LED state-of-the-art and timeline

Table 1 provides a survey of the current (2014-2015) efficacies and prices of LED retrofit lamps for various types of existing classic-technology lamps. This survey has been compiled by the study team based on information from various sources (see Table 10 in the main text for references).

As expressed by the minimum and maximum values in the table, the range of LED retrofit lamp efficacies (lm/W) and prices (euros/klm excl. VAT) is very wide. However, the average values show a smaller variation between the lamp types.

Average efficacies vary from 73 to 109 lm/W, with an overall average of 89 lm/W. The highest average values are found for NDLS LED filament lamps and LED retrofit tubes for LFL replacement (109 lm/W). The absolute highest efficacy is 148 lm/W, for a LED retrofit tube, and regards a tested value.

As regards average prices, the values for LED retrofits for MV DLS and for LV halogen capsules are relatively high due to the presence in the selection of lamps with a very high price. For these lamps the median values are considerably lower than the averages shown in the table, i.e. 22-23 instead of 36 euros/klm for the DLS, and 32 instead of 41 euros/klm for the LV capsules. Taking into account these median values, average prices vary from 10 to 32 euros/klm, with an overall average of 23.4 euros/klm. Lowest prices on the market are typically around 10 euros/klm (excl. VAT), but even lower prices can already be found.

Table 1 Current efficacy (lm/W) and price (euros/klm excl. VAT) for different types of LED retrofit lamps. For both variables, the minimum, average and maximum value are presented. N = number of lamp models on which the data are based; if there are two values, the first is for the efficacy and the second for the price. DLS data are based on full lumens (not in a cone) (Source: VHK 2015, see Table 10 for details)

LED lamp type	N	Efficacy (lm/W)			euros/klm (excl. VAT)		
		min	avg	max	min	avg	max
NDLS LED filament lamps	10	96	109	121	10.33	24.80	53.33
NDLS LED other lamps	23	58	77	104	5.83	17.27	36.00
DLS LED lamps with E14/E27 cap	43	40	79	107	9.89	36.31	165.2
DLS LED lamps with GU10 cap	58	52	77	100	9.72	36.67	105.1
LED retrofits for HL LV Reflector	5	50	73	104	11.67	23.43	49.56
LED retrofits for HL LV Capsule	6	67	93	101	9.91	41.40	71.36
LED retrofits for HL MV Capsule	5	74	84	96	8.42	22.32	41.64
LED retrofits for HL MV R7s	14/11	67	96	115	4.54	26.71	57.38
LED retrofits for LFL (tubes)	14/7	80	109	148	11.31	18.21	43.95
LED retrofits for CFLni	4/2	72	91	102	23.27	28.10	32.93
LED retrofit for HID (indicative)	(3)	90		120		10	
Average, all types			89			23.4	

Figure 1 (efficacy) and Figure 2 (prices) show the above averages and their variation, compared to the 2013 value used in MELISA (see Task 2 and 3 reports), and compared to the projections from US DoE (2014), VHK Stage 6 review report (2013), and McKinsey's Lighting the way (2012). The source data have been elaborated by the study team as explained in par. 2.10, in order to make them comparable.

The red dotted lines, starting from the current averages, are the projections proposed by the study team for discussion.

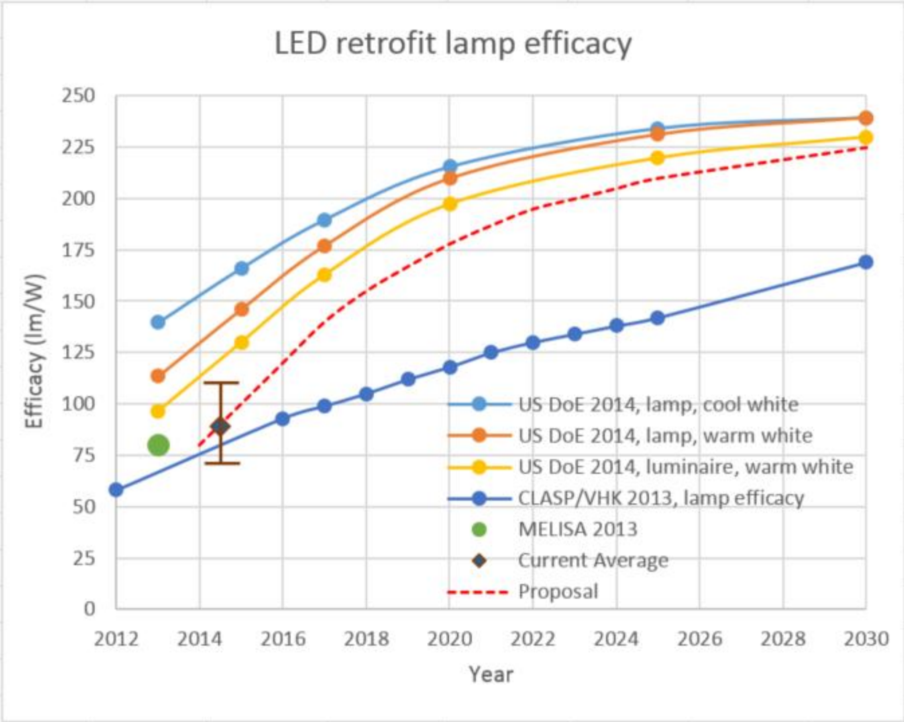

Figure 1 Projections for LED efficacies from US DoE MYPP 2014 and from the Stage 6 review report. The 2013 MELISA value is indicated as a green dot. The current (2014-2015) average LED efficacy of 89 lm/W and its variation over lamp types is also indicated. The red dotted line is the proposed projection for this study.

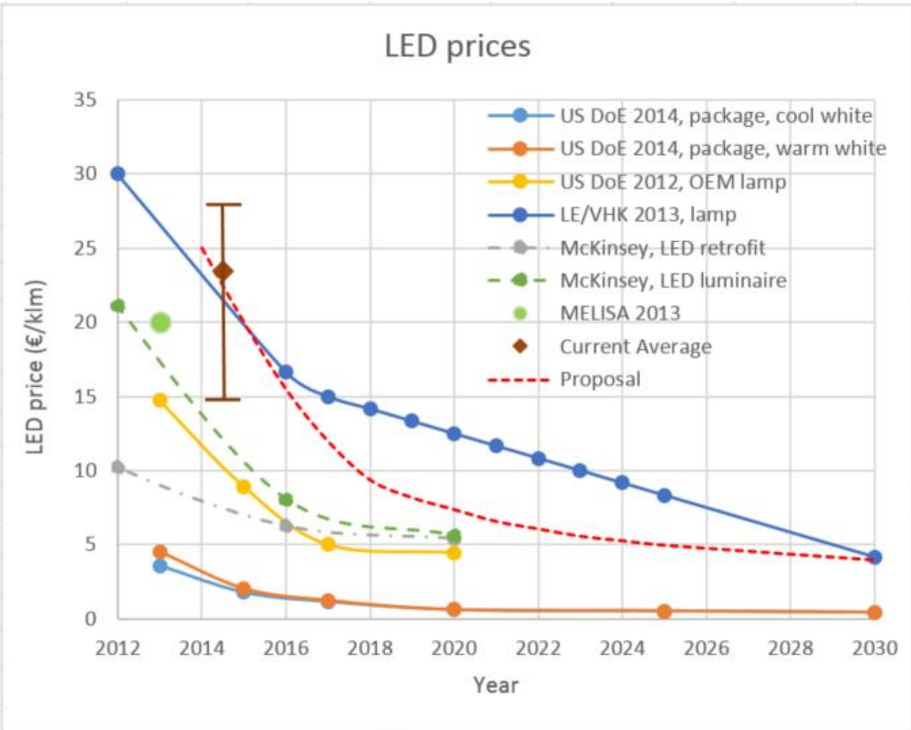

Figure 2 Projections for LED prices (in euros/klm excl. VAT) from US DoE MYPP 2014, Stage 6 review report, and McKinsey 2012. The 2013 MELISA value is indicated as a green dot. The current (2014-2015) average LED price of 23 euros/klm and its variation over lamp types is also indicated. The red dotted line is the proposed projection for this study. Note: US DoE prices have been assumed to be excluding VAT, and 1.12 US dollar = 1 euro was used for conversion. For McKinsey data 500 lm/unit was assumed.

As regards the efficacy projection, the curve proposed by the study team follows the trend of the US DoE curves, but adapting them downwards to meet the identified point of 2014-2015 average efficacy. In addition, the US DoE curves have been interpreted to represent the expected best efficacy in a given year rather than the expected average efficacy of new sold products in a given year, as needed in this study for the scenario analyses in Task 7. For this reason the study team projection stays below the US DoE efficacy curve for LED luminaires.

As regards the price projection, the starting point is the identified 2014-2015 average price/klm, which is significantly above the US DoE value for the same year, but close to the LightingEurope/VHK value (from the Stage 6 review study). Also here, the US DoE curve is thought to be more representative of the lowest expected prices, while for this study the average expected price of new sold products in a given year is required. Considering the recent fast drop in LED prices, that is generally expected to continue at least in 2015, the study team projection is more optimistic than the Stage 6 review study projection as regards the speed of change in nearby years, but ends at the same price/klm level in 2030.

As regards both projections, it is uncertain up to which point the current trends in LED development will continue. Industry worldwide is investing a lot of money in LED research and development, and it seems reasonable to expect that sooner or later they will want to see a return on this investment, i.e. developments might slow down or come (temporarily) to a halt so that industry can concentrate on earning back some money. The 'sooner or later' could be related to the phase-out of halogen lamps, with the corresponding loss of industry revenue from that lamp type. It is e.g. not unthinkable that from 2018 the average efficacy will more or less 'freeze' at 150 lm/W for some years. This process may also be related to a decrease in the number of players on the market, e.g. Samsung and Philips already scaled down or abandoned LED lighting production [5].

OLED lighting

As regards OLED lighting products, the following main conclusions can be drawn:

- There are some commercial OLED lighting products for sale, but until now these regard mainly prototypes, technology demonstrators, sample kits for designers, and premium light installations and luminaires. However, some manufacturers recently started mass production or are preparing for it.

- The highest efficacy for commercialised panels is 50 – 60 lm/W. Major manufacturers expect to reach 130 lm/W by 2018. The US Department of Energy target for 2020 is 150-170 lm/W. The potential future efficiency for OLEDs is expected to remain below the efficiency foreseen for LEDs.

- The main barrier to large-scale market introduction of OLED lighting products is their price. The current price of OLED panels is around 180 euros/klm, which is far more expensive than LED lighting, and limits OLEDs to high-end applications. Prices are expected to come down due to new production processes (soluble OLED processes instead of vacuum deposition) and to higher production volumes (production costs could be reduced by 90%).

[5] http://www.reuters.com/article/2014/10/27/us-samsung-elec-led-idUSKBN0IG0DD20141027

- The impact of OLED lighting on the European market for general lighting applications is currently negligible. This is unlikely to change significantly before 2020. The future of OLED lighting is uncertain: market researchers have widely diverging opinions. OLED lighting may never obtain a significant share of the general lighting market, but the situation might also develop in favour of OLEDs.

Considering the above, OLEDs will not be considered as one of the base cases in this study. It is also difficult to define OLED lighting as BAT or BNAT. OLED efficacies are expected to stay behind those of LEDs, and prices are expected to remain higher than those for LEDs. OLED lighting products can also not be used as retrofit solutions for the other base cases, i.e. no OLED light bulbs, spots or tubes exist.
OLEDs do offer exciting new possibilities for lighting designers, in particular when flexible, transparent, colour-tuneable panels of larger size will become available on a large scale and at lower prices. In addition their large-area diffused light is attractive for some applications, as opposed to current light sources that are point- or line-like.

A new lighting regulation should probably take into account OLEDs, to avoid that early OLEDs perform poorly and cause market souring, but also considering the efficacies that can be reached by OLEDs, i.e. to avoid unintentional barriers for market introduction of OLED products.

Laser-diode lighting

The study concludes that laser-diode lighting technology exists, that it is promising, and that research is still ongoing. There are also commercial niche applications (car head lights, projection, medical), but no existing general lighting applications have been found. It is expected that these will come to the market in 5-10 years, but it is not clear yet how efficacy, costs, light quality, thermal management aspects and safety aspects will relate to those of LED lighting. So the technology is available, even if under development, but in this moment it is not feasible to judge if this will be the best technology for the future.
Laser-diode lighting will most likely not produce retrofit lamps for existing sockets, but require a new approach to lighting design, with a central light generation point and a light distribution system.

Base case discussion and availability of LED retrofit lamps

The report discusses in detail, for all types of lamps used in general lighting applications:

- The average EU-28 (base case) characteristics. These are the same data as presented in the Task 2 and 3 reports, but ordered per lamp type, in particular with the aim to facilitate input for the EcoReports in Task 5.

- Developments in the classic lighting technology since the previous (2007-2009) eco-design preparatory studies on lighting, and a discussion on the state-of-the-art (for those lamp types where this is relevant).

- Replacement options. The focus is on (BAT) LED retrofit lamps and their current characteristics, but substitution by improved lamps of the same classic technology (if still on the market), control gear substitution, and use of LED luminaires are also discussed.

- Non-availability, limited availability or problems related to LED retrofit lamps.

The main aim of this part of the report is to identify if there are difficulties or obstructions regarding the shift in sales from the classic-technology base cases (LFL, CFL, HID-lamps, GLS-lamps, Halogen lamps) to the LED base case. This shift in sales, together with the LED timeline proposed before, will be the central point in the scenario analyses of Task 7, and determine the energy savings, environmental impact advantages, and economic impacts for consumers and industry.

The main conclusions from this part of the report follow.

Linear fluorescent lamps (LFL)

Linear Fluorescent Lamps T12 and T8 halo-phosphor have been phased out and thus have to be substituted by another technology. LFL T8 tri-phosphor and LFL T5 are still on the market and have good efficacies, around 100 lm/W. A large variety of models exist: high-efficiency, high-output, (extra) long life, etc.

LFLs function on external ballasts that can be electro-magnetic (lower efficiency) or electronic (higher efficiency, high frequency advantages). Although recent data lack, it is expected that by now 75% of the new sold ballasts is electronic. Electro-magnetic ballasts are expected to be phased out by regulation 245/2009 from September 2017, for economic reasons.

LFLs function in luminaires that provide specific light distributions and anti-glare features. In many cases light calculations have been performed to verify that the amount of light arriving on the task areas meets the standards.

A large variety of LED retrofit tubes is available, in particular with G13 cap, for substitution of LFL T12 and T8. LED retrofit tubes with G5 cap (for T5 retrofit) are less wide spread and produced only by smaller companies, secondary brands. These retrofit tubes typically have an efficacy above 100 lm/W (slightly above the LFLs they aim to replace), but models with (tested) efficacies up to 148 lm/W are already on the market, while models with 200 lm/W have been realized on laboratory scale and should enter the market soon.

Most of the LED retrofit tubes require the existing ballast to be replaced or by-passed. The re-wiring requires qualified personnel, entails costs, and has consequences for the safety certification of the luminaires. Plug-and-play solutions are available and do not have these drawbacks, but they have higher cost to begin with, and some energy losses from existing ballasts remain.

Most retrofit tubes provide a directional light (beam angles from 120 to 150° are typical), implying that they have a light distribution that is different from the one of the existing LFLs. When they are mounted in existing luminaires, with optics designed for the LFLs, the light distribution will not be as before, and new calculations may be required to check light levels in the task areas. However, the directionality of the LED tubes potentially has advantages, i.e. less lumen could be installed to have the same light level in the task area. In existing luminaires it might be an option to remove the optics, avoiding their losses. Alternatively, optics optimized for LED tubes can be used, i.e. a dedicated LED luminaire.

Per unit length, LED retrofit tubes typically offer a lower luminous flux than the LFLs they aim to replace, but this may be acceptable.

In particular in closed luminaires and for the higher lumen lamps, the thermal aspects of mounting LED retrofit tubes in existing luminaires have to be assessed, also considering that LED efficacy and lifetime decrease with temperature.

Another aspect to consider is that LED lifetime is typically longer than for LFL (although there are long-life versions), but lumen maintenance may be worse.

Consequently it is expected that a mix of LFL (T8 tri-phosphor and T5), LED retrofit tubes, and LED luminaires will be used to substitute existing LFLs in the coming years.

High-intensity discharge (HID) lamps

High-Intensity Discharge lamps are typically used in industrial and commercial applications, street lighting and sports lighting. They are characterized by a high light intensity produced in a compact space. HID-lamps typically operate on external ballast and are often used in applications where light distribution and light levels have been optimized by means of calculations.

High-pressure mercury (HPM) lamps are being phased out from April 2015 [6]. They can be substituted by dedicated high-pressure sodium (HPS) lamps that operate on the same ballast [7], or by other HPS or metal halide (MH) lamps, substituting also starter and ballast. Substitution by HPS involves a colour change.

The efficacy of High-pressure sodium (HPS) lamps depends strongly on power level and colour rendering properties, but in general it is high, typically above 100 lm/W, with 140 lm/W feasible at higher powers.
HPS lamps can be substituted by improved lamps of the same type, optionally also substituting the magnetic ballast by a (dimmable) electronic ballast, or by an MH retrofit lamp. The latter have the advantage of offering white light with high CRI while HPS-lamps offer a yellow/orange light with low CRI.

Metal-Halide (MH) lamps. In recent years (2007-2013), the efficacy, colour rendering, and lifetime of MH-lamps has been improved, due to design optimisations in the arc tube, in the electrodes, and in the plasma. Due to this progress, MH-lamps now have efficacies of 100-120 lm/W (excluding ballast losses), which is already well above the 2017 Stage 3 requirements of regulation 245/2009.

As regards the material for the arc tube, two main versions of MH-lamps exist: quartz and ceramic. The more recent ceramic arc tube (CMH) allows higher operating temperatures, which also implies higher efficacies, especially when combined with 'unsaturated' working conditions. Considering the existence of high-efficacy CMH lamps, it has been proposed to raise the minimum efficacy requirements in the regulations, thus effectively phasing-out the quartz versions. However, some stakeholders have argued that the ceramic version cannot replace the quartz version in all applications: the difference in size of light source area would compromise the optical performance of many fitting types.

There is a wide variety of LED retrofit lamps for HID-lamps on the market. These retrofit options differ in their 'ease-of-use'. Some are plug-and-play solutions, requiring only substitution of the lamp itself (but maintaining existing ballast losses), while others require the existing ballast to be replaced or removed/by-passed (see remarks made for LFL). Some of the available LED retrofit kits are specific for a certain type of HID-lamp and/or for a certain type of luminaire. Most models are offered by smaller companies, secondary brands; major lamp manufacturers prefer to offer entire LED

[6] Except for blended lamps and some other exempted types, see details in par. 5.17.6
[7] These lamps will lose their exemption status from regulation 245/2009 from April 2015.

luminaires for street lighting and similar outdoor applications, rather than LED retrofit lamps.

LED retrofit lamps cannot meet the high light intensities in compact space of the HID-lamps, and therefore tend to be heavier and with larger dimensions than the HID-lamps they aim to replace, especially in the higher lumen range. In all retrofit options attention is therefore required to make sure that the lamp fits in the available space in the luminaire, that thermal management conditions are met, and that the amount and distribution of the light will be satisfactory (e.g. new lighting calculations may be necessary to ensure that street lighting requirements are still met).

Since decades, HPM lamps are known to be far less efficient than HPS- or MH-lamps, but nevertheless they have often not been retrofitted. In part this is due to habits (it is easy to continue ordering the same lamps) and in part to economic reasons. Municipalities, sport clubs, theatres, etc. have to make complex choices on how to spend their budget, and, notwithstanding the long term economic benefits, investments in lighting may not be a priority/possibility.
Many cities in Europe are converting their street-lighting to LED, using a mix of LED retrofit lamps and luminaire substitutions. Many other municipalities will probably not have made this choice, but that is less publicized.
Notwithstanding the possibilities for 'energy performance contracting' and funding, it is expected that for economic reasons the shift from HID- and FL-lamps to LED lighting will not be immediate and straightforward, and that a mix of LED and non-LED options will be used in the coming years.

Compact fluorescent lamps without integrated ballast (CFLni)

Compact Fluorescent lamps without integrated ballast are used predominantly in the non-residential sector. The lower wattage lamps are applied in desk luminaires, down-lighters in offices, corridors, stairs and restrooms, signs, orientation and security lighting. The higher wattage lamps are also used in some outdoor and street-lighting applications where they now experience the competition of improved HID- and LED-lamps.

No LED retrofit lamps for CFLni have been found in the catalogues of major lighting manufacturers. This is interpreted as a sign that this market is not sufficiently interesting, and/or that for many consumers the substitution of CFLni's by LED retrofits may not be an attractive option. Note that, similar to the situation discussed for LFLs and HID-lamps, there is a ballast problem: in most cases the existing ballast has to be removed or by-passed and a new LED control gear has to be installed (if not integrated in the lamp). The associated costs and luminaire safety certification problems might induce many consumers to stick with CFLni or to substitute the entire luminaire.
However, technically there are no obstructions, because several smaller manufacturers are offering LED retrofit lamps for CFLni. Some are plug-and-play versions that can operate on the existing ballast. However when the ballast is not removed, their losses remain and these can be significant.

Linear halogen lamps with R7s cap

As regards linear halogen lamps with R7s cap, LED retrofit lamps are on the market, but present some potential problems. The lateral dimensions of most LED retrofits are considerably larger than those of the halogen lamps they aim to replace. The halogen lamps have a diameter of 10-12 mm, while most of the LED lamps that are offered as

replacements are around 55 mm. In some luminaires this will cause geometric lock-in problems.
In addition there may be light distribution differences: most R7s LED retrofits found in the market today have beam angles from 120° to 180°, and do not shine in all directions like the halogen lamps do. Consequently, there is no guarantee that the light distribution from the LED retrofits will be satisfactory.
A third aspect is that halogen lamps with R7s cap exist up to 44,000 lm, while the highest capacity LED lamp with R7s cap has only 5,200 lm. This high lumen difference appears for each lamp length. Consequently, for high lumen halogen lamps with R7s cap no LED retrofit seems to be available yet.
Recent developments seem to slightly improve this situation: R7s LED models are now offered with 360° light emission, a diameter of 29 mm (some with 20 mm), and an efficacy up to 115 lm/W, but lumen output is still low compared to the halogen lamps they aim to replace.

Mains-voltage halogen capsules with G9 cap

For MV HL capsules with G9 cap, the space available for a LED control gear and for cooling is extremely limited. As a consequence, all LED retrofits are more bulky than the halogen capsules they aim to replace, and in some luminaires this might cause geometric lock-in problems. Major lamp suppliers offer only low lumen LED retrofit lamps (up to 200 lm). Higher lumen models are available from smaller brands (up to 480 lm). Some are advertised as replacements for 50W halogen lamps, but they have only about half the lumens of these lamps.

Low-voltage halogen capsules with G4 or GY6.35 cap

LV HL capsules with G4 or GY6.35 cap: Especially the higher lumen LED retrofits available today (Q1/2015) have slightly larger outer dimensions than the existing halogen lamps. In some luminaires this might cause geometric lock-in problems. High lumen output lamps are only available from new brands on the market, not from major lamp manufacturers. In addition the LED lamps that are advertised as substitute for 35 and 50W halogen lamps usually have considerably lower lumen output.

Other halogen lamps, non-halogen filament (GLS) lamps and CFLi’s

For all other halogen lamps, non-halogen filament (GLS) lamps, and CFLs with integrated ballast, broadly equivalent and affordable LED retrofit lamps are generally available on the market, at least up to capacities of 1000 lm.

As regards non-directional lamps the situation is assumed to be known considering the recent 244/2009 Stage 6 discussion, and consequently no summary is provided here (see par. 5.13.3).

As regards mains voltage directional filament lamps and their LED retrofits, the study team will issue a separate report [8], in the context of the market assessment for Stage 3 of Regulation (EU) No. 1194/2012 (see also par. 5.13.4 and 5.14.3).

[8] Market assessment on directional mains voltage filament lamps related to stage 3 of Commission Regulation (EU) No. 1194/2012, VHK for the European Commission, to be issued.

LED manufacturing

The report provides a short description of the manufacturing steps for a typical LED package.

Packaging weight and volume

The primary packaging for lamps is typically a box (paper-based material) or a blister (PET plastic, sometimes combined with paper-based material). Secondary and shipping packaging is typically a corrugated fibreboard box. Considering all packaging levels, it is estimated that 90% of the packaging material is paper-based and 10% PET.

From detailed information supplied by a LED lamp manufacturer, the study team derived relationships between the net lamp enveloping box volume, the gross per-lamp shipping volume and the gross per-lamp packaging weight. These relationships have been used as an indication for the input of related data in the EcoReports.

As regards packaging, the following conclusions can be drawn:

- For small light sources like MR16 and candle-lights, the (net) volume of a rectangular box enveloping the lamp is 0.12-0.19 dm^3.
- For medium size sources like LED bulbs and PAR20, the (net) volume of a rectangular box enveloping the lamp is 0.34-0.46 dm^3.
- For large sources like PAR30 and PAR38, the (net) volume of a rectangular box enveloping the lamp is 1-2 dm^3.
- For small and medium sized light sources with a primary package box, the gross shipment volume per lamp can be 2 to 3 times higher than the net volume. For large lamps this is around 1.5 times.
- Lamps using blisters as primary package can have a gross shipment volume that is from 5 to 9 times their net volume.

- The primary packaging weight is around 12-23 g for small lamps, 20-37 g for medium size lamps, and 70 to 120 g for large lamps. Blisters tend to be heavier than boxes.
- The total packaging weight per lamp (including also the corresponding portion of secondary and tertiary packaging) is typically 2 to 3 times higher than the weight of the primary packaging.

Bill-of-materials

Paragraph 6.3 provides a bill-of-materials (BoM) for each base case distinguished in this study, usually based on references from literature. These BoM's will be used as input for the EcoReports in Task 5. Stakeholders are invited to verify the accuracy of these BoM's.

As regards the BoM for LED retrofit lamps, in the modelling these lamps will substitute less efficient non-LED lamps (from the other base cases, with known average lumens) on the basis of an approximate lumen equivalence. Therefore a bill-of-materials for LED retrofit lamps per unit of lumen, i.e. per 1000 lm (klm), has been developed. This BoM will then be scaled in function of the lumens of the lamp that is being substituted.

As a first step, a research has been conducted to establish the net lamp weight for such a 1000 lm LED retrofit lamp. This resulted in a weight of 150 g/klm. In a next step this weight was subdivided over the various materials, using six reference BoM's from literature and from own weight measurements on a LED filament lamp. The resulting BoM is shown in Table 2. Around 43% of the weight comes from the aluminium heat sink, and another 16% from the control gear. The actual emitters (LED die, filament, package, array) account for only 2.5% of the lamp weight.

Table 2: Bill-of-Materials for a 1000 lm LED retrofit lamp with integrated control gear.

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Lens or Bulb (glass)	8.592	7-Misc.	55 -Glass for lamps	
Lens or Bulb (plastic, PC)	6.397	2-TecPlastics	13 -PC	Yes
LED (filament, die, array)	3.728	6-Electronics	49 -SMD/ LED's avg.	
Heat sink (aluminium)	64.961	4-Non-ferro	28 -Al diecast	
Heat sink (local, copper)	2.896	4-Non-ferro	32 -CuZn38 cast	
Control gear (electronics, PCB)	23.206	6-Electronics	50 -PWB 1/2 lay 3.75kg/m2	
Cap / Fitting / Electrical contact	6.970	4-Non-ferro	31 -Cu tube/sheet	
Housing/Base (porcelain, glass)	7.405	7-Misc.	55 -Glass for lamps	
Housing/Base (plastic, acrylic, PC)	10.099	2-TecPlastics	13 -PC	Yes
Housing/Base (potting resin)	13.116	2-TecPlastics	15 -Epoxy	
Other metals (ferrous)	0.540	3-Ferro	24 -Cast iron	
Other metals (non-ferrous)	2.028	4-Non-ferro	27 -Al sheet/extrusion	
Solder paste	0.061	6-Electronics	53 -Solder SnAg4Cu0.5	
Subtotal lamp	150.000			
packaging cardboard/paper	36.000	7-Misc.	57 -Cardboard	
packaging plastic	4.000	1-BlkPlastics	10 -PET	Yes

The report also presents a material breakdown for a LED package. The package mass of 151 mg (for approximately 75 lm) derives for 39% from anode, cathode and copper frame, for 33% from plastic housing, for 16% from the local heat sink, and for 11% from the silicon lens. The die weight of 1 mg accounts for only 0.7% of the package weight. Only 3% of this die weight is used for semiconductor material, of which 83% gallium.

End-of-life

Incandescent lamps (GLS) and halogen lamps are normally not separately collected and recycled. It is therefore assumed in the EcoReport inputs that these lamps will end up in an incinerator or a landfill as mixed domestic waste.

As regards discharge lamps (CFL, LFL, HID), the information from the Task 3 report is used, i.e. 30% is collected of which 80% is recycled.

LED lighting products have only recently been introduced on the market and they have a long lifetime, so there are no significant waste volumes yet. In principle they have to be separately collected, just as all other products under the WEEE directive (Task 3 report), but no specific data on collection and recycling percentages are available.
For the moment, for the modelling in the EcoReport, the same percentages are assumed as for the discharge lamps.

As regards packaging materials, according to Eurostat in 2012 in the EU-28, 64.6% of the package waste was recycled. This percentage will be assumed in the EcoReports.

1. Introduction

This document covers MEErP Task 4 and deals with technology aspects of light sources. It consists of two major parts:

- Technical product descriptions, including:

- 'base case' (BC) products (average products on the market),
- 'best available technology' (BAT) products,
- 'best non-available technology' (BNAT) products.

- Production, distribution and end-of-life, including:

- product weight and 'bill of materials' (BoM),
- packaging and distribution information,
- materials flow and collection efforts at end-of-life (EoL).

For further information on the meaning and use of BC, BAT, BNAT and BoM in an ecodesign preparatory study, see Annex B and the MEErP [9].

1.1. Base cases for light sources

Although the final definition of base cases [10] is part of MEErP Task 5, they have already been preliminarily established as those for which the average product characteristics have been presented in the Task 2 and Task 3 reports (from the MELISA model). This subdivision in base cases essentially derives from the subdivision that is used in standards, in Eurostat, and in the sales data received by the study team from LightingEurope. These base cases are recalled in Table 3.

LED lamps are now divided only in directional and non-directional, while no distinction has been made between LED retrofit lamps and integrated LED luminaires. This latter split up may be necessary for a good scenario modelling in Task 7.

1.2. Changes in efficacy and sales in scenarios

In all ecodesign preparatory studies the improvement options for the BC's are studied in a Business-as-Usual (BaU) reference scenario and in one or more alternative scenarios that each examine a set of policy options (ECO-scenarios).

In these BaU and ECO scenarios the sales levels for each BC usually vary with time, but are the same in all scenarios. The scenarios typically differ only in how the average energy efficiency of the BC changes with the years.

For light sources the situation is different: for all BC's except LEDs (i.e. LFL, CFL, HL, GLS, HID) no significant future changes in efficacy are expected [11], while the improvements derive from a shift in sales from the less efficient BC's to the more

[9] MEErP 2011, Methodology for Ecodesign of Energy-related Products, part 1: Methods and part 2: Environmental policies and data, René Kemna (VHK) November 28th 2011, in particular chapters 4 and 5

[10] Base cases are (fictitious) products with average characteristics that are representative for a group of products for the entire EU-28.

[11] Some efficacy improvements might still be technically feasible for some of the lamp types, but manufacturers are no longer investing in their development, as they are placing all resources on LEDs and OLEDs.

efficient BC's. This implies that the BaU and ECO scenarios will differ mainly in the sales assumptions, while for most BC's the efficacy is constant in time and identical for the BaU and ECO scenario. Only for LED lighting the efficacy will evolve with the years, and there might be slight differences between the scenarios as regards the speed of change of the LED efficacy (if this is assumed to depend on policy measures).

Table 3: Base cases discussed in this report

Main type	Acronym	Base case description
Linear fluorescent lamps	LFL T12	T12
	LFL T8h	T8 halophosphor
	LFL T8t	T8 tri-phosphor
	LFL T5	T5 new (14 - 80w) including circular
	LFL X	All other LFL (including T5 old types 4 - 13w and special FL)
Compact fluorescent lamps	CFL i	with integrated ballast (retrofit for GLS)
	CFL ni	without integrated ballast (non-retrofit)
Halogen lamps	HL LV R	Low voltage, mirrored [M16, M25 etc.]
	HL LV C	Low voltage, halogen capsule [G4, GY6.35]
	HL MV C	Mains voltage, halogen capsule [G9]
	HL MV L	Mains voltage, linear, double-ended [R7s]
	HL MV E	Mains voltage, substitute for GLS and reflector [E14, E27]
	HL MV X	Mains voltage, other, PAR 16/20/25/30 Hard glass reflectors, GU10 etc.
Incandescent lamps	GLS R	Non-halogen incandescent lamp, Reflector
	GLS X	Non-halogen incandescent lamp, Other, including clear/pearl, candles, coloured & decorative)
High intensity discharge lamps	HPM	All mercury lamps (including mixed)
	HPS	All sodium lamps
	MH	Metal halide lamps
Light emitting diode lamps	LED D	LED directional
	LED ND	LED non-directional

1.3. Remarks regarding the technical product descriptions

Considering the above, the following remarks can be made regarding the information to be provided by the technical product descriptions:

A. The average EU-28 characteristics of the products currently on the market have to be established for each BC. This has mainly been done in the Task 2 and Task 3 reports where MELISA data have been reported, but for convenience the main parameters will be summarized here per base case, also in the view of facilitating the compilation of the EcoReports in Task 5. Year 2013 will be used as a reference, being the most recent year for which data are available.

B. The rate of improvement of LED lamps has to be addressed, at least as regards efficacy increase and price decrease, but also other parameters might be relevant, e.g. colour quality, lifetime, dimmability. To some extent the rate of improvement of LED lamps sold in the EU-28 might also depend on policy measures, but that aspect will be treated in later tasks.

C. The speed with which sales will shift from BC's with lower efficacy to BC's with higher efficacy has to be studied. This also depends on non-technical factors, e.g. policy measures, but the technical aspects that influence this shift will be discussed in this report. As the shift in sales may be different for each base case, this is analysed for each base case separately.

D. The main shift in sales is expected to be from non-LED BC's to LED. However, in nearby years also other shifts can still be relevant, e.g. from GLS to HL or CFLi, or from LFL T8 to LFL T5.

E. The shift in sales towards LED can involve only light source substitution (LED retrofit solution) or substitution of the entire luminaire (integrated LED luminaires; dedicated LED solution). Although luminaires would be in the scope of the current study mainly as regards their compatibility with the light sources, the shift towards integrated LED luminaires cannot be ignored in the scenario analyses of Task 7 and thus has to be taken into account here as part of the technical description. Considering integrated LED luminaires raises specific problems as regards pricing and the bill-of-materials (see notes in par. 5.1).

F. The shift in sales towards LED poses specific technical issues for lamps operating on external ballasts, as these existing ballasts may not be compatible with the LED control gears.

G. For some types of lamps represented by the non-LED BC's there may not be a suitable LED substitute on the market yet (see details in chapter 5). This can have an impact on the shift in sales and hence is an aspect to be considered.

H. The shift in sales towards LED may differ per sector or per type of application, e.g. retailers might be more sensitive than households to replacing their halogen spots by LEDs.

I. Theoretically each non-LED base case could be conceived to have two types of BAT solutions:
   - one maintaining the same basic technology, e.g. BC LFL T8 lamp (average of the market) vs. BAT LFL T8 lamp (best on the market),
   - another changing the technology, e.g. BC LFL T8 lamp vs. BAT LED tube.

   Where relevant, both must be considered.

1.4. Guide to the report

Chapters 2 through 4 concern lighting technologies that are still under development and that typically show yearly improvements in their energy efficacy and in other parameters, such as LED and OLED [12]. These technologies provide, or will provide in the nearby future, the BAT- and BNAT-solutions for the substitution of the classical lighting technologies.

Chapter 2 is dedicated to LED technology. LED lighting solutions will appear as improvement option for many classic lighting technologies. It is therefore convenient to handle them centrally, thus avoiding repetition. The discussion in this chapter is generic on the technology, without reference to specific applications. Aspects that are specific for a certain base case will be presented in chapter 5.

[12] In this report the term LED is used to indicate inorganic LEDs, as opposed to the term OLED that indicates organic LEDs. This use of the term LED is quite common but it may differ from definitions in some standards and regulations, where the term groups all light emitting diodes, inorganic and organic.

As outlined in chapter 1, an important issue is establishing, and agreeing upon, a time-line for LED improvements, especially as regards efficacy increases and price decreases.

Chapter 3 describes other developing lighting technologies, amongst which the OLED and laser-diode technologies. These lamp types will not be further considered in this study, and consequently their description is short.

Chapter 4 deals with so called ‘Smart lamps’. This is not a separate lighting technology (most are based on LED technology), but it is felt that they could play a significant role in the context of the substitution of less energy efficient lamps by more energy efficient lamps. Smart lamps have different features and will most likely have different prices, different efficacies, and different associated regulation problems as compared to ‘normal’ LED lamps, and for this reason they are discussed separately.

Chapter 5 provides technology descriptions for each base case of Table 3. For each base case the current average characteristics (BC), the improvement options, the BAT and the BNAT are discussed. Special cases for which no adequate LED-substitution is available will be identified where applicable. As regards the technology descriptions for the non-LED lamps, there is little news and this is generally assumed to be known, but in some cases a summary of other recent documents is provided.

Chapter 6 is dedicated to production, distribution and packaging, end-of-life, and the bill-of-materials.

2. LED lighting technical description and time-line

2.1. Introduction

The aim of the following explanation of the basics of LED lighting and of the structure of LED light sources is to enable an understanding of the various types of LEDs, of the recent developments, and of the possibilities for improvements. This is intended as background information for the LED-timeline. In addition the paragraph introduces the types of materials used, as background information for the bill-of-materials presented in chapter 6.

The focus of the description is on white light emitting LEDs, as these play a central role in general illumination applications. These LEDs are realized using very different methods, materials and processes, resulting in a broad range of different properties. The technology is still evolving rapidly and therefore the methods and materials used today could be outdated and outperformed in the (nearby) future. A lot of intellectual property is involved in manufacturing LED components. For example on 1 December 2014 , the European Patent Register [13] reported 13407 patents filed related to keywords 'LED, component'. It is therefore impossible, in the context of this report, to cover all technologies and the related patents that are being developed or already present on the market.

The study team made a selection of what it believes to be the most relevant points, but anyway the description will be far from exhaustive, and may soon be outdated.

2.2. LED basics: the p-n junction, chip/die level

2.2.1. Principle and semiconductor materials

A light emitting diode (LED) is defined by IEC 62504 [14] as a 'solid state device embodying a p-n junction, emitting incoherent optical radiation when excited by an electric current'.

The p-n junction is created in a semiconductor material, that can be based on inorganic crystalline metals or on organic molecules. The description in this chapter is limited to the inorganic type (commonly referred to as LED), while the organic type (OLED) is handled in paragraph 3.1.

For the creation of the p-n junction, the semiconductor material is doped with two types of impurities:

- One that creates a layer with an excess of electrons, that consequently has a negative charge and forms the n-part of the junction. Electrons in this zone can be conceived to be on a high energy level, also referred to as 'conduction band'.

- Another that creates an adjacent 'hole-rich' layer with a deficit of electrons, that consequently has a positive charge and forms the p-part of the junction. Electrons in this zone can be conceived to be on a low energy level, also referred to as 'valence band'.

The difference between the two energy levels is called the 'bandgap' (Figure 3).

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[13] http://worldwide.espacenet.com/?locale=en_EP

[14] IEC FDIS 62504, 'General Lighting – Light Emitting Diode (LED) products and related equipment – Terms and Definitions', IEC 2014 (final draft International Standard, version submitted for voting).

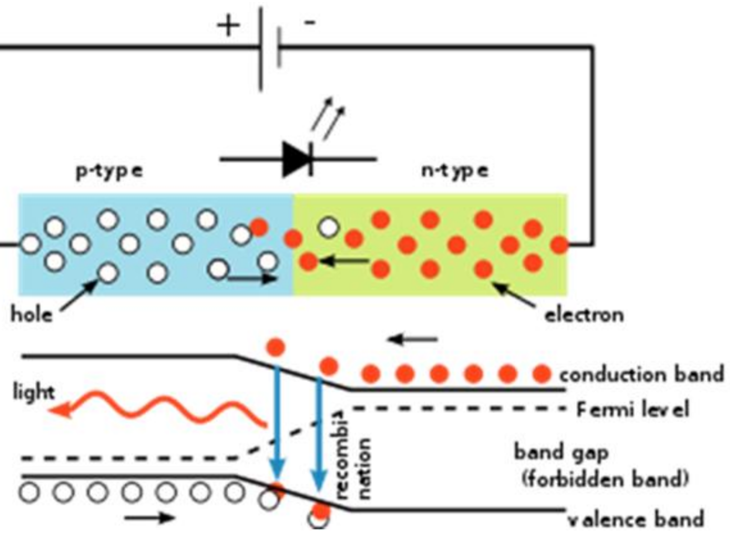

Figure 3: LED principle of operation (source: [15]). The figure is schematic; in reality the n- and p-type layers are very thin (from some microns to tens of microns) and in-plane dimensions are much larger than the thickness. In addition a third 'active layer' is usually present between the n- and p-layers.

When the p-n junction is attached to external electrodes with different voltages [16], electrons and holes will flow into the junction from opposite sides. When they meet, the electron will fall from the higher to the lower energy level, emitting the energy difference as a photon that has an energy corresponding to the bandgap [17]. The energy of the photon determines the wavelength (colour) of the emitted light.

The bandgap of the p-n junction and hence the colour of the emitted light depends on the type of semiconductor material and on the type and concentration of the dopants used. The semiconductor material used for LED light sources is usually a combination of elements from groups III and V of the periodic table. The main group III element is gallium (Ga), often mixed with aluminium (Al) and/or indium (In). The group V elements frequently used include nitrogen (N), arsenic (As) and phosphor (P). Examples of semiconductor materials that can be used are shown in Table 4.

The vast majority of white light LEDs manufactured today are based on a blue-emitting gallium nitride (GaN) or indium gallium nitride (InGaN) LED source (used in combination with a yellow-emitting cerium-doped yttrium aluminium garnet (Ce3+ YAG) phosphor to convert the blue light to white, see par. 2.3. One possibility is to use silicon tetrahydride (SiH_4) to provide the electron-donating Si-dopant for the n-layer and trimethyl aluminium to provide the Al-dopant for the p-layer [18].

Other semiconductor materials that can be considered for blue-emitting LEDs are based on zinc-oxide, zinc-selenide, silicon, or silicon-carbide, but they are in the research stage [19].

US DoE [21] indicates semiconductor materials as a core technology research priority task.

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[15] http://en.wikipedia.org/wiki/Light-emitting_diode

[16] The required voltage difference can vary from 1.6 to 4.4 V, depending on the semiconductor material and dopants used; typically it is around 3 V.

[17] A wider bandgap corresponds to a higher photon energy and thus to a shorter wavelength (towards the blue side of the spectrum)

Table 4: Colour of emitted LED light and examples of semiconductor materials used (Sources: [18] [19] [20]).

Colour	Wavelength	Semiconductor materials
infrared	850-940 nm	GaAs, AlGaAs
red	630-660 nm	AlGaAs, GaAsP, GaP
amber	605-620 nm	GaAsP, AlGaInP
yellow	585-595 nm	AlGaP, GaAsP, GaP
green	550-570 nm	AlGaP, GaN
blue	430-505 nm	InGaN, GaN
ultraviolet	370-400 nm	InGaN, AlGaN

2.2.2. Light extraction and heating problem

An important characteristic of most semiconductor materials used for LEDs is that they have a high refractive index as compared to air. This implies that photons emitted under a high angle with the normal to the plane of the layers will be reflected on the semiconductor-air interface and thus will not be able to leave the material. Consequently only a part of the generated light is able to leave the LED (which is obviously bad for the efficacy) and the light that is able to escape is confined in a cone with a relatively small angle around the normal to the plane, i.e. LED light is inherently directional.

The light that is not able to leave the semiconductor material, because of reflections on its surface, will eventually be transformed into heat. As a protection against overheating, and to avoid the efficacy deterioration at higher temperatures, the LED current is limited, and a good thermal design is necessary such that the heat can flow away, mainly by means of conduction. Different from other lighting technologies, LEDs can dissipate only a minor part of their heat as part of the emitted radiation.

The light extraction problem and related heating problem can be (partially) resolved by texturing the semiconductor surfaces, i.e. creating facets under different angles so that more photons can eventually escape, or by using intermediate layers, with suitable refractive index, between the semiconductor material and the air. These encapsulation layers (see par.2.4) increase the amount of light leaving the LED and can also function as lens or light diffuser.

2.2.3. Efficiencies related to the LED-chip

In subsequent paragraphs frequent reference will be made to the US DoE multi-year program plan 2014 [21] as regards the efficacy developments of LED light sources. For a better understanding of those data and of the improvement options for LEDs, the partial

[18] Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance, US DoE, June 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf

[19] Expertise Leuchtdioden, umwelt-, gesundheits- und verbraucherrelevante Aspekte von Leuchtmitteln auf basis von LED, Institut für Ökologie und Politik GmbH, August 2013 (in german)

[20] http://en.wikipedia.org/wiki/Light-emitting_diode

[21] Solid-State Lighting Research and Development, Multi-Year Program Plan, US DoE, May 2014, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf

efficiencies related to the semiconductor material (LED-chip/die level) are explained below (Figure 4).

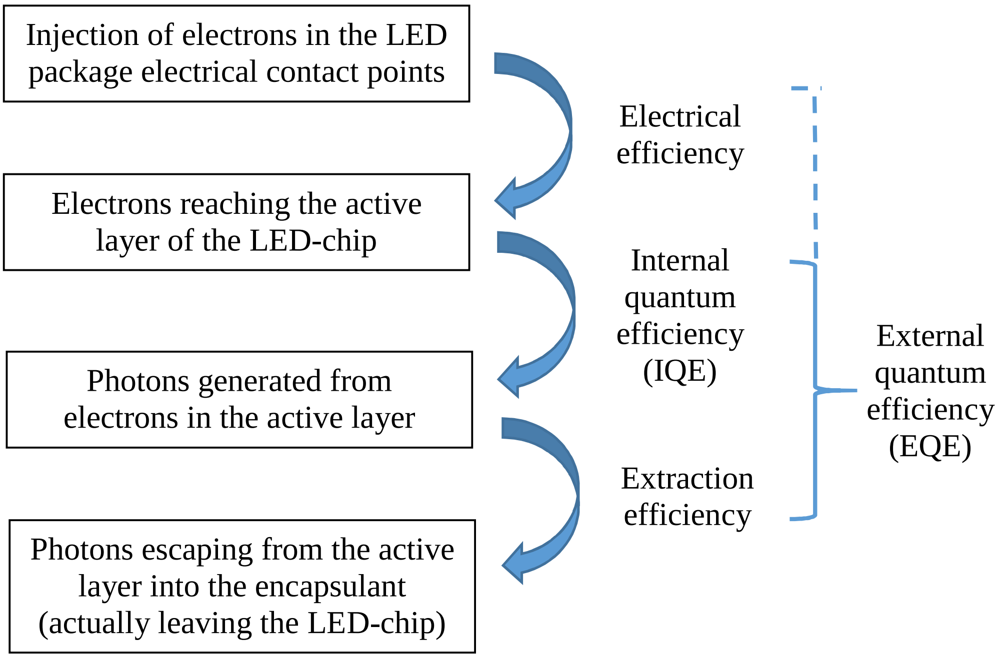

Figure 4: Partial efficiencies related to the LED-chip. Note that in some literature sources the electrical efficiency (or injection efficiency) is also considered part of the external quantum efficiency.

Electrical efficiency (also referred to as injection efficiency [22] [23])
This accounts for the efficiency with which electrical charge carriers injected into the LED package find their way to the active region of the LED device. Ohmic (resistive) losses associated with the semiconductor layers and the LED package materials represent the most important loss mechanism. A reduction in electrical efficiency is associated with an increase in the energy (voltage) required to create photons over and above the intrinsic band-gap energy (voltage) of the semiconductor active region.

Internal Quantum Efficiency (IQE, also referred to as radiative efficiency)
The electrons/holes that are injected in the p-n junction do not always lead to an electron-hole recombination that emits a photon. The ratio of the photons emitted from the active region of the semiconductor chip to the number of electrons injected into the active region, is called the internal quantum efficiency. It depends mainly on the type of semiconductor material, on its purity (absence of unwanted elements), and on the presence of imperfections in the crystal structure.

Light extraction efficiency (also referred to as optical efficiency [23])
This is the ratio of photons emitted from the semiconductor chip into the encapsulant to the total number of photons generated in the active region. This includes the effect

[22] Note that this efficiency is not strictly related to the LED-chip but also involves the current paths on the LED-package
[23] http://www.ledsmagazine.com/articles/2004/01/terminology-led-efficiency.html. For this article the injection efficiency is part of the EQE, but for US DoE the electrical efficiency is NOT part of the EQE.

of power reflected back into the chip because of index of refraction difference, but excludes losses related to phosphor conversion (see par.2.3).

External Quantum Efficiency (EQE)
This is the ratio of extracted photons to injected electrons. It is the product of the IQE and the extraction efficiency (and for some authors of the electrical efficiency). It expresses how efficiently the device converts electrons to photons and allows them to escape.

Blue LEDs currently have the highest efficiencies, while amber and green LEDs exhibit low efficiencies, see details in par. 2.5.

2.2.4. Current droop

Current droop is the decrease in the electron/hole-to-photon conversion efficiency of LEDs at high current densities. It is considered to be a reduction in the IQE, but usually characterised by means of EQE measurements.
The effects of current droop on the IQE are significant. In the US DoE MYPP 2014 [21] efficacies are defined at 25˚C and at a current density of 35 A/cm^2, but the authors observe that reducing the operating current of the LEDs to minimize current droop might lead to a 15-20% increase in efficacy.
The existence of current droop leads LED lamp manufacturers to operate the LED chips at low current densities so that a high efficacy (lm/W) can be maintained. However, this increases the number of LED chips that is necessary to reach a given lumen output and thus increases the cost of the lamp [24].
After years of research, the cause of the current droop phenomenon seems to have been identified in the Auger recombination effect. Under this effect the recombination of an electron-hole pair does not create a photon but transfers kinetic energy to another electron, that escapes from the active layer (current leakage) and is eventually dissipated as heat in the LED chip [24].
In the US DoE mypp 2014 [21] the EQE current droop represents the difference in EQE (at 25°C) between the peak value, typically occurring at very low current density, and that reported at a nominal current density of 35 A/cm^2.
Reducing the sensitivity of the internal quantum efficiency (IQE) to the current density (i.e., current droop) is a significant opportunity for improved efficacy and cost reduction.

2.2.5. Temperature effects

An increase in LED operating temperature, as will typically occur in a lamp or luminaire, leads to a reduction in the lumen output and in the efficacy.
US DoE [21] reports that many LED packages are now routinely measured at 85°C, to be closer to the device operating temperature, and that they typically exhibit a 10 to 13 percent reduction in efficacy over 25°C operation.

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[24] Auger identified as main cause of efficiency droop in LEDs, Justin Iveland et al, June 2014, http://spie.org/x108666.xml, see also: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/weisbuch_droop_tampa2014.pdf

Meyaard et al [25] report a 30% reduction in the peak EQE value (at low current density) when passing from an ambient temperature of 300 K to 450 K. This implies -0.2%/K and is close to the US DoE value.

Meyaard also observes that the temperature effect on efficiency (T-droop) can be more detrimental than the current density effect (J-droop), but that the former has received far less attention in research and that there is still a lack of understanding. He further states that one of the technology trends is to increase the chip size, thus decreasing the current density to minimize the J-droop. However, his research shows that increasing the chip size degrades the temperature-dependent performance of the LEDs (see graphs in the reference).

Reducing the thermal sensitivity of LED packages would allow the LEDs to be driven harder and thus emit more light without compromising efficacy. Lowering the operating temperature would also have beneficial effects on LED lifetime (see par. 2.8).

2.2.6. Substrates

The p-n (and other) layers of the led chip/die are created on a substrate using a process called epitaxy. Gallium nitride (GaN) LEDs, which are commonly used as the light source for white light LEDs (par. 2.5), can be grown on a range of different substrates, including sapphire, silicon carbide (SiC), bulk GaN, silicon, germanium, borosilicate glass, poly-crystal aluminium nitride (AlN), zinc oxide and diamond. Of these, the one most commonly used for growing GaN LEDs is sapphire. It is estimated that more than 80 percent of today's LEDs are built on a sapphire substrate [18] [26].

One of the drawbacks of a sapphire substrate is that its crystal structure does not match very well that of GaN, resulting in microscopic flaws that may affect LED luminosity and lifetime [27]. From this point of view SiC offers advantages.

Proponents of GaN-on-GaN believe that such LEDs produce more and higher-quality light, while gallium-nitride-on-silicon (GaN-on-Si) proponents believe that this technology can significantly reduce component cost. However, GaN-on-GaN remains more expensive than GaN-on-sapphire or GaN-on-SiC in mainstream LEDs, and GaN-on-Si has yet to deliver comparable performance to legacy LEDs [28].

LEDinside [26] observes that Si- and GaN-substrates have the ability to combine electrical parts and LED optical parts, potentially increasing product efficiency, but that the technologies are still costly and in the development stage (end 2013).

Soraa [29] claims to be the only manufacturer using GaN-on-GaN, while Cree seems to prefer SiC substrates [30]. Philips Lumileds seems to use predominantly sapphire.

The epitaxial growth of layers is not performed die-per-die, but on a larger wafer. Once the process is finished this wafer is 'cut' into the single dies. US DoE [18], citing a Yole research, clarifies that in 2010 59% of the wafers was 2" diameter, in 2012/2013 53% of the wafers was 3", while for 2015 it is expected that 55% of the wafers will have a

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[25] http://ecse.rpi.edu/~schubert/Reprints/2012-Meyaard-David-et-al-%28APL%29-Temperature-dependent-efficiency-droop-in-GaInN-LEDs-with-different-current-densities.pdf

[26] http://www.ledinside.com/outlook/2013/12/sapphire_substrate_to_dominate_led_market_in_2014

[27] http://www.digikey.com/en/articles/techzone/2013/sep/will-silicon-substrates-push-led-lighting-into-the-mainstream

[28] http://www.ledsmagazine.com/articles/print/volume-11/issue-9/features/sil-japan-2014/sil-japan-speakers-explore-the-ssl-frontier-beyond-lumens-per-watt.html

[29] Soraa, an SSL manufacturer, has an explicit vision on this: http://www.soraa.com/about.

[30] http://www.cree.com/LED-Chips-and-Materials

diameter of 6" (150 mm). The increase in wafer size enables a cost reduction, and a production capacity increase [31].

The materials and processes involved in the epitaxy and in the post-processing of GaN-on-sapphire wafers are described in detail in [18], to which the reader is referred.

In the past, the substrate was used only during the epitaxial growth process and then removed after completion of the LED-chip, with the need to mount the chip on another support to enable its further handling. However, in recent flip-chip packages it is sometimes maintained and thus plays a direct role in the efficiency assessment. In this case a patterned sapphire substrate (PSS) has to be used to obtain a sufficient light extraction efficiency (par. 2.2.2, Figure 5). The PSS-approach avoids some of the traditional processing steps and thus permits cost savings.

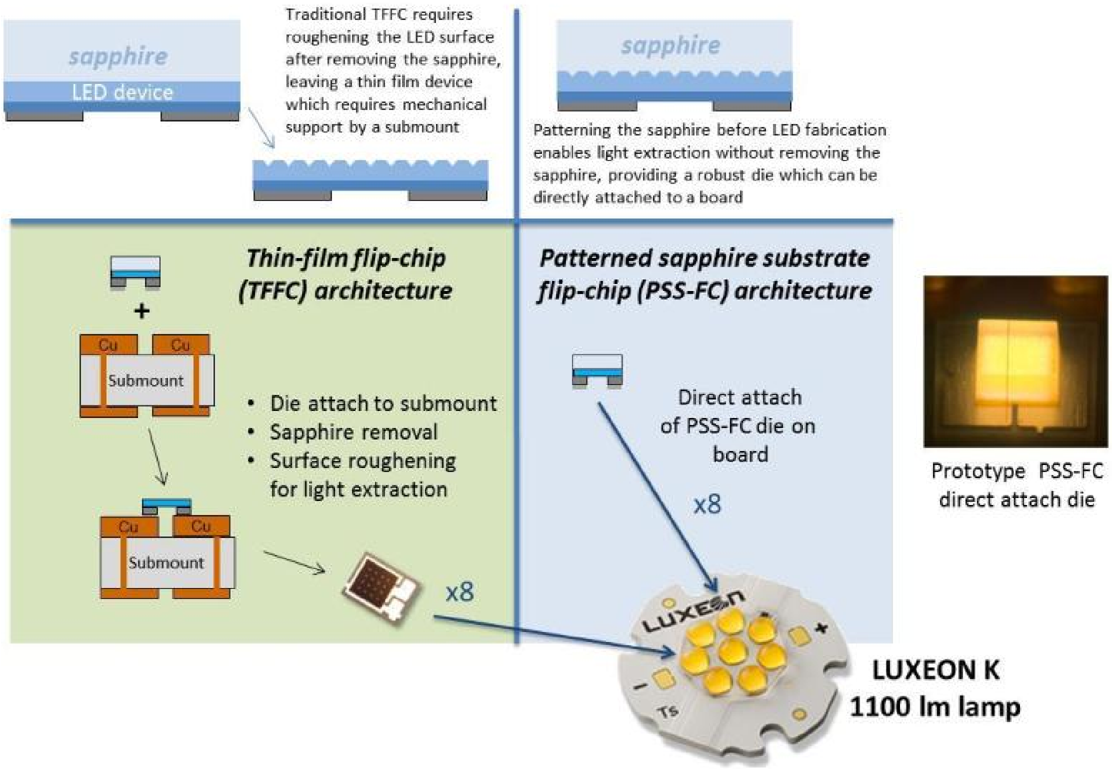

Figure 5: Comparison of the current thin-film flip-chip (TFFC) manufacturing approach with the patterned sapphire substrate (PSS) approach (Source: [32], original source: Joseph Flemish, Philips Lumileds)

2.3. Conversion of light colour using phosphors

As announced in par. 2.2.1 and further discussed in par. 2.5, one of the possibilities to create white light from a blue- or UV- LED is to use light (down-)conversion by means

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[31] http://www.ledsmagazine.com/articles/2010/12/philips-lumileds-mass-producing-leds-on-150-mm-wafers.html

[32] "Manufacturing Roadmap, Solid-State Lighting Research and Development, US DoE August 2014, Prepared by Bardsley Consulting, Navigant Consulting, SB Consulting, and SSLS, Inc., http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf

of phosphors [33]. This is the same principle that is applied e.g. in fluorescent lighting (LFL and CFL) and in mercury lamps (HPM).

2.3.1. Phosphor Basics

Generally speaking, a phosphor is a material that exhibits the phenomenon of luminescence. Somewhat confusingly, this includes both phosphorescent materials, (slow decay in brightness, > 1 ms), and fluorescent materials (fast decay in brightness, tens of nanoseconds). For application to LEDs the fluorescent materials are relevant [34].

Without entering into details, and considerably simplifying the real mechanisms, the LED-emitted photons falling on a phosphor excite the electrons in the material, i.e. bring them to a higher energy level. They stay there for a very short time and then fall back to a lower energy level, emitting a photon. The emitted photon will typically be of a higher wavelength than the received photon so that the colour of the emitted light is shifted towards red with respect to the received light. The shift in wavelength is determined by the type of phosphor material used and by its dopants.

The phosphor can be applied directly on top of the LED chip, integrated in the resin of the encapsulant/optics, or be applied remotely, for example on the glass envelope.

2.3.2. Phosphor efficiencies

The light conversion by phosphors entails losses. Not every photon received leads to a photon emitted, and this is expressed by the quantum efficiency of the phosphor. This is a measure of the total output photon energy from the phosphor compared to the input photon energy from the LED. In addition the emitted photon typically has a higher wavelength and therefore a lower energy than the received photon and this gives the so called Stokes' losses. All losses in some way become heat.
Examples of phosphor efficiencies are provided in par. 2.5.3.

2.3.3. Typical phosphors for general lighting purposes

Halophosphate LFL's (now phased out) used a phosphor with chemical formula $Ca_5(PO_4)_3(F,Cl):Sb^{3+},Mn^{2+}$. This phosphor mainly emits yellow and blue light, and relatively little green and red. In the absence of a reference, this mixture appears white to the eye, but the light has an incomplete spectrum, is often perceived as unpleasant, and does not faithfully render colours. The CRI of such lamps is typically around 60 [35].

Modern tri-phosphor LFL's employ a combination of three phosphors, emitting respectively in the blue, green and orange-red wavelengths (Table 5). This type of phosphor considerably improves colour rendering, with CRI ranging from 82 to nearly 100 [35]. Mixing the three phosphor types in different proportions, different types of white light can be obtained, corresponding e.g. to colour temperatures of 3000 K, 4000 K or 6500 K [36].

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[33] Note that the phosphors discussed here have nothing to do with the chemical element phosphor (P): most phosphors do not contain this element.
[34] Text inspired by: http://en.wikipedia.org/wiki/Phosphor . This reference also provides a list of standard phosphors.
[35] http://en.wikipedia.org/wiki/Fluorescent_lamp#Phosphors_and_the_spectrum_of_emitted_light

Table 5: Phosphors used in modern tri-phosphor LFL's (Source: [36]).

Colour	Phosphor name	Chemical formula	Wavelength
Blue	Barium Aluminate (BAM)	$BaMg_2Al_{16}O_{27}:Eu^{2+}$	450 nm
or	SrCaBaMg Chloroapatite	$(Sr,Ca,Ba,Mg)_5(PO_4)_3Cl:Eu^{2+}$	453 nm
Green	Calcium Tungstate (CAT)	$Ce_{0.65}Tb_{0.35}MgAl_{11}O_{19}$	543 nm
or	Lanthanum Phosphate (LAP)	$LaPO_4:Ce^{3+}Tb^{3+}$	544 nm
Orange-Red	Yttrium Oxide (YOX)	Y_2O_3: Eu^{3+}	611 nm

Modern blue LED lights often use cerium doped yttrium aluminium garnet (YAG, $Y_3Al_5O_{12}:Ce^{3+}$) as a phosphor to obtain white light. This phosphor is tuned to make a well-defined small part of the blue light pass while the largest part is converted to yellow light. The combination appears as white light to the observer.

As outlined in a Digi-key article [38], the YAG:Ce phosphor has several advantages:

- It is a proven technology with acceptable results and a benchmark for other LED phosphors.
- It has a fast 'decay time' (the time it takes for an electron that has absorbed a blue photon to "give up" the energy as a yellow photon and heat) and this prevents a phenomenon known as saturation quenching (normally emitted photons are "overwhelmed" and prevented from escaping by a high photon flux within the phosphor matrix).
- YAG strongly absorbs blue photons and has a high quantum efficiency (80%).
- There are no indications that YAG phosphor degrades under long-term blue LED excitation or exposure to moisture.
- The synthesis of YAG phosphor is relatively straightforward and uses the same high-purity precursors (Y_2O_3, Al_2O_3, CeO_2) that have been qualified for many years for use in traditional CRT phosphors.

However, it also has some weak points [38]:

- Temperature quenching: at elevated temperatures the electrons involved in absorbing blue photons and in emitting yellow photons can 'disappear' (ionization of the atoms). In YAG this occurs near 200˚C, which is quite close to normal LED operating temperatures.
- The chemical stability of YAG in harsh environments is under discussion and could limit the L70 lifetime of the LEDs.
- The colour temperature of the resulting light is relatively high [37] [38] [39], and the colour rendering index is rather low (CRI=70-80 [38]) due to the lack of red emission.

The CCT and CRI can be improved in several ways [38] [40] [41]:

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[36] http://www.lamptech.co.uk/Documents/FL%20Phosphors.htm , also provides the spectral power distributions.
[37] http://www.nae.edu/File.aspx?id=17158
[38] Phosphor Development Addresses Lower Efficacy of Warm-White LEDs, Steven Keeping, Digi-key article library, May 2014, http://www.digikey.com/en/articles/techzone/2014/may/phosphor-development-addresses-lower-efficacy-of-warm-white-leds
[39] Reference 37 states from 4000 to 7000 K; reference 38 reports from 5000 to 8300 K.
[40] Luminescence properties of YAG:Ce, Gd phosphors synthesized under vacuum condition and their white LED performances, Hongling Shi et al, Optical Materials Express, vol 4, no 4, p.649-655 (2014), http://www.opticsinfobase.org/ome/abstract.cfm?uri=ome-4-4-649
[41] Pr=Praseodymium (atomic number 59), Sm=Samarium (62), Eu=Europium (63), Tb=Terbium (65), Gd=Gadolinium (64), La=Lanthanum (57)

- Co-doping the YAG:Ce phosphor with the red-emitting ions Pr^{3+}, Sm^{3+} or Eu^{3+}, or
- Substituting the Y^{3+} with larger ions like Tb^{3+}, Gd^{3+} or La^{3+}.
- Using UV-LEDs instead of blue-LEDs.

However, adding a 'red' phosphor to the YAG:Ce reduces the efficacy [42] and further reduces the temperature at which quenching can occur [38]. Therefore manufacturers have been searching for new materials, and nitride or oxynitride doped with europium seems to be an interesting possibility.

As stated in the Digi-key article [18]:" One family of efficient oxynitride phosphors is the MSi2O2N2:Eu^{2+} (where M = Ca^{2+}, Sr^{2+}, Ba^{2+}) composition whose emission ranges from 575 to 675 nm with a quantum efficiency of greater than 85 percent at a temperature exceeding 200°C. The yellow, orange, and red Eu^{2+} emissions from these nitride phosphors can be combined with YAG:Ce for warm-white LEDs of higher efficacy than current commercial products. Phosphor blends of YAG:Ce and CaAlSiN3:Eu^{2+} combined with blue LEDs have already been used to manufacture high-CRI warm-white lamps."

US DoE [21] mentions phosphors among the core technology research priority tasks.

As shown in the chemical formula's above, phosphors contain rare earth elements (REE), which is a drawback for the LEDs that use them. As explained in par. 2.5, colour-mixing LEDs do not have this disadvantage [43].

2.4. Encapsulation and lenses

As indicated in par. 2.2 the encapsulation of the LED dies or chips has an important function in the light extraction efficiency. The encapsulant shall therefore have a refractive index that is compatible with the one of the semiconductor surface and that can enhance the extraction efficiency.

In addition the encapsulant has a general protective (sealing) function, to diminish the detrimental effects of environmental agents (moisture, pollution) on the semiconductor material. It can also have a support function, e.g. for the fragile gold bonding wires, or play a role in the thermal management or in the electrical insulation of the die.

Where phosphors are applied directly on the die (i.e. not remote on the glass envelope of the lamp), they can be dispersed inside the encapsulant.

In some designs lenses are applied on top of the encapsulant, or the latter is shaped directly in the form of a lens. These lenses have the function to diffuse the light or otherwise serve to obtain the desired (non-)directional light output. These primary lenses can be complemented by (or substituted by) secondary, remote lenses at luminaire or lamp level.

The encapsulation and lens material shall have (amongst others) the following characteristics:

- Suitable refraction index.
- Suitable thermal conduction coefficient.

[42] Reference 38 reports an example of a CREE lamp that has 135 lm/W in the cool-white version, but only 97 lm/W in the warm-white version. Other manufacturers' warm-white products exhibit similar lower efficacies compared with their cool-white devices.

[43] Christian Wetzel, Theeradetch Detchprohm (2014): 'Rare-Earth-Free Direct-Emitting Light-Emitting Diodes for Solid-State Lighting', IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 50, NO. 2, MARCH/APRIL 2014.

- Thermal expansion coefficient compatible with nearby materials (no introduction of thermo-mechanical stresses).
- Suitable electrical insulation properties.
- Good optical transmission (for the desired wavelengths).
- Maintenance of the optical characteristics with time (no yellowing or browning).
- No crack formation (during the production process, or with time)
- Resistance against maximum LED operating temperatures.
- Resistance against a high density blue- or UV-light flux.
- Low moisture absorption.
- Moldability in the desired shape, including micron-level detailed features, where needed.

Standard-LEDs use an epoxy resin as encapsulation and lens material, but higher quality LEDs usually apply a silicone-based material. Silicone has a better resistance against heat and against high-intensity blue light [19].

Dome type LEDs use epoxy resin while surface mount device (SMD) types use silicon. Epoxy was mainly used for low-brightness LEDs until 2010, but modern high-power LEDs typically use methyl silicone or hybrid (methyl and phenyl) silicone. In 2014 the market shares by weight were approximately 20% silicone and 80% epoxy [44] [45].

Silicone is a polymer compound that contains Si such as polysilylene, polycarbosilane or polysiloxane ($(R_2SiO)_n$). In particular the latter is often used for LEDs [44].

US DoE [21] confirms the use of silicone for encapsulation and lenses and observes that premium-grade silicone materials are very expensive and a significant cost factor in LED manufacturing. The major companies supplying LED-grade silicones are Dow Corning (US), Shin-Etsu (Japan) and Wacker Chemie (Europe).

US DoE mentions optical component materials among the core technology research tasks, but they are not indicated as a priority.

2.5. Different types of white LEDs

2.5.1. Survey of types

As was clarified in par. 2.2, the basic LED-chips emit a monochromatic colour in a narrow wavelength band. For general illumination purposes white light is typically requested and this can be obtained from the monochromatic LEDs in three different ways (Figure 6):

- Phosphor conversion or pc-LEDs:
  This solution uses a blue or near-ultraviolet LED and converts a part of the emitted light in yellow by means of YAG:Ce phosphors. This is the technique that is most widely used in LED light sources today. As explained in par. 2.3, the down-conversion of blue light into green, yellow and/or red by the phosphor entails quantum efficiency and Stokes' losses. These losses can be minimized by

[44] LED silicone encapsulant market to nearly double in size by 2017 compared to 2012, Richard Son, HIS, November 2013, https://technology.ihs.com/426144/

[45] These figures are NOT only for LEDs in general lighting applications but also include other applications such as backlighting units.

improvements in the phosphor technology, but they can never be avoided completely. Consequently, on the long term, pc-LEDs would be expected to have a lower overall efficacy than the cm-LEDs described at the next point. In addition the phosphors contain rare earth elements.

- Colour Mixing or cm-LEDs:
  This solution uses a blue, green and red LED together with a colour mixing optic. This is also referred to as an RGB-LED. As a variant, the colour amber can be added, which is then indicated as an RGBA-LED. This solution avoids the losses associated with the phosphors and potentially offers the highest efficacies for the future. However, as outlined by US DoE [18] there are some challenges in making cm-LEDs, such as multi-chip mounting and sophisticated optics and electronics for blending and maintaining the balance of colours.

- Hybrid solution:
  This solution combines a pc-LED with discrete-coloured LEDs to create the desired light output. It can be used for example to create light sources that can produce a range of white tones, from cool-white to warm-white, combining a cool-white pc-LED with yellow and red emitting LEDs and using consumer-controllable colour mixing. This solution would be expected to reach efficacies between those for pc-LEDs and cm-LEDs.

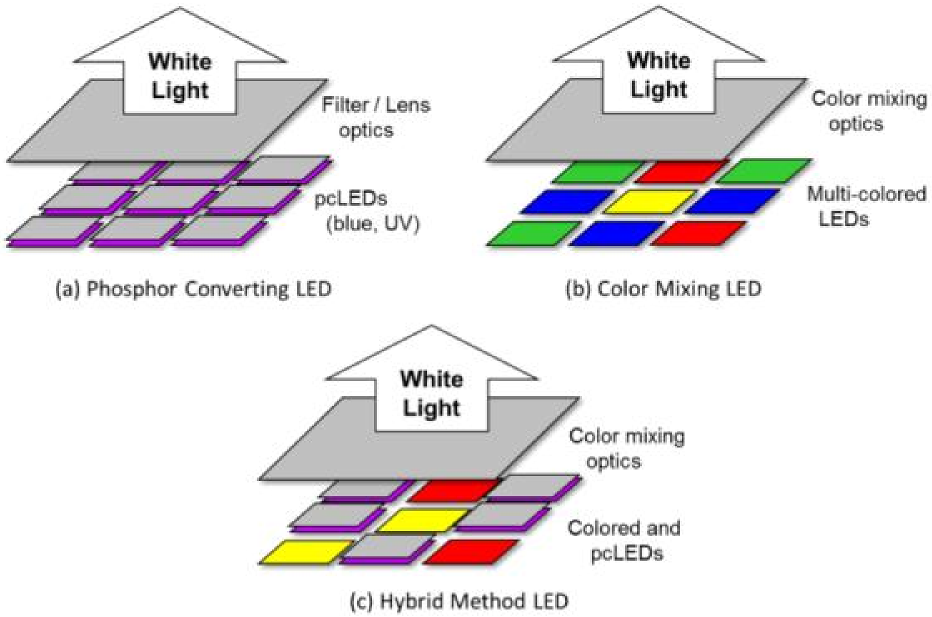

Figure 6: Three methods for creating white light with light emitting diodes (source: [18]).

2.5.2. Comparison of package efficiencies for white LED solutions

In its 2014 multi-year program plan (MYPP)[21], US DoE analyses the technological elements impacting SSL system efficacy, identifies the state-of-the-art performance levels, and creates efficacy projections. As this appears to be the most recent source on which a LED timeline can be based, a summary of the main points is provided below. For full details please consult the reference.

The MYPP-analysis compares the various white-LED solutions by means of a simulation, considering:

- current density 35 A/cm^2,
- temperature 25˚C,
- warm-white LED with CCT=3000K, CRI=85, R9>0 [46],
- cool-white LED with CCT=6200K and CRI=70.

For each of the four white-LED solutions (pc-LED, RGB, RGBA and hybrid=pc-LED with red-LED) a typical spectrum is defined (Figure 7) and then optimized, while maintaining the target CCT and CRI, by varying peak wavelength, spectral width and intensity until the highest possible luminous efficacy of radiation (LER_{max}) is obtained.

The LER is the amount of light in lumens, obtained from a given spectrum, per optical watt. The LER is expressed in $lm/W_{optical}$. Multiplying the LER by the power conversion efficiency (PCE), expressed in $W_{optical}/W_{electrical}$ the usual light source efficacy in $lm/W_{electrical}$ is obtained [47].

LER_{max} is the theoretical maximum efficacy of an SSL product (with the target CCT and CRI), given perfect conversion of electricity to light (i.e. with PCE=100%). If a real light source has a value LER_{real}, LER_{real}/LER_{max} can be conceived as its spectral efficiency.

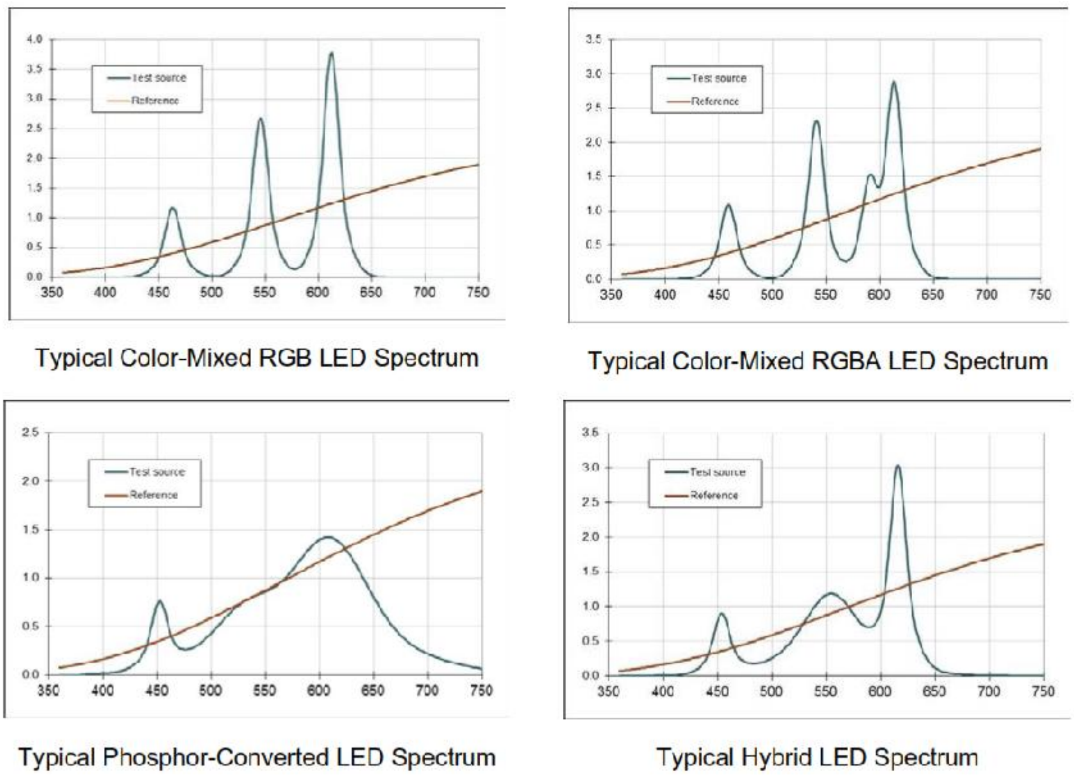

Figure 7: Typical simulated optical spectra for the four white-LED solutions, compared to the blackbody curve (CCT 3000K, CRI 85, R9>0) (Source: [21])

[46] R9 is a saturated red colour that is not considered in the CRI (that uses R1 through R8) but often retained important to express the colour rendering properties of a light source. See for example, http://www.eyelighting.com/resources/lighting-technology-education/general-lighting-basics/r9-color-rendering-value/

[47] As reference information, the IEASNA Lighting Handbook, 8th edition, 1993, p. 204, gives 348 lm/W as maximum efficacy for a perfect cool-white lamp, and 683 lm/W as the absolute maximum for a monochromatic yellow-green light of 555 nm wavelength.

The result of the US DoE simulation is shown in Table 6, that be commented as follows:

- The current (2013) power conversion efficiency $W_{optical}/W_{electrical}$ is highest for the blue LED (55%) and the red LED (44%). For the green LED (22%) and the amber LED (8%) the PCE is significantly lower. The target (2020) values are considerably higher. Note for example that the PCE of blue LEDs is expected to increase from 55% in 2013 to 80% in 2020.

Table 6: Estimated efficacies for a white LED with CCT 3000K, CRI 85, R9>0, for an RGB LED (top left), an RGBA LED (top right), a pc-LED (bottom left) and a hybrid LED (bottom right). FWHM = full width at half maximum, a measure for the peak width (Source: [21])

Emissions	Blue LED		Green LED		Red LED	
Peak Wavelength (nm)	463		546		612	
FWHM (nm)	20		20		20	
PCE (%)	Current	Target	Current	Target	Current	Target
	55	80	22	35	44	55
LER (lm/W)	400					
Efficacy (lm/W)	Current			Target		
	133			191		

Emissions	Blue LED		Green LED		Amber LED		Red LED	
Peak Wavelength (nm)	459		539		590		615	
FWHM (nm)	20		20		20		20	
PCE (%)	Current	Target	Current	Target	Current	Target	Current	Target
	55	80	22	35	8	20	44	55
LER (lm/W)	402							
Efficacy (lm/W)	Current				Target			
	85				153			

Emissions	Blue LED		Green Phosphor		Red Phosphor	
Peak Wavelength (nm)	454		536		612	
FWHM (nm)	20		100		110	
	Current	Target	Current	Target	Current	Target
PCE (%)	55	80	-	-	-	-
Effective Phosphor Conversion Efficiency (%)*	-	-	44	67	37	56
LER (lm/W)	316					
Efficacy (lm/W)	Current			Target		
	123			189		

Emissions	Blue LED		Green Phosphor		Red LED	
Peak Wavelength (nm)	460		539		612	
FWHM (nm)	20		100		20	
	Current	Target	Current	Target	Current	Target
PCE (%)	55	80	-	-	44	55
Effective Phosphor Conversion Efficiency (%)*	-	-	45	68	-	-
LER_{max} (lm/W)	368					
Efficacy (lm/W)	Current			Target		
	165			231		

- The effective phosphor conversion efficiency (44% for green, 37% for red) is the product of phosphor quantum efficiency, Stokes' efficiency (par. 2.3) and the PCE of the blue LED. As the latter is 55%, considering only the phosphor the efficiencies are 80% (green) and 67% (red).

- For colour-mixing LEDs the LER_{max} is around 400 $lm/W_{optical}$. Multiplying this with the typical 2013 PCE's for the various colours, a LED package efficacy of 133 $lm/W_{(electrical)}$ is obtained for RGB and 85 lm/W for RGBA. The latter value is lower due to the very low PCE for amber coloured LEDs. In 2020 the target efficacy values are 191 and 153 lm/W respectively. Research is required in particular to improve the PCE's for amber, green and red LEDs. The US DoE simulations do NOT include the additional losses deriving from colour-mixing.

- For phosphor-converted LEDs the LER_{max} is 316 $lm/W_{optical}$, and thus considerably lower than for the cm-LEDs. The low value is due to the phosphors emitting a significant part of the optical energy in the non-visible infrared range. Compared with the cm-LEDs, the pc-LEDs do not have the drawback of the low PCE for green and amber colours, but they are subject to the phosphor losses. The resulting 2013 efficacy is 123 $lm/W_{(electrical)}$, with a 2020 target of 189 lm/W. As pointed out by US DoE, improvements can be obtained by increasing the PCE for blue LEDs and by narrowing the emission bandwidth for the green and red phosphors.

- Hybrid LEDs are reported to have a LER_{max} of 368 lm/$W_{optical}$ and a resulting 2013 efficacy of 165 lm/$W_{(electrical)}$ (target for 2020: 231 lm/W). This is better than the pc-LED values because the broadband red phosphor of the pc-LED has been substituted by a narrowband red LED in the hybrid solution. US DoE states that the hybrid approach is a promising alternative in the short term due to the ready availability of a narrow red source. However, the AlGaInP-based material often used for the red LED is reported to have a very different thermal behaviour than the GaN-based material used for the blue LED, and this necessitates additional control systems that add complexity.

- The above results are for a warm-white LED with CCT=3000K, CRI=85 and R9>0. For white LEDs with different CCT or CRI the results will be slightly different. For cool-white LEDs the reference [21] provides less extensive data, but in particular the efficiencies related to the green LED (cm-solution) and the green phosphor (pc-solution) are important. In general a lower CCT and a higher CRI imply lower efficacies.

- The above results are for a current density of 35 A/cm^2 and a temperature of 25˚C. For this condition the maximum LED efficacy is projected to be 250 lm/W. Reducing the operating current to minimize current droop can produce a 15 to 20 percent increase in efficacy. Increasing the operating temperature, from 25°C to 85˚C (closer to the actual operating temperature) could lead to a 10-13% reduction in efficacy.

2.5.3. Efficiency details for a pc-LED

The efficiencies and efficacy of pc-LEDs are further detailed in Figure 8 and Table 7. Although it is uncertain whether all of these targets can actually be realized in a commercial, marketable product, they suggest that there is significant potential for an improvement over today's LED performance [21].

In Table 7 the power conversion efficiency of the blue LED is computed as the product IQE * extraction efficiency * electrical efficiency * package efficiency. For the first three efficiencies, see par. 2.2. The exact meaning of the package efficiency is not explained by the US DoE document, but it is expected to relate to the optical efficiency of encapsulants or lenses [48]. The phosphor conversion efficiency is the product of quantum efficiency and Stokes' efficiency, see par.2.3.

[48] On p.79 of reference 21 the package efficiency is defined as "*the ratio of lumens out of the LED package to the power applied to the LED package at room temperature, thus not including the driver, luminaire optical or thermal losses*.", but this definition does not seem to be compatible with the use as part of the PCE.

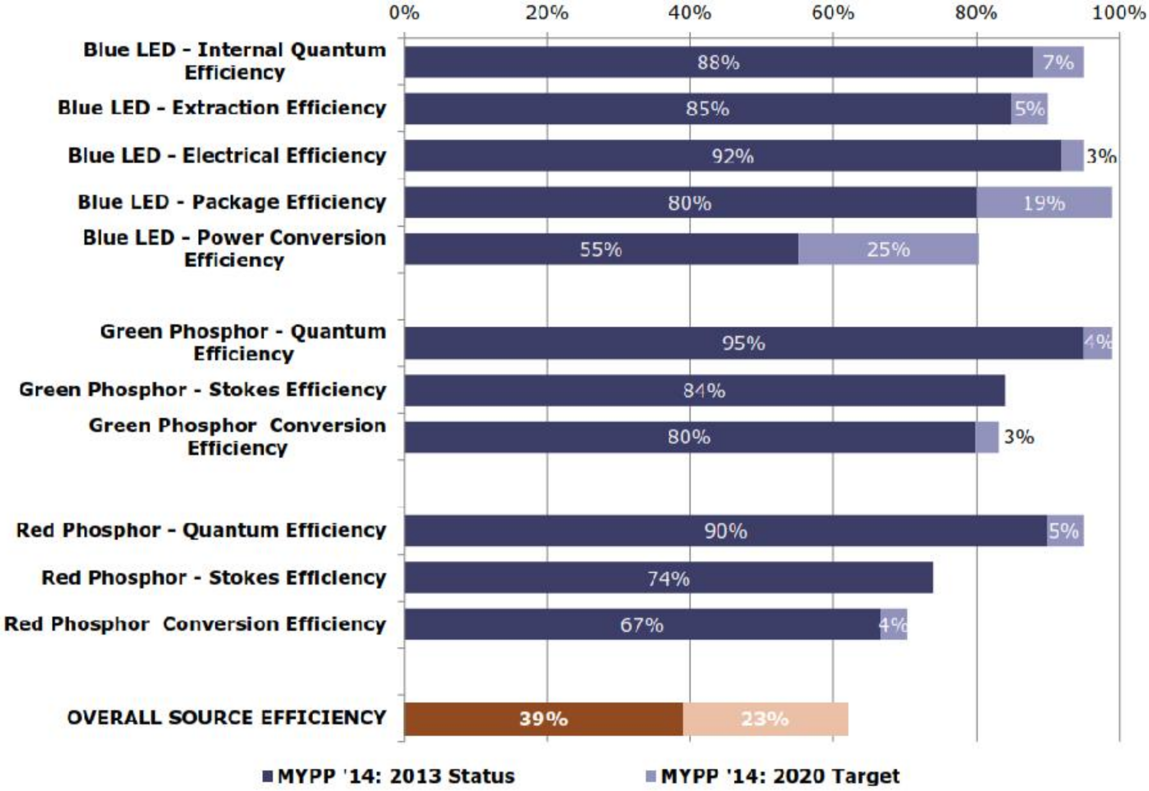

Figure 8: Warm-white pc-LED package loss channels and efficiencies (CCT 3000K, CRI 85, R9>0, temperature 25˚C, current density 35 A/cm^2) (Source: [21])

Table 7: Summary of warm-white pc-LED package efficiencies and efficacies (Source: [21])

Metric		2013 Status	2020 Target	Goal
LER (lm/W)		316	375	395
Blue LED	Internal Quantum Efficiency	88%	95%	95%
	Extraction Efficiency	85%	90%	90%
	Electrical Efficiency	92%	95%	95%
	Package Efficiency	80%	99%	99%
	Power Conversion Efficiency	55%	80%	80%
Green Phosphor	Quantum Efficiency	95%	99%	99%
	Stokes Efficiency	84%		
	Conversion Efficiency	80%	83%	83%
Red Phosphor	Quantum Efficiency	90%	95%	95%
	Stokes Efficiency	74%		
	Conversion Efficiency	67%	71%	71%
Overall Source Efficiency		39%	62%	62%
PC-LED Efficacy (lm/W)		123	232	247

2.5.4. Efficiency details for a cm-LED

The efficiencies and efficacy of cm-LEDs are further detailed in Figure 9 and Table 8. The reference notes that there is a lack of commercial cm-LED products so that the current status is an estimate of what could be done today. The efficiency is limited in particular by the lack of efficient green (direct-emitting) LEDs. cm-LEDs are theoretically capable of higher efficacies than pc-LEDs, but the benefit may be offset by the need for colour-mixing optics. In addition there may be stability issues.

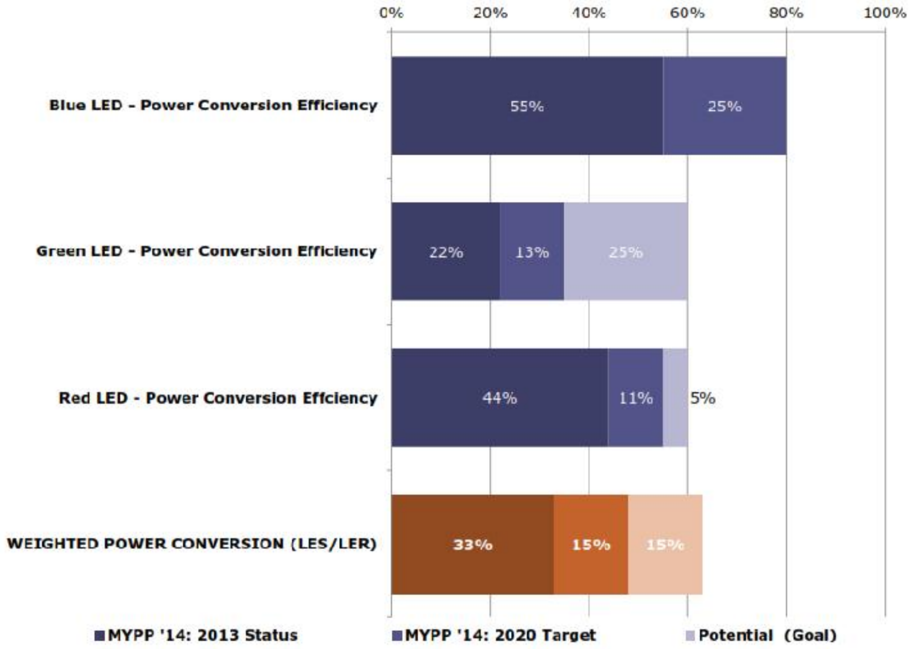

Figure 9: Warm-white cm-LED package loss channels and efficiencies (CCT 3000K, CRI 85, R9>0, temperature 25˚C, current density 35 A/cm²) (Source: [21])

Table 8: Summary of warm-white cm-LED package efficiencies and efficacies (Source: [21])

Metric		2013 Status	2020 Target	Goal
LER (lm/W)		400		
Blue LED	Power Conversion Efficiency[1]	55%	80%	80%
Green LED	Power Conversion Efficiency	22%	35%	60%
Red LED	Power Conversion Efficiency	44%	55%	60%
Weighted Power Conversion (LES/LER)		33%	39%	63%
CM-LED Efficacy (lm/W)		133	191	250

2.5.5. Filling the 'green gap'

In 2014, in the context of the HI-Q-LED project, OSRAM Opto Semiconductors announced two innovating solutions for the 'green gap' [49] [50].

The first solution is a green-emitting LED based on indium gallium nitride (InGaN) semiconductors which achieved a record efficacy of 147 lumens per watt (lm/W).

The second solution is based on a blue-emitting LED with a green full-conversion phosphor solution. This green LED was demonstrated to reach a record-breaking 274 lm/W at a low current density of 1.5 A/cm^2, 209 lm/W (210 lm) at 45 A/cm^2, and 160 lm/W (500 lm) at 125 A/cm^2 [51].

2.5.6. US DoE prediction of efficacies and prices for white LED packages

In its 2014 multi-year program plan the US DoE [21] presents a survey of the developments in white LED package prices and efficacies, starting in 2009 and with predictions up to 2020 (Figure 10). Price information from the same source is shown in Table 9 while Figure 11 shows the expected efficacy development for pc-LEDs.

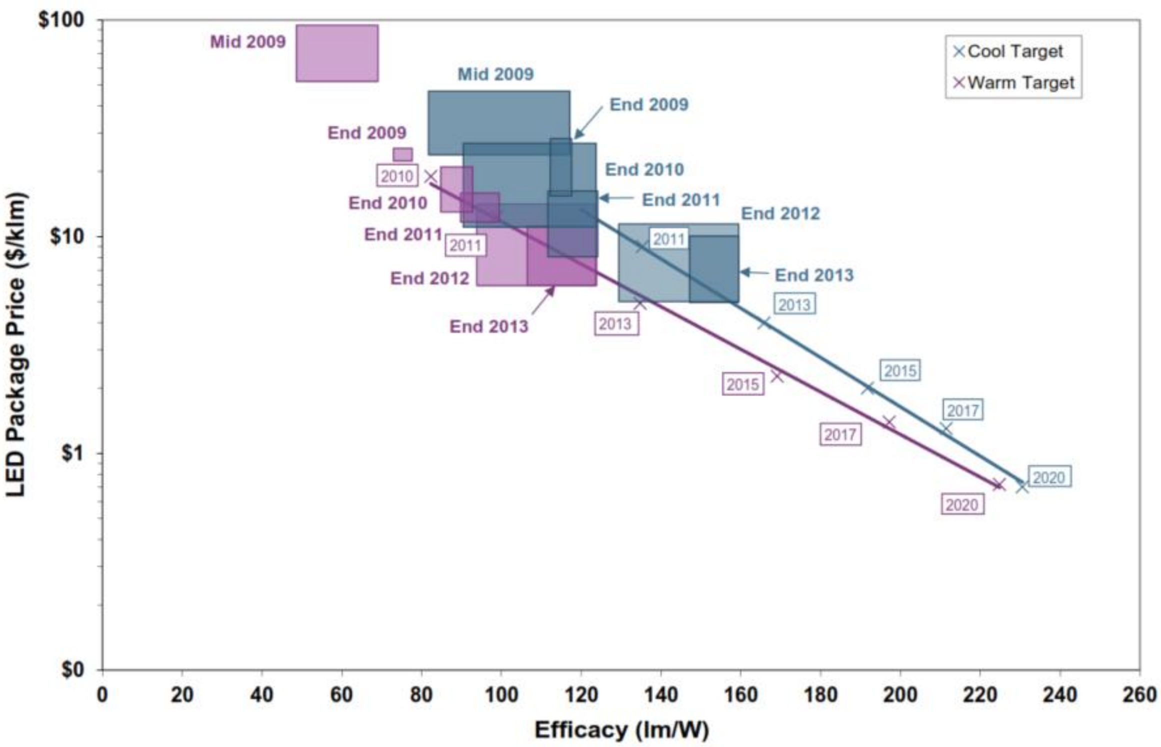

Figure 10: Price-efficacy trade-off for LED packages. (Source: US DoE [21], figure 2.9). Data are normalized to a current density of 35 A/cm^2 and a temperature of 25˚C. Cool-white assumes CCT=4746-7040 K with CRI>70; warm-white assumes CCT=2580-3710 K and CRI>80. Rectangles represent regions mapped by maximum efficacy and lowest price for each time period. The MYPP projections have been included to demonstrate anticipated future trends.

[49] Green LEDs have a relatively low efficiency (see preceding paragraphs), and this problem is known as the 'green gap'.

[50] http://www.osram-os.com/osram_os/en/press/press-releases/led-for-automotive,-consumer,-industry/2014/osram-achieves-record-figures-with-green-leds/index.jsp

[51] Note the 'current droop' effect (par. 2.2.4): efficacy strongly decreases with current density.

Table 9: Summary of LED package price and performance projections (Source: US DoE [21], table 2.3)

Metric	2013	2015	2017	2020	Goal
Cool-White Efficacy (lm/W)	166	192	211	231	250
Cool-White Price ($/klm)	4	2	1.3	0.7	0.5
Warm-White Efficacy (lm/W)	135	169	197	225	250
Warm-White Price ($/klm)	5.1	2.3	1.4	0.7	0.5

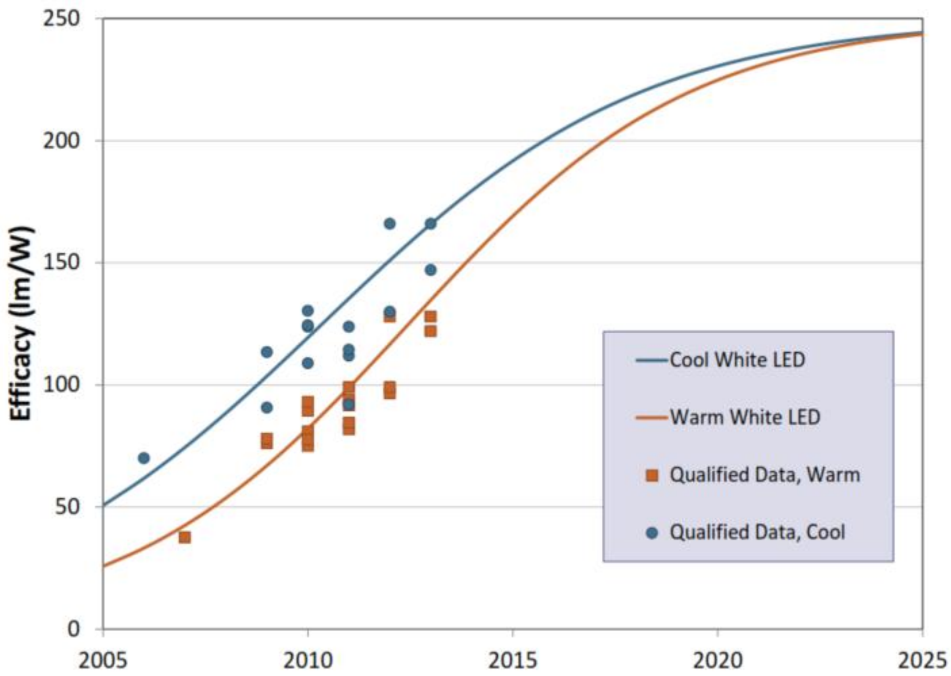

Figure 11: White-light PC-LED package efficacy projections for commercial product. (Source: US DoE [21], figure 4.1). Cool-white values for 2013, 2015, 2017, 2020 respectively 166, 191, 211 and 231 lm/W. Warm-white values for 2013, 2015, 2017, 2020 respectively 135, 169, 197 and 225 lm/W.

The following remarks can be made regarding the above information:

- By 2020 the prices of white LED packages are expected to be below 1 euro/klm with efficacies around 230 lm/W. The price drop is in line with the latest market news (Q4/2014) that forecasts further price reductions in 2015 in a heavily populated market [52, 53, 54, 55].

[52] http://www.ledinside.com/news/2014/10/nichia_forecasts_led_industry_price_wars_to_intensify_in_2015
[53] http://bizled.co.in/top-trends-that-will-dominate-global-led-industry-in-2015/?utm_source=LG&utm_medium=LG&utm_campaign=LG
[54] http://www.ledinside.com/intelligence/2014/12/ledinside_top_10_led_industry_development_trends_for_2015
[55] http://www.ledinside.com/intelligence/2014/11/as_led_lighting_penetration_surges_dominant_players_to_maintain_market_share

- The data regard package efficacies. They are useful for illustrating technology improvement trends, but from the consumer point of view it is more relevant to consider the efficacies of the retrofit lamps and LED-luminaires that will be manufactured using these LED packages. The latter efficacies are significantly lower, see par. 2.10.2.

- High efficacy and low price are not always achieved simultaneously for the same device. US DoE notes that higher efficacy products continue to demand higher prices, and lower prices correlate with reduced performance. However, while peak efficacy values have not increased significantly over the past year (2013), prices for the highest performing products have continued to fall, and the spread in efficacy values has narrowed.

- The data shown above are normalized for a current density of 35 A/cm^2 and a temperature of 25˚C. Real operating conditions of the packages inside lamps or luminaires are bound to be different. In addition US DoE itself questions the adequacy of the type of normalization used.

2.6. White LED package configurations

IEC 62504 defines a LED package as a: "single electrical component encapsulating principally one or more LED dies, possibly including optical elements and thermal, mechanical, and electrical interfaces". A note clarifies that the package does not include the control unit of the control gear, does not include a cap, and is not connected directly to the supply voltage.
LED packages are the basis for the creation of LED-modules and LED-lamps.

A wide variety of package configurations exists on the market. The related terminology includes low-, mid- and high-power packages, matrix/array type, surface-mounted device (SMD), chip-on-board (COB), flip-chip (FC), chip-scale-package (CSP), and others.

There seem to be different definitions as regards the low-, mid- and high-power classification, but as an indication [56]:

	current	power	lumen
▪ Low-power packages:	5-20 mA	0.01-0.1 W	0.1-6 lm
▪ Mid-power packages:	30-150 mA	0.1-0.5 W	0.2-20 lm
▪ High-power packages:	20-1500 mA	0.5-5 W	> 50 lm

Traditionally LED-chips were mounted as fabricated in the epitaxial growth process, top-side up, and typically wire-bonding was used to connect the top electrical chip contacts to an external electronic circuit [57].
Using the flip-chip technology, the LED-chip is mounted top-side down on the support structure (also functioning as heat spreader). Contact pads are created on top of the chips during the last phases of LED wafer processing, depositing also a small quantity of solder. During mounting, the chip is 'flipped-over' and positioned in such a way that

[56] http://www.strategies-u.com/articles/2014/03/mid-power-led-packages-are-getting-brighter-providing-the-output-of-high-power-led-packages.html

[57] This traditional technology is also referred to as MESA-LED or vertical-LED. Instead of wire-bonding, copper-filled holes can also be used to connect the top-contacts to the bottom side, mounting the chip top-side up.

its electrical contacts match those on the sub-mount. Reflow-soldering then creates the final electrical connection [58].

The flip-chip technology no longer needs wire-bonding (cost reduction), enables a smaller package size (smaller lamps, increased design freedom, reduced material content), and a lower thermal resistance between the chip and the support structure, allowing higher operating currents.

As stated by 'Research and Markets': "Whereas Flip Chip LED represented only 11% of overall high power LED packaging in 2013, we expect this component to represent 34% by 2020. Flip Chip LED will take market share from vertical LED that will represent 27% of overall high power LED packages by 2020" [59].

The flip-chip technology is at the base of chip-scale packages. These packages are less than 1.2 times the chip size [60], relatively new in LED applications, but widely used in the semi-conductor industry for years. "Basically, a CSP represents a single chip direct mountable package that is the same size as the chip. Regarding LED devices, CSPs are made of a blue FC LED die on which a phosphor layer is coated" [59].

Using the flip-chip technology, the substrate on which the chip had been grown had to be removed because it would otherwise block the light emission. Recently, transparent sapphire substrates have been applied that avoid the need for this removal [61], enabling an additional cost reduction.

SMD LED chips are first packaged one-by-one and then combined into matrices or arrays by surface-mounting them on printed circuit boards (PCB). They are typically recognizable in the module or lamp as a large series of small yellow points (the separate encapsulations / phosphor coatings).

The chip-on-board (COB) technology mounts a number of bare chips (without casing or connections), or a chip containing several diodes, directly on the PCB (or other substrate), and then packages them together (encapsulation, phosphor coating). They are typically recognizable in the module or lamp as one large yellow area (the combined encapsulation /phosphor coating). The result is a lower thermal resistance and a higher LED chip density, enabling higher light levels (e.g. for street lighting), larger-area lamps, increased efficacy, and improved life expectancy [62].

Due to the technologies described above, in recent years there has been considerable progress in LED package design, with significant associated cost savings. An example is the evolution of the Philips Lumileds packages that evolved from the 2006 Luxeon K2 with in-plane dimensions of 7.3 x 7.3 mm (not counting the electrical leads) and a height around 6 mm, to the 2013 Luxeon chip-scale package with approximate in-plane dimensions of 1 x 1 mm and a height (thickness) around 0.25 mm. This development is further clarified and revealingly illustrated in an article of LEDinside [63] that shows an approximate 80% reduction in package level costs.

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[58] Various types of connection-techniques and soldering processes exist.

[59] http://www.prnewswire.com/news-releases/led-packaging-technology-and-market-trends-2014-278987811.html

[60] http://en.wikipedia.org/wiki/Chip-scale_package

[61] http://www.ledsmagazine.com/articles/2013/02/philips-lumileds-announces-bare-led-die-and-new-multi-emitter-components-at-sil.html

[62] https://planetled.com.au/blog/what-are-cob-led-lights/
http://www.thelightbulb.co.uk/resources/the_ultimate_guide_to_led_light_bulbs
http://www.digikey.com/en/articles/techzone/2014/mar/why-and-how-chip-on-board-cob-leds-reduce-cost-and-save-energy-in-lighting-designs
https://www.google.nl/search?q=cob+led+images&ie=utf-8&oe=utf-8&gws_rd=cr&ei=WflAVZmZJoPpatafgZgO

[63] Philips Lumileds: Chip Scale Packaging for LEDs, LEDinside, 12 december 2013
http://www.ledinside.com/knowledge/2013/12/philips_lumileds_chip_scale_packaging_for_leds

The variety of LED package types existing on the market can be assessed by examining e.g. the catalogues of Philips Lumileds [64], Osram Opto Semiconductors [65] and Cree [66]. Each package is more suitable for certain applications, as explained for example in the Philips applications guide [67].

2.7. LED control gears / drivers

2.7.1. Introduction to LED control gears

Single LED chips have an exponential relationship between forward current and forward voltage [68]. This implies that around their operating point (typically around 3 V) small voltage variations will cause very large current variations and consequently very large variations in light emission intensity. Such variations in forward voltage can occur with temperature [69]. This can easily lead to exceeding the maximum current specified by the manufacturer, to overheating, and to reduced lifetime or failure. For this reason single LED chips are current-controlled.

However, lamp and luminaire manufacturers rarely use single LED chips to produce the desired light characteristics. For convenience and for economic reasons, single LED chips are often pre-assembled in groups, connecting them in series and/or in parallel, and forming LED-strips, LED-strings, LED-modules or LED-arrays. It then depends on the way in which the LED chips have been grouped if current-control or voltage-control is most appropriate.

Consequently, LED control gears can be 'constant current' or 'constant voltage'. The type of control gear depends on the type of LED load, and the two types are not interchangeable.

Constant voltage drivers (10 V, 12 V, 24 V) are used where LED modules are connected in parallel and where the number of loads is variable. They are used for example in coves (LED-strips), under-cabinet lighting, and signage applications. Amperor [68] signals as advantages that design engineers and installers are familiar with this technology and that costs are potentially lower. These LED control gears are similar or identical to the low voltage power supplies of halogen lights [70].

Constant current drivers (350 mA, 700 mA, 1050 mA) are used for single LED lamps or where a number of lamps or luminaires is connected in series. Typical applications are down-lighters, sconces [71], or other LED lamps or luminaires with one LED module per control gear. This solution provides a more consistent brightness and is more reliable when it comes to avoiding that the specified maximum current is exceeded [68]. As this

[64] COB, chip-on-board: http://www.lumileds.com/products/cob-leds/luxeon-cob
COB compact: http://www.lumileds.com/products/cob-leds/luxeon-cob-compact-range
High-power LEDs, e.g.: http://www.lumileds.com/products/high-power-leds/luxeon-m
Mid/Low power LEDs, e.g.: http://www.lumileds.com/products/luxeon-mid-power/luxeon-3014
Matrix/Array: http://www.lumileds.com/products/matrix-platform/luxeon-k

[65] http://www.osram-os.com/osram_os/en/products/product-catalog/leds-for-general-lighting/index.jsp

[66] http://www.cree.com/LED-Components-and-Modules/Products

[67] http://www.lumileds.com/lighting-applications/general-illumination

[68] http://www.amperor.com/products/led/constant_voltage_constant_current_led_driver.html

[69] http://ledlight.osram-os.com/wp-content/uploads/2011/01/Thermal-Characteristics-of-LEDs-02-.pdf

[70] This does NOT imply that it is straightforward to design a low voltage LED retrofit lamp that will work on any installed MV-LV transformer for halogen lamps. See also remarks in paragraph 5.9.3.

[71] A sconce is a type of light fixture affixed to a wall in such a way that it uses only the wall for support, and the light is usually directed upwards, but not always. It does not have a base on the ground.

solution is the most relevant for general lighting purposes, the discussion in this paragraph will be limited to constant current drivers.

In addition, single LED chips will light up only when the current flows in forward direction, essentially meaning that they need a direct current (DC). When subjected to an alternating current (AC) they would light up only half of the time, and at 50 Hz line frequency this would lead to perceivable flicker [72]. Consequently, the main function of a LED control gear usually is to convert the AC mains voltage input in a direct current output of the desired amplitude.

In addition to the main AC-DC conversion, the LED control gear can have various auxiliary functions:

- Protection of the LED components against line voltage fluctuations.
- Power factor control, i.e. limitation of the harmonic currents returned to the grid.
- Limitation of electro-magnetic interference with other devices (EMI).
- Bleeder circuit for power supply to other control devices such as dimmers through the LED control gear, in '2-wire' configurations.
- Dimming.
- Control of the colour or of the CCT or CRI of the white light.
- Reception and transmission of radio-frequency signals.

Technically, a LED control gear can be made with nearly any desired characteristics. However, the demand for additional functions (dimming) or for more severe requirements (power factor, EMI, flicker) will usually increase the cost of the driver, consume more material resources, and can also have an impact on the required space, on the energy efficiency, and on the standby power consumption.

Different lighting applications and products require a wide range of light outputs, leading to a large variety of LED packages on the market, in a variety of circuit architectures, and in a variety of luminaires. In new LED packages, some of the power supply functionality can be embedded in the package itself. AC LED packages are designed to run directly on AC line power. High-voltage LEDs contain multiple LED electrical junctions in series to raise the operating voltage of the package and overcome some driver efficiency losses that may be associated with high drive current. Luminaire designers can take advantage of these products to reduce the cost and improve the efficiency of the power supply within the luminaire [21].

Due to all the variety of functions and the variety of design requirements, a broad range of control gear circuit topologies are on the market. For example on 26 November 2014, the European Patent Register reported 217 European patents filed related to the keywords 'LED, driver', meaning that there is also intellectual property involved.

2.7.2. Basic LED control gear, direct-AC configurations

The basic electronic circuit to convert an AC input in a DC output is to use a full-wave diode bridge rectifier, Figure 12. However, the output current from this circuit still has the sine-wave variation, even if the negative parts have been converted to positive [76].

[72] There are anyway solutions for LEDs functioning on AC, see for example http://www.ledsmagazine.com/articles/2006/05/running-leds-from-an-ac-supply.html,

One of the simplest direct AC solutions is to have the bridge rectifier followed by a constant current regulator (CCR) [73], see Figure 13. The main advantages of this approach are that few components are needed, that the circuit is very compact for integration in a lamp base, and that lifetime can be long. Depending on the implementation of the current regulator, this circuit can also prevent that the light output changes with line voltage fluctuations, which might be a feature needed in some electrical grids (see Task 3 paragraph 7.2.2).

The LED string voltage, i.e. the number of LEDs in series, has to be compatible with the supply voltage. For this reason, long strings of mid power LEDs are frequently used instead of a few high power LEDs. If the LED string voltage is sufficiently high compared to the input AC voltage, the losses in the CCR can be kept to a reasonable level while achieving > 0.9 power factor [74]. Losses will increase with line voltage and a minimum line voltage is needed.

In this circuit lamp flickering at 100 Hz might occur [74]. This is not perceived by most users in standard conditions, but in presence of fast moving objects it will manifest itself [75]. Using a suitable dimming circuit, this topology can be dimmed (par. 2.7.4).

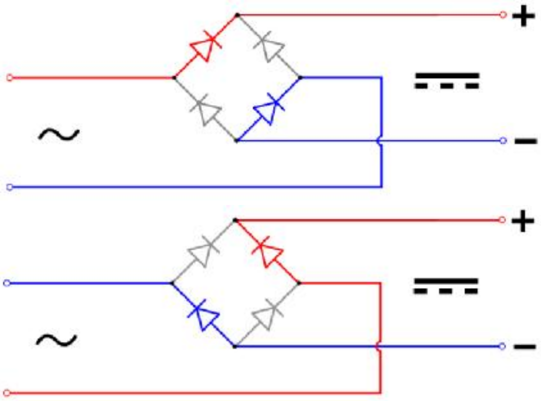


Figure 12: Basic circuit for conversion of an AC power supply in a DC current by means of a full-wave diode bridge rectifier. As illustrated by the blue and red lines, when the polarity of the input changes, the polarity of the output remains the same (Source: [76])

Figure 13: Example of a basic circuit of AC driver based on a full wave diode rectifier with a solid state constant current regulator circuit, connected to a string of mid power LEDs (source: [73]).

[73] CCR's are compact of-the-shelf components based on transistors, see for example the Onsemi data sheet of NSIC2020BT3G for 'Constant Current Regulator & LED Driver for A/C of Applications, 'http://www.onsemi.com/pub_link/Collateral/NSIC2020B-D.PDF

[74] The CCR provides its constant current only for a portion of the time, in proximity of the top of the sine wave, when the input voltage exceeds a threshold value. For the parts of the sine wave where voltage is low, no current is transmitted. This on/off behaviour can cause flicker. See illustration in: http://www.ledjournal.com/main/blogs/the-march-of-mid-power-leds-into-general-lighting/#sthash.iMfAovyp.dpuf

[75] An easy test to verify if this type of control gear is installed, is to move your hand fast in front of the lamp and check if any stroboscopic effects appear.

[76] See illustration on http://en.wikipedia.org/wiki/Diode_bridge

Another basic circuit uses a so-called capacitive power supply (Figure 14). A capacitor is added to the circuit to smoothen the waveform, providing a constant current with the time-averaged (root mean square) value of the original wave, but with a small ripple remaining. The current is controlled to the desired level by choosing the value of the reactance (C3 in the figure). R1 is added to safely discharge capacitor C3.

The power factor of this solution is poor, and the capacitor might become bulky if the power becomes large. Hence, it can only be used at low power. The circuit is more efficient compared to the previous circuit but cannot be dimmed. In addition this circuit will not compensate for line voltage fluctuations.

An example of a LED lamp using such a very compact basic driver is a so-called LED filament lamp as illustrated in Figure 39.

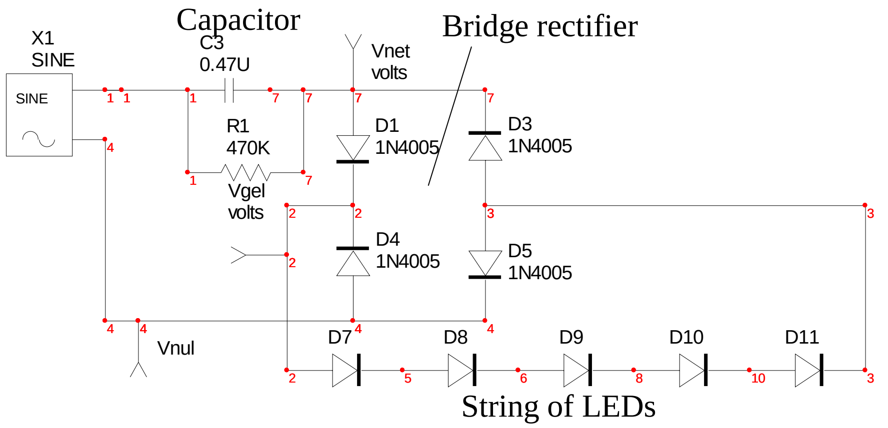


Figure 14: Example of a basic circuit for an AC driver based on a full wave diode rectifier with a capacitive power supply, attached to a string of mid power LEDs (source: VITO)

2.7.3. More sophisticated LED control gear based on switched-mode power supply

The direct-AC control gears discussed in the previous paragraph require the choice of the number of LEDs to match the AC supply voltage. This severely limits the design possibilities. An obvious alternative is to adapt the voltage to the number of LEDs that the designer wants to use, but that requires a voltage transformer.

Advanced circuits use switched-mode power supplies [77] based on transistors, inductive and capacitive components with elaborated control circuits. Compared to the previous circuits, they have a more expensive bill of materials and require more space to integrate. They offer however flicker free operation, power factor correction, and high efficiency.

An example circuit for a retrofit bulb that enables triac dimming, without flickering, safe LED component insulation from the line voltage, and a high power factor is discussed in par. 2.7.4 on dimming requirements.

[77] A switched-mode power supply is an electronic power supply that incorporates a switching regulator to convert electrical power efficiently. It transfers mains power to a load (lamp), while converting voltage and current characteristics. The pass transistor of a switching-mode supply continually switches between low-dissipation, full-on and full-off states, and spends very little time in the high dissipation transitions, which minimizes wasted energy. Voltage regulation is achieved by varying the ratio of on-to-off time. Switched-mode power supplies may also be substantially smaller and lighter than a linear supply due to the smaller transformer size and weight. (adapted from Wikipedia)

Figure 15 shows a block diagram and a control gear demo board for a 100 Watt LED street lighting application. It contains a power factor correction (PFC) circuit, electromagnetic interference filters (EMI), interfaces for DALI and 0-10V control signals, interfaces for wireless control signals, and a Safe Extra-Low Voltage (SELV) output driver containing a high frequency transformer. The efficiency of this control gear is reported to be around 90% for output powers above 25% of the maximum power. The standby power at 220 V AC input voltage is reported as 0.13 W.

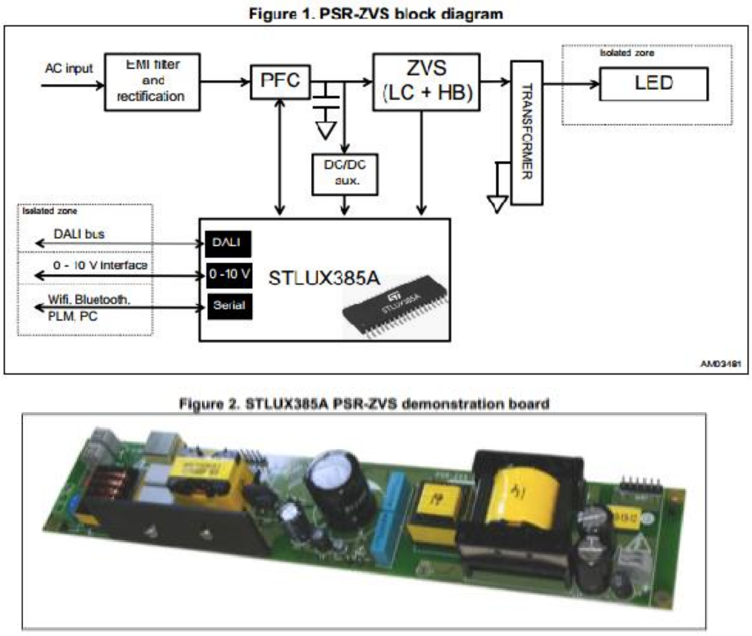


Figure 15: 100 W LED street lighting application board using STLUX385A, block diagram (top) and demo board (bottom) (Source: ST Microelectronics [78]).

2.7.4. LED control gear and dimming

For general background information on dimming see par. 7.2 of the Task 3 report.

All LEDs can be dimmed by controlling the current, but a dedicated current control circuit with interfacing system should be incorporated in the control gear when this function is needed. Two popular methods for dimming LEDs by controlling the time-averaged current are pulse-width modulation (PWM) and constant current reduction (CCR, also referred to as analogue dimming). Both methods have their advantages and disadvantages, as described in par. 7.2.2 of the Task 3 report.

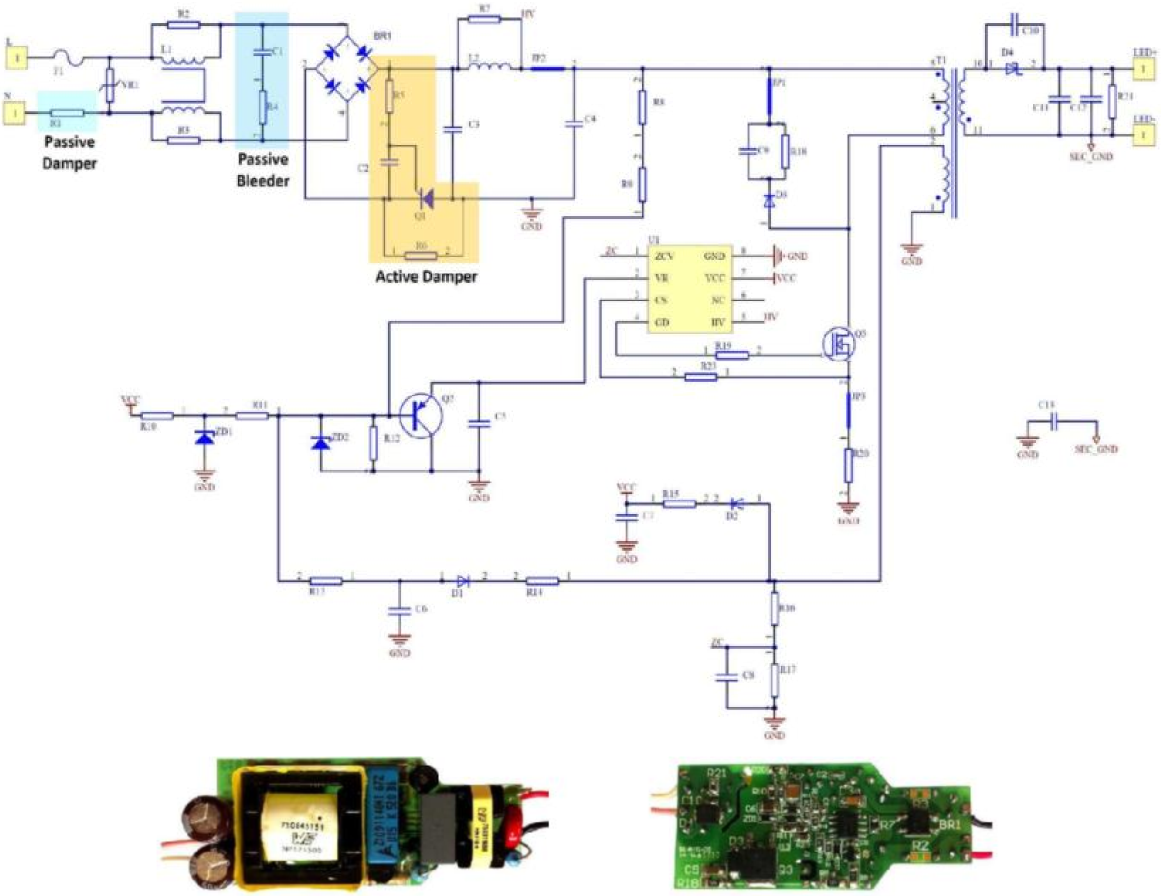
Not all LED lamps are dimmable, because the control gear design did not foresee this function, and those that are dimmable are not compatible with all types of dimmers. In particular for installations that are currently using filament (e.g. halogen) light sources this may mean that owners will have to replace much more than just the light source in order to obtain a roughly similar environmental performance. The problem is that triac [79] based dimmers can work smoothly with resistive loads such as incandescent lamps,

[78] http://www.st.com/st-web-ui/static/active/en/resource/technical/document/application_note/DM00098387.pdf

79 TRIAC, from triode for alternating current, is a genericized trade name for an electronic component that can conduct current in either direction when it is triggered (turned on). The bi-directionality makes TRIACs very convenient

but when they work with non-resistive loads such as switch-mode LED control gears, flickering issues can occur, primarily due to insufficient hold-up current as well as current oscillation especially during triac firing [80].

In order to improve the compatibility with triac based dimmers, usually bleeder circuits and damping circuits are implemented in the LED control gears. A solution for this problem is illustrated in Figure 16, where a passive bleeder circuit formed by C1 and R4 (light blue area) is incorporated to maintain input current above the hold-up current threshold of the triac. Two damping resistors, R1 and R6, are used to damp the oscillation as well as reduce inrush current [81] (orange area).



switches for alternating current circuits, also allowing them to control very large power flows with milliampere-scale gate currents. Applying a trigger pulse at a controlled phase angle in an AC cycle allows control of the percentage of current that flows through the TRIAC to the load (phase control), which is commonly used, for example, in controlling the speed of low-power induction motors, in dimming lamps, and in controlling AC heating resistors. (adapted from Wikipedia)

[80] Infineon application note 'AN-EVALLED-ICL8002G-B1' on 'Phase Cut Dimmable Isolated Flyback Converter for LED Retrofit Bulb with ICL8002G & CoolMOS™ 800V CE

[81] As the damping resistors can cause significant power losses, they can be bypassed shortly after the triac firing so as to improve efficiency. This is achieved with the circuit formed by R5, C2, and thyristor Q1. Each time when the triac turns on, due to the time delay produced by R5 and C2, thyristor Q1 will remain off and as a result the inrush current is limited by R6. When Q1's gate voltage is charged to its triggering level, it will turn on and bypass R6. Thereafter Q1 will remain in conduction until the current drops below its holding current level at the end of each cycle. In theory adding a simple resistor could do the job, but this would cause significant loss.

Figure 16: Reference design for a phase-cut dimmable isolated flyback converter for a LED retrofit bulb. (source:Infineon [82])

Some solutions are presented [83] for dimmers based on SCR (triac) technology to solve the flickering phenomenon thanks to the continuous current applied through the gate. However they still need a minimum load.

Other dimmers [84] use so-called transistor technology (MOSFET) instead of triacs. They are often referred to as universal dimmers. Some of them can work as sine cutters or as trailing-edge dimmers. It is undocumented if this type of technology overcomes the flicker problem.

Some manufacturers provide external adapters that can be connected parallel to the lamp [85], and that can facilitate dimming of LED lamps and/or operation on 2-wire circuits (cost 3.6 euro).

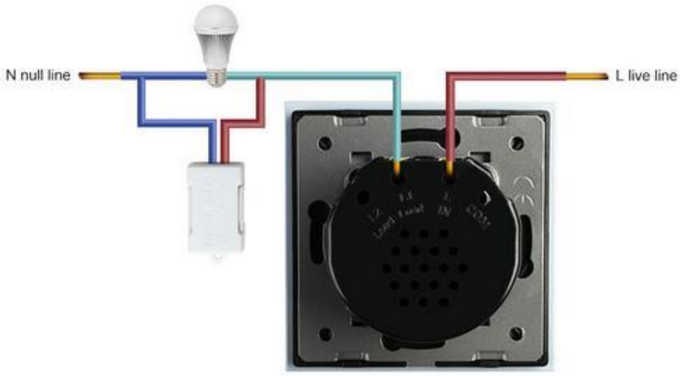


Figure 17: External adapter installed parallel to the lamp to enable switches and dimmers in 2-wire circuits as illustrated (source: Livolo [85]).

2.7.5. LED control gear and power factor correction

Simple LED control gears with bridge rectifiers as discussed in par. 2.7.2 easily result in harmonic currents on the AC line that could be inacceptable in some electrical grids (see Power Factor in Annex F.3 of Task 3). Electronic control gears with pure sine wave electronic power factor corrector (PFC) circuits do overcome this problem [86]. They provide power factor correction and simultaneously fit the harmonic currents on the (severe) limits from standard IEC 61000-3-2. This feature is always incorporated in electronic control gears with power levels above 25 W, because the active PFC circuit is needed to meet these limits.

In some cases, extra-low safety voltage might be needed (EN 60335). In those cases, the driver should also include an insulation transformer.

[82] http://www.infineon.com/cms/en/product/power/led-driver-ic-and-lighting-ic/dc-dc-led-driver-ic/evaluation-boards-led-driver-ic/EVALLED-ICL8002G-B1/productType.html?productType=db3a304435c2940f01363f0900826be5

[83] ST microelectronics (2/2013), UM1512 User manual on 'STEVAL-ILD003V1: SCR dimmer, EU version'.

[84] http://www.helvar.com/sites/default/files/product_datasheets/454_Transistor_Dimmer_datasheet_iss06.pdf

[85] http://www.livolo-france.com/en/home/32-livolo-lighting-adapter.html

[86] Supratim Basu, T.M.Undeland, PFC Strategies in light of EN 61000-3-2, EPE-PEMC 2004 Conference in Riga, LATVIA, 1-3 September 2004

2.7.6. LED control gear and product lifetime

A LED driver can be an important point of failure. For an integrated product, the lifetime and related maintenance factor (MF) is made up by the sum of the individual components [87]. For designs with LED series or parallel LED strings, the lumen maintenance and lifetime will depend on the driver topology [88]. For example, past studies have shown that electrolytic capacitors are an important point of failure [89].

2.7.7. LED control gear, BAT characteristics

External LED control gears typically had efficiencies of 90% [90] [91] and therefore, in consultation with industry, the 1.1 correction factor was added in regulation 874/2012.

In recent years, progress has been made in converter efficiencies, especially in the photovoltaic industry, where efficiencies are nowadays above 96% [92]. Photovoltaic panels are also diodes, and, considering the technical similarities, top-performance external LED drivers would also be expected to achieve 96-97 % efficiency [93].

A short market review showed that so called 'offline LED drivers [94]' with AC input voltage, power factor corrector, safe isolation and dimming, can be found with up to 95 % efficiency [93], depending on the wattage.

Current-control LED drivers operated from a DC voltage (12/24 V) can be found on the market today with efficiencies up to 97% [95] [96].

2.8. LED lifetime and lumen maintenance

US DoE [21] points out that uncertainties in product lifetime and reliability are barriers to adoption of LEDs. Lumen maintenance of LED-based lighting products is becoming better understood; however, predicting catastrophic failure and unacceptable colour shift is still difficult and requires new research and an improved testing and modelling framework.

The lifetime of LED packages depends both on the current density used and on the junction temperature. This is illustrated by the data for the Philips Luxeon K2 shown in Figure 18. Note that the $B_{50}L_{70}$ lifetime [97] is nearly halved for each 10˚C increase in junction temperature. For additional information, see also [98].

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[87] http://www.ibe-biv.be/media/pdf/Studiedag_2014/03_Hanselaer.pdf

[88] http://ledlight.osram-os.com/wp-content/uploads/2010/05/AppGuideCurrentDistributioninParallelLEDStrings.Web_.pdf

[89] http://www.lrc.rpi.edu/programs/solidstate/pdf/Han-SPIE2009-7422.pdf

[90] http://www.helvar.com/products/led-drivers

[91] http://www.tridonic.com/com/en/products/lca-50w-100-400mA-one4all-lp-pre.asp

[92] http://www.photon.info/upload/BRO_INV_DE_ONLINE_01_14_4211.pdf

[93] http://www.meanwell.com/product/led/LED.html (type HLG-40H .. -600H)

[94] http://www.linear.com/products/Offline_LED_Driver

[95] https://www.digikey.com/Web%20Export/Supplier%20Content/RecomPowerInc_945/PDF/recom-dc-input-constant-current-led-driver-modules.pdf?redirected=1

[96] http://www.meanwellusa.com/product/led/LED.html Module type series

[97] Time in years after which the lumen output decreased to 70% of the initial value for 50% of the samples

[98] http://www.lumileds.com/technology/luxeon-technology/lumen-maintenance-and-reliability

High-power LED lamps typically do not fail catastrophically with increased temperature, i.e. fail to emit light, but slowly decrease in light output over time [99], which has an impact on their Lamp Lumen Maintenance Factor (LLMF). Industry is typically using the American standard IES LM-80 for the measurement of lumen depreciation, which foresees a 6000 hours testing [100]. Usually the $B_{50}L_{70}$-lifetime is reported, i.e. the time in years where the light output of 50% of the samples drops below 70% of the initial output. As most LED light sources do not reach the $B_{50}L_{70}$-lifetime within the 6000 hours testing, an exponential extrapolation based on the lumen depreciation in the 1000 – 6000 hours interval is made according to IES TM-21 (Figure 19).

From tests on the durability of 90 LED lamp models (5 samples each) performed between 2011 and 2015 by consumer organisations [101], ANEC&BEUC draw the following conclusions:

- 4 out of the 15 models purchased in 2011 did not comply with regulation 1194/2012 since they lost over 20% of their light intensity after 5000 hours.
- this failure was observed in only 3 out of the 75 models purchased later in 2012 and 2013 and no failure was observed in the latest purchase.
- among the oldest bulbs, 18% of those purchased until early 2012 failed before passing the 5000 hours test compared to 3 % of those acquired later in 2012 and 2013.
- more than one third of the light bulbs purchased in 2011 and early 2012 burned out after 10.000 h, while only 10% of the bulbs purchased in 2012 and 2013 failed.
- In general these findings illustrate a positive development.

[99] CREE Application note 'Cree® XLamp® LED Long-Term Lumen Maintenance' (2015): http://www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/XLamp_lumen_maintenance.pdf

[100] The international equivalent is IEC 62717 for LED modules and IEC 62722-2-1 for luminaires, see Task 3 report par. 3.3.1, section on LED lighting products. See also Task 1 report par. 4.1.1 and 4.1.2.

[101] http://media.deco.proteste.pt/download/2522f15319ad4b0431bae9684f7cc63c09be77b5/tmpf26.pdf (in portuguese, information provided to the study team by ANEC&BEUC)

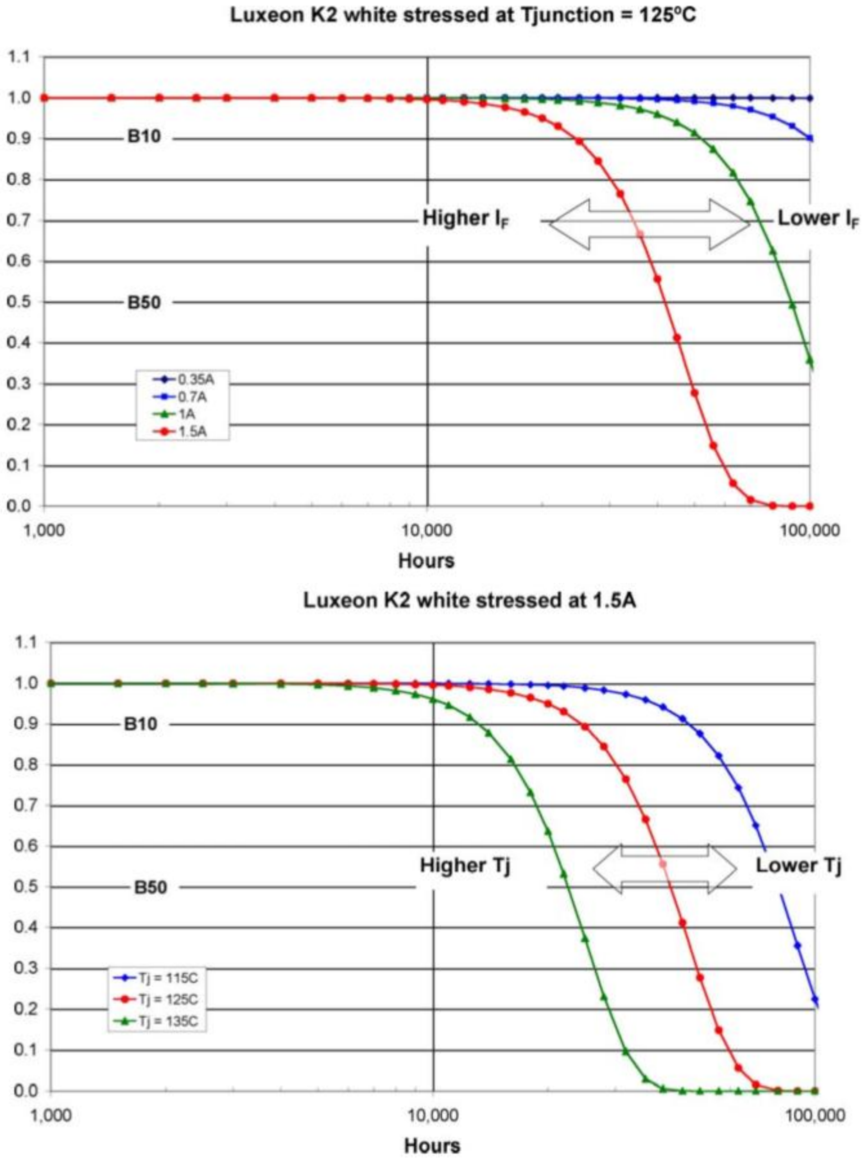

Figure 18: Dependency of the lifetime of the Philips Luxeon K2 LED package (now discontinued) on the forward current and on the temperature of the junction. The vertical axis gives the fraction of surviving samples. The horizontal axis gives the useful lifetime, probably L70 (source: [102])

[102] http://www.ledjournal.com/main/wp-content/uploads/2012/05/Philips_Understanding-Power-LED-Lifetime-Analysis.pdf

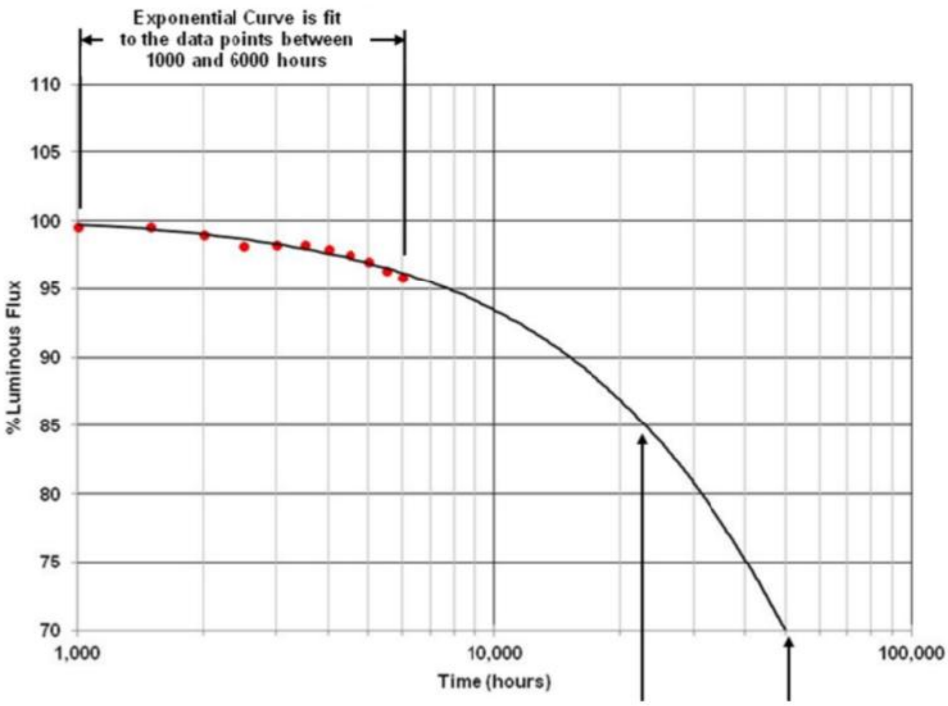

Figure 19 Example of extrapolation of lumen depreciation measurements up to 6000 h to the point where the L85 or L70 lifetime is reached (Source: Cree [99])

2.9. Differences between LEDs and other light sources

This paragraph summarizes the main differences in characteristics between LED lighting and non-LED lighting technologies. This is relevant background information for chapter 5 where the replacement of non-LED lamps by LED lamps is discussed:

- LEDs have a higher efficacy than incandescent lamps, halogen lamps, and CFLs. Currently (2014-2015) their efficacy is comparable to that of LFLs and HID-lamps. It is expected that in a few years LED efficacy will surpass the best efficacy of all other lamp types (par. 2.10, chapter 5).
- LEDs have (much) higher lifetimes than most other lamp types, but when comparing different lamp types their lumen maintenance characteristics also have to be taken into account, in particular for non-residential applications as office- and street-lighting.
- The efficacy and the lifetime of LEDs decrease as the operating temperature increases (par. 2.2.5, 2.8). LEDs are therefore not suitable for high-temperature applications such as oven lamps.
- LED lamps have a lower power and therefore potentially generate less heat, but they release this heat in a different manner. Filament lamps and HID lamps radiate most heat away, in the form of infrared 'light'. An LFL T8 (HF) will convert 32 % of input energy into light, 27 % into infrared radiation heat, and 41 % into convection heat (air) [103].

[103] OSRAM (2013), p. 56: Technical application guide Double capped fluorescent lamps: T8, T5 HE and T5 HO, T5 short and Single capped fluorescent lamps: T5 FC Part 2: Attachments'

LEDs generate their heat inside the chip and do not radiate it away with the light. The heat has to be initially removed mainly by conduction to the lamp base, or by conduction to a dedicated heat sink and then by convection to the surrounding air. In recent low power LED lamps the heat sink is no longer present, but higher power lamps still need it.
The different way in which heat is released may cause thermal problems [104] when using LED retrofit lamps in existing luminaires, in particular when closed. The presence of the heat sink may lead to larger lamp dimensions and larger lamp weight, which can cause lock-in problems in existing luminaires.
The 'cool light beam' of LEDs offers advantages in some applications, e.g. food display lighting.

- Some applications, e.g. projection, require a small high-intensity light source (high lm/mm^2 or Cd/m^2 of projected emitter surface). HID-lamps are suitable for these applications, but LED lamps cannot provide comparable light intensities [105].

- Single LED chips are inherently directional. Non-directional lamps can be created by spatially combining several LED chips in a suitable way or by using optical elements. The light distribution characteristics of LED retrofit lamps can anyway be different from those of the lamps they aim to replace (e.g. retrofit tubes in par. 5.4.5). This has to be taken into account when using LED lamps in luminaires with existing optics, but the directionality of the LED light can also reduce optical losses and thus constitute a potential for energy savings.

- Using the LED technology it is relatively easy to change the colour of the light, by varying the composition of the phosphors and/or by combining red, green, amber and blue LEDs. The variety of white-light LED models offered on the market is typically wider than for the lamps with classic technology. LED lamps can have user-tuneable colours (white with different CCT, or non-white). In addition LED lamps can be easily designed to have specific spectral characteristics (grow lights, food display, special spectra related to health aspects). Dim-to-warm solutions also exist on the market. Different colours will typically have different efficacies, e.g. for warm white LEDs the efficacy is lower than for cool-white LEDs.

- Most LED lamps are declared to have a CRI$\geq$80, as required by regulation 1194/2012 for indoor use. This is not on the same level as the CRI near 100 of filament lamps but sufficient for most applications. LED lamps with CRI 90-95 are available for special applications requiring this. Higher CRI is usually associated with slightly lower efficacy.

- Most LED lamps are declared to have a colour consistency within 6 McAdam ellipses, as required by regulation 1194/2012. This is sufficient for most

[104] Reduced efficacy and lifetime, light shutting off due to thermal protection, thermal damage to the LEDs, overheating of the entire zone with fire risk in the worst case.
[105] The typical surface luminance is: 680 Cd/m² for a 1000 lm OLED panel of 50x50 cm , 12 K Cd/m² on the fluorescent lamp surface, 75K Cd/m² on an LPS lamp, 150 K Cd/m² on frosted HPS , 70000 K Cd/m² on a lamp filament and up to 100000 K Cd/m² on ah HID arc. Sources:
Reineke, Sebastian, Michael Thomschke, Björn Lüssem, and Karl Leo. "White organic light-emitting diodes: Status and perspective." Reviews of Modern Physics 85, no. 3 (July 2013): 1245-1293. © 2013 American Physical Society
http://www.lighting.philips.com/main/prof/oem/hid-systems/high-pressure-sodium/son-h/928152409830_EU/product

applications, but there may be special applications where the resulting colour differences are not acceptable.

- Dimmable LED lamps are on the market and they are expected to work with the compatible dimmers listed by the lamp manufacturer. Problems may be encountered when using these LED lamps on existing dimmers that are not on the list (see Task 3 report par. 7.2).

- Health-related aspects of LED lamps are not essentially different from those for other types of lamps, although some people remain concerned about blue-light hazard, see details in the Task 3 report par. 5.1.

2.10. LED Timeline for lamps and luminaires

2.10.1. Average LED efficacy and price in 2015

This paragraph tries to establish a timeline for LED lamps and luminaires. A proposal is made for the evolution of LED lamp efficacies and LED lamp prices. The starting point, i.e. the 2015 average efficacy and price of new sold LED retrofit lamps, is derived from data in chapter 5 and summarized in Table 10.

Table 10 Current efficacy (lm/W) and price (euros/klm excl. VAT) for different types of LED retrofit lamps. For both variables the minimum, average and maximum value are presented. N = number of lamp models on which the data are based; if there are two values, the first is for the efficacy and the second for the price. (Source: VHK 2015, see notes)

LED lamp type	N	Efficacy (lm/W)			euros/klm (excl. VAT)			note
		min	avg	max	min	avg	max	
NDLS LED filament lamps	10	96	109	121	10.33	24.80	53.33	1
NDLS LED other lamps	23	58	77	104	5.83	17.27	36.00	1
DLS LED lamps with E14/E27 cap	43	40	79	107	9.89	36.31	165.2	2
DLS LED lamps with GU10 cap	58	52	77	100	9.72	36.67	105.1	2
LED retrofits for HL LV Reflector	5	50	73	104	11.67	23.43	49.56	3
LED retrofits for HL LV Capsule	6	67	93	101	9.91	41.40	71.36	4
LED retrofits for HL MV Capsule	5	74	84	96	8.42	22.32	41.64	5
LED retrofits for HL MV R7s	14/11	67	96	115	4.54	26.71	57.38	6
LED retrofits for LFL (tubes)	14/7	80	109	148	11.31	18.21	43.95	7
LED retrofits for CFLni	4/2	72	91	102	23.27	28.10	32.93	8
LED retrofit for HID (indicative)	(3)	90		120		10		9
Average, all types			89			23.4		10

1 Derived from data in Table 39. Prices have been divided by 1.2 to remove VAT.
2 Derived from the database used for the "Market assessment on directional mains voltage filament lamps related to stage 3 of Commission Regulation (EU) No. 1194/2012, VHK for the European Commission, April 2015." See also par. 5.13.4. The lumens for directional lamps are originally defined in a 90° or 120° cone. To make results more comparable with those for non-directional lamps, lumen values have been increased by 20%. This percentage has been derived from catalogue data that provided both total lumens and lumens in the cone, but is anyway approximate.
The average price for these lamps results high due to the presence in the database of some very expensive lamps. The median price is considerable lower than the average: 22-23 euros/klm.
3: Data based on Table 31
4: Data based on Table 33.
The median price is around 32 euros/klm, considerably lower than the average of 41.
5: Data based on Table 35
6: Data based on Table 37
7: Data based on Table 22
8: Data based on Table 29

9: Data based on Table 44

10: Average non-weighted for lamp quantities: it is the arithmetic average of the averages per lamp type. For DLS lamps and LV capsules, the median values have been used to compute the overall average.

As expressed by the minimum and maximum values in the table, the range of LED retrofit lamp efficacies (lm/W) and prices (euros/klm excl. VAT) is very wide. However, the average values show a relatively small variation between the lamp types.

Average efficacies vary from 73 to 109 lm/W, with an overall average of 89 lm/W. The highest average values are found for NDLS LED filament lamps and LED retrofit tubes for LFL T8 replacement. The absolute highest efficacy is 148 lm/W, for a LED retrofit tube, and regards a tested value (see Table 22 and references there).

As regards average prices, the values for LED retrofits for MV DLS and for LV halogen capsules are relatively high due to the presence of lamps with a very high price. For these lamps the median values are considerable lower than the averages in the table, i.e. 22-23 instead of 36 euros/klm for the DLS and 32 instead of 41 euros/klm for the LV capsules. Taking into account these median values, average prices vary from 10 to 32 euros/klm, with an overall average of 23.4 euros/klm. Lowest prices on the market are typically around 10 euros/klm (excl. VAT), but even lower prices can already be found.

2.10.2. US DoE prediction

At luminaire level or at retrofit lamp level, the efficacy is lower than the one reported in par. 2.5 for LED packages, due to additional losses (Table 11):

- Luminaire thermal efficiency
  Inside the lamp/luminaire the LED package will usually be warmer than the 25°C used for the LED package efficiency. The higher operating temperature will lead to a lower efficacy (par.2.2). Improved luminaire designs can lower the operating temperature, for example by reducing the number of thermal interfaces in the thermal path of the luminaire. One possibility is to mount the LED packages directly on the heat sink instead of mounting them first onto a circuit board and then mounting this board on the heat sink. US DoE [21] reports a 2013 luminaire thermal efficiency [106] of 86% and projects 93% for 2020.

- Driver efficiency
  The driver efficiency of a LED luminaire or LED retrofit lamp describes the efficiency of the power supply in converting alternating current (AC) line power to an electrical input suitable for running the LED package(s) [107]. US DoE [21] reports a 2013 driver efficiency of 85% and projects 93% for 2020. For further information on drivers see par.2.7.

- Luminaire electrical efficiency
  The package efficacy reported by US DoE [21] contains the assumption of a current density of 35 A/cm^2. As clarified in par.2.2, the efficacy can be increased by reducing the current density (reduced current droop). The luminaire electrical efficiency reported in Table 11 refers to the benefit obtained by driving the LED

[106] Intended as the ratio of the lumens emitted by the LED package in thermal equilibrium under continuous operation in a luminaire, to the lumens emitted by the package as typically measured and reported in production at 25°C.

[107] The driver efficiency also includes the efficiency of the electronics needed to adjust for changes in conditions (e.g. temperature or age) so as to maintain brightness and colour or for active control of the lighting system (dimming).

package at a lower current. In 2013 this benefit is assumed to be 15%, but it is projected to diminish to 9% by 2020 [108].

- Luminaire optical efficiency
  LED Luminaires or LED retrofit lamps typically include glass envelopes, lenses, optical mixing chambers, remote phosphors, reflectors and/or diffusers to obtain the desired light output. These features reduce the overall efficacy. US DoE [21] reports a 2013 fixture/optical efficiency of 85% and projects 94% for 2020. A possible design improvement is to integrate specific lens functionality into the primary optic/encapsulant of the LED package, thus avoiding the need for a secondary optic in the luminaire.

The overall luminaire efficiency is projected to increase from 71% in 2013 to 89% in 2020. For a warm-white pc-LED this would imply passing from a 96 lm/W luminaire in 2013 to a 200 lm/W luminaire in 2020. The final target luminaire efficacy for US DoE is 230 lm/W.

As regards the 2013 prices of LED retrofit lamps, US DoE [21] reports:

- A19 replacement lamp, 800 lm, 10 W, 60W equivalent, 14 euros/klm (16 $/klm) (expected to decrease to around 4.4 euros/klm (5 $/klm) by 2020).
- PAR38, 900 lm, 18 W, 75 W equivalent, 32.6 euros/klm (37 $/klm).
- MR16, 500 lm, 10 W, 35 W equivalent, 31.7 euros/klm (36 $/klm).
- 6" downlight, 625 lm, 11.5 W, 65 W equivalent, 37.8 euros/klm (43 $/klm).

Table 11: Breakdown of LED luminaire efficiency projections. Data are for luminaires using warm-white pc-LED packages with CCT=2580-3710K, CRI>80. The overall luminaire efficiency (%) is the product of thermal-, driver-, optical- and electrical-efficiency. The luminaire efficacy (lm/W) is the product of package efficacy (at 35 A/cm^2, 25˚C) and overall luminaire efficiency. (Source: [21])

Efficiency Channel	2013	2015	2020	Goal
Package Efficacy Projection[2] (lm/W)	135	169	225	250
Thermal Efficiency (increased T_{op})	86%	88%	93%	95%
Driver Efficiency	85%	87%	93%	96%
Fixture/Optical Efficiency	85%	89%	94%	96%
Electrical Efficiency (reduced I_{op})	115%	113%	109%	105%
Overall Luminaire Efficiency	71%	77%	89%	92%
Luminaire Efficacy[3] (lm/W)	96	130	200	230

[108] The lower current implies lower lumen output and thus the need for a higher number of packages. This has cost implications.

2.10.3. Other predictions regarding LED timeline

The Stage 6 review report [109] presented efficacy and price projections for MV LED retrofit lamps. For convenience, the information has been copied in Table 12, adding a line with prices in euros/klm excl. VAT, for ease of comparison with other data.

In its 2012 report "Lighting the way" [110], McKinsey & Company provide an analysis of the global lighting market. This report also contains a projection of the LED price evolution, for retrofit lamps and for dedicated luminaires (indicated as LED full). These prices are per unit. For (approximate) comparison with other data, they have been converted to euros/klm assuming an average lamp has 500 lm. These data are shown in Table 13.

Table 12 MV LED retrofit lamp, efficacy and price projections EU 2012-2025 (Source: Stage 6 review, table 2. Original sources: for efficacy CLASP 2013, based on US DoE MYPP 2012 projections; for EU lamp consumer prices incl. VAT (500 lm lamp) up to 2020 LightingEurope; 2021-2030 prices extrapolation by VHK.) The last line in the table has been added by the study team and gives the price information in euros/klm excl. 20% VAT.

Year	2012	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2030
lm/W	58	93	99	105	112	118	125	130	134	138	142	169
price in € / 500 lm incl. VAT	18	10	9	8.5	8	7.5	7	6.5	6	5.5	5	2.5
price in € / klm excl. VAT	30.0	16.7	15.0	14.2	13.3	12.5	11.7	10.8	10.0	9.2	8.3	4.2

Table 13 LED price projection by McKinsey 2012. The euros/klm values have been added by the study team, assuming an average of 500 lm/unit.

	Year	2011	2012	2016	2020
LED retrofit	€/klm	13.16	10.22	6.24	5.40
LED full	€/klm	26.72	21.10	8.06	5.62
LED retrofit (original data)	€/unit	6.58	5.11	3.12	2.70
LED full (original data)	€/unit	13.36	10.55	4.03	2.81

2.10.4. Proposed Timeline for LED lamps

Figure 20 summarizes the efficacy projections from the preceding paragraphs. The top two lines are for white LED packages (par. 2.5.6). The yellow line (third from above) is for warm white LED luminaires and has been derived from the package efficacy using the additional package-to-luminaire losses from par. 2.10.2, including also driver and optics losses. The lowest, nearly straight, line presents the projection from the Stage 6 review.

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[109] "Review study on the stage 6 requirements of Commission regulation (EC) No 244.2009 Final Report", VHK (pl) / VITO for the European Commission, Delft/Brussels 14.6.2013, SPECIFIC CONTRACT No ENER/C3/ 2012-418 LOT 2/01/SI2.645913 Implementing Framework Contract No ENER/C3/2012-418-Lot 2. http://www.eup-network.de/fileadmin/user_upload/Technical_Review_Study_by_VHK_VITO.pdf?PHPSESSID=a60a9114e01af59471374f5814656e0c

[110] "Lighting the way: Perspectives on the global lighting market", McKinsey & Company, second edition, August 2012. This is an update of the earlier report of 2011. http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/automotive%20and%20assembly/lighting_the_way_perspectives_on_global_lighting_market_2012.ashx

The green dot for year 2013 indicates the MELISA value (80 lm/W), more or less the average of the US DoE and Stage 6 review projections. The MELISA value is also compatible with the current (2014-2015) average LED lamp efficacy of 89 lm/W (par. 2.10.1), that is also indicated in the figure, together with its range of variation (of the averages) over the various lamp types.

The red dotted line is the projection that is proposed for this study.

Figure 21 summarizes the price projections from the preceding paragraphs. The bottom two lines are for white LED packages (par. 2.5.6). The solid yellow line (third from below) is for OEM LED lamps [111]. The dotted lines are the projections derived from McKinsey 2012 (par. 2.10.3), respectively for retrofit lamps and for integrated luminaires. The upper line presents the projection from the Stage 6 review.

The green dot for year 2013 indicates the MELISA value (20 euros/klm), more or less the average of the US DoE and Stage 6 review projections. The MELISA value is slightly optimistic as compared to the current (2014-2015) average LED lamp price of 23 euros/klm (par. 2.10.1), that is also indicated in the figure, together with its range of variation over the various lamp types. The MELISA value is anyway within this variation.

The red dotted line is the projection that is proposed for this study.

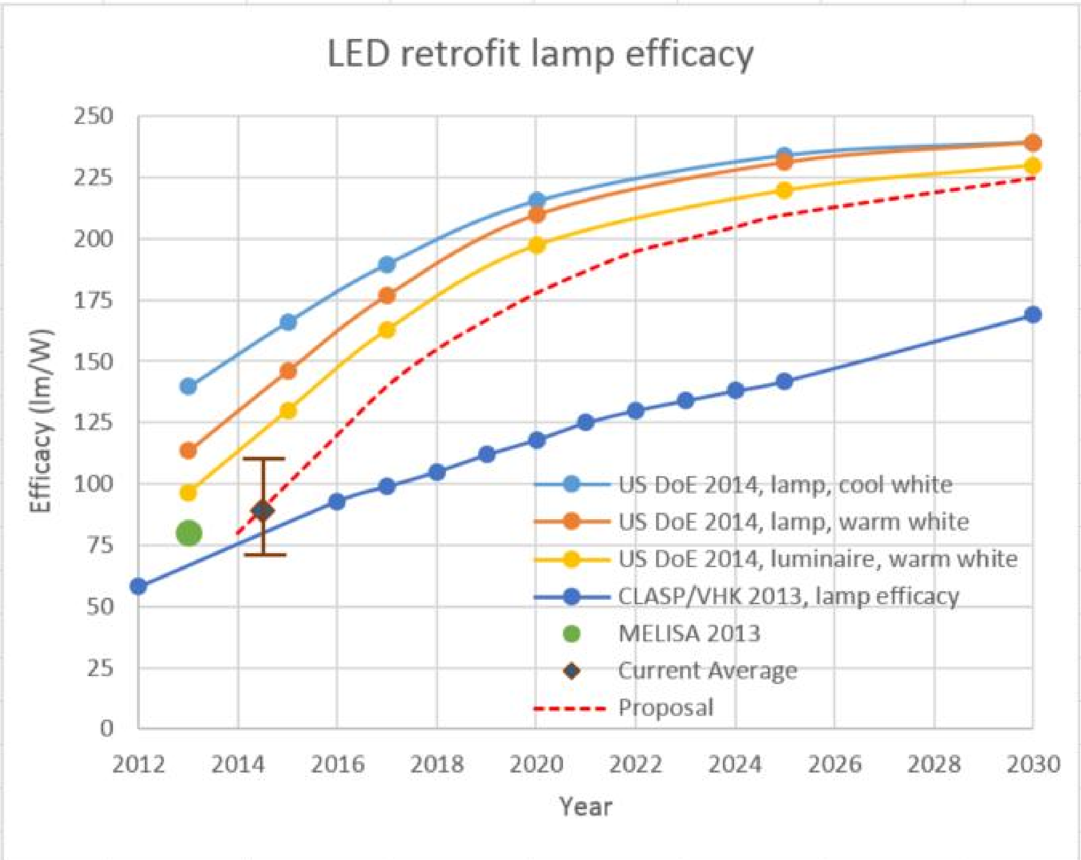


Figure 20 Projections for LED efficacies from US DoE MYPP 2014 and from the Stage 6 review report. The 2013 MELISA value is indicated as a green dot. The current (2014-2015) average LED efficacy of 89 lm/W and its variation over lamp types (from par. 2.10.1) is also indicated. The red dotted line is the proposed projection for this study.

111 US DoE MYPP 2012, as reported in the Stage 6 review report

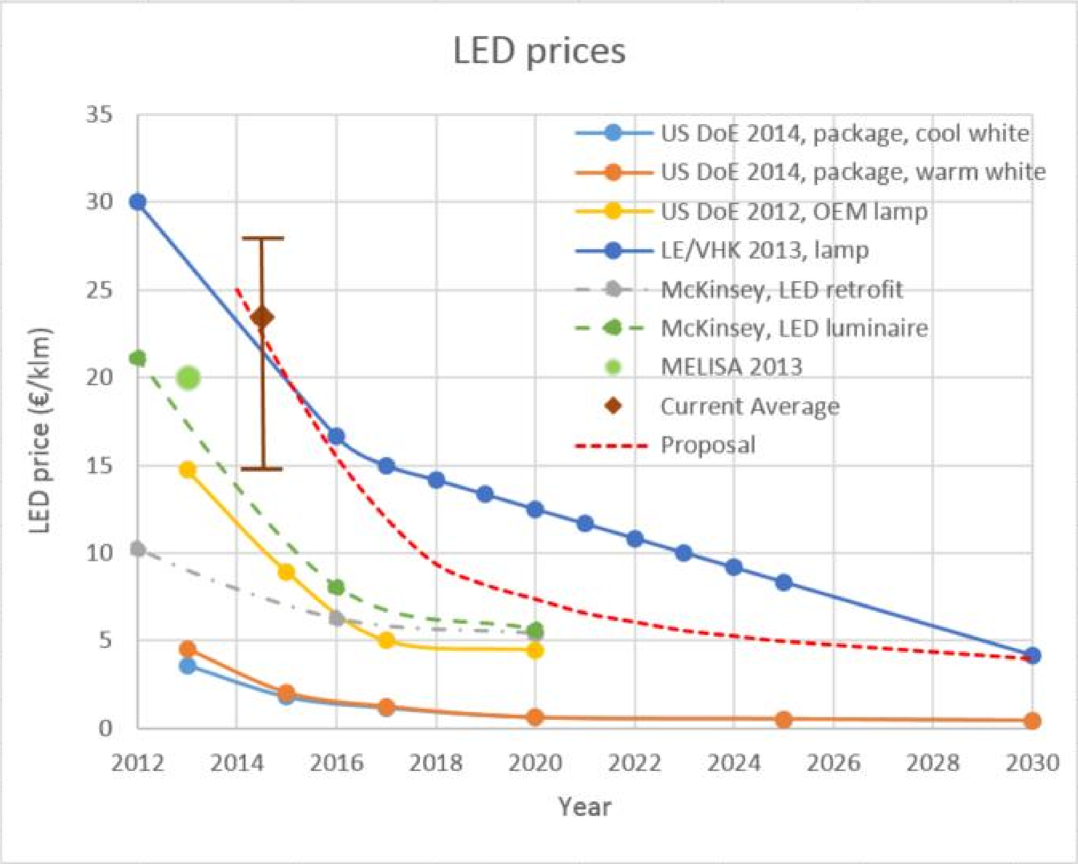


Figure 21 Projections for LED prices (in euros/klm excl. VAT) from US DoE MYPP 2014, Stage 6 review report, and McKinsey 2012. The 2013 MELISA value is indicated as a green dot. The current (2014-2015) average LED price of 23 euros/klm and its variation over lamp types (from par. 2.10.1) is also indicated. The red dotted line is the proposed projection for this study. Note: US DoE prices have been assumed to be excluding VAT, and 1.12 US dollar = 1 euro was used for conversion.

As regards the efficacy projection, the curve proposed by the study team follows the trend of the US DoE curves, but adapting them downwards to meet the identified point of 2014-2015 average efficacy. In addition, the US DoE curves have been interpreted to represent the expected best efficacy in a given year rather than the expected average efficacy of new sold products in a given year, as needed in this study for the scenario analyses in Task 7. For this reason the study team projection stays below the US DoE efficacy curve for LED luminaires.

As regards the price projection, the starting point is the identified 2014-2015 average price/klm, which is significantly above the US DoE value for the same year, but close to the LightingEurope/VHK value (from the Stage 6 review study). Also here, the US DoE curve is thought to be more representative of the lowest expected prices, while for this study the average expected price of new sold products in a given year is required. Considering the recent fast drop in LED prices, that is generally expected to continue at least in 2015, the study team projection is more optimistic than the Stage 6 review study projection as regards the speed of change in nearby years, but ends at the same price/klm level in 2030.

As regards both projections, it is uncertain up to which point the current trends in LED development will continue. Industry worldwide is investing a lot of money in LED research and development, and it seems reasonable to expect that sooner or later they will want to see a return on this investment, i.e. developments might slow down or come (temporarily) to a halt so that industry can concentrate on earning back some money. The 'sooner or later' could be related to the phase-out of halogen lamps, with the corresponding loss of industry revenue from that lamp type. It is e.g. not unthinkable that from 2018 the average efficacy will more or less 'freeze' at 150 lm/W for some years. This process may also be related to a decrease in the number of players on the market, e.g. Samsung and Philips already scaled down or abandoned LED lighting production [112].

[112] http://www.reuters.com/article/2014/10/27/us-samsung-elec-led-idUSKBN0IG0DD20141027

3. Other developing lighting technologies

3.1. OLED lighting

A description of OLED lighting and an analysis of the 2014 state-of-the-art has been provided in the Task 1 report par. 1.6.1. The following main conclusions were drawn there:

- OLEDs emit a diffuse (non-directional) light over a large area, as opposed to LEDs that are essentially directional point light sources. Consequently OLEDs are more suitable as lighting panels, not as retrofit lamps for the traditional lighting technologies.

- There are some commercial OLED lighting products for sale, but these seem to regard mainly sample kits for designers and premium light installations and luminaires. They are to be considered prototypes or technology demonstrators. OLED lighting panels are still too expensive to be considered for general lighting service.

- The highest efficacy for commercialised panels is 50 – 60 lm/W [113]. Major manufacturers expect to reach 130 lm/W by 2018. The US Department of Energy target for 2020 is 150-170 lm/W. The potential future efficiency for OLEDs is expected to remain below the efficiency foreseen for LEDs.

- The impact of OLED lighting on the European market for general lighting applications is negligible. This is unlikely to change significantly before 2020. The future of OLED lighting is uncertain. OLED lighting may never obtain a significant share of the general lighting market, but the situation might also develop exponentially in favour of OLEDs.

- A new lighting regulation should probably take into account OLEDs, to avoid that early OLEDs perform poorly and cause market souring, but also considering the efficacies that can be reached by OLEDs, i.e. avoid unintentional barriers for market introduction of OLED products.

As an addition to the above the following recent information is presented:

- LG Chem now offers engineering samples of its flexible plastic-based OLED panels for 220 euros ($250), and mass production is expected by July 2015. Prices will be lower when mass production starts. The new panels can be flexed further than the current thin-glass based flexible OLEDs, and are more durable.
  LG Chem also started to produce the world's largest white OLED - at 320x320 mm. These panels are 0.88 thick and feature 60 lm/W, CRI of over 90 and an output level at 800 lm - 1,200 lm. Each panel costs 598 euros ($680; lower for bulk orders) [114].
  LG Chem is planning the construction of a new production line for OLED lighting by 2017 (163 million euros ($185 million) investment). This will

[113] In March 2014 Konica Minolta announced the world's most efficient OLED lighting panel at 131 lm/W, raised to 139 lm/W in June 2014. This panel has 15 cm², life 55,000 h, 1000 cd/m², CRI 81, CCT 2857 K. www.oled-info.com/konica-minolta-break-their-own-record-worlds-most-efficient-oled-panel-139-lmw

[114] OLED newsletter January 2015. http://www.oled-info.com/lg-details-price-their-320x320-mm-and-truly-flexible-oled-lighting-panels

increase production capacity and lower prices dramatically. The internal discussion on this Gen-5 line started in 2012, and it was first planned to be built in 2015 [115].

- According to an analysis of OLED-info [116], based on the scarce pricing information available (from LG Chem and Philips), the current price of OLED panels is around 176 euros/klm ($200/klm), which is far more expensive than LED lighting, and limits OLEDs to high-end applications. Prices are expected to come down due to new production processes (soluble OLED processes instead of vacuum deposition) and to higher production volumes (production costs could be reduced by 90%).
  It may not be completely honest to compare LED and OLED on a lumen-basis. For many applications, LEDs are too bright and require indirect lighting or anti-glare shields. OLEDs have a low-brightness diffuse light and can directly be used, enabling less lumen to be installed for the same application.

- Konica Minolta recently started mass producing flexible OLED lighting panels, in its new roll-to-roll flexible OLED lighting plant, with a monthly capacity of a million panels at full capacity. Konica produces both white and colour-tuneable flexible panels. The white panel is 150x60 mm in size (0.35 mm thick) and weights 5 grams. The colour-tuneable is smaller (50x30 mm, 0.29 mm thick, 0.6 grams). Both panels are flexible with a curvature radius of 10 mm 117.

- UBI Research forecasts that the OLED lighting market will reach 72 million euros ($82 million) in 2015, and grow to 4.1 billion euros ($4.7 billion) by 2020. Prices are expected to drop quickly when capacities expand, meaning that UBI sees very large OLED lighting panel sales starting in 2016. UBI is more optimistic than other market researches. IDTechEx see a 176 million euros ($200 million) panel market in 2019 that will grow to 1.7 billion euros ($1.9 billion) in 2025. Cintelliq sees OLED competing with LEDs in 2016, and 500 million 100x100 mm OLED lighting panels produced in 2023. Some believe that OLED lighting will never really manage to take off. IHS for example estimates that the market will only reach 22.9 million euros ($26 million) by 2020 [118].

- Fraunhofer FEP's COMEDD developed new colour-tuneable transparent OLED lighting panels. According to the Fraunhofer colour tuneability is the most wanted feature (after flexibility) by lighting designers [119].

Following the conclusions on OLED lighting from Task 1, and the additional recent information presented above, OLEDs will NOT be considered as one of the base cases in this study. It is also difficult to define OLED as BAT or BNAT. Current prices for OLED

[115] OLED newsletter April 2015
http://www.oled-info.com/lg-chem-plans-build-185-million-gen-5-oled-lighting-fab-2017

[116] http://www.oled-info.com/how-do-oled-lighting-panels-compare-led-lighting-early-2015

[117] OLED newsletter March 2015
http://www.oled-info.com/konica-minolta-still-track-start-flexible-oled-lighting-production-fall
http://www.oled-info.com/konica-minolta-build-flexible-oled-lighting-r2r-fab-monthly-capacity-1-million-panels

[118] OLED newsletter March 2015
http://www.oled-info.com/ubi-sees-oled-lighting-market-growing-82-million-2015-47-billion-2020

[119] OLED newsletter April 2015
http://www.oled-info.com/fraunhofer-institute-shows-transparent-color-tunable-oled-lighting-panels

lighting products are too high to seriously consider them as a best-technology. In addition OLED efficacies are expected to stay behind those of LEDs, and prices are expected to remain higher than those for LEDs. OLED lighting products can also not be used as retrofit solutions for the other base cases, i.e. no OLED light bulbs, spots or tubes exist.
OLEDs do offer exciting new possibilities for lighting designers, in particular when flexible, transparent, colour-tuneable panels will become available on a large scale and at lower prices. In addition their large-area diffused light is attractive for some applications, as opposed to current light sources that are point- or line-like.

Considering that OLEDs are not considered as a base case or BAT/BNAT, no further technical description is provided here. Details on OLED technology, availability and characteristics of OLED lighting products, and future projections can be found in:

- US DoE 2014 MYPP [120],
- US DoE 2014 Manufacturing roadmap [121],
- OLED handbook 2015 [122].

Some selected information from the US DoE sources is reported below for convenience, see the references for details and further explanation.

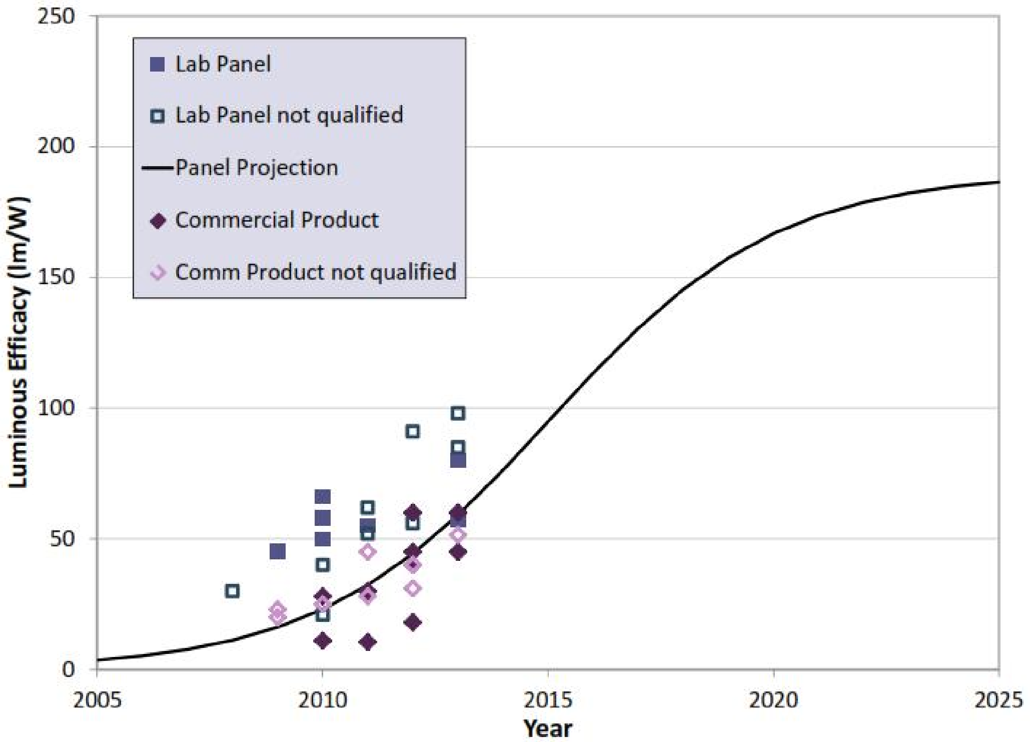
Table 14 Summary of 2013-2014 laboratory results of OLED panels (Source: US DoE 2014 MYPP, table 3.7 [120])

Developer	Efficacy (lm/W)	Luminance (cd/m^2)	Area (cm^2)	CRI (Ra)	CCT (K)	L_{70} (1000 hours)	Drive (V)
Konica Minolta	131 118	1,000 3,000	15	82	2800	27.5[1]	
SEL/Sharp	113 105	1,000 5,000	81		3270	400[1]	8[3] 8.4[3]
Panasonic	110 98	1,000 3,000	25	81	2600	40 10	5.5[2] 6.0[2]
UDC	70 60	1,000 3,000	~200	85 86	3030 2880	165 25	7.1[3] 7.8[3]
LG Chem	82	3,000	16[4]	84	2900	30	8.5[3]
CDT/Sumitomo	56 48	1,000 3,000	13	80 82	2900		4.3[5] 4.8

Notes:
1. Scaled from data provided for L_{50} assuming L_{50} is two times L_{70}
2. Tandem device producing two photons per injected electron
3. Triple stack device producing three photons per injected electron
4. This technology has been scaled up to yield similar performance in 76 cm^2 panels.
5. Single-stack device with solution processed layers up to the emissive layer and an evaporated ETL/cathode

120 Solid-State Lighting Research and Development, Multi-Year Program Plan, US DoE, May 2014, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf
121 DOE(2014): 'Manufacturing Roadmap Solid-State Lighting Research and Development Prepared for the US Department of Energy August 2014', Prepared by Bardsley Consulting, Navigant Consulting, SB Consulting, and SSLS, Inc, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf
122 http://www.oled-info.com/handbook/

Table 15 White-light OLED panel efficacy projection (Source: US DoE 2014 MYPP, table 4.3 and figure 4.2 [120])



Metric	2013	2015	2017	2020	Goal
LER (lm/W)	325	330	335	340	360
Internal Quantum Efficiency	75%	85%	90%	90%	90%
Electrical Efficiency	80%	80%	80%	82%	84%
Extraction Efficiency	31%	45%	54%	64%	70%
Panel Efficacy (lm/W)	60	100	130	160	190
L_{70} Lumen Maintenance (1,000 hours)	15	25	35	40	50

Note: Projections assume CRI > 80, CCT = 2580-3710K.

Table 16 OLED panel cost, estimated progress ($/m^2, multiply by 0.88 to have €/m^2) (Source: US DoE 2014 Manufacturing roadmap, table 1.6 [121])

	2013	2014	2016	2020	2025
Integrated Substrate	250	200	150	40	20
Organic Deposition	600	500	250	70	30
Assembly and Test	350	300	200	50	20
Overhead[d]	300	200	100	20	10
Total (unyielded)	1,500	1,200	700	180	80
Yield of Good Product (%)	25	40	70	75	80
Total Cost	6,000	3,000	1,000	240	100

3.2. Laser-diode lighting

Recently, lighting products have appeared on the market that employ laser-diodes as the basic light source for the emission of white light, in applications such as projection systems, automotive high-beam front lighting and medical applications. Research on this topic is ongoing and seems promising, but the technology is still expensive and limited to niche-markets for the named applications. No general lighting applications using laser-diodes have been found on the market.

As regards the projection applications, there are three technology options [123]:

- Use a blue laser diode (e.g. instead of a high-intensity discharge lamp). To create the other primary colours, the blue light is made to pass through a rotating phosphor wheel with openings. The phosphor creates yellow light while the blue light passes unconverted through the openings. A colour wheel next converts the yellow light in green and red. The blue light is diffused separately. The red, green and blue are then mixed, send through a lens, and projected. This is also referred to as phaser (phosphor-laser) technology.
- Pure laser (3P- or RGB-laser): uses three primary lasers of blue, green and red colour. The advantages are stated to be high light output, increased colour gamut and improved contrast. These projection systems are ideal for large-format applications such as cinema.
- Hybrid approach. This is a laser-phosphor system with the addition of one or two other light sources (typically LED), primarily with the aim to increase the amount of red light.

The advantages of laser-based projectors are stated to be increased brightness, longer lifetimes and reduced maintenance. Green lasers are still inefficient and speckle a lot, while green LEDs are not bright enough, and consequently the phosphor conversion is often used to generate this colour (but phosphors tend to disperse the light). Red lasers are stated to need a lot of cooling, but LEDs or phosphor conversion can be used [123]. Laser-based projectors have approximately twice the cost of traditional projectors [124].

As regards medical applications, Osram offers the ITOS Phaser 3000 [125], based on phaser technology, as a light source for medical operation head-luminaires and devices for microscopy and endoscopy. The light source provides 2100 lm with an input of 180 W (12 lm/W) and is claimed to be equivalent with a 300 W xenon lamp, but with a sixty times longer lifetime (30,000 vs. 500 hours).

The automotive laser-diode headlights are reported to have an efficacy of 170 lm/W as compared to 100 lm/W for LEDs. Their intensity is so high that the light extends about twice as far as LED high-beams, but because of the same high intensity, for safety reasons, the lights can be activated only at speeds above 60 km/h, and only if sensors do not detect any other lights ahead. Flashing with these lights is also disabled and they

[123] http://www.christiedigital.com/SupportDocs/Anonymous/Christie_laser_phosphor_article.pdf
http://www.christiedigital.com/Documents/Presentations/simuniversity2014/SIM%20U%202014%20-%2008%20-%20Solid%20state%20illumination%20challenges%20and%20opportunities%20-%20Arlington%20-%20Simon%20Guthrie.pdf

[124] http://dmd.hitachi-america.us/supportingdocs/forhome/DisplayTechnologiesGroup/lcdprojectors/SupportingDocuments/Hitachi-Lamp-Technology-Facts.pdf

[125] http://www.osram.com/osram_com/products/led-technology/specialty-lighting/led-modules/itos/itos-phaser-3000/index.jsp?productId

are not offered on the US market because they exceed brightness standards [126]. The originally concentrated light is managed by means of a series of lenses (low-beam) or by means of a small composite mirror consisting of 420,000 micro-mirrors that can be individually oriented (high-beam) [127] [128]. Note that CCT and CRI are not critical for this application; controlling the light beam is more important.

As regards the use of laser-diodes for general lighting purposes, there are some difficulties to overcome [129]:

- Lasers have an extremely narrow spot size, but this can be modified with suitable optics.
- Intense laser beams have optical safety issues, so protections will have to be implemented.
- Lasers have a very narrow line-width, i.e. they are essentially mono-chromatic. Even combining red, blue, green and yellow sources would not be expected to provide a good colour rendering. However, Sandia tests show that user perception is much better than this initial expectation and that lasers should not be a-priori discarded for CRI-reasons.

As pointed out by Christopher Mims [130], LEDs and laser-diodes (LD) are based on the same technology, but LDs use mirrors on both sides of the LED, and the reflection back and forth of the light creates an amplification effect, an avalanche of stimulated emission. Potentially, LEDs and LDs can have the same basic power conversion efficiency [131], but LDs can be driven harder, i.e. using higher currents without suffering the 'current droop' as LEDs do (par. 2.2.4), so that 2000 times more light can be produced per square centimetre.

This does not imply that LED bulbs could be replaced by LD bulbs in the future: such hypothetical bulbs would catch fire from the large amount of heat they produce, and the enormous amount of light emitted would be blinding. Instead of using classic light bulbs to fit existing sockets, the general lighting application that researchers have in mind would use a limited number of small powerful lasers in central positions, redistributing their light by means of fibre-optic cables, or by just 'shooting' it through the air, from one light-guide to another. At the destination, light-transmitting plastic elements could take that light and evenly distribute it into a warm, diffuse glow.

Consequently, similar to OLEDs, LDs need a completely new approach to lighting design, not a retrofitting approach.

[126] http://www.autonews.com/article/20140722/CUTAWAY01/140639991/osram-provides-bmw-i8s-laser-lights
[127] http://www.welt.de/motor/article139919970/So-funktioniert-das-Laserlicht-von-Audi-und-BMW.html
[128] http://www.osram-os.com/osram_os/en/news--events/spotlights/technology/2014/perfect-vision/index.jsp
http://europe.autonews.com/article/20140107/ANE/301109994/bmw-audi-will-introduce-laser-headlamps-this-year
[129] http://www.ledsmagazine.com/articles/2011/11/lasers-could-offer-alternative-to-led-light-sources.html
A. Neumann, J. J. Wierer, W. Davis, Y. Ohno, S. R. J. Brueck, and J.Y. Tsao, "Four-color laser white illuminant demonstrating high color-rendering quality." Opt. Express 19, A982-A990 (2011). http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-19-104-a982 (abstract)
[130] http://qz.com/146761/forget-led-bulbs-the-future-of-interior-lighting-is-lasers/
http://www.azom.com/news.aspx?newsID=38951
[131] However, compared to the 70% efficiency of today's LEDs, laser-diodes are now at 30%: http://www.enlightenmentmag.com/led-update/laser-vs-led

The University of California [132] produced a cool white laser-diode light source with CCT 4400 K, CRI 57, 76 lm/W and 252 lm. A warm white light source had CCT 2700 K, CRI 95, 19 lm/W and 53 lm.

Nobel Prize winner Nakamura states that we can expect to see laser diodes in lighting products within the next five years, and that they are a 'great opportunity for the next lighting products', but he also admits that a lot of work is still to be done [133].

It can be concluded that the laser-diode lighting technology exists, that it is promising, and that research is still ongoing. There are also commercial applications (car head lights, projection, medical), but no existing general lighting applications have been found by the study team. It is expected that these will come to the market in 5-10 years, but it is not clear yet how efficacy, costs, light quality, thermal management aspects and safety aspects will relate to those of LED lighting. So the technology is available, even if under development, but in this moment it is difficult to judge if this will be the best technology for the future. Laser-diode lighting will most likely not produce retrofit lamps for existing sockets, but require a new approach to lighting design, with a central light generation point and a light distribution system.

3.3. Induction lighting technology

Induction fluorescent lamps (also called electrodeless fluorescent lamps) produce light through a similar process to other fluorescent lamps, but without electrodes. Instead of using metal prong electrodes, a radiofrequency (RF) power supply sends an electric current to an induction coil (a wire wrapped around a plastic or metal core) positioned outside the walls of the lamp. The current passing through the coil generates an electromagnetic field. This field excites mercury in the gas fill, and the ionised mercury emits ultraviolet (UV) radiation. When struck by the UV radiation, the phosphor(s) coating the inside of the glass bulb emit visible light.

<u>Advantages</u>

- A mature technology.
- A very long lifespan due to the lack of electrodes, often between 50,000 and 100,000 hours depending on lamp model and quality of electronics used.
- Relatively low energy consumption compared with standard HIDs with lamp efficiencies of between 62 and 90 Lm/W (with higher power lamps generally being more energy efficient).
- Minimal Lumen depreciation compared with other fluorescent lamp types (because filament evaporation and depletion is absent).
- Reasonable colour performance with products offered across a broad spectrum of colour temperatures (2,700K –6,500K) and typical colour rendering index (CRI) of 80 to 90.
- Low-temperature operation (half that of metal halide).
- High power factor due to low-loss, high frequency electronic ballasts (typically 98% efficient).
- Virtually maintenance free
- Flicker-free

[132] http://www.laserfocusworld.com/articles/2013/09/ucsb-laser-plus-phosphor-white-lighting-is-efficient-and-stable.html

[133] http://luxreview.com/article/laser-diodes-are-the-future-says-nobel-prize-winner-nakamura

- "Instant-on" and hot re-strike capability unlike most mercury-vapour, sodium-vapour and metal halide lamps used in commercial-industrial lighting applications.

Disadvantages

- Have low lumen density, necessitating large fixtures (e.g. an induction lighting fixture intended to replace a 400W metal halide fixture is required to be about the size of an office fluorescent “troffer”). This limits the use of induction lighting fixtures due to poor aesthetics and high wind loading factors.
- Exhibit poor directionality, giving rise to fixture inefficiencies despite acceptable source efficiencies.
- Lower quality lamps often emit high levels of radio frequency interference due to insufficient shielding.
- Have a reputation for failing to illuminate in cold weather.
- Contain a small amount of mercury.

The first significant introductions of the technology occurred in the early 1990s. Several major lighting manufacturers (IMT/QL (ex-Philips), Osram, GE and a significant number of Chinese suppliers) currently supply or have supplied such lamps. Available products include light sources and whole fixtures for a variety of applications such as high bay fixtures, floodlights and street lights.

When LEDs first appeared, induction products competed well against them, partly because they were more affordable. However, the recent improvement in performance and reduction in cost of LEDs makes induction lighting a less attractive option. There are potentially some applications where induction lighting may have significant benefits over LEDs. However, these are not immediately obvious and it is unlikely induction lighting will make significant inroads in the European market.

Induction lighting is a mature technology, with real world data available. Not much more development is expected as induction lighting was more valued for long life than energy efficiency, and LEDs have both of these qualities.

Two Lighting Research Center reports give comparative performance of induction lighting:
http://www.lrc.rpi.edu/programs/nlpip/publicationDetails.asp?id=931&type=1;
http://www.lrc.rpi.edu/programs/nlpip/lightingAnswers/plasma/advantages.asp

General lighting standards apply to induction lighting, depending on the application. The relevant IEC standards are IEC 62532:2011 - Fluorescent induction lamps - Safety specifications, and IEC 62639:2012 - Fluorescent induction lamps - Performance specifications.

Because induction lighting is a mature technology and is currently under pressure from rapidly developing LED and plasma lighting technologies, it is unlikely to play a significant role in future lighting scenarios and regulations. No sales figures or market studies on induction lighting have been identified. Consequently the technology will not be addressed as a specific base case in this study.

3.4. Plasma lighting technology

Plasma lamps combine the reliability of the solid-state drive technology with the high brightness and full spectrum of HID sources.

Plasma lamps use a dielectric resonant cavity to couple power into a high intensity discharge vessel. An RF signal is generated by the solid-state power amplifier and guided into an electric field around the lamp[134] (the lamp itself is usually very small, about the size of a marble, and thus behaves as a near point source of light). The high concentration of energy in the electric field vaporizes the contents of the bulb to a controlled plasma state at the centre of the lamp and generates an intense source of light. The temperature inside the bulb (around 5,800K) is similar to the surface of the sun and produces a comparable spectrum of light.

Advantages

- Can be very small compared with a HID lamp of similar light output.
- Can be powered using solid-state electronics, which provide high reliability and allow precise control over the lamp's operation.
- Do not need metal electrodes to deliver power into the light source, resulting in a more robust quartz vessel that eliminates early failure and lumen degradation.
- Is a directional light source, is easily dimmable, has a rapid turn-on and re-strike, and can operate in any orientation.
- Typically has lower installation, maintenance and operating costs and higher energy efficiency, relative to HID lamps.
- Has a CRI up to 95 and the potential for tailored spectra to suit specific applications. This means lamps can be used for a wide range of purposes from visible light to UV applications[135].
- Can operate at several gigahertz (e.g. Ceravision), providing flicker-free light.

Disadvantages

- Has relatively slow warm-up time, approx. 45 seconds to full light output (compared with LED, which reaches full light output virtually instantaneously) and 2 minute re-strike time.
- Produces ultraviolet (UV) radiation in addition to light. The level of UV emission depends on the characteristics of the plasma emitter. Lamp chemistry can be used to govern UV emissions.
- May contain a small amount of mercury (substantially less than a typical HID source of equivalent power)[136].
- Typically have high levels of UV output which require specialist glass/coatings to remove where used in high population areas.

Several manufacturers supply plasma light engines and lighting fixtures for various applications from cinematography through street lighting to grow lamps. Major current or recent manufacturers include Ceravision (UK), Luxim (now LUMA America), Plasma International (Germany), Topanga Technologies (USA) and Sipp Industries, Inc. (USA). Ceravision recently teamed up with Dipolar (Sweden), a well-established developer of power supply and microwave equipment for the global market.

[134] Some manufacturers use wave guides to achieve a forward-emitting radiation pattern, while others place the lamp within the electric field to produce an omni-directional radiation pattern.

[135] For example, Ceravision's plasma technology allows the choice of a wide range of chemical doses and so the output can be accurately specified from anywhere in the spectrum.

[136] Ceravision offers flexible dose chemistry, including Mercury free options.

Plasma lighting continues to evolve, although a lot of the research is proprietary and not publically available. Research goals include stability of the light system and low-temperature performance.

The main uses of plasma lighting in the current market are general applications where high-intensity point light sources are desirable (e.g. high bay fixtures, street lights, parking garage lighting), horticultural “grow” lighting and film / cinematographic studio lighting.

Several field trials have been reported by the Lighting Research Centre: (http://www.lrc.rpi.edu/programs/nlpip/lightingAnswers/plasma/experience.asp)

- Scottsburg Municipal Electric Utility, Scottsburg, Indiana (2009 - 2011)
- Sacramento Municipal Utility District, Sacramento, California (2011)
- Ports America, Oakland, California and Newark, New Jersey (2010 - 2012)
- Hydro One, Leamington, Ontario, Canada (2010)

These studies show a range of technical issues that can be expected with newly-developed technology, including electronic driver failures, difficulty starting the plasma lamps in low ambient temperatures, and electromagnetic interference. Subsequent developments in plasma lighting technology appear to have addressed these issues.

Various commercially available plasma lighting technologies provide similar reliability and lifetime to LED lighting. The directionality of LED light is good and properly balanced high-end LED fixtures are beginning to achieve satisfactory CRI and colour temperatures inherent to plasma lighting. However, lumen density of LEDs is lower than plasma technologies which, when combined with the required heat sinks, typically makes LED fixtures larger, heavier, and more expensive than a plasma fixture for the same lumen output. LED do have the advantage of instantaneous turn on. Consequently LED are a good fit for lower lumen and non-space restricted applications, but plasma technologies are potentially more applicable to space constrained, high lumen applications.

Further, plasma lighting sources provide a near perfect "single point-source" with good colour characteristics which give the potential for application in scientific, theatrical and entertainment applications is a single point-source.

In 2014, ANSI Accredited Standards Committee 136 (C136) for Roadway and Area Lighting approved ten standards for publication, and has been updating a number of other ones. The C136 scope includes all types of street and area lighting, including lamp types, pole construction and support, tunnel lighting, enclosed architectural luminaires, system selection guides, lighting controls, ingress protection, ancillary devices, and more. Plasma lighting is among the issues being investigated, and various standards from the ANSI C136 series already apply to plasma lighting where it is used for roadway and area lighting.

The ASC 137 Lighting Systems Committee (launched by NEMA in August 2014) will develop and approve standards that may be relevant to plasma lighting under its defined scope, part of which is: “To develop standards and specifications for indoor and outdoor lighting systems installed in an application with consideration of human health and comfort, personal security, the physical environment, energy consumption and daylight integration”.

A good summary table showing characteristics of plasma lighting relative to LED, HID and induction lighting is provided by the LRC:

(http://www.lrc.rpi.edu/programs/nlpip/lightingAnswers/plasma/advantages.asp)

Published information, as of June 2013, from LUXIM and Topanga show that commercially available plasma lighting systems have CRI values between 70 and 95 and CCT values between 3200 and 7650 K.

Plasma grow lights range in price from around US $3.50 – US $5.50 per watt. For example, a 300W plasma grow light complete with microwave source, amplifier, lamp and fixture is priced around US $1,200.

Photography / cinematography plasma lighting is priced around US $13 – US $15.50 per watt. For example, the 300W Hive Honey Bee Theatrical Spot costs US $3,995.

No commercial pricing was found for street, stadium, car park or warehouse plasma lighting. Upfront cost of plasma lighting is relatively high, but the cost of ownership is reasonable because the expected service life is generally around 50,000 hours (with >70% lumen maintenance at this time).

Plasma lighting is being trialled by local councils in Australia (New South Wales) and in various US States. It is not expected that plasma lighting is considered by any regulations anywhere in the world. No specific sales figures on plasma light sources have been found. Plasma lighting systems appear to have a very small niche for high-efficiency applications requiring luminaire power of 250W or greater. LED luminaires in this power range may struggle with thermal management, glare (from multiple point sources) and size / weight of lamp fixtures.

3.5. Graphene light bulbs

In a recent series of articles [137], the coming to the market of graphene light bulbs is announced. The articles are rather confusing as to how and where this graphene is actually being used, but the application seems to be in LED lamps. Some articles give the idea that it regards a LED filament lamp, the filaments being coated with graphene to improve heat conduction. Other articles suggest that graphene is used in some way in the semiconductor material itself. Technical details, performance characteristics, and clear price information are lacking.

3.6. FIPEL lighting technology

see Task 1 report par. 1.6.2.

3.7. ESL lighting technology

see Task 1 report par. 1.6.3.

[137] http://spectrum.ieee.org/nanoclast/semiconductors/materials/commercial-viability-of-graphenebased-light-bulb-gets-promoted
http://www.independent.co.uk/news/science/first-graphene-light-bulbs-to-go-on-sale-this-year-10142026.html
http://www.graphenestakeholders.org/gsa-news/graphene-led-lights/
http://eandt.theiet.org/news/2015/mar/graphene-lightbulb.cfm
http://www.dailymail.co.uk/sciencetech/article-3017900/Graphene-light-bulbs-sale-year-generation-energy-efficient-bulbs-10-longer-LEDS.html
http://optics.org/news/6/2/6
http://www.nature.com/nmat/journal/v14/n3/full/nmat4205.html#close

4. Smart lamps

4.1. Definition of 'smart lamps'

The following definitions for smart or connected lamps have been found in literature:

- Draft standard prEN 50491-12 defines a smart device as: "A smart device may be a load, generator or local storage equipment. The smart device can be a part of the premises energy management system and offers extended functionality for load management e.g. load shifting, demand response" [138].
- A smart light source is a light source with some level of sensing and intelligence combined with the ability to communicate, usually wirelessly [139].

Definition in the context of ecodesign:

- A smart light source is a light source containing electronics inside the housing of the lamp to provide one or more functions beyond the primary performance function, i.e. convert electricity into light.

Examples of secondary functions provided by smart lamps are:

- To remotely 'control' the primary performance function 'light' without the need of additional electronics in the fixture (or ballast) and without manipulating the mains voltage signature, i.e. turning the light on/off, light dimming, colour control, colour temperature control, by means of a digital communication channel (including power-line communication);
- To 'locate and configure lights' in building automation, e.g. to assist in assigning control addresses and control functions to installed lamps;
- To 'locate users' within a building for various tasks such as sales promotion support, to locate users in case of adaptive lighting, to find empty workplaces, etc.;
- To act as 'repeaters for communication signals' to extend the range;
- To 'act as sensor hubs', providing a multitude of parameters like sound volume, daylight, motion or presence;
- To provide operating metrics of the lamp or 'luminaire monitoring', e.g. on LED lumen maintenance or temperature;
- To provide 'access points for communication signals', e.g. infrared remote controls to interface with the building automation system.
- To 'learn the users day-to-day routine' and adjust itself accordingly. For instance Stackligthings' Alba automatically responds to changes in its environment by adjusting brightness and colour temperature, all without user intervention. It can change brightness and colour based on the time of day, the room and even who's in the room. It will dim or shut off the lights when there's a lot of ambient light or if you've left for work.
- To provide 'audio' (integrated loudspeaker) functionality;
- To support the 'grid balance'. For instance The AdrON is an LED lamp that has internal batteries and Impedance and Grid Frequency Monitoring technology that can detect excessive pressure on a Grid in real time and then automatically and undetectably switch to its own internal batteries;
- To visually 'notify' the user of certain 'events' (mail, door ringing, alert).

[138] prEN 50491-12 'Smart Grid interface and framework for Customer Energy Management'
[139] Gartner, http://www.gartner.com/newsroom/id/2839717

The two main differentiators with smart bulbs, besides the secondary performance function, are the communication method and the light colour. The communication technologies most commonly used and corresponding communication architectures are explained in the next paragraph.

The other differentiating feature is whether the bulb is white-only or capable of coloured light through its red-green-blue (RGB) LEDs or bi-colour LEDs (white, yellow). White-only bulbs are less expensive and can produce a more reliable white. The bi-colour LED bulbs offer the feature to change the white colour from warm to cold, so-called dim-to-warm lamps that mimic filament lamp dimming. Most RGB lights offer up to 16 million colours. RGB lights are promoted for mood lighting and health and wellbeing aspects. Promoted light modes are ‘reading’, ‘relax’, ‘concentrate’ and ‘energize’ mode. However, the ability of RGB lights to consistently over time produce a particular set of colours or colour temperature is currently doubtful: the three R, G, B LEDs age at different rates and their colour mix will shift. It is also unlikely that a group of smart lights produce a visually identical colour temperature.

It has to be emphasized that smart lamps are only dimmable digitally via the communications control channel. A smart lamp is not compatible with traditional dimming and will not function at all if the voltage drop is below a certain level.

4.2. Communication of ‘Smart lamps’

Most smart bulbs today use wireless communication for the control channel. Some manufacturers provide also solutions based upon power-line communication (PLC, Figure 22) or wired communication like Ethernet. In case of Ethernet, Power over Ethernet (PoE) can be used, providing power to the smart lamp.

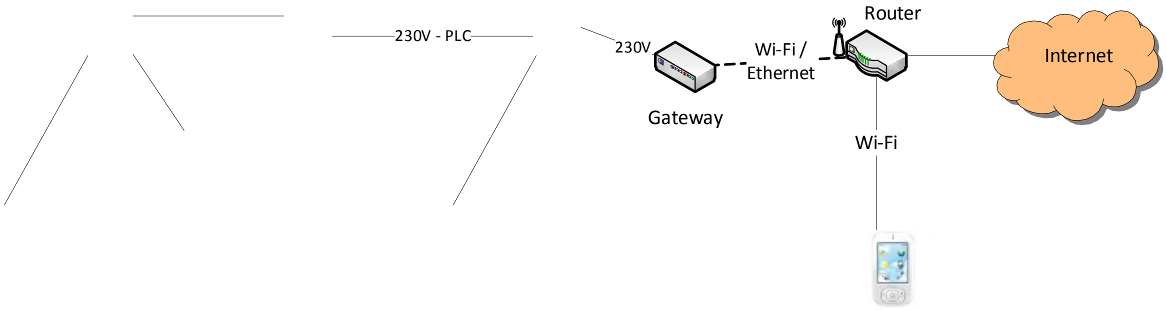


Figure 22: a PLC network configuration

The following wireless communication technologies are used by the smart lamps:

- Some form of (proprietary) RF technology with a dedicated remote control (Figure 23). Compared to the other communication technologies the integration potential of this solution is rather limited;

Figure 23: a smart lamp with dedicated remote control

- Wi-Fi communication (star topology, see Figure 24), connecting directly to the buildings' local area network (LAN). It requires a router/gateway but in most homes this device is already part of the buildings' infrastructure;

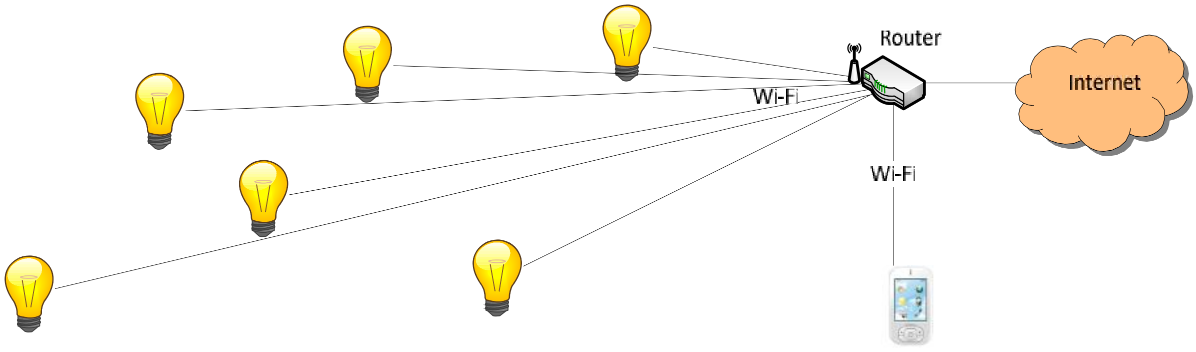


Figure 24: a star network configuration

- Bluetooth Low-Energy (BLE), also referred to as Bluetooth 4.0 (and up). The lamps using this technology are paired (Figure 25) ad hoc with a smart control device like a smartphone or tablet. BLE requires no other hardware than the bulb and your BLE-capable smart device. Its simplicity makes it easier to get the lights up and running, but limits the system's ability to interact with the environment. The Bluetooth Special Interest Group (SIG) announced that the next version of Bluetooth will have meshed capabilities (Figure 26). Already today some Bluetooth technology providers are offering proprietary meshed BLE technologies, which is picked up by some smart lamp providers;

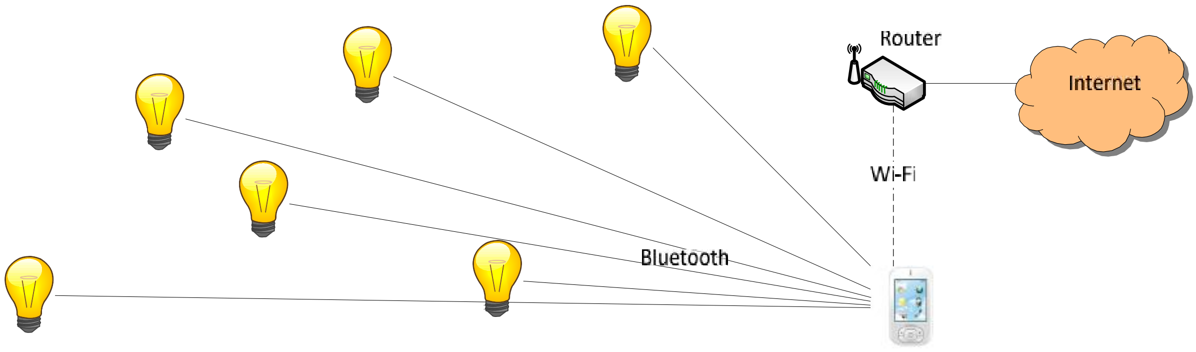


Figure 25: an ad-hoc star network configuration

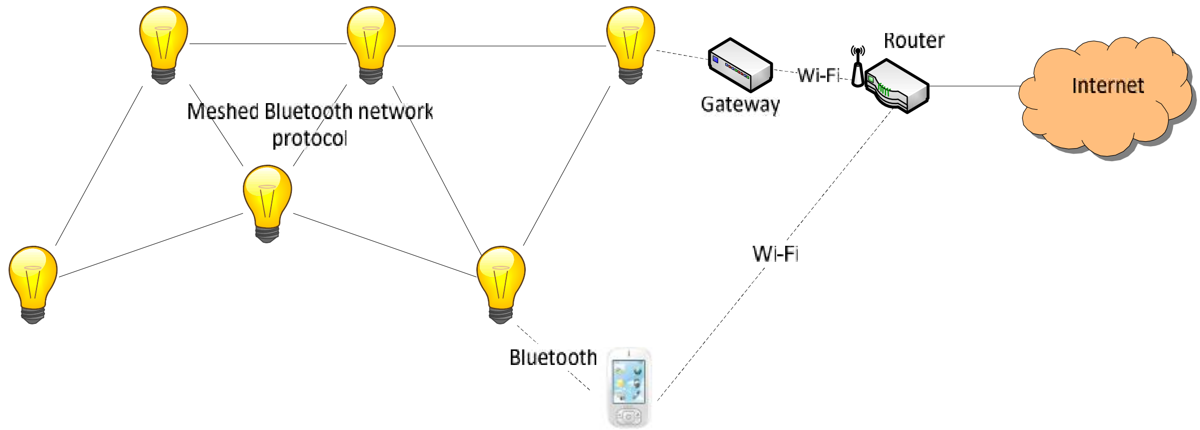


Figure 26: an ad-hoc and permanent mesh network configuration

- Meshed communication technologies (Figure 27) like ZigBee or Z-Wave. It requires a gateway to link the meshed network to the LAN. Some LAN routers/gateway today are offering ZigBee or Z-Wave functionality integrated in the LAN router/gateway;

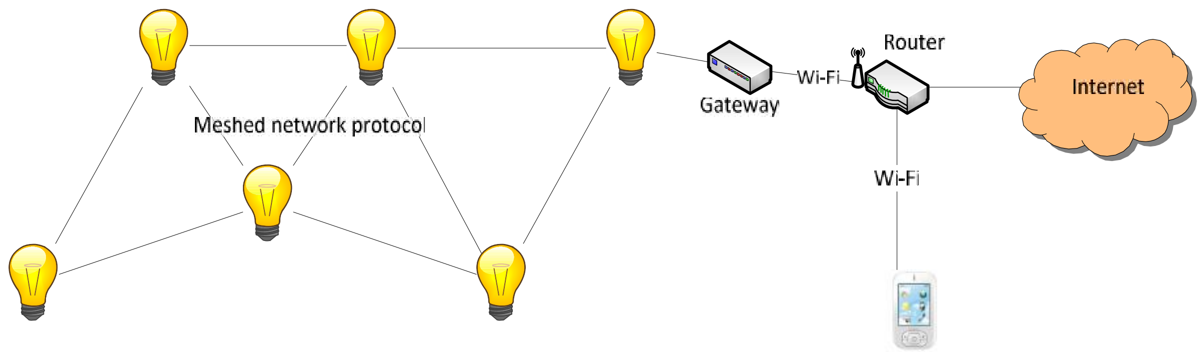


Figure 27: a mesh network configuration

The “intelligence” can be located in the smart bulb, in the hub/gateway or provided by some service in the cloud. For instance, turning the lamps on in the morning can be triggered by a daylight sensor or scheduler integrated in the smart lamp, in the hub/gateway or provided by a cloud service like IFTTT (If This Then That). The location of the intelligence depends partially on the communication architecture. In case of a paired Bluetooth connection there is no hub/gateway and no direct connection to the cloud, meaning the intelligence has to be located in the smart bulb (or in the connected smart control device).

4.3. Aspects of smart lamps that could play a role in regulating them

- There are proprietary and open standard communication systems. Open standards have the benefit for the end-user that there is no vendor lock-in effect. Along with interoperability also security and privacy aspects are important as smart lamps get connected to the local (and global) data network. As such, the smart lamps can be considered as a subset of the

'Internet of Things". The preparatory eco-design study on smart appliances [140] looks at the 'interoperability' aspect of smart appliances.

- Communication technology is also evolving continuously at a fast pace meaning the 'next' smartphone may not be able to communicate with older technology. This means that the economic product life time could be limited compared to the technical life time of the LED.

- So far, most product specifications do not include power consumption information in standby or networked state. However, connected smart lamps use some standby power to listen on the communication control channel. It will also be important to define the operational modes. The energy label on the package is unclear for smart lamps because the standby consumption is not considered in the energy label. For instance a lamp using 9W in maximum operating state and producing 600 lumen will have an efficacy of 600/9=67 lm/W. The same lamp being a 'smart lamp', having a standby power consumption of 0.45W and assuming 1000 active lighting hours per year, will have an efficacy of 600*1000/(9*1000+0.45*(8760-1000))=45 lm/W on a year basis. Due to the standby consumption term in the formula, the (annual) efficacy ratio will drop if the number of operating hours decreases. Hereby the assumption is that the lamp is not switched off mechanically, and is operating at maximum power during the operating hours. The number of operating hours is defined as the number of hours per year the lamp is not in switched off or in standby/networked power mode.

- Lumen/power consumption information related to colour is only provided by a few manufacturers.

- Most smart lamps use LED technology with a lifespan of 15,000 to 50,000 hours. However, the additional performance functions of smart lamps could turn these lamps into 'user consumption' products causing the consumer to replace the product before the lifespan of the LED technology. Consumers may replace the product when they are not satisfied anymore with the secondary performance function or want to upgrade to a newer smart lamp with other secondary performance functions.

4.4. Smart lamps and energy use

Smart lamps could increase energy use because:

- Connected smart lamps use some standby power to listen for commands on the communication control channel. The power consumption is determined by the used communications technology. Technologies like Wi-Fi consume a lot more energy in standby mode than communication technologies like Z-Wave, ZigBee or BLE.
- Some smart lamps systems require an additional hub, meaning additional power consumption.

Smart lamps could decrease energy use:

- Smart lamps provide a means for building/home automation. This could have a positive effect on energy usage when functions like 'all lights off' are integrated in the solution. This feature could be manually or automatically

[140] http://www.eco-smartappliances.eu/Pages/welcome.aspx

activated when the user leaves the building. More information is in the lighting systems study.

- Home automation in the residential sector is considered as a nice to have feature when there is still some budget left. An aspect of smart lamps is that this technology can be introduced gradually in the building. Most smart lamps make use of wireless or power-line communication technology meaning no change to the hardwire infrastructure is needed. This could lead to an uptake of home automation or smart home technology, improving energy efficiency in other not-lighting domains.
- The colour setting, dimming and grouping feature in most smart lamps, along with the ease of use of these features, providing 'mood' or 'ambience' settings could have a positive impact on the energy consumption.
- The control communication channel offers mostly the possibility to upgrade the firmware of the smart lamp. This could mean that smart lamps could become more efficient in time just by upgrading its software.

4.5. Trends in smart lamps and BNAT

At this stage, smart lamps are considered as standalone solutions, not aimed at replacing the whole buildings' lighting infrastructure. This, however, could change when the price of smart lamps drops and (lifetime) interoperability, security and privacy are guaranteed. Gartner quote [141]:

" More lights get smarter, laying the foundation for more Internet of Things applications. The LED migration is, in turn, stimulating a huge increase in the installation of intelligent lighting controls such as occupancy sensors, photo sensors and wireless networks that link them.

Sales of these technologies will more than double between 2013 and 2020, reaching $2.7 billion annually by the end of the forecast period, predicts Navigant Research. "The market for lighting controls in commercial buildings has expanded and transformed dramatically in recent years, as creative ways to visualize lighting usage and new strategies to manage lighting energy consumption proliferate," Foote said.

Just one player in this market, Digital Lumens, has more than 100 million square feet of smart lights installed."

4.6. Conclusion

Clearly, this is a new area of light sources' application that fits in the trend towards the so-called internet-of-things [142]. It is expected that many new light sources brought in the market will become 'smart' in the near future together with the uprise of the internet-of-things (IoT). These smart devices will have communications capabilities and form machine-to-machine (M2M) communication networks. Just as important, these networks are creating a communications network for other efficiency applications. One example involves climate change: occupancy sensors in smart lamps can be coordinated for heating and cooling profiles. They also could be a valuable complement to security systems and policies.

[141] http://www.greenbiz.com/blog/2014/01/30/5-trends-watch-commercial-lighting
[142] http://en.wikipedia.org/wiki/Internet_of_Things

5. BC, BAT and BNAT technical description per base case

5.1. Introduction

This chapter contains a separate paragraph for each base case listed in Table 3.

For each base case the chapter presents the BC-characteristics of the average EU-28 lamp [143]. In addition the improvement options, and the BAT and BNAT options are discussed.

Where relevant, two BAT options are presented: the BAT within the base case technology and the BAT when switching to LED lighting.

As regards the latter, the focus is on LED retrofit lamps. Although LED luminaires can typically be identified as the BAT solution [144], the large variety in possible luminaires makes it practically impossible to handle them in this preparatory study, at least from the prices and resources point of view. LED luminaires and LED retrofit lamps will therefore initially be considered equivalent, using the lowest efficacy of the two in a conservative approach, and using the prices and resources for retrofit lamps. The additional price and resources impact of LED luminaires will then be considered a posteriori where deemed necessary.

An exception is made for LED luminaires that substitute LFL's in office lighting or HID-lamps in street lighting. In particular for the latter, it seems to be more common to substitute the entire luminaire when switching to LED technology. See more detailed remarks in the paragraphs dedicated to these lamp types.

As little or no further technological progress is expected for the non-LED base cases, the BNAT option for these base cases is often a generic improved LED lamp, with a reference to the general LED trends of chapter 2.

The basic technology description for the non-LED base cases is often short. Typically, reference is made to previous studies, and only recent developments, if any, are described here.

As explained in chapter 1, the improvements for light sources mainly derive from a shift in sales from the traditional less-efficient base cases towards LEDs. It is therefore examined if there are lamp types within the base cases for which no adequate LED substitute is available, or if there are other factors that could slow down the shift in sales.

[143] This is the actual 'Base Case' in the sense of the MEErP. The characteristics have been taken mainly from data in the Task 2 and Task 3 reports

[144] LED luminaires usually permit a better optical and thermal optimisation than LED retrofit solutions, enabling, in principle, to install less lumens and to obtain a slightly higher efficacy (for reduced operating temperature).

5.2. Linear fluorescent lamps, T12

5.2.1. LFL T12, BC description

These lamps have now been phased out (Regulation 245/2009, see exceptions in par. 5.2.5) and the remaining stock is small, so this base case will have a minor impact on scenario analyses.

T12 lamps use halo-phosphor which results in a poor colour rendering (CRI ≥ 60) that does not meet the criteria for indoor work places in EN 12464-1 (CRI ≥ 80). For that reason these lamps were not considered in the 2007 VITO study on office lighting [145]. Lamp efficacy and lifetime are low as compared to other, more modern LFL-types.

The main technical requirement that held these lamps on the market is due to their cold temperature behaviour, with application of a special control gear for the cold conditions. T12 lamps are still in use in some outdoor industrial plants, street lighting, and indoor cooling warehouses. Many of these lamps for cold climate conditions have an external ignition strip and are exempted from regulation 245/2009, see section 6.2.5.

The average EU-28 characteristics for this base case are summarized in Table 17. They are based on the information presented in the Task 2 and 3 reports.

Table 17: Average EU-28 characteristics for the LFL T12 base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	0.076	1.11	1.19	
Lifetime (yr)	11.4	3.6	4.9	
Stock (mln units)	7.7	12.4	20.1	
Capacity (lm)	2450	2450	2450	
Efficacy (lm/W)	70	70	70	
Power (W)	35	35	35	Exclusive ballast power
Ballast efficiency (%)	80%	80%	80%	Magnetic ballast
Burning Hours (h/a)	700	2200	1623	
Electricity rate (euros/kWh)	0.191	0.119	0.131	
Price (euros/unit)	10.10	8.42	8.52	
Installation cost (euros/unit)	0.00	6.16	5.75	[146] [147]
Maintenance cost (euros/unit/life)	0.00	2.26	1.40	[146]

[145] Preparatory Studies for Eco-design requirements of EuPs, Final Report, Lot 8: Office lighting, Study for the European Commission DGTREN unit D3, contact Andras Toth, by VITO in cooperation with Laborelec and Kreios, April 2007, Contract TREN/D1/40-2005/LOT8/S07.56452, available through 'eup4light.net'

[146] Installation costs are based on a time of 10 minutes per light source and an hourly rate of 37 euros/hour. The 10 minutes is an estimated weighted average between 3 min/lamp for group replacements and 20 min/lamp for individual (spot) replacements, see Task 3 par. 7.5. These costs regard only the light sources, not the installation of new luminaires, nor the changing of control gears.

Maintenance costs are per light source, for the lifetime of the light source (not per year). The estimate is based on a time of 1.5 minute per luminaire cleaning operation, an average of 2 light sources per luminaire, one cleaning operation per year, and an hourly rate of 37 euros/hour. See also Task 3 par. 7.5.

[147] T12 lamps with magnetic ballasts use a starter, such a starter costs about 1 euro and was usually replaced together with the lamp. This is NOT included in the cost shown in the table.

5.2.2. LFL T12, Improvement options

As these lamps have been phased out, no improved lamps of the same type will come to the market. Four improvement/replacement options with other lamp types have been identified:

1) Substitute the LFL T12 by a LFL T8 tri-phosphor. This leads to an efficacy and lifetime improvement, in particular when high-frequency electronic ballasts are applied. For the characteristics of LFL T8 tri-phosphor see par. 5.4.1.

   For operation in cold conditions, several manufacturers offer double envelope T8 tri-phosphor retrofit lamps [148], that will operate directly on the existing ballast and are compatible with existing optics.

   For operation in non-cold conditions, the ballast can also be substituted, in particular by a (dimmable) electronic one, offering additional energy efficiency benefits, and enabling the use of normal T8 tri-phosphor lamps with lower cost. See par. 5.4.4 for additional information on ballasts.

   A third variant would be to substitute the entire T12 luminaire by a T8 luminaire.

2) Substitute the LFL T12 by a LFL T5 new. As LFL T5 have a different cap (G5) than LFL T12 (G13), direct retrofit solutions do not exist and the entire luminaire would have to be substituted. For the characteristics of LFL T5 see par. 5.5.1. Special high output, constant temperature, T5 lamps are available for low temperature applications, using mercury amalgam and special electrodes [149].

3) Substitute the LFL T12 by a LED tube retrofit. For the characteristics of LED tube retrofits and for remarks on the substitution of LFL's by LED tubes, see par. 5.4.5.

4) Substitute the LFL T12 by a LED luminaire. For a discussion on LED luminaires for LFL replacement, see par. 5.4.6. This is identified as the BAT-solution, also considering system-level improvement opportunities that will be addressed in the Lot 37 lighting systems study.

In past years it is likely that most consumers used option 1, replacing the T12 by a T8t, either as direct retrofit, or also substituting the ballast, or substituting the entire luminaire.

In future it is expected that the majority of the still installed T12 will be replaced by either LFL T8t or by LED lighting.

5.2.3. LFL T12, BAT description

The BAT solution for LFL T12 replacement is substitution by a LED luminaire. The same solution is also applicable for T8 or T5 replacement, see par. 5.4.6 for details.

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[148] http://www.lighting.philips.com/main/prof/lamps/fluorescent-lamps/tl-d/master-tl-d-xtreme/927982384014_EU/product

[149] OSRAM (2014): 'Technical application guide Double capped fluorescent lamps: T8, T5 HE and T5 HO, T5 short and Single capped fluorescent lamps: T5 FC, Part 1: Products and Technology'

5.2.4. LFL T12, BNAT description

See the common description for all LFL types in par. 5.4.7.

5.2.5. LFL T12, Special cases and non-availability of improving substitutes

The following T12 lamps are exempted from regulation 245/2009 and consequently are not being phased-out:

- Diameter of 38 mm (T12), lamp cap G-13 Medium BiPin base, +/– 5 m (+magenta, –green) colour compensating filter value limit (cc). CIE coordinates x=0.330 y=0.335 and x=0.415 y=0.377.

These lamps were used in cinema film recording, and they were based on halo-phosphor with an outer colour compensation filter to mimic daylight conditions. They are discriminated by their colour coordinates and have a high colour temperature (5500 K). With the advent of digital cinema recording, it is possible that this exemption has become obsolete. However, a comparable CFLni cinema lamp remains available on the market. It should be verified with stakeholders if this exception is still needed.

- Diameter of 38 mm (T12) and equipped with an external ignition strip.

The external ignition strip provided lamp heating to facilitate lamp starting in cold conditions. Different solutions for operating in cold environments have been presented above. Therefore it is expected that this exemption can be dropped.

5.3. Linear fluorescent lamps T8 with halophosphor

5.3.1. LFL T8h, BC description

These lamps have now been phased out (Regulation 245/2009) and the remaining stock is rapidly decreasing. Halo-phosphor lamps were so-called second generation fluorescent lamps, introduced in the 1940's. They use a halo-phosphate phosphor, see par. 2.3.3. These phosphors provided either good colour rendering or efficacy but not both at the same time. In the 1970's a third generation lamp was introduced based on rare earth phosphor that provides better colour rendering, efficacy, lifetime and lumen maintenance. These tri-phosphor lamps are discussed in par. 5.4.

The average EU-28 characteristics for this base case are summarized in Table 18. They are based on the information presented in the Task 2 and 3 reports.

Table 18: Average EU-28 characteristics for the LFL T8h base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	0.139	2.03	2.17	
Lifetime (yr)	11.4	3.6	5.7	
Stock (mln units)	81.3	70.9	152	
Capacity (lm)	2400	2400	2400	
Efficacy (lm/W)	75	75	75	
EEI (-)	0.22	0.22	0.22	Fcor=1.19; Label class A
Power (W)	32	32	32	Exclusive ballast power

Table 18: Average EU-28 characteristics for the LFL T8h base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Ballast efficiency (%)	80%	80%	80%	Magnetic ballast
Burning Hours (h/a)	700	2200	1398	
Electricity rate (euros/kWh)	0.191	0.119	0.131	
Price (euros/unit)	10.10	8.42	8.52	
Installation cost (euros/unit)	0.00	6.16	5.77	[146] [150]
Maintenance cost (euros/unit)	0.00	2.64	1.23	[146]

5.3.2. LFL T8h, Improvement options

As these lamps have been phased out, no improved lamps of the same type will come to the market. Three improvement/replacement options with other lamp types have been identified:

1) Substitute the LFL T8h by a LFL T8 tri-phosphor. In a standard solution, the retrofit T8t lamp will have the same power as the T8h lamp that it replaces, but deliver a higher light output [151].

   Alternatively, a special lower-wattage retrofit lamp can be chosen, for example substituting a 36 W T8h lamp by a 32 W T8t lamp [152]. These lamps have a modified lamp voltage in order to operate on an existing magnetic ballast with a lower wattage. They use a xenon gas that causes a reduction in the discharge voltage. The single limitation is that xenon-filled T8 Eco tubes are stated to be sensitive to ambient temperature variations, so this retrofit can only be applied in standard temperature conditions.

   In both solutions the retrofit lamps also offer an extended lamp life time and lumen maintenance, which will reduce installation and maintenance costs.

   For the characteristics of LFL T8 tri-phosphor see par. 5.4.1.

2) Substitute the LFL T8h by a LED tube retrofit. For the characteristics of LED tube retrofits, see par. 5.4.5.

3) Substitute the LFL T8h by a LED luminaire. For a discussion on LED luminaires for LFL replacement, see par. 5.4.6. This is identified as the BAT-solution, also considering system-level improvement opportunities that will be addressed in the Lot 37 lighting systems study.

In past years it is likely that most consumers used option 1, replacing the T8h by a T8t, either as equal-wattage or lower-wattage retrofit, or also substituting the ballast, or substituting the entire luminaire.

[150] T8 lamps with magnetic ballasts use a starter, such a starter costs about 1 euro and was usually replaced together with the lamp. This is NOT included in the cost shown in the table.

[151] E.g.: https://www.lampdirect.be/nl/philips-tl-d-super-80-36w-840-120cm-master

[152] E.g.: https://www.lampdirect.be/nl/osram-t8-l-32w-840-g13-es-cool-white?gclid=CJvnppeFtMQCFUnLtAodhxgAYg

In future it is expected that the majority of the still installed T8h will be replaced by either LFL T8t or by LED lighting.

5.3.3. LFL T8h, BAT description

The BAT solution for LFL T8 halo-phosphor replacement is substitution by a LED luminaire. The same solution is also applicable for T12, T8 tri-phosphor or T5 replacement, see par. 5.4.6 for details.

5.3.4. LFL T8h, BNAT description

See the common description for all LFL types in par. 5.4.7.

5.3.5. LFL T8h, Special cases and non-availability of improving substitutes

No special cases or non-availability of substitutes have been identified.

5.4. Linear fluorescent lamps T8 with tri-phosphor

5.4.1. LFL T8t, BC description

These lamps are the most sold LFL's in the EU-28, with a share of approximately 70% in 2013. The stock of installed lamps is high, being estimated around 1.4 billion lamps in 2013. LFL's T8 with tri-phosphor are the most frequently applied lamps for office lighting. According to a 2014 study [153], the most popular LFL T8 characteristics in Europe are power 36 W, length 4-foot, and CCT 4100 K. For this power, regulation 245/2009 requires an efficacy of at least 93 lm/W [154] [155].

These lamps are a replacement option for the phased out T12 and T8 halophosphor lamps.

Basic technological background information on LFL T8t can be found in the 2007 VITO study [145], with updates available in the Omnibus study [156]. Since 2007, the main R&D investments in LFL T8t were made to reduce mercury content and to improve efficiency, lifetime and lumen maintenance, mainly by changes in the gas filling.

Traditionally fluorescent lamps are filled to a very low pressure with a mixture of krypton and/or argon. The gas filling reduces the required starting voltage for the discharge, protects the electrodes, adjusts the balance of ionised mercury atoms, and randomises free electron movement in the discharge.

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[153] CLASP, November 2014, "Mapping & Benchmarking of Linear Fluorescent Lighting". http://clasponline.org/en/Resources/Resources/PublicationLibrary/2014/Benchmarking-Analysis-Linear-Fluorescent-Lighting.aspx

[154] For other powers, in particular for lower powers, the required efficacy is lower, see Regulation 245/2009, annex III, table 1, for T8. For example for 30W: efficacy > 80 lm/W, for 25 W: efficacy > 76 lm/W, for 15 W: efficacy > 63 lm/W.

[155] The real measured efficacy is often lower, also due to the allowed tolerance, see Task 3 report par. 3.6.3 figure 28.

[156] "Omnibus Review Study on Cold Appliances, Washing Machines, Dishwashers, Washer-Driers, Lighting, Set-top Boxes and Pumps Final Report", VHK (NL) / VITO (B) / Viegand Maagøe A/S (DK) / Wuppertal Institut für Klima, Umwelt, Energie GmbH (D), Brussels/Delft 01.04.2014, prepared for the European Commission DG-ENER-C3, SPECIFIC CONTRACT No ENER/C3/2012-418 LOT2/03/SI2.654805 Implementing Framework Contract No ENER/C3/2012-418-Lot 2.

A relatively recent development is the addition of xenon to the gas filling [157], to achieve an additional energy saving. This technique is employed in the latest generation of 'Eco' series T8 lamps. Xenon causes a reduction in the discharge voltage, thus decreasing the power consumed by the tube on electromagnetic ballasts. However, the major efficacy increase derives from phosphor improvements.

Xenon-filled T8 Eco tubes are stated to be sensitive to ambient temperature variations. Under ideal operating conditions they can achieve an efficacy increase up to 10% as compared to krypton T8 types, but this advantage can be significantly reduced if the ambient temperature is not suitable.

Another development is the introduction of fluorescent lamps filled with neon [157], to obtain a very high power loading per unit lamp length. Contrary to krypton, neon can be used to increase the tube voltage. It is used most frequently in the High Output (HO) and Very High Output (VHO) lamps. A drawback is that neon is particularly destructive towards lamp electrodes, and it is customary to employ additional anode wires or plates to take some of the load away from the cathode coil, and thus minimise the lifetime reduction when using this gas.

For each fluorescent lamp diameter there is an optimum lamp length. In short lamps the electrode losses dominate, e.g. a 60 cm T8 18 Watt lamp has an efficacy of 75 lm/W (25°C on electromagnetic ballast). The optimum length in T8 tubes is at 36 W (120 cm) with an efficacy of 93 lm/W (25°C on EM ballast). The longest T8 lamp of 1750 cm (70 W) has a lower efficacy of 89 lm/W because the arc column becomes less efficient. Due to this phenomenon, regulation 245/2009 has tabular requirements [154].

Lamp lifetime significantly depends on the frequency of switching and on the type of starting (instant or programmed rapid). A large variety of LFL T8t exists on the market, e.g. standard, high-efficiency (HE), high-output (HO), extended life, etc.. See the Task 3 report Annex E.3 for examples.

Fluorescent lamps are temperature sensitive. High luminous efficacy is achieved when an optimum mercury vapour pressure exists in the discharge tube. This pressure depends on the temperatures on the inner tube wall and on the related condensation of mercury in the cool zones. The cold spot of a T8 fluorescent lamp is located in the middle of the glass tube length. Good conditions for the luminous flux and lamp performance exist when the temperature at the cold spot is around 50°C. Only at this temperature a mercury vapour pressure is reached for an optimal UV generation. Under design-conditions this maximum luminous flux should occur when the ambient temperature is 25˚C [158] [159].

Although further research could probably result in additional minor improvements, the leading manufacturers prefer to invest in LED solutions. Consequently no significant changes in T8 tri-phosphor characteristics are expected for the future.

LFL T8t can be equipped with magnetic ballast (50 Hz operation) or electronic ballast (high-frequency operation). The latter allows a significant efficacy gain, of 10% or more

[157] http://www.lamptech.co.uk/Documents/FL%20Gases.htm

[158] This is a very different approach from T5 lamps where the cold spot is located near the metal cap. In addition T5 lamps are often optimized for an ambient temperature of 35˚C, see par. 6.5.

[159] For optimum operation and stabilisation, new lamps should be aged for 100 h at full output so that the surplus of dosed mercury can migrate to the cold spot in the lamp. Therefore retrofitting T8 with T5 lamps is not an obvious option.

[160]. In stage 3 of regulation 245/2009, applicable from 2017, the minimum efficiency requirements for LFL ballasts will be raised. The potential impact of this change on magnetic ballasts is discussed in section 6.4.4.

As regards the shares of magnetic and electronic ballast in new installations, see the Task 2 report (rev.1) chapter 8. Available data are confusing, but the share of electronic ballasts in 2014 is expected to be around 75-80%.

The average EU-28 characteristics for this base case are summarized in Table 19. They are based on the information presented in the Task 2 and 3 reports.

Table 19: Average EU-28 characteristics for the LFL T8t base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	15.7	229	245	
Lifetime (yr)	18.6	5.9	6.4	
Stock (mln units)	168	1208	1376	
Capacity (lm)	2400	2400	2400	
Efficacy (lm/W)	80	80	80	
EEI (-)	0.20	0.20	0.20	Fcor=1.19; Label class A
Power (W)	30	30	30	Exclusive ballast power
Ballast efficiency (%)	91%	91%	91%	Electronic ballast
Burning Hours (h/a)	700	2200	2017	
Electricity rate (euros/kWh)	0.191	0.119	0.122	
Price (euros/unit)	10.10	8.42	8.52	
Installation cost (euros/unit)	0.00	6.16	5.76	146 150
Maintenance cost (euros/unit)	0.00	2.96	2.60	146

5.4.2. LFL T8t, Improvement options

It is not expected that there will still be significant technological progress in LFL T8 tri-phosphor lamps, so no improved lamps of the same type will come to the market. The existing lamps can of course be replaced by one of the same type, optionally changing a magnetic ballast for an electronic one. In addition, two improvement/replacement options with other lamp types have been identified:

1) Substitute the LFL T8t by the same type, but replace the magnetic ballast by an electronic ballast. Since the late 80's most luminaires were designed to operate both with an electronic and a magnetic ballasts and they also allow a ballast repair or replacement. As a consequence retrofitting a luminaire with electronic ballast is a technically feasible option. It only requires the time to rewire, that is about the same as installing a new luminaire. For additional information see par. 5.4.4.

[160] The efficacy gain is approximately expressed by the difference in power in table 17 of regulation 245/2009, for the same lumen output, between operation on a 50 Hz ballast and on a HF ballast. For example a T8 with nominal power 36 W will have a rated/typical wattage of 36 W on 50 Hz ballast but 32 W on HF ballast.

2) Substitute the LFL T8t by a LED tube retrofit. For the characteristics of LED tube retrofits and a discussion on this substitution, see par. 5.4.5.

3) Substitute the LFL T8t by a LED luminaire. This is identified as the BAT-solution, also considering system-level improvement opportunities that will be addressed in the Lot 37 lighting systems study. For a discussion on LED luminaires for LFL replacement, see par. 5.4.6.

The current market trend seems to be substitution by LED lighting, options (3) or (4).

5.4.3. LFL T8t, BAT description, maintaining LFL technology

The best available LFL T8t on the 2012 market have been reported by CLASP [161] and are shown in Table 20. For details on the 32 W lamp with an efficacy of 100 lm/W, see [162].

Table 20: LFL T8 tri-phosphor, best available on the market (Source: CLASP 2013, table 4-2, Comparison of EC No 245/2009 MEPS threshold to market and potential for improvement [161])

Lamp Wattage	245/2009 MEPS Requirements	Manufacturer Catalogue Best Products 2012	Improvement Over Existing MEPS
T8 Fluorescent Lamps			
18W	75 lm/W	16W @ 87.5 lm/W	17%
36W	93 lm/W	32W @ 100 lm/W 32W @ 110 lm/W*	18%
58W	90 lm/W	50W @ 104 lm/W*	15%

* This lamp retails in Japan

5.4.4. LFL, BAT description, Ballasts

As observed above, in stage 3 of regulation 245/2009, applicable from 2017, the minimum efficiency requirements for LFL ballasts will be raised. Annex III point 2.1 C of the regulation requires $\eta_{ballast} \geq EBbFL$ [163], where the latter is defined in Annex II point 3 (g), for lamps with power between 5 and 100 W, as:

$$EBb = P_{lamp}/(2*sqrt(P_{lamp}/36)+38/36*P_{lamp}+1)$$

For a 36 W LFL this implies $\eta_{ballast} \geq 0.88$.

The relationship between efficiency and weight for magnetic ballasts (Table 21) shows that the stage 3 efficiency limit would be expected to imply an increase in weight, amongst which copper wire, thus also increasing cost and volume for this type of ballast. In practice it is therefore expected that electromagnetic ballasts will be phased-out by

[161] CLASP (2013) Estimating potential additional energy savings from upcoming revisions to existing regulations under the ecodesign and energy labelling directives: a contribution to the evidence base. Available: http://www.eceee.org/all-news/press/2013/2013-02-19/eceee-clasp-report-estimating-potential

[162] https://www.lampdirect.be/nl/philips-tl-d-hf-super-80-32w-840-120cm-master?gclid=CIHlkpWKtMQCFazMtAodpHsAfw

[163] Efficiency Base Ballast for fluorescent lamps

stage 3, for economic and technical reasons, at least from low-cost and low-weight applications.

Table 21: Relationship between weight and efficiency of magnetic ballasts for a 36 W LFL T8 (Source: VITO 2007)

Ballast class	Efficiency	Weight (kg)	Notes
Class C [1 2]	76%	0.53	
Class B2	79.5%	0.67	o/w 0.071 copper wire
Class B1 [2]	83.4%	0.8	o/w 0.089 copper wire
Stage 3 compliant	88%	>1 expected	

1 Before stage 1 of regulation 245/2009, class C ballasts were commonly used as specified in the preceding directive 2000/55/EC. They allowed 45 Watt input power for a 36 Watt lamp operated with ballast lumen factor of 0.95, hence an efficiency of 0.95x36/45 or 76 %.

2 http://www.helvar.com/sites/default/files/product_datasheets/MB_for_T8_lamps.pdf

In regulation 245/2009 class A2/A2BAT are non-dimming ballasts and class A1/A1BAT are dimming ballasts. The minimum efficiency requirement for an electronic ballast for a 36 W LFL T8 is 84.2% in class A3, 88.9 % in class A2 and 91.4 % in class A2BAT. In practice few manufacturers [164] go beyond the A2 or A2BAT efficiency, even if further efficiency gains could be expected from technological developments in switching semiconductors (e.g. wide band gap materials [165]) and magnetic materials. However, new developments in this area are unlikely due to the high redesign costs and the competition of LED drivers and solutions.

5.4.5. LFL T8t, BAT description, LED retrofit tube

A broad range of LED retrofit tubes is available on the market from all major lighting manufacturers and many new companies entered this market (Figure 28). The qualified parts list of the Designlight Consortium [166] alone reported 9182 4 foot (120 cm) retrofit lamps available in the US (31/3/2015).

Figure 28: Example of a LED retrofit tube for substitution of an LFL T8.

[164] With claims of 93-95% efficiency for electronic ballasts
[165] http://energy.gov/articles/wide-bandgap-semiconductors-essential-our-technology-future
[166] http://www.designlights.org/qpl

The DoE Commercially Available LED Product Evaluation and Reporting (Caliper [167]) tested T8 LED lamps in 2014. When comparing the results to fluorescent lamps, their findings were [168]:

- Linear LED lamps are directional lamps that use the upper half of the volume for thermal management and/or integral driver.
- They usually have a lower rated lumen output per lamp length, e.g. 2400 lm versus 3600 lm for a 120 cm lamp.
- The initial efficacy (100h) of tested products was between 80 and 115 lm/W with one up to 143 lm/W (3/2014).
- Directional emission may increase the efficiency of luminaires.
- There is a broad variety of colour temperatures and CRI.
- There are at least seven electrical configurations for retrofitting.
- Rated life times are much higher compared to fluorescent lamps.

Justifications for the lower lumen output of LED retrofit lamps:

- On magnetic ballasts, the standard Ballast Lumen Factor (BLF) is at 230 VAC but taking line voltage fluctuations into account this can be as low as 0.75 at 207 VAC [169]. This means that the 3600 lm rated lamp will have in reality only 2700 lumen output at 207 VAC. Many LED retrofit tubes have integral drivers that control the lumen output independent from the line voltage.

- Due to their directional emission, LED retrofit tubes can often by-pass the luminaire optics and their losses. This benefit is available in ceiling mounted troffer luminaires. Avoiding the conversion of LFL omnidirectional light into directional light, the LED directionality can offer an efficiency advantage of approximately 12% compared to LFL in luminaires with prismatic lenses, and 23% compared to luminaires with parabolic louvers [170].

- Ceiling mounted lamps and luminaires most often do not emit light outside the 120° zonal light flux area because this would contribute to discomfort glare in the field of view. Therefore they comply with comfortable limits of flux distribution ratios in the field of view [171]. Therefore also directional lamps have been defined with 120° flux area and this complies with the CEN flux code (EN 13032-2) (see lot 9). Most LED tubes can also be rotated to perfectly fit the horizontal installation angle and prevent also glare.

- Especially when retrofitting T8 and T12 halo-phosphor lamps, a lower lumen output per lamp length is needed, see 5.3.

Technical limitations when retrofitting LED tubes:

- When retrofitting LED tubes in existing directional luminaires with optics, the light distribution will change. Better lighting quality, light distribution and glare characteristics could be obtained by using dedicated LED luminaires, even when they have a slightly lower luminaire efficacy.

[167] http://energy.gov/eere/ssl/caliper-testing
[168] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_21-4_t8.pdf
[169] Lot 9 preparatory study, VITO 2007
[170] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ns/lf-replacements_webcast.pdf
[171] IEASNA Lighting handbook (1947), ‘Fig. 2-21 Zonal limits of comfortable flux distribution ratios’, P 2-26.

- Ceiling suspended omnidirectional LFL luminaires that provide direct and indirect light can de facto not be retrofitted due to the directional light output of the LED retrofit tubes currently available [168].

- Rewiring the luminaire is needed for electrical configurations that by-pass the existing ballast, this might drop the safety-responsibility from the luminaire manufacturer [172]. As a consequence at least a new name plate and product ID should be given to the luminaire. This requires additional safety investigation and administrative work.

- LED performance (efficacy, lumen maintenance, life time) is compromised with increased temperature as explained in chapter 2, hence the maximum lumen output of retrofit tubes is limited and might be insufficient for some applications.

- Fluorescent lamps have very high lumen maintenance over their lifetime, e.g. 90% at 20000 h on electronic ballast. When LED retrofit lamps are used until their end of life this is often much lower, e.g. 80 % or 70%. In work places, what counts is the minimum or maintained illuminance, and not the initial lumens (e.g. EN 12464). This has to be taken into account when comparing options.

Plug-and-play retrofit LED tubes

The impression of the study team is that the majority of the LED retrofit tubes found on the market today requires a rewiring of the existing luminaire to by-pass the existing ballast.

However, recently so called plug-and-play lamps [173] have come to the market, that can directly replace an LFL T8 in the existing configuration, without any further action. Some of these LED lamps have control gears that will automatically detect the type of ballast installed and behave accordingly. These lamps can operate on a wide range of existing ballasts, including magnetic and electronic ballasts. Other plug-and-play lamps have been specifically designed for operation on instant-start electronic ballasts, for example.

The plug-and-play lamps have the control gear integrated in the tube. This implies that a small part of the tube length is occupied by the control electronics and hence may not be available for light emission. The integrated solution is also more challenging when additional functions have to be integrated in the control gear, such as 0-10 V dimming, a DALI interface, or a wireless receiver. In addition the location of the control gear inside the tube can pose specific thermal management problems. External control gears offer advantages from these points of view.

Plug-and-play lamps have a higher cost, but that is partially compensated by avoiding the cost related to rewiring. Plug-and-play lamps will typically have a lower (system) efficacy because they are subject to the losses in the existing ballast.

[172] http://www.osram.com/media/resource/hires/343557/substitube-installation-instructions.pdf

[173] http://www.ledsmagazine.com/articles/print/volume-11/issue-6/features/led-tubes/how-do-plug-and-play-t8s-stack-up-against-ballast-bypass-led-lamps.html

BAT LED retrofit tubes

On the Olino website [174] a list of T8 LED retrofit tubes can be found with test results. These results can be summarized as follows:

- Length 150 cm: 50 tubes with efficacy > 107 lm/W, maximum 148 lm/W, of which 27 tubes with CRI>80. No dimmable tubes are listed.
- Length 120 cm: 44 tubes with efficacy > 100 lm/W, maximum 141 lm/W, of which 12 tubes with CRI>80. Only 2 dimmable tubes are listed with best efficacy 85 lm/W.
- Length 90 cm: 1 tubes with efficacy > 100 lm/W, maximum 108 lm/W, of which 0 tubes with CRI>80 (maximum 71). No dimmable tubes are listed.
- Length 60 cm: 7 tubes with efficacy > 100 lm/W, maximum 119 lm/W, of which 4 tubes with CRI>80 (maximum 95). No dimmable tubes are listed.
- Length 30 cm: 0 tubes with efficacy > 100 lm/W, maximum 72 lm/W.

The highest efficacies, up to 148 lm/W (tested) are impressive, but it is rather surprising that so many of the listed tubes have a tested CRI below 80 (usually between 70 and 80), implying that they do not meet the requirements from regulation 1194/2012. Maybe even more surprising, of the over 100 models listed by Olino, only two are declared as dimmable.

Most of the models listed by Olino are non-A-brands and many are sold only by the manufacturer itself, with prices available on request. When tracing the Olino-information to the manufacturer- or retailer-websites the supplied data are sometimes very scarce and/or not fully convincing.

Considering that the lamps have been tested, they actually exist(ed) and demonstrate a technical feasibility, but it is not always easy to understand if the lamps are actually for sale and available to a large public. This makes it difficult to actually establish what the BAT is.

Table 22 presents a selection of the highest-efficiency LED retrofit tubes tested by Olino [175]. Lamps with CRI<80 have been excluded. Lamps that could not be traced to a manufacturer- or retailer-website with convincing information were also omitted. The information in the table has been further integrated with catalogue information on some A-brand LED retrofit tubes.

In addition, some manufacturers offer T5 (16 mm) LED tubes with G13 cap and efficiencies up to 141 lm/W [176].

174 http://www.olino.org/advice/us/overview/results?fitting=TL&length=120

175 http://www.olino.org/advice/nl/overview/results?fitting=TL&length=120&lamptype=tube_bar_strip_tl

176 http://www.narva-bel.de/clicksystem/csdata/download/1/de/leaflet_sl_t5_linear_lens_technology__spt_narva_en_1436.pdf

Table 22: Selection of highest-efficiency T8 LED retrofit tubes with G13 cap. The top half of the table presents data as tested by Olino [175], except for life data that are manufacturer declared values. The bottom half of the table presents catalogue information for some A-brand LED retrofit tubes currently on the market. Data accessed in March 2015. See notes for additional information.

Description	W	lm	lm/W class	CCT	CRI	Angle (deg)	Dim	Life (kh)	Price (€)	Note
120 cm, tested Olino										
Saled - 120 cm 20W 4000K VDE high	19.9	2811	141 A++	3900	83	142	no	50		1
EAE - Led Tube 120 cm frosted cover 856	18.8	2142	114 old A	5638	80	132	no			2
I-Save energy T8LED 1200mm 25W 840	24.2	2630	109 A+	4205	83	129	no	50		3
Lemnis Lighting Asia - 120 cm glass led tube	21.7	2312	106 A+	5289	95	123	no	50		4
150 cm, tested Olino										
Luxerna - TL Eco 150 cm 4000K clear	24.2	3588	148 A++	3926	83	116	no	50		5
abalight - 1500 mm opal cover TUBE-T8-1500-25-840-10	25.6	3210	125 A++	3923	84	146	no	50		6
A-brands										
OSRAM ST8-HA4-250 22W/840 230V 1200 mm mit Starter	22	2500	114 A+	4000	>80	150	no	50	29.20	7
Philips MASTER PERF 1200mm 21W840 T8 I ROT	21	2100	100 A+	4000	85	140	no	50	45.38	8
Philips CorePro LEDtube 1200mm 20W 840 C	20	1600	80 A	4000	80-89	150	no	30	18.09	9
Cree Lighting LEDT8P-48-21L-40K-B1	20	2100	105	4000	90		yes	50	23.32	10
GE LED 18/T8 1200MM/840/220-240V BX1/30	18	1550	86 A+	4000	80	130	no	50	23.90	11
GE LED 23/T8 1200MM/840/220-240V BX1/30	23	2150	93 A+	4000	80	130	no	40	25.90	11
GE 93010222 LED 27/T8 1500MM/840/220-240V BX1/20	27	3000	111 A+	4000	80	130	no	40		12
Havells-Sylvania ToLEDo Superia Tube 4Ft 26W 2600LM 840	26	2600	100 A+	4000	85	120	no	50	43.95	13

1 http://www.olino.org/us/articles/2015/03/04/saled-led-tube-120-cm-20w-4000k-vde-high
http://www.saled.nl/en/catalogue/led-tubes/vde-certified/120-cm-hoogtebuis-9-15-meter/

2 http://www.olino.org/us/articles/2012/11/17/europe-asia-electronics-holding-ltd-hongkong-led-tube-light-120-cm-frosted-cover-856 Class A on scale A-G
http://www.europe-asia-electronics.com/led_lighting/DS%20Brilliance%20Series.pdf
http://www.eae-europe.com/downloads/DS_Brilliance_Series.pdf

3 http://www.olino.org/us/articles/2014/04/23/i-save-energy-gmbh-led-tube-light-t8led-1200mm-25w-840 ; http://www.i-save-energy.com/en/led-high-bay/led-tubes-t8/plusled-1200-mm-25-w.html

4 http://www.olino.org/us/articles/2014/02/02/lemnis-lighting-asia-120-cm-glass-led-tube
http://www.lightandvision.nl/folders/producten/lemnis_tube_light.pdf

5 http://www.olino.org/us/articles/2015/03/16/luxerna-tl-eco-150-4000k-clear
http://www.luxerna.de/produkte/roehre-tl

6 http://www.olino.org/us/articles/2014/04/25/abalight-led-tube-1500-mm-opal-cover-tube-t8-1500-25-840-10 ; http://www.abalight.de/index.php/de/produkte/led-leuchtmittel-retrofit/led-tubes/led-tubes-1500/artikeldetails.html?artno=11841

7 http://leuchtmittelhandel.com/OSRAM-SubstiTUBE-Advanced-ST8-HA4-20-W/840-1200-mm-mit-Starter
Price incl. VAT and inclusive starter ; http://www.osram.com/osram_com/products/led-technology/lamps/led-tubes/substitube-advanced/index.jsp?productId=ZMP_1131249

8	https://www.budgetlight.nl/philips-master-ledtube-performance-t8-10-5w-840-cool-white-roteerbaar.html?gclid=CjwKEAjw9PioBRDdpqy0-ofG3DgSJAACe5NEfYMw9L8Z8JNDzh5uZ4-uyp7-kM8kmKdI6rFWF__QkhoC68Hw_wcB Price incl. VAT, for 1 piece http://www.ecat.lighting.philips.co.uk/l/lamps/led-lamps-and-systems/led-tubes/master-ledtube-performance/929000283902_eu/
9	https://www.budgetlight.nl/philips-corepro-ledtube-1200mm-20w-840-c.html Price incl. VAT, for 1 piece http://www.ecat.lighting.philips.co.uk/l/lamps/led-lamps-and-systems/led-tubes/corepro-ledtube/929000296632_eu/
10	https://www.platt.com/platt-electric-supply/LED-Tube-Type-T8/Cree-Lighting/LEDT8P-48-21L-40K-B1/product.aspx?zpid=140713 Compatible with >90% of electronic T8 ballasts. Dimming and efficacy depending on ballast http://www.cree.com/Lighting/Products/Indoor/Lamps/T8-Series Original price: $26.5
11	http://leuchtmittelhandel.com/GE-LED-18/T8-1200MM/840/220-240V-BX1/30 Price incl. VAT, for 1 piece http://www.gelighting.com/LightingWeb/emea/images/LED-T8-Tubular-Lamps-Data-sheet-EN_tcm181-67008.pdf
12	http://catalog.gelighting.com/lamp/led-lamps/tube/f=ge-energy-smart-tube/p=93010222/d=0/?r=emea
13	https://www.factoryprices.nl/product/sylvania-0027021-toledo-superia-tube-2ft-11w-1200lm-840-100-240v-g13-4000k-186722.html ; http://www.havells-sylvania.com/en/products/0027024

5.4.6. LFL all types, BAT description, LED luminaire for LFL replacement

LED luminaires for upgrading the efficiency of existing installations are also available and offer similar efficacies as retrofit tubes (100-143 lm/W) [177] (3/2015).

There are several grounds for retrofitting luminaires instead of retrofitting LED tubes in existing luminaires:

- Due to the technical limitations and barriers related to service, warranty and liability mentioned in section 6.4.5 on LED retrofit tubes.
- Because this is part of the complete redesign of the interior.
- Because the task area function and its lighting requirements changed and a complete optical redesign is needed, for more details see lighting system study [178].
- Because complementary savings can be obtained by connecting and introducing lighting control systems, for more details see lighting system study.
- Thermal design can be optimized to lower the LED module temperature and this can have a positive impact on lamp lumen maintenance (LLMF) [179]. Therefore LED luminaires can show better performance compared to their LED retrofit tube equivalents when maintained lumen output is taken into account instead of initial lamp lumen.

The extra cost relative to the LED retrofit tube can be as low as 20 euro for a bare batten luminaire.

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[177] http://www.zumtobel.com/com-en/products/efficiencyupgrade.html

[178] http://ecodesign-lightingsystems.eu/welcome

[179] http://www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/XLamp_lumen_maintenance.pdf

5.4.7. LFL all types, BNAT description

In march 2014 OSRAM presented a 1.2m long LED-tube capable of an efficiency of 215 lm/W at 3900 lm, with a colour temperature of 3000 K and a CRI=90 [180] [181]. This tube used a self-developed phosphor for conversion of blue LED light into a greenish white, special reflective materials, and innovative optics that minimize light absorption. The lamp is operated with a specifically developed control unit featuring a 95% efficiency. Series production of this technology is expected from 2015.

In 2013, Philips [182] announced a similar result: a LED-tube reaching 200 lm/W with a CCT= 3000-4500 K, a CRI>80 and R9>20. Essentially this is a hybrid solution with a pc-LED based on blue light and phosphor conversion to green, combined with a red LED.

5.4.8. LFL T8t, Special cases and non-availability of improving substitutes

Shortcomings of current (BAT) LED retrofit tubes for some LFL applications have been indicated in par. 5.4.5, e.g. relatively low lumen output, low CRI, not suitable for direct-indirect lighting applications, and potential dimming problems. As shown by the BNAT developments in par. 5.4.7, these shortcomings would be expected to be solved within the next two or three years.

5.5. Linear fluorescent lamps T5

5.5.1. LFL T5, BC description

This base case includes T5 (16 mm diameter) lamps with power between 14 and 80 W, including circular lamps. This category includes the most efficient LFL's sold in the EU-28 today and they are often applied in office lighting. The T5-lamps are based on tri-phosphor and use electronic ballasts, which explains part of their improved efficacy (par. 5.4.4). It is estimated that 22-30% of the LFL's sold in EU-28 in 2013 were of the T5 type [183]. Table 1 of regulation 245/2009 makes a distinction between high-output (HO) and high-efficiency (HE) lamps [184]. The highest efficacy requirement of 94 lm/W (at 25˚C) is specified for HE-lamps of 35 W. The efficacy requirements are lower for lower power HE-lamps and for HO-lamps.

Basic technological background information on LFL T5 can be found in the 2007 VITO study [145], with updates available in the Omnibus study [156].

As compared to T8t-lamps, that show a decrease in luminous flux at ambient temperatures above 25˚C, T5-lamps have been optimized for an ambient temperature of 35˚C [185]. This is realized by mounting one of the electrodes on a longer stem in such a way that it is put deeper inside the glass tube. Under this condition a cold spot is

[180] http://www.osram-licht.com/fileadmin/media/pdf/annual-report/2014/OSRAM_en_yearbook_2014.pdf

[181] http://www.osram.com/osram_com/press/press-releases/_trade_press/2014/osram-constructs-the-worlds-most-efficient-led-lamp/index.jsp

[182] http://www.newscenter.philips.com/main/standard/news/articles/20130411-details-of-the-200lm-w-tled-lighting-technology-breakthrough-unraveled.wpd#.VJmUycCc4

[183] In MELISA (Task 2 report) 22% of all LFL; in reference 65 it is 30% of LFL T12+T8+T5.

[184] The regulation does not seem to define these terms, and the difference is not always clear, e.g. a 21 W HE lamp seems to have a higher light output than a 24 W HO-lamp

[185] OSRAM (2014): 'Technical application guide Double capped fluorescent lamps: T8, T5 HE and T5 HO, T5 short and Single capped fluorescent lamps: T5 FC, Part 1: Products and Technology'

created behind one of the electrodes in the lamp, as opposed to T8 lamps where it is in the middle (par. 5.4.1). The more compact dimension of T5-lamps (diameter 16 mm) as compared to T8t-lamps (26 mm) also enables a reduction of the dimensions and cost of the luminaire optics.

After entry into force of regulation 245/2009, important improvements were introduced for T5-lamps. Thanks to better gas fillings and improved fluorescent powders (see also the description for T8 in par. 5.4.1), the new 'energy savers' or 'eco-types' are offering efficacies up to 114 lm/W at 35°C (this means in luminaires designed for T5-lamps; excl. ballast losses). For comparison, the maximum efficacy of a T8 tri-phosphor lamp operated on an electronic ballast is 103 lm/W at 25 °C cold spot temperature.

A relatively recent development is the addition of xenon to the gas filling, which causes a reduction in the discharge voltage. This permits an energy saving at the same lumen output for lamps operating on current-controlled ballasts or dimmable ballasts [186], or a higher light output, for lamps operating on power-controlled gear.

In addition mercury amalgam technology is used in T5 high-output (HO) lamps, to have a larger temperature range with optimum performance, increasing the efficiency in dimming mode and/or in cold operating conditions.

As for T8t-lamps, the efficacy depends on lamp length/power, see par. 5.4.1.

Although further research could probably result in additional minor improvements, the leading manufacturers prefer to invest in LED solutions. Consequently no significant changes in characteristics are expected for the future.

The average EU-28 characteristics for this base case are summarized in Table 23. They are based on the information presented in the Task 2 and 3 reports.

Table 23: Average EU-28 characteristics for the LFL T5 base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	4.84	70.8	75.6	
Lifetime (yr)	28.6	9.1	9.5	
Stock (mln units)	33.7	467	501	
Capacity (lm)	2275	2275	2275	
Efficacy (lm/W)	91	91	91	
EEI (-)	0.165	0.165	0.165	Fcor=1.10; Label class A^{+}
Power (W)	25	25	25	Exclusive ballast power
Ballast efficiency (%)	91%	91%	91%	Electronic ballast
Burning Hours (h/a)	700	2200	2099	
Electricity rate (euros/kWh)	0.191	0.119	0.121	
Price (euros/unit)	9.50	7.92	8.02	
Installation cost (euros/unit)	0.00	6.16	5.77	[146]
Maintenance cost (euros/unit)	0.00	4.39	4.09	[146]

[186] http://download.p4c.philips.com/l4b/9/927994384055_eu/927994384055_eu_pss_enggb.pdf

5.5.2. LFL T5, Improvement options

As explained above, it is not expected that there will still be significant technological progress in LFL T5 lamps, so no improved lamps of the same type will come to the market in future. However, the now installed 1st generation T5-lamps can be substituted by more efficient 2nd generation T5-lamps. In addition, LED-substitutes are available, leading to the following options:

1) Substitute the 1st generation T5 HO&HE lamps with more efficient 2nd generation T5-lamps. In the case that they are operated on current control or dimmable ballasts, this can provide an energy saving around 10%. Alternatively, or in addition, an electronic ballast of A3 class (regulation 245/2009 table 17) can be substituted by an A2 class, with potential energy savings up to 8%.

2) Substitute the LFL T5 by a LED tube retrofit. Intuitively this option might seem very similar to LFL T8t substitution by a LED retrofit tube (par. 5.4.5), but current investigation shows that it is not: availability of LED T5 retrofits is limited. See remarks in par. 5.5.4.

3) Substitute the LFL T5 by a LED luminaire. This has been identified as the BAT solution. For a discussion on LED luminaires for LFL replacement, see par. 5.4.6.

In this moment, options 1 and 3 seem the most likely substitution options.

5.5.3. LFL T5, BAT description, maintaining LFL technology

The state-of-the-art as regards LFL T5 was recently reported by CLASP [161] (Table 24) and by the Omnibus study [156] (Table 25). As shown in these tables, the best available technology lamps have an efficacy that is higher than the minimum requested by regulation 245/2009 [187].

Table 24: LFL T5, best available on the market (Source: CLASP 2013, table 4-2, Comparison of EC No 245/2009 MEPS threshold to market and potential for improvement [161])

Lamp Wattage	245/2009 MEPS Requirements	Manufacturer Catalogue Best Products 2012	Improvement Over Existing MEPS
T5 Fluorescent Lamps[22]			
14W	86 lm/W	13W @ 91 lm/W	6%
28W	93 lm/W	25W @ 103 lm/W	11%
35W	94 lm/W	32W @ 98 lm/W	4%

Note 22: Efficacy values reported are at 25°C. These lamps exhibit higher efficacy when measured at 35°C.

[187] In its comments on the Task 0-3 reports, IALD expressed the following concern: “Proposals that would compromise the availability of T5 HO lamps for example would require extensive, and costly, replacement of fittings and lamps in many schemes.”

Table 25: Progress in linear fluorescent lamp technology. HE= high-efficiency; HO=high-output; es=energy saving. (source: Omnibus study table 6-8 [156])

Wattage [W]	Type	CRI	Colour temp [K]	Efficacy [lm/W @ 35°]	Efficacy [lm/W @ 25°]
28	HE regulation				93
28	HE standard	>80	4000	104	94
25	HE eco/es	>80	4000	114 (116)	103
28	HE standard	>80	6500	97	88
25	HE eco/es	>80	6500	106	96
24	HO regulation				73
24	HO standard	>80	4000	87	78
20	HO eco/es	>80	4000	99	83
24	HO standard	>80	6500	81	72?
20	HO eco/es	>80	6500	93	77

5.5.4. LFL T5, BAT description, LED retrofit tube

LED retrofit tubes for substitution of LFL T5 are available on the market [188], but the choice is limited as compared to LED retrofit tubes for LFL T8t (par. 5.4.5). In addition, major (LED) lighting manufacturers as Philips, Osram, General Electric, Havells-Sylvania, Megaman and CREE, do not have LED tubes with G5 cap in their catalogues (March 2015).

The probable reasons for this situation are:

- The number of T5 lamps being replaced in a year is considerably smaller than the number of T8 lamps being replaced, so the market is less interesting.
- The improvement potential of LED tubes with respect to LFL T5 is still too small, also considering the price difference.
- The technical limitations identified in par. 5.4.5 for LED T8 tubes have a stronger influence for T5 tubes. In particular for LFL T5 HO lamps, no LED replacements with comparable lumen output might be available.

A confirmation from stakeholders is sought on this point.

The characteristics of the LED T5 tubes are more or less the same as those of the T8 tubes, with (declared) efficacies ranging from around 100 to 140 lm/W. Prices seem to be around 50 euros/piece. Note that some of the referenced tubes are in reality T8 (26 mm diameter), but with a G5 cap.

The availability of only secondary brands from small companies has the same drawbacks as noted for the LED T8 retrofits tested by Olino (par. 5.4.5), i.e. information is often scarce or does not seem to be convincing, prices are often only available on request, and it is not always clear if the advertised tubes are actually for sale to a large public.

[188] http://www.narva-bel.de/en/Products_LED_lamps_Semicon_Light_SL/T5_G5L_1868.html
https://www.watt24.com/Lampen/LED-Retrofit/G5/LED-T5-Umruestset-1x1149mm-4000K.html
http://www.encomm.co.uk/downloads/T5-tube.pdf
http://www.syhdee.com/productshow-35-119-1.html
http://www.alibaba.com/product-detail/T5-led-lamps-G5-caps-hot_573918424.html
http://www.alibaba.com/product-detail/12W-G5-base-T8-LED-tube_723006284.html

Therefore it has been preferred not to present a table with technical data and prices for T5 LED retrofit tubes.

5.5.5. LFL T5, BNAT description

When LED efficacy increases it can be expected that LED retrofit tubes become economic alternatives with similar performance as the projections for T8 retrofit tubes. See the common description for all LFL types in par. 5.4.7.

5.5.6. LFL T5, Special cases and non-availability of improving substitutes

T5 lamps with power > 80 W are exempted from regulation 245/2009. The impression of the study team is that no such lamps are on the market, so it should be verified with industry if this exemption is still necessary.

As regards the availability of LED retrofit tubes, see par. 5.5.4.

5.6. Linear fluorescent lamps, other types

5.6.1. LFL X, BC description

This base case covers all LFL types not included in the T12, T8h, T8t and T5 base cases. It includes older T5 types (4-13 W) and special fluorescent lamps, e.g. circular T9 [189], T4 tubes [190], T6, T10 and others. The 2013 stock is around 7% of the total LFL stock and decreasing. This base case is therefore of minor importance for resources study and scenario analysis.

The older, low-wattage, T5 types have T5-dimensions (16 mm diameter), but use the electrode-technology and thermal design of T8 lamps, meaning that the cold spot is in the middle of the lamp as opposed to T5 lamps where it is located next to the lamp cap. Some of these lamps could still use the halo-phosphor technology. These lamps are also commonly known as TL mini lamps and have cap G5 [191].

In tertiary lighting they are frequently used in emergency lighting and exit signs. Special versions are on the market that fit well with battery operated applications.

Due to their compact dimensions they were also used in small furniture and in portable lamps.

The average EU-28 characteristics for this base case are summarized in Table 26. They are based on the information presented in the Task 2 and 3 reports.

[189] http://www.osram.com/osram_com/products/lamps/fluorescent-lamps/fluorescent-lamps-t9/index.jsp

[190] http://www.lightbulbs-direct.com/eterna-t4-6w-231mm-3400k/p2091/

[191] e.g. http://download.p4c.philips.com/l4bt/4/435290/tl_mini_consumer_products_435290_ffs_aen.pdf

Table 26: Average EU-28 characteristics for the LFL X base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	1.24	18.1	19.3	
Lifetime (yr)	15.7	5.0	5.8	
Stock (mln units)	34.2	126	160	
Capacity (lm)	1032	1032	1032	
Efficacy (lm/W)	86	86	86	
EEI (-)	0.188	0.188	0.188	Fcor=1.24; Label class A
Power (W)	12	12	12	Exclusive ballast power
Ballast efficiency (%)	83%	83%	83%	Mainly magnetic ballast
Burning Hours (h/a)	700	2200	1879	
Electricity rate (euros/kWh)	0.191	0.119	0.121	
Price (euros/unit)	9.50	7.92	8.02	
Installation cost (euros/unit)	0.00	6.16	5.77	[146]
Maintenance cost (euros/unit)	0.00	2.68	2.11	[146]

5.6.2. LFL X, Improvement options

No future technological improvements are expected for lamps of this base case. Being exempted from regulation 245/2009, these lamps are still on the market so that lamps of the same type are available as replacement option.

No specific research on the availability of LED retrofit lamps was performed, but considering the situation for the LFL T5 base case discussed in par. 5.5.4, it is assumed that such retrofits will generally not exist.

Consequently two improvement/replacement options have been identified:

1) Substitute the LFL X by one of the same type, but replacing the electromagnetic ballast by an electronic ballast. Electromagnetic ballasts have a very poor efficiency, e.g. 42.7 % for a T5 8W class B2 ballast (see Table 17 in Regulation 245/2009). Replacing them with electronic ballasts typically provides 20-40 % energy saving.

2) Substitute the LFL X by a LED luminaire. This has been identified as the BAT solution. For a discussion on LED luminaires for LFL replacement, see par. 5.4.6.

In the residential sector it is expected that most people will switch to dedicated LED luminaires, in particular for portable applications.

In the tertiary sector, strict safety regulations apply for emergency lighting and exit signs, which might induce a choice for the lamps with exactly the same specifications as those issued with the luminaire.

In general a natural phase-out of LFL X lamps is expected, in favour of LED solutions.

5.6.3. LFL X, BAT description

The BAT solution for substitution of LFL X are LED luminaires, with a performance similar to that for LFL T8, see par. 6.4.6.

5.6.4. LFL X, BNAT description

See the common description for all LFL types in par. 5.4.7.

5.6.5. LFL X, Special cases and non-availability of improving substitutes

The following lamps included in this base case are exempted from regulation 245/2009:

- T5 lamps with power ≤ 13 W
- LFL with a diameter of 7 mm (T2) and less.

5.7. Compact fluorescent lamps with integrated ballast

5.7.1. CFLi, BC description

This base case covers compact fluorescent lamps with integrated ballast. These non-clear lamps are typically used as substitutes for phased-out incandescent lamps, in particular for applications with relatively high operating hours where switching is not frequent (start-up time; switching withstand). For a basic technology description please refer to the 2009 VITO study on domestic lighting [192].

The base case includes both directional and non-directional CFLi's, but the share of directional lamps is expected to be very small and ignored here. The non-directional lamps are subject to regulation 244/2009 that also introduced minimum quality requirements (see Task 0 report). The lamps of this base case typically have energy label class A under regulation 874/2012.

Similar to the situation described for LFL's, no significant progress and investments are expected anymore in CFLi technology, because all developments are focusing on LEDs. Consequently BAT CFLi's are assumed to be similar to the average base case characteristics estimated for the EU-28 and will not be specifically addressed.

The average EU-28 characteristics for this base case are summarized in Table 27. They are based on the information presented in the Task 2 and 3 reports.

As regards capacity, power and efficacy, these data are expected to be representative for the period up to 2013. In recent years CFLi sales are decreasing, and the impression is that this regards in particular the sales in the low wattage range, where LED lamps are increasingly used. Consequently, the average capacity and power of CFLi's might slightly increase in coming years. As higher wattage CFLi's have a higher efficacy, the average efficacy of sold lamps would also be expected to rise.

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[192] Preparatory Studies for Eco-design requirements of EuPs, Final Report, Lot 19: Domestic lighting, Study for the European Commission DGTREN unit D3, contact Andras Toth, by VITO in cooperation with Bio Intelligence Service, Energy Piano and Kreios, October 2009, Contract TREN/07/D3/390-2006/S07.72702, available through 'eup4light.net'

Table 27: Average EU-28 characteristics for the CFLi base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	162	108	271	
Lifetime (yr)	12	12	12	
Stock (mln units)	2296	1531	3827	
Capacity (lm)	523	523	523	
Efficacy (lm/W)	55	55	55	
Power (W)	9.5	9.5	9.5	Inclusive ballast power
Ballast efficiency (%)	100%	100%	100%	Included in lamp efficacy
Burning Hours (h/a)	500	500	500	
Electricity rate (euros/kWh)	0.191	0.119	0.162	
Price (euros/unit)	5.26	4.39	4.91	
Installation cost (euros/unit)	0.00	1.85	0.74	[193]
Maintenance cost (euros/unit)	0.00	11.10	4.44	[193]

5.7.2. CFLi, Improvement options

As explained above, it is not expected that there will still be significant progress in CFLi technology, so no improved lamps of the same type will come to the market. The existing lamps can of course be replaced by one of the same type. Two improvement/replacement options with other lamp types have been identified:

1) Substitute the CFLi by a NDLS LED retrofit lamp. For the characteristics of these LED retrofits, see par. 5.13.3. The same type of LED retrofit can also be used for non-directional incandescent lamps and mains voltage halogen lamps [194].

2) Substitute the CFLi by a LED luminaire. For the moment this is handled as equivalent to a LED retrofit lamp, see remarks in par. 5.1.

5.7.3. CFLi, BAT description, NDLS LED retrofit lamp or luminaire

See par. 5.13.3.

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[193] Installation costs are based on a time of 3 minutes per light source and an hourly rate of 37 euros/hour. The 3 minutes assume easily accessible lamps and mainly group replacements, see also Task 3 par. 7.5. These costs regard only the light sources.
Maintenance costs are per light source, for the lifetime of the light source (not per year). The estimate is based on a time of 1.5 minutes per luminaire cleaning operation, 1 light source per luminaire, one cleaning operation per year, and an hourly rate of 37 euros/hour. See also Task 3 par. 7.5.

[194] This largely neglects the difference between clear and frosted lamps. It is assumed that in most cases the frosted CFL lamp can be substituted by either a frosted or a clear LED lamp. See also remarks in par. 6.13.3.

5.7.4. CFLi, BNAT description

In general the BNAT solution for substitution of CFLi's is to use LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.7.5. CFLi, Special cases and non-availability of improving substitutes

CFLi's are available up to 320 W (23000 lm) in cap E40 and 100 W (6365 lm) in cap E27 [195]. The maximum lumen output of LED retrofit lamps with integrated control gear is limited and high lumen output LED retrofit lamps are relatively more expensive. Consequently, direct LED retrofit solutions for high-capacity CFLi's are expected to be scarce.

For these high capacities, HID-lamps are also available. When the luminaire has sufficient space, these CFLi's can be used to retrofit for example HPM-lamps, removing or bypassing the ballast.

As regards the availability of LED retrofit lamps for these high-capacity CFLi's see also remarks in par. 5.17.3 on LED substitutes for HID-lamps, but most of these retrofits have an external LED control gear. For substitution by LED luminaires, see also par. 5.17.4.

5.8. Compact fluorescent lamps without integrated ballast

5.8.1. CFLni, BC description

This base case covers compact fluorescent lamps without integrated ballast. From the technical point of view, CFLni's are identical to CFLi's (par. 5.7), except that they use an external ballast (electromagnetic or electronic) and have different caps. They exist in a large variety of shapes and caps, for which individual minimum energy efficiency limits have been specified in regulation 245/2009 [196].

The lamps are used in a variety of applications, predominantly in the non-residential sector. The lower wattage lamps are mainly applied in desk luminaires, down-lighters in offices, corridors, stairs and restrooms, signs, orientation and security lighting. The higher wattage lamps are also used in outdoor and street-lighting applications (see the 2007 VITO study [247]) where they now experience the competition of improved HID- and LED-lamps.

Similar to the situation described for LFL's and CFLi's, no significant progress and investments are expected anymore in CFLni technology, because all developments are focusing on LEDs.

The average EU-28 characteristics for this base case are summarized in Table 28. They are based on the information presented in the Task 2 and 3 reports.

[195] http://www.megamanlighting.com/en/cfl-lighting/cfl-lamps

[196] Regulation 245/2009, Annex III, tables 2, 3 and 4. See also amendments in regulation 347/2010

Table 28: Average EU-28 characteristics for the CFLni base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	21.5	50.2	71.7	
Lifetime (yr)	14.3	6.3	8.4	
Stock (mln units)	283	350	633	
Capacity (lm)	633	633	633	
Efficacy (lm/W)	55	55	55	
Power (W)	12	12	12	Exclusive ballast power
Ballast efficiency (%)	91%	91%	91%	Electronic ballast
Burning Hours (h/a)	700	1600	1197	
Electricity rate (euros/kWh)	0.191	0.119	0.138	
Price (euros/unit)	5.26	4.39	4.65	
Installation cost (euros/unit)	0.00	6.16	4.32	[197]
Maintenance cost (euros/unit)	0.00	19.42	10.74	[197]

5.8.2. CFLni, Improvement options

As explained above, it is not expected that there will still be significant progress in CFLni technology, so no improved lamps of the same type will come to the market. The existing lamps can of course be replaced by one of the same type, optionally substituting the electromagnetic ballast by an electronic one [198]. Two improvement/replacement options with other lamp types have been identified:

1) Substitute the CFLni by a LED retrofit lamp. For a discussion on this option and for the characteristics of available LED retrofits, see par. 5.8.3.

2) Substitute the CFLni by a LED luminaire. These LED luminaires are not CFL-specific, i.e. the same luminaire could also be used to substitute other lamp types. For non-residential applications, see par. 5.4.6 for examples of office lighting luminaires and par. 5.17.4 for examples of outdoor and street lighting luminaires.
   For the moment, for residential applications, luminaire substitution is handled as equivalent to the use of a LED retrofit lamp, see remarks in par. 5.1.

[197] Installation costs are based on a time of 10 minutes per light source and an hourly rate of 37 euros/hour. The 10 minutes is an estimated weighted average between 3 min/lamp for group replacements and 20 min/lamp for individual (spot) replacements, see Task 3 par. 7.5, considering also a mix of indoor and outdoor applications. These costs regard only the light sources, not the installation of new luminaires, nor the changing of control gears.
Maintenance costs are per light source, for the lifetime of the light source (not per year). The estimate is based on a time of 5 minutes per luminaire cleaning operation (considering a mix of indoor and outdoor applications), 1 light source per luminaire, one cleaning operation per year, and an hourly rate of 37 euros/hour. See also Task 3 par. 7.5.

[198] Electromagnetic ballasts for low wattage CFLni's are very inefficient, for example a class B2 magnetic ballast for a TC-L 11 W CFLni has a minimum efficiency of only 59.6 % according to Regulation 245/2009 table 17. Substitution by an A2 BAT ballast would increase this to at least 83%.

5.8.3. CFLni, BAT description, LED retrofit

No LED retrofit lamps for CFLni have been found in the catalogues of major lighting manufacturers as Philips, Osram, General Electric, Havells Sylvania and Megaman. This is interpreted as a sign that this market is not sufficiently interesting, and that for many consumers the substitution of CFLni's by LED retrofits may not be an attractive option. Note that, similar to the situation discussed for LFL's and HID-lamps, there is a ballast problem: in most cases the existing ballast has to be removed or by-passed and a new LED control gear has to be installed (if not integrated in the lamp). The associated costs and luminaire safety certification problems might induce many consumers to stick with CFLni or to substitute the entire luminaire.

However, technically there are no obstructions, because several smaller manufacturers are offering LED retrofit lamps for CFLni. Table 29 provides examples of such lamps that have been identified as possible BAT substitutes for CFLni's [199]. Some are plug-and-play versions that can operate on existing ballast. However when the ballast is not removed, their losses remain and these can be significant [200].

Table 29: Examples of LED retrofit lamps for substitution of CFLni. Data accessed in March 2015. See notes for additional information.

Description	W	lm	lm/W class	CCT	CRI	Angle (deg)	Dim	Life (kh)	Price (€)	Note
Topledshop LED retrofit G24D	8	750	94	3000	80	310	No	30	17.45	1
Saled16 W PS-L Basic (4 pins)	16	1648	102	3000 4000 6000	80	180 270 360	?	?	?	2
Lightwell 9W G24q	9	850	94	2800/ 5000		180	No	45	27.99	3
LUNERA G24d (2-pins) or G24q (4-pins)	13	883-994	68-76	2700-4000	84	>180	No	50	?	4

1 http://www.topledshop.nl/LED-Lamp-diverse-fittingen/LED-Lamp-230V-8W-G24D-Wit-Warmwit.html Has integrated control gear: existing ballast to be removed or by-passed
2 http://www.saled.nl/nl/catalogus/led-ps/ps-l-basic/ Has integrated control gear: existing ballast to be removed or by-passed. Available in 6W (588 lm), 8W (787 lm), 12W (1236 lm), 16W (1648 lm)
3 http://www.lightrabbit.co.uk/9-watt-high-power-g24-pl-lamp-led-replacement-4-pin.html Has integrated control gear: existing ballast to be removed or by-passed. Price: £23.99 *1.4 / 1.2.
4 http://www.lunera.com/helenlamp_g24d/ ; http://www.lunera.com/helenlamp_g24q/ Plug-and-play solution: works on existing ballast of listed types. Not suitable for lensed down-lights. Vertical and horizontal version available. Capacity depends on CCT and mounting, from 883 lm (horizontal 2700K) to 994 lm (vertical 4000K)

5.8.4. CFLni, BNAT description

In general the BNAT solution for substitution of CFLni's is to use dedicated LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

[199] For other examples of LED retrofit lamps for CFLni:
https://www.ledsplus.com/led-light-bulbs/cfl
http://www.ledtronics.com/Products/products_new.aspx?category=CFL+Style+Bulbs&sub=Y&connection_type=G24D+%282-Pin%29&connection_type=G24Q+%284-Pin%29&connection_type=GX23D+%282-Pin%29
https://www.earthled.com/collections/g24-led-replacement-bulbs-g24q-led-replacement
http://www.ledecolights.com/products/led-pl-lamp
http://www.olino.org/advice/nl/overview/results?fitting=G23&lamptype=tube_bar_strip_tl
http://www.leditlight.net/g23-230v-pl-led-lamp-5watt-neutraal-wit.html

[200] E.g. the minimum efficiency in class B2 (Regulation 245/2009) is only 59 % for a popular 11 W CFLni ballast.

5.8.5. CFLni, Special cases and non-availability of improving substitutes

The following lamps are exempted from regulation 245/2009:

- single capped fluorescent lamps (without integrated ballast) having a diameter of 16 mm (T5) 2G11 4 pin base, Tc = 3200 K with chromaticity coordinates x=0.415 y=0.377 and Tc = 5500 K with chromaticity coordinates x=0.330 y=0.335.

These are lamps with high colour rendering and/or daylight spectrum properties.

5.9. Halogen lamps, low voltage, mirrored

5.9.1. HL LV R, BC description

This base case covers low voltage (typically 12 V) halogen reflector lamps, including MR11 with GU4 cap, MR16 with GU5.3 cap, R37 with BA15d cap, R56 with B15d cap, etc. It does not include low voltage halogen capsules (see par. 5.10).

For the technology description please refer to the 2009 VITO study [192] and to the Stage 6 review report [217]. As detailed in the latter document, low voltage halogen lamps generally have higher efficacies than their mains voltage relatives, being able to benefit from infrared coatings, dichroic reflectors and xenon gas filling. Most installed lamps in this base case have energy label class C or B according to regulation 874/2012 (Figure 29).

Being directional lamps, they are subject to regulation 1194/2012 that requires an EEI<0.95 for 'other filament lamps' from Stage 2 (September 2014) and this remains unchanged in Stage 3 (September 2016). This EEI implies that HL LV R lamps now being sold should be energy label class B or better [201]. It is expected that most lamps now meet this requirement and that there will not be any significant future technology improvement.

Figure 29 Examples of low voltage halogen reflector lamps. Left: argon filled class C lamp (now phased out by regulation 1194/2012); right: xenon filled class B lamp with infrared coating and dichroic reflector.

The average EU-28 characteristics for this base case are summarized in Table 30. They are based on the information presented in the Task 2 and 3 reports.

[201] In general dichroic reflectors perform better than aluminium coated reflectors but they allow more heat to pass backwards, so luminaires should allow this, see IEC 60598 No Cool Beam symbol.

Table 30: Average EU-28 characteristics for the HL LV R base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	131	32.8	164	
Lifetime (yr)	4.4	4.4	4.4	
Stock (mln units)	546	137	683	
Capacity (lm)	490	490	490	
Efficacy (lm/W)	14	14	14	
Power (W)	35	35	35	Exclusive control gear
Ballast efficiency (%)	94%	94%	94%	MV-LV transformer
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	3.79	3.16	3.66	
Installation cost (euros/unit)	0.00	1.85	0.37	193
Maintenance cost (euros/unit)	0.00	4.07	0.82	193

5.9.2. HL LV R, Improvement options

As explained above, it is not expected that there will still be significant technological progress in low voltage halogen reflector lamps, so no improved lamps of the same type will come to the market in future. Three improvement/replacement options have been identified:

1) Substitute the still installed class C HL LV R lamp by a class B HL LV R lamp, compliant with regulation 1194/2012 stage 3. Considering that class C lamps have now been phased out, the existing installed mix of class C and class B light sources will gradually migrate to a situation where all installed lamps are class B. The substitution of halogen lamps by halogen lamps will be considered, but the relatively small improvement deriving from the phase out of class C lamps will be neglected in the scenario analyses, as compared to the shift in sales towards LED lamps, that will have a far higher impact.

2) Substitute the HL LV R lamp by an LV DLS LED retrofit lamp. For the BAT characteristics of these LED retrofits and related remarks, see par. 5.9.3.

3) Substitute the HL LV R lamp by a LED luminaire. For the moment this is handled as equivalent to a LED retrofit lamp, see remarks in par. 5.1.

5.9.3. HL LV R, BAT description, LED retrofit lamp or luminaire

Table 31 provides examples of LED retrofit lamps identified as a BAT substitute for low voltage halogen reflector lamps. See also Figure 30 for illustration.

As noted by US DoE in July 2012 [202], some older LED MR16 retrofits may present geometric lock-in problems in existing luminaires, but these problems seem to have been solved by modern LED lamps: today suitable LED retrofits are available for most situations.

In this improvement option, the LED retrofit lamp has to function on the MV-LV transformer that was previously installed for the halogen lamp. This transformer can be of the magnetic or the electronic type, with many different design schemes being used for the latter. The control gear for a universal LED retrofit should be compatible with all these existing transformers. In addition note that the output of the existing transformer is still an alternating current, so the LED control gear should anyway perform the AC-DC conversion (rectifier bridge, par. 2.7.2) and create the required constant current (CCR or capacitor, par. 2.7.2).

Note that regulation 1194/2012, Annex III, sub 2.2 requires LED lamps to comply with 'state-of-the-art requirements for compatibility with equipment designed for installation between the mains and filament lamps', starting from Stage 2 (September 2014). This should ensure that LED lamps work on installed MV-LV transformers. As regards the potential dimming problems arising from this solution, see the Task 3 report par. 7.2.4.

Regulation 1194/2012 also specifies functionality requirements for LED lamps, including LSF, LLMF, switching withstand, start- and warmup-time, colour rendering and power factor [203].

Most LV LED DLS lamps are dimmable, this is probably related to the simplified LV LED driver. LV LED retrofit lamps with high CRI >90 are also available but more expensive and they have lower efficacy, see Parathom Pro lamp in Table 31. Without correction for anti-glare shield this lamp would not pass the minimum efficacy criteria of stage 3 in regulation 1194/2012.

Table 31: Examples of LED retrofit lamps for substitution of HL LV R.

Description	W	lm	lm/W class	CCT	CRI	Angle (deg)	Dim	Life (kh)	Price (€)	Note
Parathom Pro MR16 20 Adv 8W/927 36D	5.0	210	42	2700	90	36	yes	50	12.49	1
Philips Master LED Spot MR16 (GU5.3) 7W	7.0	385	55	2700	80	36	yes	40	10.83	2
CorePro LED Spot MR16 (GU5.3) 5W	5.0	325	65	2700	80	36	yes	15	4.55	3
IKEA GU 5.3 MR16	3.5	200	57	2700	80	36	yes	25	3.33	4
Olino test TopLEDshop - MR16 6W 2700K	5.8	502	87	2753	82	47	yes	25	11.21	5, BAT

1 https://www.lampdirect.be/nl/osram-parathom-pro-mr16-20-adv-5w-927-36d-gu5-3
2 https://www.lampdirect.be/nl/philips-ledspot-lv-d-7-35w-827-mr16-36d-master
3 http://www.leds.de/en/LED-lamps-oxid/Philips-CorePro-LED-Spot-MR16-GU5-3-5W-warmwhite.html
4 http://www.ikea.com/be/nl/catalog/products/70288022/
5 http://www.topledshop.nl/LED-Lampen-dimbaar/LED-Lamp-12V-6W-Warmwit-MR16-dimbaar.html

[202] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_mr16-lamps.pdf, SSL MR16 fact sheet of July 2012.
[203] These apply to all LED lamps, directional and non-directional, low voltage and mains voltage.

Figure 30 Examples of LED retrofit lamps for substitution of low voltage halogen reflector lamps.

5.9.4. HL LV R, BNAT description

In general the BNAT solution for substitution of HL LV R's is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.9.5. HL LV R, Special cases and non-availability of improving substitutes

Different from NDLS G9-, G4- and R7s-lamps, reflector lamps have sufficient outer dimensions to enable an adequate cooling of LED retrofit lamps. As a consequence no special cases of non-availability related to maximum lumen output are identified.

Up to our knowledge HL LV R lamps are not used in high temperature applications such as ovens. As a consequence no special cases of non-availability related to high temperature applications are identified.

LED retrofits are also coming to the market for applications that require excellent colour rendering and stability [204], but they have (1/2015) relative low efficacy (25-36 lm/W). Consequently, for these applications HL LV R (class B) might remain the technology of choice. An example of a special application halogen lamp is a low voltage (12 V) MR-16 bulb that reproduces the full colour spectrum of natural daylight with ultra-low UV and IR [205]. These lamps are often applied in museums and are halogen lamps with a blueish filter. The colour temperature is above 3400 K and they can be clearly discriminated. Some LED manufacturers [206] start offering solutions with improved colour spectrum that are used in museums.

5.10. Halogen lamps, low voltage, capsules

5.10.1. HL LV C, BC description

This base case covers low voltage halogen capsules with G4, GY6.35 and similar caps. As regards technology, the same remarks apply as made in par. 5.9.1. As illustrated in Figure 31 and Figure 32, the existing lamps are energy label class C or B according to regulation 874/2012.

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[204] http://fastvoice.net/2015/01/23/im-test-farbtreue-12-volt-led-spots-von-civilight-heitronic-und-maxtrack/
[205] Solux (2015): https://www.solux.net/cgi-bin/tlistore/soluxbulbs.html
http://www.adlsupply.com/halogen-bulbs/mr16-reflectors/ushio-mr16/ushio-1003341-fmw-fg-ws-5300
[206] http://www.soraa.com/applications/museums-galleries
http://www.xicato.com/applications-gallery?&field_project_type_value%5b0%5d=museums_galleries&&&items_per_page=12&all=all

Although these lamps are often used with external reflectors, they are non-directional and therefore subject to the requirements of regulation 244/2009, including its Stage 6 for clear lamps, which implies that these lamps should be class B starting from September 2016 [207]. As detailed in the Stage 6 review report [217], low voltage halogen lamps of class B are available on the market.

Figure 31: Non-directional low voltage halogen capsules class C. Caps: G4 (left), GY6.35 (right). Common power range from 6 to 75 W. Common voltage range: 6-48 V (most popular: 12 V and 24V). Rated product life 2000-4000 h. Prevalently used with external reflector in spot-lights (ceiling, furniture, etc.), desk-lamps and small decorative lamps. Declared as energy label classes 'C'. Consumer list prices of A-brands, including tax, up to € 3.5 per unit (class 'C') or € 4.5 per unit (class 'B'). Street prices of grey-brands, including tax, as low as € 1.1 per unit (class 'C'). (Source: Stage 6 review report [217])

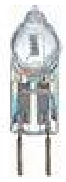

Figure 32: Non-directional low voltage halogen capsules class B. Common power range from 20 to 60 W. Rated product life 4000 h. Prevalently used with external reflector in spot-lights (ceiling, furniture, etc.), desk-lamps and small decorative lamps. Declared as energy label class'B'. Consumer list prices of € 4.5. Those lamps rely on a spherical envelope with infrared coating and reflection for heat recovery to increase lamp efficacy. (Source: Stage 6 review report [217])

The average EU-28 characteristics for this base case are summarized in Table 32. They are based on the information presented in the Task 2 and 3 reports.

Table 32: Average EU-28 characteristics for the HL LV C base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	33.7	8.42	42.1	
Lifetime (yr)	4.4	4.4	4.4	
Stock (mln units)	169	42.3	211	
Capacity (lm)	490	490	490	
Efficacy (lm/W)	14	14	14	
Power (W)	35	35	35	Exclusive control gear
Ballast efficiency (%)	94%	94%	94%	MV-LV transformer
Burning Hours (h/a)	450	450	450	

[207] Discussion on Stage 6 is ongoing and the September 2016 data might be changed.

Table 32: Average EU-28 characteristics for the HL LV C base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	3.16	2.63	3.05	
Installation cost (euros/unit)	0.00	1.85	0.37	193
Maintenance cost (euros/unit)	0.00	4.07	0.82	193

5.10.2. HL LV C, Improvement options

It is not expected that there will still be significant technological progress in low voltage halogen capsules, so no improved lamps of the same type will come to the market in future. Three improvement/replacement options have been identified:

1) Substitute the still installed class C HL LV capsule by a class B HL LV capsule. The same remarks apply as made for HL LV R in par. 5.9.2.

2) Substitute the HL LV capsule by an LV LED retrofit. For the current characteristics of these LED retrofits and related remarks, see par. 5.10.3. In some applications LED retrofit lamps might have lock-in problems. In that case the entire luminaire should be substituted, or the consumer should stick with halogen lamps.

3) Substitute the HL LV capsule by a LED luminaire. For the moment this is handled as equivalent to a LED retrofit lamp, see remarks in par. 5.1.

5.10.3. HL LV C, BAT description, LED retrofit lamp or luminaire

For remarks on the design of LED control gears for operation on existing MV-LV transformers, see par. 5.9.3. Note that in the case of the capsules the space available for the LED control gear is even more limited than for the MR16 case.

Especially the higher lumen LED retrofits available today (Q1/2015) have slightly larger outer dimensions compared to the existing halogen lamps. In some luminaires this might cause geometric lock-in problems [208].

High lumen output lamps are only available from new brands on the market, not from major lamp manufacturers. In addition the LED lamps that are advertised as substitute for 35 and 50W halogen lamps usually have considerably lower lumen output.

Table 33 provides examples of LED retrofit lamps identified as a BAT substitutes for low voltage halogen capsules. See also Figure 33 for illustration. Additional references show prices starting from below 1 euro, but for many advertised lamps the information is incomplete [209].

[208] For example 'G4, indoor spotlight for boats': http://www.nauticexpo.com/prod/marinetech-gmbh-cokg/indoor-spotlight-boats-halogen-30216-248500.html

[209] http://www.miniinthebox.com/nl/g4-2w-24x3014smd-6000-6500k-cool-white-light-led-corn-bulb-12v_p831371.html?currency=EUR&litb_from=paid_adwords_shopping&gclid=Cj0KEQjwgoKqBRDt_IfLr8y1iMUBEiQA8Ua7XVFd_avxmLYKjaQg6zQj7ZOolfBbCfoV7gfda50Zb9EaAiaE8P8HAQ
http://www.ledlight-ledbulb.com/html/LED-light-bulb/G4-G9-GY6.35-LED-bulbs/Index.Html

As regards the functionality requirements for LEDs, see par. 5.9.3. Functionality requirements from regulation 1194/2012 also apply to these non-directional LEDs.

Table 33: Examples of LED retrofit lamps for substitution of HL LV C.

Description	W	lm	lm/W class	CCT	CRI	L (mm)	D (mm)	Life (kh)	Price (€)	Note
Halogen lamps (ref)										
Osram Halostar 20W 12V G4	20	320	16	2800	100	33	10	2	0.85	1
Osram Halostar 35W 12V GY6.35	35	630	18	2900	100	44	12	2	0.85	1
Osram Halostar 50W 12V GY6.35	50	910	18	3000	100	44	12	2	0.85	1
LED lamps										
Osram LED Star G4 2,1 W	2.1	140	67	2700	80	36	14	15	9.99	2
Philips CorePro LEDcapsule LV G4	1.2 2.0	105 200	88 100	3000	80	39 45	14	15	5.99 6.49	3
Heitronic 1,8W	1.8	180	100	2700	80	43	15	30	8.85	4
LumenStar® LED G4	4.2	420	100	3000	80	38	22	35	11.95	5
Dimmable 12V GY6.35 led bulb	5.5	550	101	2700-6500	80	47	25	50	5.45	6

1 http://www.osram.com/osram_com/products/lamps/halogen-lamps/halostar/halostar-standard/index.jsp ; https://www.lampdirect.nl/osram-halostar-standard-20w-12v-g4-clear?display_type=2&qcd=1&s2m_channel=544&dfw_tracker=2402-4050300003924&gclid=Cj0KEQjwgoKqBRDt_IfLr8y1iMUBEiQA8Ua7XZ170HJ3vU8tZk8x4e4EE1IuGt3SovkvHHC_X1JfPYMaArZS8P8HAQ
2 http://www.osram.com/osram_com/products/lamps/led-lamps/consumer-special-led-lamps/led-star-pin-g4-12-v/index.jsp ; http://www.conrad.be/ce/nl/product/1227426/OSRAM-LED-lamp-G4-Steekfitting-21-W-20-W-Warmwit-12-V?ref=searchDetail
3 http://download.p4c.philips.com/l4bt/4/429760/corepro_ledcapsule_lv_429760_ffs_aen.pdf ; https://www.lampdirect.nl/philips-corepro-ledcapsulelv-2-20w-830-g4?display_type=2&qcd=1&s2m_channel=544&dfw_tracker=2402-8718696419168&gclid=Cj0KEQjwgoKqBRDt_IfLr8y1iMUBEiQA8Ua7XeJ8ujggoAPewwVwmNXMaxeoqGCGRqSn-C-9SjDL1ckaAlA08P8HAQ
4 http://www.reichelt.de/HEIT-16065/3/index.html?&ACTION=3&LA=446&ARTICLE=143100&artnr=HEIT+16065&SEARCH=G4+led
5 http://www.amazon.de/LumenStar%C2%AE-Dimmbar-warmwei%C3%9F-Abstrahlwinkel-vergleichbar/dp/B00699GRX0/ref=sr_1_6?s=lighting&ie=UTF8&qid=1428499416&sr=1-6&keywords=G4+led
6 http://www.alibaba.com/product-detail/dimmable-12v-6w-led-bulb-gy6_1802979887.html Original price $4.6-6

Figure 33: Examples of LED replacement lamps for low voltage halogen capsules with G4 or GY6.35 cap. (Sources: [219] [210])

5.10.4. HL LV C, BNAT description

In general the BNAT solution for substitution of HL LV capsules is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

[210] http://www.lightinthebox.com

5.10.5. HL LV C, Special cases and non-availability of improving substitutes

As explained before, there are currently problems with available LED retrofits in the high lumen output range and geometry lock-in problems.

There are special applications for example in photography, stage and studio lighting where special versions of halogen lamps are used due to their full spectrum, high colour temperature and stability [211]. Some versions have short life time (e.g. 100 h) and relative high efficacy (e.g. 25 lm/W). These are niche products and it is unclear if it is technically feasible and economically justified to provide LED alternatives.

5.11. Halogen lamps, mains voltage, capsules

5.11.1. HL MV C, BC description

This base case covers mains voltage halogen capsules with G9 caps (Figure 33). For the technology description please refer to the 2009 VITO study [192] and to the Stage 6 review report [217].

These lamps are non-directional lamps and as such they are subject to the requirements for clear lamps of regulation 244/2009, but they are exempted from its Stage 6 [217] [212]. This implies that their power should not exceed 0.8 * (0.88√Φ+0.049Φ) W, where Φ is the rated luminous output (in lm). This corresponds to the lower limit of energy label class C according to regulation 874/2012 (EEI<0.8).

Figure 34: Example of a mains voltage halogen capsule with G9 cap

The average EU-28 characteristics for this base case are summarized in Table 34. They are based on the information presented in the Task 2 and 3 reports.

Table 34: Average EU-28 characteristics for the HL MV C base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	53.3	13.3	66.6	
Lifetime (yr)	3.3	3.3	3.3	
Stock (mln units)	184	46.0	230	
Capacity (lm)	420	420	420	
Efficacy (lm/W)	12	12	12	
Power (W)	35	35	35	
Ballast efficiency (%)	100%	100%	100%	No control gear

[211] http://www.ushio.com/products/avphoto/h-halogenSE.php

[212] In its comments following the 1st stakeholder meeting of 5 February 2015, the Danish Energy Agency suggests to include minimum ecodesign requirements for R7s and G9 in a future stage 7. This is observed to be especially urgent for the G9 lamps as G9 adapters exist, giving a major loophole in the existing regulation.

Table 34: Average EU-28 characteristics for the HL MV C base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	3.79	3.16	3.66	
Installation cost (euros/unit)	0.00	1.85	0.37	193
Maintenance cost (euros/unit)	0.00	3.05	0.61	193

5.11.2. HL MV C, Improvement options

As for other halogen lamps, it is not expected that improved mains voltage halogen capsules will come to the future market after all models have reached label class C (as by now they should have). Two improvement/replacement options have been identified:

1) Substitute the HL MV capsule by an MV LED G9 retrofit. For the current characteristics of these LED retrofits and related remarks, see par. 5.11.3. In some applications LED retrofit lamps might have lock-in problems. In that case the entire luminaire will have to be substituted.

2) Substitute the HL MV capsule by a LED luminaire. For the moment this is handled as equivalent to a LED retrofit lamp, see remarks in par. 5.1.

5.11.3. HL MV C, BAT description, LED G9 retrofit lamp or luminaire

Table 35 provides examples of LED retrofit lamps with G9 cap, identified as a BAT substitute for mains voltage halogen capsules. See also Figure 35 for illustration.

Note that in this case the space available for a LED control gear and for cooling is extremely limited. As a consequence, all LED retrofits are more bulky than the halogen capsules they aim to replace, and in some luminaires this might cause geometric lock-in problems. Major lamp suppliers as Osram and Philips offer only low lumen lamps (up to 200 lm). Higher lumens are available from smaller brands (up to 480 lm). Some are advertised as replacements for 50W halogen lamps, but they have only about half the lumens of these lamps (Table 35, note 6).

The functionality requirements of regulation 1194/2012, Annex III, sub 2.2 are applicable also to these non-directional LEDs.

Table 35: Examples of LED retrofit lamps with G9 cap for substitution of HL MV C.

Description	W	lm	lm/W class	CCT	CRI	L (mm)	D (mm)	Life (kh)	Price (€)	Note
halogen lamps (ref)										
Philips EcoHalo MV Clickline G9	18 53	204 850	11 16	2800	100	22	13	2	3.99 3.99	1
LED lamps										
LumenStar® LED G9 Lampe 5W	5.0	400	80	3000	80	63	32	35	7.49	2
MENGS® G9 5W LED	5.0	480	96	3000	80	48	15	50	5.35	3, BAT

Philips CorePro LEDcapsuleMV 2.5-25W 827 G9	2.5	205	82	2700	80	53	18	15	6.49	4
Osram LED star pin G9	1.9	140	74	3000	82	58	18	15	5.83	5
THG LB60G9W04-2	5.0	450	90	3000-3500		71	30		3.79	6

1 http://download.p4c.philips.com/l4bt/3/325401/ecohalo_clickline_g9_325401_ffs_aen.pdf Available in 18, 28, 42 and 53 W versions ; https://www.lampdirect.nl/philips-ecohalo-clickline-18w-g9-230v-cl
2 http://www.amazon.de/LumenStar%C2%AE-Lampe-warmwei%C3%9F-Abstrahlwinkel-vergleichbar/dp/B00BKZKZ2C/ref=sr_1_2?s=lighting&ie=UTF8&qid=1428500490&sr=1-2&keywords=LumenStar%C2%AE
3 http://www.amazon.de/MENGS%C2%AE-Leuchtmittel-Abstrahlwinkel-Energiespar-W%C3%A4rmeabgabe/dp/B00OYT6V10/ref=sr_1_10?s=lighting&ie=UTF8&qid=1428500722&sr=1-10&keywords=g9+led+7w
4 http://download.p4c.philips.com/l4bt/4/433911/corepro_ledcapsule_mv_433911_ffs_aen.pdf ; https://www.lampdirect.be/nl/philips-corepro-ledcapsulemv-2-5-25w-827-g9
5 http://www.osram.com/osram_com/products/lamps/led-lamps/consumer-special-led-lamps/led-star-pin-g9/index.jsp ; https://www.conrad.nl/nl/osram-led-lamp-g9-steekfitting-19-w-20-w-warmwit-230-v-1082723.html?WT.mc_id=gshop&gclid=Cj0KEQjwgoKqBRDt_IfLr8y1iMUBEiQA8Ua7XZfyc5MmsnvLplvxuujtfpCR0FCCdx77K-JkfgZm88oaAoC28P8HAQ&WT.srch=1
6 http://www.amazon.co.uk/THG-Equivalent-Spotlight-Decorative-Lighting/dp/B00F0IAUF2 ; Price: £12.99 (for pack of 4) *1.4 /1.2 /4

Figure 35: Examples of LED replacement lamps for mains voltage halogen capsules with G9 cap. (Sources: [213])

5.11.4. HL MV C, BNAT description

In general the BNAT solution for substitution of HL LV capsules is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.11.5. HL MV C, Special cases and non-availability of improving substitutes

G9 lamps are also used and sold for ovens [214]. In this case the G9 lamp is the most efficient solution (BAT) because waste heat is not lost and no external converter is needed. LED lamps are not suitable for use in ovens.

In some luminaires, LED retrofit lamps may present geometric lock-in problems.

[213] http://www.osram.it; http://www.leroymerlin.it
[214] E.g. OSRAM HALOPIN OVEN 40 W 230 V G9 with 490 lm and CT 2700 K. http://www.osram.com/osram_com/products/lamps/halogen-lamps/halopin/halopin-oven/index.jsp

5.12. Halogen lamps, mains voltage, linear, double-ended (R7s)

5.12.1. HL MV L, BC description

This base case covers mains voltage linear double-ended halogen lamps with R7s caps (Figure 36). For the technology description please refer to the 2009 VITO study [192] and to the Stage 6 review report [217].

These lamps are non-directional lamps and as such they are subject to the requirements for clear lamps of regulation 244/2009, but they are exempted from its Stage 6 [217]. This implies that their power should not exceed $0.8 * (0.88\sqrt{\Phi}+0.049\Phi)$ W, where Φ is the rated luminous output (in lm). Different from the situation for the mains voltage halogen capsules, this does NOT exactly correspond to the lower limit of energy label class C according to regulation 874/2012, because for high-lumen lamps (>1300 lm) as those discussed in this base case, that regulation defines the reference power as 0.07341Φ, and not as $0.88\sqrt{\Phi}+0.049\Phi$.


Figure 36: Examples of mains voltage linear double-ended halogen lamps (source: [86])

The average EU-28 characteristics for this base case are summarized in Table 36. They are based on the information presented in the Task 2 and 3 reports.

Table 36: Average EU-28 characteristics for the HL MV L base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	30.4	7.6	38.0	
Lifetime (yr)	2.2	2.2	2.2	
Stock (mln units)	69.6	17.4	87.0	
Capacity (lm)	3000	3000	3000	
Efficacy (lm/W)	12	12	12	
Power (W)	250	250	250	
Ballast efficiency (%)	100%	100%	100%	No control gear
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	3.16	2.63	3.05	
Installation cost (euros/unit)	0.00	1.85	0.37	[193]
Maintenance cost (euros/unit)	0.00	2.03	0.41	[193]

5.12.2. HL MV L, Improvement options

As for other halogen lamps, it is not expected that improved mains voltage linear double-ended halogen lamps will come to the future market after all models have complied with the maximum power of regulation 244/2009 (as by now they should have). As long as halogen R7s lamps are allowed on the market, the same lamp type can obviously be used for substitution. In addition two improvement/replacement options have been identified:

1) Substitute the HL MV L by an MV LED R7s retrofit. For the current characteristics of these LED retrofits and related remarks, see par. 5.12.3. This solution may present problems for high lumens and/or due to geometric lock-in problems. In that case the entire luminaire has to be replaced, or the consumer should stick to halogen lamps (if still on the market).

2) Substitute the HL MV L by a LED luminaire. For the moment this is handled as equivalent to a LED retrofit lamp, see remarks in par. 5.1.

5.12.3. HL MV L, BAT description, LED R7s retrofit or luminaire

Table 37 provides a selection of linear halogen lamps with R7s cap and examples of LED retrofit lamps, identified as potential BAT substitutes. See also Figure 37 for illustration.

As also noted in the Stage 6 review report [217], the lateral dimensions of most LED retrofits are considerably larger than those of the halogen lamps they aim to replace. The halogen lamps have a diameter of 10-12 mm, while most of the LED lamps that are offered as replacements are around 55 mm. In some luminaires this will cause geometric lock-in problems (Figure 38). Given the cost and art value of some luminaires, not all consumers might be willing to replace their luminaire.

In addition there may be light distribution differences: most R7s LED retrofits found in the market today have beam angles from 120° to 180°, and do not shine in all directions like the halogen lamps do. Consequently, there is no guarantee that the light distribution from the LED retrofits will be satisfactory.

A third aspect is that halogen lamps with R7s cap exist up to 44,000 lm, while the highest capacity LED lamp with R7s cap has only 5,200 lm. This high lumen difference appears for each lamp length in Table 37. Consequently, for high lumen halogen lamps with R7s cap no LED retrofit seems to be available yet.

Recent developments seem to slightly improve this situation: LED2day announces for May 2015 two R7s LED models, lengths 78 and 118 mm, with a 360° light emission, a diameter of 29 mm, and an efficacy up to 115 lm/W (see notes 5 and 6 in the table). Similar lamps are available from Marino Cristal (note 17 in table) and have a diameter of only 20 mm. However, the lumens are still low compared to the halogen lamps they aim to replace.

Table 37: Examples of Halogen reference lamps with R7s cap (HL MV L) and corresponding LED retrofit lamps.

Description	W	lm	lm/W class	CCT	CRI	Angle (deg)	L (mm)	D (mm)	Life (kh)	Price (€)	Note
Halogen lamps (ref)											
Osram HALOLINE SST 120 W 230 V R7S	120	2250	19 C	2950	100		75-80	12	2000	2.10	1
Philips Plusline ES Small 118mm 2y 400W R7s 230V 1BB	400	8600	21.5 D	2900	100		118	11	2000	3.95	2
Philips Plusline large DEBig 1000W R7s 230V T11 CL	1000	21500	21.5 C	2900	100		189	11	2000	7.99	3
Philips Plusline large DEBig 1500W R7s 230V T11 CL	1500	33000	22 C	2900	100		254	11	2000	7.99	3
GE TU*K8 2000W 230V R7S 331MM BX GE 1/10MIH	2000	44000	22 D	3000	100		332	10	2000	3.50	4
LED lamps											
LED2day R7s 5W LED warm-wit en dimbaar	6	550	92	3000		360	78	29	30000	16.63	5
LED2day R7s 10W warm-wit en dimbaar	10	1150	115	3000		360	118	29	30000	24.96	6
Marino Cristal	8	800 900	100 113	3000 4000	80	360	118	20		22.42	17
MEGAMAN R7s LED 118 mm (LJ0209)	9	600	67 A	2800 4000	80	<180	118	56x29	25000	23.85	7
ELBRO LEDModul R7s 14W	14	1300	93 A	3000 6500	75-80	120	118	54	30000	74.60	8
Lumenbest LBR7S-3	15	1400	85	2700-7000	80		189	54x35	80000	10.70	9
ELBRO LEDModul R7s 20W	20	1900	95 A	6500	75-80	180	189	54	30000	96.60	10
LED2day R7s 20W LED 189mm ww	20	1950	97	2700		200	189	55x38	30000	39.60	11
2015 New R7S LED 35W CREE SMD5730 Dimmable	35	3150	90	2700-6500		180	189	54	50000	14.30	12
OED-S55189-C50WD	50	5000-5200	100	2700-6500	>75	200	189	55x38			13
EDLED 25w led r7s light 254mm	25	2400	96	3500-5500	>75	160	254	55x35	50000	43.10	14
OED-S55254-25W	25	2400	96	2700-6500	>75	180	254	55x35	50000		15
OED-S55330-36W	36	3600	100	2700-6500	>75	180	330	55x35	50000		16

1 http://www.osram.com/osram_com/products/lamps/halogen-lamps/haloline/haloline-superstar/index.jsp ; http://www.leuchtmittelmarkt.com//themes/kategorie/detail.php?artikelid=179693&source=2
2 http://download.p4c.philips.com/l4bt/3/323050/plusline_es_small_323050_ffs_aen.pdf ; https://www.budgetlight.nl/philips-plusline-es-small-118mm-2y-240w-r7s-230v.html?gclid=CjwKEAjwmfKpBRC8tb3Mh5rs23ASJACWy1QPYcLLRYR3MBVP2X4VmZo93G1sDs6yPYLQvmv4DxNIghoCAEfw_wcB
3 http://download.p4c.philips.com/l4bt/3/322839/plusline_large_double_ended_322839_ffs_aen.pdf ; https://www.lampdirect.nl/philips-plusline-large-1500w-r7s-230v-255mm
4 http://catalog.gelighting.com/lamp/halogen/halogen-linear/f=halogen-linear-high-watt/p=30886/d=0/?r=emea ; http://energylite.co.uk/?p=3482 original price £2.49
5 http://www.led2day.nl/led-r7s-halogeen-staafjes/r7s-5w-led-360-graden-78mm-super-warm-wit-en-dimbaar-410 ; announced to come to the market in May 2015
6 http://www.led2day.nl/led-r7s-halogeen-staafjes/r7s-10w-led-360-graden-118mm-super-warm-wit-en-dimbaar ; announced to come to the market in May 2015
7 http://www.megaman.cc/products/led/led-r7s/LJ0209/?voltage=220v; http://www.amazon.de/Megaman-Sockel-Ersatz-Halogenstab-warmwei%C3%9F-neutralwei%C3%9F/dp/B00BCG0YG6
8 http://www.voltus.de/beleuchtung/led-system/leuchtmittel/lampensockel-r7s/elbro-ledmodulr7s14w-moduleinsatz-fuer-halogenstrahler.html Class A on scale A-G

9 http://nl.made-in-china.com/co_lumenbest/product_Halogen-Replacement-189mm-LED-R7s-Lamp_hogrrhgsy.html original price $11.60
10 http://www.voltus.de/out/pictures/media/LEDModuleR7S.pdf ; http://www.voltus.de/beleuchtung/led-system/leuchtmittel/lampensockel-r7s/elbro-ledmodulr7s20w-moduleinsatz-fuer-halogenstrahler.html Class A on scale A-G
11 http://www.led2day.nl/led-r7s-halogeen-staafjes/r7s-20w-led-189mm-warm-wit Site provides warning to verify space in luminaire because LED lamp dimensions are larger than those of replaced halogen lamp
12 http://www.aliexpress.com/item/2015-New-R7S-LED-15W-25W-35W-CREE-SMD5730-Dimmable-led-r7s-78mm-J78-118mm-J118/32268518818.html?s=p original price $15.50
13 http://www.oed-group.com/plus/view.php?aid=358 original price $46.80
14 http://www.aliexpress.com/item/high-power-25w-led-r7s-light-254mm-replace-300w-halogen-lamp/32296209806.html
15 http://oedgroup.en.made-in-china.com/product/rXCEGYibancq/China-25W-2400lm-254mm-R7s-LED-Lamp-to-Replace-250W-Halogen-Lamp.html
16 http://oedgroup.en.made-in-china.com/product/pXjEAgHuOnkb/China-36W-330mm-R7s-LED-Lamp-to-Replace-330mm-360W-Halogen-Lamp.html
17 http://www.marinocristal.com/pages/materiale_elettrico.php?cid=3&scid=8&sscid=0&aid=454 ; http://www.prometeoelectronics.it/scheda.php?id=3361&name=Linear%20r7s%20led%20117/118mm%208w%20360%C3%82%C2%B0%20warm%20light%203000k%20360%C3%82%C2%B0

Figure 37: Examples of LED replacement lamps for mains voltage linear halogen lamps with R7s cap. (Sources: Stage 6 review (left); Voltus.de [215](right))

Figure 38: Wall mounted surface uplighter with R7s halogen lamp. It is likely that LED retrofit lamps with the same lumen would geometrically not fit in this luminaire (source : Flos Fort Knox Wall [216])

5.12.4. HL MV L, BNAT description

As also indicated before, current LED retrofit solutions may be limited by geometric lock-in, by light distribution requirements, and/or by maximum light capacity. Although a development has been identified for R7s LED lamps towards smaller diameters and to

[215] http://www.voltus.de/out/pictures/media/LEDModuleR7S.pdf
[216] http://www.lempa.lt/en/fixtures/wall/flos-fort-knox-wall/

360° light emission, the problems related to R7s substitution by LED retrofit lamps are not expected to be solved on the short term.

R7s halogen lamps offer a very high light intensity in a compact space, and LEDs are expected to have difficulties in meeting this also in the future. In addition, the higher lumen LED lamps are likely to have thermal problems in many existing luminaires.

It is therefore expected that LED luminaires rather than LED retrofit lamps will be used to substitute R7s halogen lamps. This point of view is supported by the fact that major lamp manufacturers like Philips and Osram do not have R7s LED lamps in their catalogue while they do offer a wide variety of e.g. floodlight luminaires (one of the applications where R7s halogen lamps are used).

Therefore, the BNAT solution for substitution of HL MV linear lamps with R7s cap is to use improved future LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.12.5. HL MV L, Special cases and non-availability of improving substitutes

See remarks in the previous paragraphs.

5.13. Halogen lamps, mains voltage, GLS and reflector substitute (E14, E27)

5.13.1. HL MV E, BC description

This base case covers mains voltage halogen lamps with E14 or E27 cap that are mainly used to substitute the now phased-out incandescent (GLS) lamps.

The non-directional lamps of this BC are subject of the so called Stage 6 discussion (see Task 0 report, par. 2.6). The technical/economic backgrounds for that discussion have been described in detail in the Stage 6 review report (2013) [217] and in a recent study (2015) aiming at updating that report [218].

Stage 6 of Commission Regulation (EC) No 244/2009 [219] requires clear non-directional lamps to have a maximum power of $0.6 * (0.88\sqrt{\Phi}+0.049\Phi)$ [220], which corresponds to the lower limit of energy label class B (for non-directional lamps) according to Commission Delegated Regulation (EU) No 874/2012, i.e. an Energy Efficiency Index (EEI) of 0.60 [221].

The Stage 6 review report concluded in June 2013 that there are no mains voltage halogen lamps on the market that fulfil this requirement, and that it is not technically feasible to produce 'Stage 6 conform' MV halogen lamps for the EU at a competitive price and at a reasonable investment level. The 'update-study' [218] anyway found halogen lamps for sale on the internet that claim to be class B. These are the same Philips lamps, with integrated MV-LV transformer, that were identified in the Stage 6 review report [217]

[217] "Review study on the stage 6 requirements of Commission regulation (EC) No 244.2009 Final Report", VHK (pl) / VITO for the European Commission, Delft/Brussels 14.6.2013, SPECIFIC CONTRACT No ENER/C3/ 2012-418 LOT 2/01/SI2.645913 Implementing Framework Contract No ENER/C3/2012-418-Lot 2. http://www.eup-network.de/fileadmin/user_upload/Technical_Review_Study_by_VHK_VITO.pdf?PHPSESSID=a60a9114e01af59471374f5814656e0c

[218] "European LED Market Evolution and Policy Impacts", Danish Energy Agency, Energy Piano, CLASP, March 2015. http://clasponline.org/en/Resources/Resources/PublicationLibrary/2015/New-Data-Show-that-LED-Mass-Market-in-Europe-Will-Occur-Sooner-than-Predicted.aspx

[219] Stage 6 applies from 1 September 2016 but this date might be postponed by the ongoing discussion

[220] Φ being the luminous flux (lm)

[221] This is exact only for lamps up to 1300 lm.

but that were there stated to be out of production. In this moment (March 2015) these lamps do NOT appear in the Philips lamp catalogue.

The directional lamps of this BC will be subject, from September 2016, to Stage 3 of Regulation 1194/2012, that requires an EEI<0.95, corresponding to label class B (for directional lamps). This requirement is conditional and is being studied as part of this preparatory study. The market assessment will be reported separately [222], but the conclusion is similar to the one for non-directional lamps, i.e. there was a Philips lamp with integrated MV-LV transformer that met the class B requirement, but it seems to be out of production, and in this moment there are no directional mains voltage halogen lamps on the market that meet the Stage 3 requirement. Considering the information from the Stage 6 review, it is also unlikely that such lamps will reappear.

The average EU-28 characteristics for this base case are summarized in Table 38. They are based on the information presented in the Task 2 and 3 reports.

Table 38: Average EU-28 characteristics for the HL MV E base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	242.1	60.5	302.7	
Lifetime (yr)	3.3	3.3	3.3	
Stock (mln units)	640	160	800	
Capacity (lm)	432	432	432	
Efficacy (lm/W)	12	12	12	
Power (W)	36	36	36	
Ballast efficiency (%)	100%	100%	100%	No control gear
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	2.63	2.19	2.54	
Installation cost (euros/unit)	0.00	1.85	0.37	193
Maintenance cost (euros/unit)	0.00	3.05	0.61	193

5.13.2. HL MV E, Improvement options

As explained above, it is not expected that new, improved lamps of the same type will come to the market. As long as regulations will allow, HL MV E lamps can of course be substituted by lamps of the same type.

Four improvement / replacement options with other lamp types have been identified:

1) Substitute the mains voltage halogen lamp by a CFL. As also noted in the Stage 6 review report, this is an option in particular for applications with relatively high operating hours where switching is not frequent (start-up time; switching withstand). However, CFL's are not clear, cannot give a glitter effect, and have

[222] Market assessment on directional mains voltage filament lamps related to stage 3 of Commission Regulation (EU) No. 1194/2012, VHK for the European Commission, to be issued.

a lower CRI than halogen lamps. Use of CFL's would be beneficial for energy consumption and for total mercury emission balance.

2) Substitute the MV halogen lamp with E-cap by a MV halogen capsule with G9 cap, using a G9-to-E14/E27 adapter (see Stage 6 review report, figure 10). From the light quality, energy consumption and monetary points of view this is more or less equivalent. It is an option only if MV HL E would be phased out while MV HL C (G9) would be allowed on the market [223].

3) Substitute the MV halogen lamp with E-cap by a LV halogen, using an adapter and an external transformer. For directional lamps an example could be to use an HL LV R, MR 16 with GU 5.3 cap and a socket adapter GU5.3-to-E27. For non-directional lamps an HL LV C (capsule) could be used. A complication is that a rewiring of the luminaire is necessary to insert the MV-LV transformer. This would also shift the legal product responsibilities from the original manufacturer to the installer. In general, low voltage halogen lamps have a better energy efficiency than mains voltage halogen lamps [224].

   It is not expected that options 1), 2) and 3) will be frequently used, even if MV halogen lamps with E-cap are phased out, and they will therefore not be considered in the sales shifts between base cases in the scenario analyses.

4) Substitute the MV halogen lamp with E-cap by a LED retrofit lamp (or substitute the entire luminaire by a LED luminaire, see remarks in par. 5.1). This is identified as the BAT solution, see next paragraphs for the characteristics.

5.13.3. HL MV E, BAT description, Non-directional LED retrofit

A large variety of non-directional LED retrofit lamps with E14 or E27 cap is available on the market as a BAT-solution to replace an HL MV E. Note that the same LED lamps can also substitute a CFLi or a GLS lamp. Lamps belonging to the HL MV E base case for which no adequate LED substitute is currently available, if any, are identified in par. 5.13.6.

Recently, three reports were issued with the aim to demonstrate that suitable LED retrofit lamps for non-directional HL MV E exist and are affordable for consumers. The authors of these reports are clearly in favour of maintaining the Stage 6 requirements of regulation 244/2009, or even raising the minimum efficacy requirements, thus phasing out HL MV E lamps as soon as possible (September 2016). These reports contain up-to-date information on the prices, efficacies and other characteristics of LED retrofit lamps for non-directional HL MV E, that have been used by the study team to define the BAT characteristics. One of the reports was criticized by industry association LightingEurope. A short summary of these documents is presented below:

- A February 2014 Danish study [225] focuses on non-directional lamps with E27/B22d and E14/B15d caps, considering the shapes Standard (A60), Round (P45) and Candle (B35,C35). Both frosted and clear lamps are included. The study assumes that this selection covers 95% of all non-directional HL MV E lamps. Replacement schemes are

[223] G9 lamps are now exempted from regulation 244/2009 stage 6.
[224] See the Stage 6 review report for an explanation
[225] "Availability of non-directional LED replacement lamps", Casper Kofod – Energy piano, Peder Øbro – ÅF Lighting, 27 February 2014, study done for the Danish Energy Agency

presented for many lamp types, first from incandescent lamps to halogen lamps, and then to LED lamps. The study indicates where suitable LED retrofit lamps are available and where gaps exist. Although some gaps were identified (mainly dimmability and potential geometrical lock-in problems), the main conclusion of the study is that:
"This study verifies with market examples for both lamps and luminaires that already now in January 2014, LED replacements are available for nearly all original non-directional GLS and halogen applications. The lack of replacement lamps is very limited and they are expected to be available before September 2016".
The study also estimates that only 5% of the installations requires the use of clear lamps, while for the major part clear and frosted lamps seem to be interchangeable. In the opinion of the authors a replacement scheme from frosted or clear GLS, first to clear halogen lamps, and then to frosted LED lamps can represent 90% of the cases.
The study provides a useful insight, but being based on lamps available in 2013, the study team preferred to use the more recent data from the following studies.

- A November 2014 / March 2015 Swedish-Belgian-CLASP-ECEEE study [226] [227] tested 17 types of non-directional LED lamps and one reference HL MV E lamp (10 samples for each lamp). The lamps were bought in August/September 2014 on the European market. Particular attention is paid to clear lamps that can provide the 'sparkling effect' required in some luminaires, and the characteristics of 'LED filament lamps' (a promising 2014 newcomer on the European market, Figure 39) are highlighted.

Figure 39 Example of an AC Mains-Voltage Non-Directional LED Filament Lamp. For test data on these lamps and for details on technology and manufacturing see the source [226].

As regards LED retrofit lamp prices and efficacies, the study concludes that retail prices are lower and efficacies are higher than was predicted by the Stage 6 review report based on the data available in 2013 (Figure 40). Efficacies of the tested lamps ranged from 63 to 121 lm/W. Prices ranged from 6.16 to 28.42 euros per 500 lumens (including VAT). The averages reported are 12.52 euros/500lm and 98 lm/W.

[226] "Test report – Clear, Non-directional LED lamps", 19 November 2014, Swedish Energy Agency, Belgian Federal Ministry for Health, Food Chain Safety and Environment, CLASP European Programme, European Council for an Energy Efficient Economy, http://www.eceee.org/ecodesign/products/domestic_lighting/Report_on_Testing_ClearLED_lamps.v5.5a.pdf

[227] March 2015 update of the report with test results after 1000 h and a response to LightingEurope's critique on the original report: http://www.eceee.org/ecodesign/products/domestic_lighting/TestingClearLEDLamps1000hTestUpdatefinal.pdf

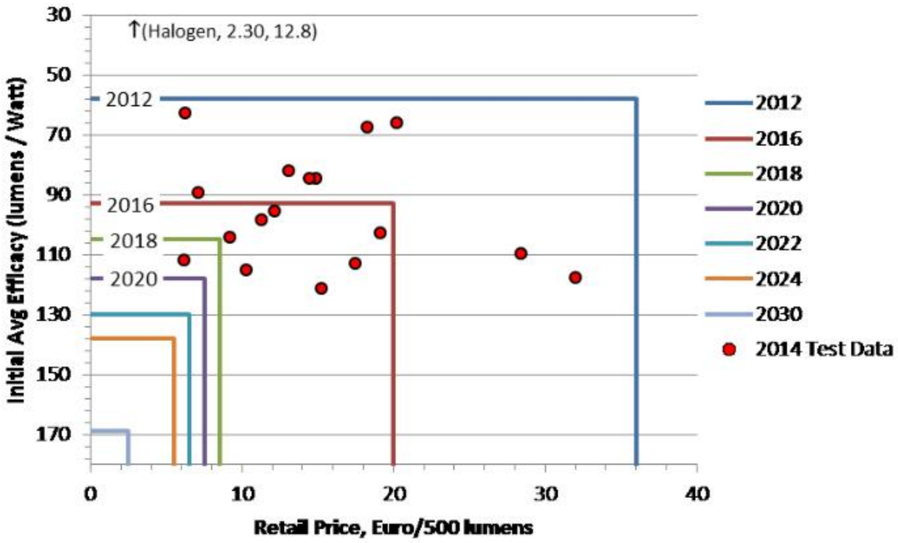

Figure 40 Example of MV LED Non-Directional Retrofit Clear LED Lamps: Projections made in 2013 on price/performance ratio vs. real 2014 values (Source [226]).

The study further concludes that:

- Clear LED lamps do offer consumers an aesthetic, pleasant light. CCT 2700-2900 K, Colour rendering (CRI > 80, some with CRI>90), absence of flicker, and light distribution pattern are deemed satisfactory.
- Dimming problems were encountered, but industry is working to improve this.
- The new LED lamps meet the quality requirements of EU No 1194/2012 (except for some colour consistency and premature failure problems), but this result is only indicative due to the limited sample size tested, and life-tests (LSF, LLMF) are still ongoing.
- Some reliability problems are reported, but 'this doesn't mean LED filament lamps are worse than other lamps' (testing is ongoing).

▪ In a December 2014 press release [228], LightingEurope criticizes the Swedish-Belgian-CLASP-ECEEE study, stating that:
  - The conclusion of the test report is questionable, partly misleading, and containing incorrect information, with 47% of the tests based on non-compliant lamps.
  - Supporting this report and documents is acting irresponsibly towards the EU community and its consumers.
  - Confirms that many of the LED lamps in the European market are non-compliant.

In this context it is also noteworthy that LightingEurope announced in March 2015 that in 2014 it started the Compliant Lighting Initiative (CLI) [229]. This is an attempt to remove non-compliant lamps from the market and to create a 'level playing field'. CFL, LED and halogen lamps will be independently tested on behalf of LE and non-compliances will be reported to the manufacturers and to market surveillance authorities.

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[228] "Lighting Europe Concludes the 'Test report – Clear, Non-directional LED lamps' is Flawed", 11 December 2014, LightingEurope, http://www.lightingeurope.org/uploads/files/LightingEurope_finds_flaws_in_CLASP_report.pdf

[229] http://www.lightingeurope.org/uploads/files/LightingEurope_Press_Release_Compliant_Lighting_Initiative_March_2015.pdf

- The March 2015 DEA-CLASP study [218] aims to update the 2013 Stage 6 review report [217] for the availability of more recent data on lamp sales and on LED characteristics. Being issued in support of the Stage 6 discussion, the study is dedicated to non-directional lamps that can substitute HL MV E (or GLS) lamps.
  The study confirms the conclusions of the two studies described above as regards price and efficacy developments, and as regards the availability of adequate LED retrofit lamps for non-directional HL MV E. The study also expresses a concern that class B compatible halogen lamps might come to the market (see remarks in par. 5.13.1) and suggests to amend the Stage 6 formulation to require A class lamps.
  For the purpose of determining BAT data for LED retrofits, the study is of particular relevance because it reports recent (2014) price, efficacy and other data for 19 types of LED lamps from testing by PremiumLight and from national testing in Austria, Denmark and Sweden. The study underlines that testing takes time and that as a consequence the reported test results are already outdated. The 2015 prices will be lower and efficacies higher. As an illustration of the rapid developments, the authors report data on the Sunflux E27 LED lamps:
  - Tested in 2014: 7.5W, 470 lm, 63 lm/W, 2700 K, Ra 95 and 270°.
  - New model in 2015: 5W, 450 lm, 90 lm/W, 2700 K, Ra>90 and 360°

  The tested lamps are reported to have capacities ranging from 260 to 1665 lm, prices ranging from 3.51 to 21.63 euros/500lm, and efficacies ranging from 58 to 110 lm/W.

Table 39 provides examples of recent, tested, LED retrofit lamps for substitution of non-directional mains voltage halogen lamps with E-caps. The data in this table have been taken from the measured data reported in the studies discussed above [218] [226], but lifetimes are declared data (not tested). Lamps that clearly do not meet the colour consistency requirements of regulation 1194/2012 (maximum 6 MacAdam ellipses) have been omitted from the table. Considering testing uncertainties and tolerances, the lamps that almost meet this requirement and/or the CRI>80 requirement, have been given the benefit of the doubt, and are included in the table.

Considering the data in the table the following (2014) BAT characteristics can be indicated for LED retrofit lamps for non-directional mains voltage halogen (or GLS, CFLi) lamps with E-cap:

- Efficacy: 110-120 lm/W
- Price (2014): 5-8 euros / 500 lm (incl. VAT)
- Capacity: 260-1660 lm
- CCT: 2650-3000 K (not excluded that higher CCT exist)
- CRI: 80-85 typical; BAT: 90-95
- Consistency: < 6 MacAdam ellipses typical; BAT: around 3 ellipses.
- Lifetime: typically 20000 h or above (not tested)
- Dimmability: yes (but see general remarks in Task 3 report)

Table 39: Examples of LED retrofit lamps for substitution of non-directional mains voltage halogen (or GLS, CFLi) lamps with E-caps. Compiled by the study team based on data in references [218] [226]. For further details and links, see the references.

Description	Power (W)	Capacity (lm)	Efficacy (lm/W)	Euros / 500 lm (incl. VAT)	CCT (K)	CRI (Ra)	MacAdam ellipses	Life (h)	Declared dimmable
LED filament lamps (Figure 39)									
Wholesale Lighting MS-B22-6W-OMNI	4.9	598	121	12.6	3045	81	3.8	30000	no
Segula, no. 474732	5.6	655	118	32.0	2558	81	5.1	20000	no
LED Lampen Direct, 4 Watt Polaris	4.0	462	115	10.3	2637	79	2.9	15000	no
Star Trading Direct lampa E27 Nr. 338-71	4.1	459	112	6.2	2731	81	3.4		no
SoftLED Glühfaden Birne 6 W	6.1	673	110	7.4	2790	89		30000	
vosLED Light Bulb Clear, 5.5W, Filament	5.5	607	110	28.4	2761	91	4.6	25000	no
NCC-Licht / LED Filament	6.8	707	104	9.2	2587	79	6.4	20000	no
LED Connection Filament Lamp	7.6	782	103	19.2	2889	83	5.6	40000	no
LED24.cc / E27 LED Glühfaden Birne	7.6	748	98	11.3	2907	83	5.4		no
Lighting Ever 100047-WW-EU	3.8	359	96	12.2	2730	80	5.0	50000	no
Other LED lamps									
Megaman LED classic MM21048	16.1	1665	104	9.7	2710	81		30000	
Verbatim LED Classic 9.5 W	9.5	888	93	5.2	2977	81		25000	
Osram LED Superstar Classic A60	9.8	880	90	4.8	2627	80		25000	yes
Osram PARATHOM Classic A ADV 10W 827	9.6	863	90	7.2	2739	80	3.3	20000	yes
Panasonic LDAHV10L27CGEP	10.5	895	86	13.4	2719	79		25000	
Osram Parathom Classic Std 10W	10.3	874	85	6.1	2713	80		20000	
Philips “Clear LED bulb” - GLS 6W A60 827	5.9	501	85	14.9	2705	82	6.2	25000	yes
Philips LED bulb 13 W	13.1	1076	82	7.4	2723	82		25000	
IKEA Ledare	12.6	1032	82	4.8	2676	90			yes
Osram Parathom Classic A Adv 6W	6.2	493	80	13.6	2795	81		20000	yes
Posco 9 W, no. PBLAE093W2C00	9.2	715	78	3.5	3041	83		40000	
Xavax LED lampe 11 W	10.3	794	77	9.4	2713	82		25000	yes
GE Energy Smart 10 W	9.0	660	73	9.0	2705	81		25000	
Luxinia Sunflux 11 W	11.3	828	73	16.0	2653	95		26000	
Philips Master LED bulb 12 W	11.1	768	69	7.9	2703	85			
Megaman LED Classic LG2509.5	10.2	696	68	16.3	2916	78		25000	
LED Connection “Classic LED bulb”	6.3	426	68	18.3	2830	80	1.7	30000	yes
Verbatim LED Classic 4 W	3.9	260	67	12.3	2768	82		25000	
Star Trading LED filament lampa, candle	4.3	285	66	20.2	2825	83	3.3		yes
Osram LED Star Classic B 4 W	4.0	264	66	21.6	2773	82		25000	
IKEA Ledare Circular (E27)	15.9	1026	63	4.9	2657	91			yes
IKEA “LEDARE” / 602.553.62	9.5	596	63	6.3	2673	90	4.7	25000	yes
IKEA Ledare 10 W	10.0	597	58	5.5	2663	92		25000	yes

5.13.4. HL MV E, BAT description, Directional LED retrofit

The Stage 3 market assessment for regulation 1194/2012 [222] shows that a large variety of directional LED retrofit lamps with E14 or E27 cap is available on the market as a BAT-solution to replace an HL MV E reflector lamp. The same LED lamps can also substitute a GLS-R lamp with the same cap and similar shape.

The market assessment compiled a database for mains-voltage directional lamps that contains 240 lamps with E-caps [230], of which 73 reference models (incandescent and halogen lamps) and 167 LED lamps. Seventy percent of the LED lamps already meets the EEI<0.2 criterion of regulation 1194/2012 stage 3. This situation is expected to further improve towards September 2016. The highest efficacy lamps have 80-90 lm/W [231].

The same database contains price data for 101 directional LED retrofit lamps, of which 43 with E14 or E27 cap and 58 with GU10 cap. For these lamps, Figure 41 shows the price in euros/klm (excl. VAT) in function of luminous flux (measured in 90˚ or 120˚ cone), and the number of models with price in a given interval. Prices range from 12 to 198 euros/klm, with an average of 44 euros/klm and a median around 28 euros/klm. These data are based on the directional lumens, i.e. measured in a 90˚ or 120˚ cone according to regulation 1194/2012. The data have been used in Table 10, but there they have been corrected to total lumens.

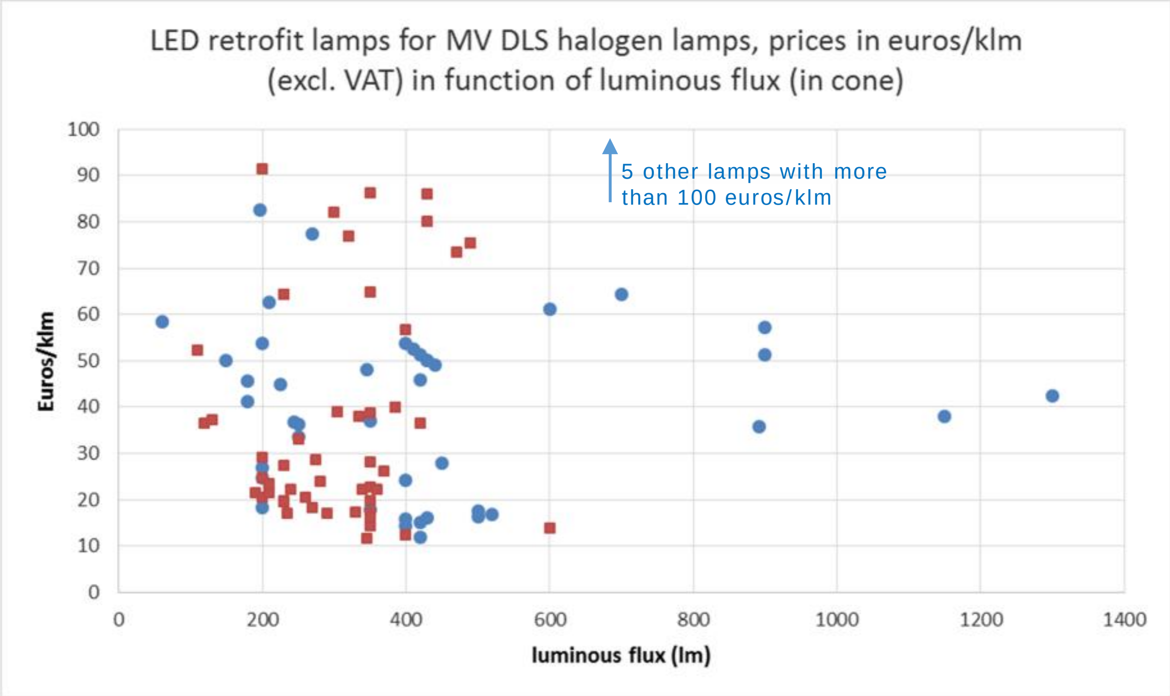
5.13.5. HL MV E, BNAT description

In general the BNAT solution for substitution of mains voltage halogen lamps with E-cap is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.13.6. HL MV E, Special cases and non-availability of improving substitutes

E27/14 halogen lamps are also used and sold for high-temperature applications like ovens. In this case the halogen lamp is the most efficient solution (BAT) because waste heat is not lost and no external converter is needed. LED lamps are not suitable for use in ovens.

[230] In total there are 625 models, but the major part has GU10 caps, see par. 5.14.3.
[231] According to the definition of regulation 1194/2012, i.e. measuring the luminous flux in a 90 or 120˚ cone.



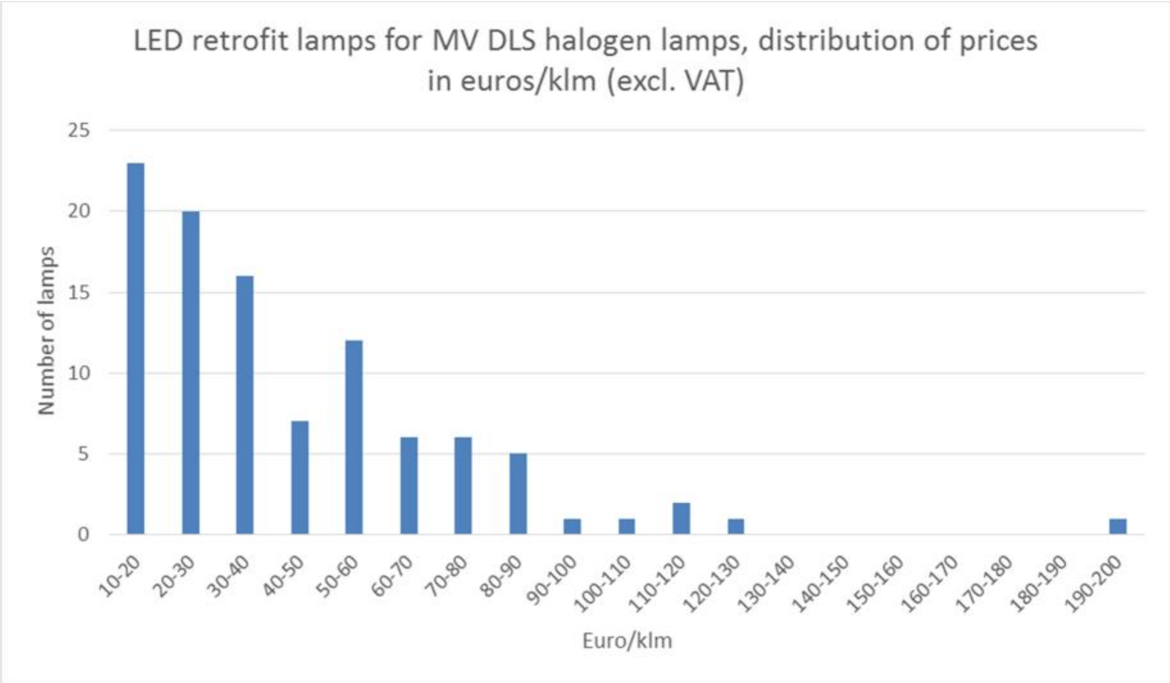


Figure 41 LED retrofit lamps for MV DLS halogen lamps: price in euros/klm (excl. VAT) in function of luminous flux (measured in 90° or 120° cone) and number of models with price in a given interval. In the top figure, blue dots are lamps with E14/E27 cap while red squares are lamps with GU10 cap. The bottom figure is for lamps with all cap types. These data have been used in Table 10. (Source: VHK, based on the database of the MV DLS market assessment).

5.14. Halogen lamps, mains voltage, PAR and other (GU10, etc.)

5.14.1. HL MV X, BC description

This base case covers all other mains voltage halogen lamps not contained in other base cases. It includes mainly directional lamps (PAR16,20,25,30, hard glass reflectors) with GU10 cap.

Identical to the directional lamps discussed for the HL MV E base case, the lamps of this BC will be subject, from September 2016, to Stage 3 of Regulation 1194/2012, that requires an EEI<0.95, corresponding to energy label class B (for directional lamps) according to regulation 874/2012. As explained in par. 5.13.1, this requirement is conditional and is being examined as part of this preparatory study. This market assessment [222] did not find any directional mains voltage halogen lamps with GU10 cap that meet the class B requirement. Existing lamps are usually in the D-class. Considering the information from the Stage 6 review [217], it is also unlikely that B-class compatible lamps will be available in the future.

The average EU-28 characteristics for this base case are summarized in Table 40. They are based on the information presented in the Task 2 and 3 reports.

Table 40: Average EU-28 characteristics for the HL MV X base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	127	31.7	158	
Lifetime (yr)	3.3	3.3	3.3	
Stock (mln units)	446	112	558	
Capacity (lm)	420	420	420	
Efficacy (lm/W)	12	12	12	
Power (W)	35	35	35	
Ballast efficiency (%)	100%	100%	100%	No control gear
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	14.21	12.84	13.73	
Installation cost (euros/unit)	0.00	1.85	0.37	[193]
Maintenance cost (euros/unit)	0.00	3.05	0.61	[193]

5.14.2. HL MV X, Improvement options

As explained above, it is not expected that new, improved lamps of the same type will come to the market. As long as regulations will allow, HL MV X lamps can of course be substituted by lamps of the same type.

Four improvement / replacement options with other lamp types have been identified:

1) <u>Substitute the directional mains voltage halogen lamp by a CFLi reflector</u>. This option is not expected to be a frequent consumer choice, considering that LED

alternatives are more attractive. The option is not further considered in this study.

2) Substitute the MV halogen lamp with GU10-cap by a MV halogen capsule with G9 cap, using a G9-to-GU10 adapter [232]. This is an option only if MV HL X (GU10) would be phased out while MV HL C (G9) would be allowed on the market. However, the GU10 lamp was directional while the G9 capsule by itself is not, and would thus need an additional external reflector. Hence, this is option is NOT further considered in this study.

3) Substitute the MV halogen lamp with GU10-cap by a LV halogen with GU5.3 cap, using an adapter and an external transformer. GU10-to-GU5.3 adapters exist on the market [233], but the MV-LV transformer does not seem to be integrated. Consequently, a rewiring of the luminaire is necessary to insert the MV-LV transformer. This would shift the legal product responsibilities from the original manufacturer to the installer. It is not expected that this option will be frequently chosen by consumers and therefore it is not further considered in this study.

4) Substitute the MV halogen lamp with GU10-cap by a LED retrofit lamp (or substitute the entire luminaire by a LED luminaire, see remarks in par. 5.1). This is identified as the BAT solution, see next paragraphs for the characteristics.

5.14.3. HL MV X, BAT description, directional LED with GU10 cap

The Stage 3 market assessment for regulation 1194/2012 [222] shows that a large variety of mains-voltage directional LED retrofit lamps with GU10 cap is available on the market as a BAT-solution to replace an HL MV X. The market assessment compiled a database for mains-voltage directional lamps that contains 273 lamps with GU10-caps [234], of which 57 reference models (incandescent and halogen lamps) and 216 LED lamps.

As regards number of models, lumen levels, beam angles, and colour temperatures, the variety of the GU10 LED lamps is larger than the variety for the halogen lamps. More than 99% of these LED lamps has a declared CRI ≥ 80, and models with CRI > 90 are also available. In general the declared lamp characteristics meet the functionality requirements of regulation 1194/2012 table 5 [235].

The highest efficacy found is around 80 lm/W [236] [237] [238] (energy label class A++).

As regards efficacy and prices in function of luminous flux, see Figure 41.

Narrow beam DLS that optimise the functional lumen within a 90° cone often use a string of high-power LEDs in combination with lenses. Wide beam DLS that optimise the functional lumen within a 120° cone frequently use a string of mid-power LEDs. The latter solution also permits the use of low-cost control gears.

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[232] See for example: http://vidardq.en.alibaba.com/product/598111398-215603911/G9_to_GU10_lamp_adapter.html

[233] See for example: http://www.dhgate.com/store/product/10pcs-gu10-to-g5-3-adapter-base-socket-converter/212619962.html

[234] In total there are 625 models; the major part has GU10 caps.

[235] These requirements regard lamp survival factor, lumen maintenance, switching withstand, starting- and warmup-time, premature failure rate, colour rendering, colour consistency and power factor.

[236] According to the definition of regulation 1194/2012, i.e. measuring the luminous flux in a 90 or 120˚ cone.

[237] http://www.verbatim-europe.nl/nl_26/product_verbatim-led-gu10-8-5w-4000k-660lm_60221.html

[238] http://www.svetila.com/it/lampadine-lampade-66/lampade-led-990/led-gu10-90-260v-1087/led-spot-glass-5w-cw-gu10-9084.html

Figure 42: Narrow beam DLS with high-power LEDs and lenses (left) and wide beam DLS using a string of mid-power LEDs (right).

5.14.4. HL MV X, BNAT description

In general the BNAT solution for substitution of mains voltage halogen lamps with GU10-cap is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.14.5. HL MV X, Special cases and non-availability of improving substitutes

No special cases or non-availability of LED retrofit lamps have been identified.

5.15. Incandescent lamps, reflector

5.15.1. GLS R, BC description

This base covers directional incandescent (non-halogen filament) lamps, e.g. R39, R50, R80, etc., mainly with Edison or bayonet cap. The large majority is expected to operate on mains voltage. These lamps are subject to the requirements of regulation 1194/2012 that starting from September 2014 (Stage 2) requires an EEI<1.75, corresponding to class D for directional lamps according to regulation 874/2012 [239]. Almost all lamps still on the market are E-class and consequently these lamps have effectively been phased out.

The average EU-28 characteristics for this base case are summarized in Table 41. They are based on the information presented in the Task 2 and 3 reports.

[239] The class indication is exact only for lamps up to 1300 lm.

Table 41: Average EU-28 characteristics for the GLS R base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	28.8	7.2	36.0	
Lifetime (yr)	2.2	2.2	2.2	
Stock (mln units)	83.1	20.8	104	
Capacity (lm)	513	513	513	
Efficacy (lm/W)	9.5	9.5	9.5	
Power (W)	54	54	54	
Ballast efficiency (%)	100%	100%	100%	No control gear
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	1.37	1.14	1.32	
Installation cost (euros/unit)	0.00	1.85	0.37	[193]
Maintenance cost (euros/unit)	0.00	2.03	0.41	[193]

5.15.2. GLS R, Improvement options

These lamps have been phased out, and no improved versions of the same lamp type will come to the market in future. Three improvement / replacement options with other lamp types have been identified:

1) Substitute the GLS-R by a CFLi reflector. This option is not expected to be a frequent consumer choice, considering the current trend in CFLi sales and considering that LED alternatives are more attractive. The option is not further considered in this study.

2) Substitute the GLS-R by a directional HL MV E or HL MV X (if necessary using a GU10-to-E27/E14 adapter). For the characteristics of the mains voltage halogen lamps, see par. 5.13.1 and 5.14.1. As discussed in those paragraphs, this is a valid option only as long as these halogen lamps are allowed on the market.

3) Substitute the GLS-R by a LED retrofit lamp (or substitute the entire luminaire by a LED luminaire, see remarks in par. 5.1). This is the same BAT solution as discussed in par. 5.13.4 (E-cap) and par. 5.14.3 (GU10 cap).

5.15.3. GLS R, BAT description, LED retrofit lamp

The LED retrofit lamps for GLS-R are the same as those presented for directional halogen lamps, see par. 5.13.4 (E-cap) and par. 5.14.3 (GU10 cap).

5.15.4. GLS R, BNAT description

In general the BNAT solution for substitution of mains voltage halogen lamps with GU10-cap is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.15.5. GLS R, Special cases and non-availability of improving substitutes

GLS-R filament lamps are also sold for applications that can benefit from the infrared emission, such as health care [240]. Filament lamps convert electricity mainly into infrared radiation and are therefore the BAT for this application.

No special cases or non-availability of substitutes have been identified.

5.16. Incandescent lamps, other

5.16.1. GLS X, BC description

This base case covers all other incandescent (non-halogen filament) lamps, including clear/pearl, candles, coloured & decorative. They are all non-directional lamps, and consequently subject to the requirements of regulation 244/2009. All lamps with more than 60 lm have effectively been phased-out since September 2012 (Stage 4) [241].

The average EU-28 characteristics for this base case are summarized in Table 42. They are based on the information presented in the Task 2 and 3 reports.

Table 42: Average EU-28 characteristics for the GLS X base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	98.7	24.7	123	
Lifetime (yr)	2.2	2.2	2.2	
Stock (mln units)	366	91.4	457	
Capacity (lm)	513	513	513	
Efficacy (lm/W)	9.5	9.5	9.5	
Power (W)	54	54	54	
Ballast efficiency (%)	100%	100%	100%	No control gear
Burning Hours (h/a)	450	450	450	
Electricity rate (euros/kWh)	0.191	0.119	0.177	
Price (euros/unit)	0.84	0.70	0.81	
Installation cost (euros/unit)	0.00	1.85	0.37	193
Maintenance cost (euros/unit)	0.00	2.03	0.41	193

5.16.2. GLS X, Improvement options

These lamps have been phased out, and no improved versions of the same lamp type will come to the market in future. Three improvement / replacement options with other lamp types have been identified:

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[240] http://www.ecat.lighting.philips.co.uk/l/lamps/special-lamps/infrared-lamps/infrared-industrial-heat-incandescent/923801345506_eu/

[241] For exemptions see the Task 0 report or the regulation itself.

1) Substitute the NDLS GLS by a CFLi. See remarks in par. 5.13.2. Considering the current trend in CFLi sales and considering that LED alternatives are more attractive This option is not expected to be a frequent consumer choice. The option is not further considered in this study.

2) Substitute the NDLS GLS by a non-directional HL MV E. For the characteristics of the latter, see par. 5.13.1. As discussed there, this is a valid option only as long as these halogen lamps are allowed on the market.

3) Substitute the NDLS GLS by a LED retrofit lamp (or substitute the entire luminaire by a LED luminaire, see remarks in par. 5.1). This is the same BAT solution as discussed in par. 5.13.3.

5.16.3. GLS X, BAT description, LED retrofit lamp

The LED retrofit lamps for NDLS GLS are the same as those presented for non-directional halogen lamps, see par. 5.13.3.

5.16.4. GLS X, BNAT description

In general the BNAT solution for substitution of mains voltage halogen lamps with E-cap is to use improved future LED retrofit lamps or LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.16.5. GLS X, Special cases and non-availability of improving substitutes

No special cases or non-availability of substitutes have been identified.

5.17. High intensity discharge, mercury lamps

5.17.1. HPM, BC description

According to the definitions of regulation 245/2009: " 'High-pressure mercury (vapour) lamp' means a high intensity discharge lamp in which the major portion of light is produced, directly or indirectly, by radiation from mercury operating at a partial pressure in excess of 100 kilopascals". The base case also includes blended lamps [242] [243].

Most of the non-blended lamps operate on an external ballast, usually of the magnetic type, and the majority is non-directional [244], emitting a cool-white light (3300-3700 K) with poor colour rendering (CRI 50-72) [243]. As other HID-lamps, they are typically used in industrial and commercial applications, street lighting and sports lighting. Compared to other types of high-intensity discharge lamps (HPS, MH) the efficacy of HPM-lamps

[242] According to the amendment of regulation 347/2010: a 'blended lamp' is defined as "*a lamp containing a mercury vapour lamp and an incandescent lamp filament connected in series in the same bulb*". These lamps are also known as 'mixed-light' lamps. They do not need a ballast because this function is performed by the filament lamp connected in series.

[243] See for example: http://download.p4c.philips.com/l4bt/3/323092/ml_323092_ffs_aen.pdf

[244] Considering the light sources themselves, i.e. not considering the luminaire.

is low, typically from 40 to 60 lm/W depending on the lamp wattage [245]. Mercury content increases with power but is generally high, around 34 mg for a 175 W lamp [246]. These lamps do not need an external ignitor. For further technical description of these lamps, see the 2007 VITO study on street lighting [247] and the CLASP 2013 study [248]. As sales in EU-28 are decreasing, no further investments are being made in improving this technology. Sales and stock for these lamps are low and this base case is therefore of minor importance.

Non-directional HPM lamps are subject to regulation 245/2009 (as amended by regulation 347/2010), and in particular to the efficacy requirements of table 9 of this regulation. Starting from April 2015 [249], the efficacy shall be at least 50 lm/W for the lowest wattage lamps (≤ 40 W) and at least 75 lm/W for lamps with power above 125 W [250]. As HPM-lamps are not able to meet these criteria, they are expected to be phased-out [251]. Some blended lamps are exempted from the regulation, see par. 5.17.6.

Directional HPM-lamps are subject to regulation 1194/2012 that requires an EEI<0.5 starting from September 2014 (Stage 2) and EEI<0.36 from September 2016 (Stage 3). In the past there were mercury blended reflector lamps on the market [252], but it is not clear if these are still being sold.

The average EU-28 characteristics for this base case are summarized in Table 43. They are based on the information presented in the Task 2 and 3 reports.

Table 43: Average EU-28 characteristics for the HPM base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	0	2.23	2.23	
Lifetime (yr)	(11.4)	2.0	2.0	
Stock (mln units)	0	5.56	5.56	
Capacity (lm)	(10000)	10000	10000	
Efficacy (lm/W)	(40)	40	40	
Power (W)	(250)	250	250	Exclusive ballast power
Ballast efficiency (%)	(83%)	83%	83%	Mainly magnetic
Burning Hours (h/a)	(700)	4000	4000	

245 Blended lamps have efficacies from 11 up to 28 lm/W.
246 http://download.p4c.philips.com/l4bt/3/332443/mercury_vapor_standard_332443_ffs_aen.pdf
247 Preparatory Studies for Eco-design requirements of EuPs, Final Report, Lot 9: Public Street lighting, Study for the European Commission DGTREN unit D3, contact Andras Toth, by VITO in cooperation with Laborelec and Kreios, January 2007, Contract TREN/D1/40-2005/LOT9/S07.56457, available through 'eup4light.net'
248 CLASP (2013) Estimating potential additional energy savings from upcoming revisions to existing regulations under the ecodesign and energy labelling directives: a contribution to the evidence base. Available: http://www.eceee.org/all-news/press/2013/2013-02-19/eceee-clasp-report-estimating-potential
249 Date of entry into force of the regulation (April 2009) plus six years.
250 See the regulation for intermediate values.
251 From the same April 2015 date, high pressure sodium lamps designed to operate on high pressure mercury vapour lamp control gear (retrofit lamps for HPM) are no longer exempted from the requirements in table 7 of regulation 245/2009 and thus have to meet the same requirements as other HPS lamps.
252 http://www.lamptech.co.uk/Spec%20Sheets/Philips%20MLR160.htm Detailed photometric data is unknown but with a beam angle of 120° it is unlikely that these lamps are directional lamps according to regulation 1194/2012.

Table 43: Average EU-28 characteristics for the HPM base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Electricity rate (euros/kWh)	(0.191)	0.119	0.119	
Price (euros/unit)	(20.40)	17.00	17.00	
Installation cost (euros/unit)	(0.00)	9.25	9.25	253
Maintenance cost (euros/unit)	(0.00)	12.33	12.33	253

5.17.2. HPM, Improvement options

As explained above, these lamps are phased-out starting from April 2015 [254], and no improved lamps that meet the criteria of the regulation are expected to come to the market. Five improvement / replacement options with other lamp types have been identified:

1) Substitute the HPM by a HPS retrofit lamp with integrated ignitor on existing ballast [255]. For the characteristics of HPS lamps, see par. 5.18.1 and Table 44 (note 3). Note that this involves a colour change, as HPS lamps emit a yellow/orange type of light. This is a low-cost least-effort option that has been on the market for some time. However, starting April 2015, these HPS retrofits do no longer benefit from a special exemption in regulation 245/2009 [251].

2) Substitute the HPM lamp and ballast by a HPS lamp, ballast and ignitor. For the characteristics of HPS lamps, see par. 5.18.1 and Table 44 (note 4). As in the previous option, this involves a colour change. This provides significant more savings than the previous option, but an expensive rewiring is needed, and it is judged unlikely that many users will choose this option.

3) Substitute the HPM by a MH retrofit lamp [256]. For the characteristics of MH-lamps, see par. 5.19.1 and Table 44 (note 2). These lamps have an integrated electronic control gear. Energy saving is about 20%. Currently these lamps are suitable to substitute the lower lumen HPM lamps (50-100 W).

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[253] Installation costs are based on a time of 15 minutes per light source and an hourly rate of 37 euros/hour. The 15 minutes is an estimated weighted average between 10 min/lamp for group replacements and 20 min/lamp for individual (spot) replacements in street lighting applications, see Task 3 par. 7.5. These costs regard only the light sources, not the installation of new luminaires, nor the changing of control gears.
Maintenance costs are per light source, for the lifetime of the light source (not per year). The estimate is based on a time of 10 minutes per luminaire cleaning operation (assuming group cleaning in street lighting applications), 1 light source per luminaire, one cleaning operation per year, and an hourly rate of 37 euros/hour. See also Task 3 par. 7.5.

[254] Except for exempted blended lamps.

[255] Special retrofit lamps are on the market that can be operated on existing ballasts without the need for an ignitor, see https://www.lampdirect.be/nl/philips-son-h-220w-220-e40?gclid=COSL3Yaft8QCFQ_KtAodxHMAtA ; http://www.lighting.philips.com/main/prof/oem/hid-systems/high-pressure-sodium/son-h/928152409830_EU/product . These lamps save about 10 % energy and provide significant more lamp lumen.

[256] See for example: http://www.havells-sylvania.com/nl_BE/products/0020242 , available from Q4 2015.

4) Substitute the HPM by a LED retrofit lamp [257]. For the characteristics of the latter, see par. 5.17.3. The existing ballast needs to be replaced by an external LED control gear, or it has to be removed or by-passed, in the case of LED retrofit lamp with integrated gear. Retrofit kits are available only for low wattage HPM. The optical and thermal conditions will need to fit for luminaires that were not designed for LED light sources. This option requires a considerable investment, but with the potential of high energy savings.

5) Substitute the HPM by a LED luminaire. For the characteristics of the latter, see par. 5.17.4. Compared to the LED retrofit solution, the substitution of the entire luminaire optimizes both the optical and thermal conditions. Potential savings are even higher, but so are the initial investments.

Since decades, HPM lamps are known to be far less efficient than HPS- or MH-lamps, but nevertheless they have often not been retrofitted [258]. In part this is due to habits (it is easy to continue ordering the same lamps) and in part to economic reasons. Municipalities have to make complex choices on how to spend their budget, and, notwithstanding the long term economic benefits, investments in lighting may not be a priority/possibility. However, HPM lamps will now be phased out, so one of the options indicated above will have to be chosen.

Many cities in Europe are converting their street-lighting to LED, using a mix of LED retrofit lamps and luminaire substitutions [259] [260] [261]. Many other municipalities will probably not have made this choice, but that receives less attention from the media.

Notwithstanding the possibilities for Energy Performance Contracting and funding [262] [263] [264], it is expected that for economic reasons the shift from HID- and FL-lamps to LED lighting will not be immediate and straightforward, and that a mix of all options listed above will be used.

5.17.3. BAT description: HPS-, CMH- and LED-retrofit lamps for HPM lamps

Table 44 shows HPM reference lamps together with HPS and CMH retrofit lamps, and some LED retrofit lamps. There is a wide variety of LED retrofit lamps for HPM (or for HID-lamps in general) on the market [265].

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[257] See for example: http://www.eyelighting.com/products/lamps/ledioc-led-upgrade// and http://www.saled.nl/en/catalogue/led-streetlighting-sources-/bs-s-hp/

[258] VITO 2007, lot 9 preparatory study on street lighting

[259] http://www.newscenter.philips.com/main/standard/news/press/2014/20141219-madrid-upgrades-city-infrastructure-with-philips-lighting.wpd#.VT1EvJPrdwo

[260] http://sustainablecitiescollective.com/david-thorpe/216631/more-and-more-cities-are-switching-led-street-lighting

[261] http://www.saled.nl/en/references/municipalities

[262] http://www.streetlight-epc.eu/fileadmin/redakteure/Streetlight-EPC/Project_outputs/WP2/Guide/Guide-European-EN.pdf

[263] http://luxreview.com/article/european-commission-funding-available-for-multi-city-intelligent-lighting-development

[264] http://luxreview.com/article/the-pitfalls-of-savings-based-led-street-lighting-deals

[265] http://www.gogreenledinternational.com/led-retrofits/
http://www.eclipselightinginc.com/pages/products/retrofit-kits/led-retrofit-kits.php
http://www.greenelectricalsupply.com/energy-efficient-lighting-led-retrofit-bulbs.aspx
http://www.ledglobalsupply.com/led-commercial-bulbs/?sort=priceasc
http://www.myledlightingguide.com/ledretrofit.aspx
http://www.neptunlight.com/products/26/1/led-acorn-retrofit-kits-and-lamps.html
http://www.duromec.com/products.html; http://www.duromec.com/
http://www.ledlampshining.com/news/what-size-led-lamp-replaces-hps-lamp-43.html
http://www.ledcornbulbs.com/about-us/How-to-replacing-a-HPS-by-LED-corn-light--58.html

The retrofit options differ in their 'ease-of-use'. Some are plug-and-play solutions, requiring only substitution of the lamp itself, while others require the existing ballast to be replaced or removed/by-passed.
In all retrofit options attention is required to make sure that the lamps fit in the space available in the luminaire, that thermal management conditions are met, and that the amount and distribution of the light will be satisfactory (new lighting calculations may be necessary to ensure that street lighting requirements are still met). Some of the available LED retrofit kits are specific for a certain HID-lamp type and/or for a specific type of luminaire.
In the same way as observed for R7s-lamps, the impression is that major lamp manufacturers prefer to offer entire LED luminaires for street lighting and similar outdoor applications, rather than LED retrofit lamps.
The topic of HID-lamp substitution will be further addressed in the Lot37 lighting systems study.

The Saled retrofit lamps have the highest efficacy (120 lm/W), but they are available only for the lower lumen HPM-lamps (up to 6,500 lm). Other LED retrofit lamps are available up to 38,000 lm but have a lower efficacy (90-95 lm/W).

Table 44: Examples of HPM reference lamps, HPS- and CMH-substitutes, and LED retrofit lamps. The LED-lamps are intended as HID-lamp replacements, not specifically for HPM.

Description	W	lm	lm/W class	CCT	CRI	Dimming	L (mm)	D (mm)	Life (kh)	Price (€)	Note
HPM lamps (ref)											
Philips HPL N 100W E26 A23 HG	100	4400	44	3700	45		138	73	24000		1
Philips HPL N 250W E39 HG CL 211 91	250	11500 12000	46	5800 4100	20 40		211	91	24000		1
Philips HPL N 400W E39 HG	400	21000	52	4200	50		290	122	24000		1
Non-LED retrofits											
Havells-Sylvania Relumina 85W WDL E27 (CMH)	85	7500	88 A+	3000	84		178	62	18000		2
Havells-Sylvania Relumina 170W WDL E40 (CMH)	170	15000	88 A+	3000	84		228	87	18000		2
Philips SON H 110W E27 (HPS retrofit)	110	8000-9600	84	2000	25	no	156	71	28000		3
Philips SON H 220W E40 (HPS retrofit)	220	19000	87	2000	25	no	227	91	26000	19.49	3
Philips SON H 350W E40 (HPS retrofit)	350	34000	98	2000	25	no	290	122	26000	20.99	3
Philips SON APIA Plus Xtra 100W E40 (HPS BAT)	100	10000	100 A+	1950	25		186	76	40000	(60)	4

http://store.ledlightingwholesaleinc.com/led-retrofit-kits
https://www.1000bulbs.com/category/led-retrofit-for-hid-post-top/
http://www.shineretrofits.com/led-retrofit-kit-guide-street-pole-parking-lot-gas-station-canopy-garage-wall-pack-courtyard-acorn
http://www.ecosmartinc.com/catlite21.php
http://energy.gov/eere/ssl/gateway-demonstration-outdoor-projects
http://www.cree.com/Lighting/Products/Outdoor/Streetlights/Traditional-Post-Top-LED-Upgrade-Kit
http://www.menards.com/main/electrical/light-bulbs/led-light-bulbs/nasun-led-retrofit-replacements-of-hps-metal-halides-and-mercury-vapor/p-1846743.htm
http://www.led-energystar.com/Mercury-Vapor-LED-replacement-bulb.html

Table 44: Examples of HPM reference lamps, HPS- and CMH-substitutes, and LED retrofit lamps. The LED-lamps are intended as HID-lamp replacements, not specifically for HPM.

Description	W	lm	lm/W class	CCT	CRI	Dimming	L (mm)	D (mm)	Life (kh)	Price (€)	Note
Philips SON APIA Plus Xtra 250W E40 (HPS BAT)	250	31300	120 A+	1950	25		227	91	45000	(60)	4
Philips SON APIA Plus Xtra 400W E40 (HPS BAT)	400	55400	136 A++	1950	25		290	122	45000	(60)	4
LED retrofits											
Saled BS-S HP	27 54	3240 6480	120	3000/ 4000	>80		197 258	93x 107	50000		5
CroLED E40 80/100/120W	80 100 120	7200 9000 10800	90 A	6500			280 300 340	120		75 93 104	6
MLLG-GI-LED-RETRO from 35 to 400W	65 150 400	6000 13500 38000	92-95	4100- 5500	>75	Yes	119 264 320	58/119 38/122 76/240	70000 (L70)		7

1 http://download.p4c.philips.com/l4bt/3/332443/mercury_vapor_standard_332443_ffs_aen.pdf

2 http://www.havells-sylvania.com/media/Sylvania%20Lamps/English/Relumina%20-%20English.pdf These are CMH lamps with integrated starter specifically intended for HPM retrofit. Works on existing HPM control gear. Available from Q3 2014

3 http://download.p4c.philips.com/l4bt/3/323223/son_h_323223_ffs_aen.pdf These are HPS lamps specifically intended for HPM retrofit. Works on existing HPM control gear. https://www.lampdirect.be/nl/philips-son-h (for prices)

4 http://download.p4c.philips.com/l4bt/3/344246/master_son_apia_plus_xtra_344246_ffs_aen.pdf This has been identified as a BAT HPS solution to replace HPM. In this case, starter and ballast also have to be replaced. Price estimated by study team as lamp 22+ballast 18+starter 20 euros. Installation costs have to be added.

5 http://www.saled.nl/nl/catalogus/led-straatverlichting-lichtbron/bs-s-hp/ Available in powers of 27, 36, 45 and 54 W. Lamps have an integrated gear. Existing gear to be removed or bypassed.

6 http://www.amazon.de/Leuchtmittel-Hochleistung-Beleuchtung-AC100-240V-Strahler/dp/B00M7YK63I/ref=sr_1_1?ie=UTF8&qid=1429712506&sr=8-1&keywords=100+W+E40+led+lampe (and similar) for Indoor use only (?)

7 http://www.myledlightingguide.com/ledretrofit.aspx (see links to LED retrofit kits for various powers) These lamps are not bulb-like, but flat with E26/E39 cap or mounting bracket. The existing control gear has to be removed and replaced by the LED control gear (optionally dimmable).

5.17.4. All HID, BAT description, LED luminaire

The benefits of LED luminaires over LED retrofit lamps are explained and calculated in the Lot37 lighting system study [266]. The most important barrier to substitute the entire luminaire is the combined cost of the product and its installation. As regards the latter, replacing the luminaire takes about 10 minutes extra compared to a lamp replacement, which is about 10 euro extra.

Luminaire prices (excl. VAT) in the VITO 2007 street lighting preparatory study ranged from 140 euros for a 125 W HPM luminaire (slow traffic) to 220 euros for a 250 W HPS luminaire. A quick market scan (3/2015) shows that prices for such standard luminaires increased only slightly. For example an 100 W ceramic MH street lighting luminaire (European brand) is available today for 212 euros.

High lumen output LED luminaires only recently entered the market and prices are still high. For example a 7800 lumen 80 W street lighting luminaire (LED, dimmable) can be found on the market for 1081 euros (excl. VAT) (European brand, single unit end user price). For LED luminaires prices are heavily related to lumen output, for example the same luminaire with 1900 lumen 20 W retails for 585 euros (excl. VAT).

[266] http://ecodesign-lightingsystems.eu/ see Table 1-14 in section 1.6.6.7 (version 3/2015)

Differences between LED luminaires and HID street lighting luminaires:

- HID luminaires do not differ much in price and volume related to the lamp wattage because they have simple cooling requirements. This also allowed the manufacturers to standardize housings and therefore reduce also the manufacturing and stock cost. LED luminaires in contrary need to be cooled more and therefore are larger for higher wattages. As a consequence the economy of scale benefit is relative less for high lumen luminaires and they can remain relative expensive compared to HID.

- LED modules need electronic drivers which are more expensive than magnetic HID ballasts and the price increases with wattage. For example a 40 W LED driver typically will cost 40 euros (excl. VAT) and a 100 Watt LED driver typically will cost 50 euros. They could also form a weak link in the total luminaire life time and repairs might be needed which would drive up total cost of ownership.

- In many tertiary lighting applications the improvement potential is not only related to initial lumen output of an HID lamp compared to initial lumen output of a comparable LED luminaire. Many other parameters are relevant such as dimming, lumen maintenance, utilization factor, light output ratio etc. The full scope is explained in the Lot37 lighting systems study. In general LED luminaires do not have the extra luminaire optical losses to be taken into account and are also more capable to distribute the light better according to the installation requirements, therefore they need most often less lamp lumen in the application (e.g. -20%).

5.17.5. HPM, BNAT description

In general the BNAT solution for substitution of HPM lamps is to use improved future LED luminaires. The characteristics for these LED lamps will follow the trends outlined in chapter 2.

5.17.6. HPM, Special cases and non-availability of improving substitutes

Non-directional HID-lamps (including HPM-lamps) with the following characteristics are excluded from regulation 245/2009, as amended by regulation 347/2010:

- blended high intensity discharge lamps having:
  - 6 % or more of total radiation of the range 250-780 nm in the range of 250-400 nm, and
  - 11 % or more of total radiation of the range 250-780 nm in the range of 630-780 nm, and
  - 5 % or more of total radiation of the range 250-780 nm in the range of 640-700 nm.
- blended high intensity discharge lamps having the peak of the radiation between 315-400 nm (UVA) or 280-315 nm (UVB).
- high intensity discharge lamps with Tc > 7 000 K.

- high intensity discharge lamps having a specific effective UV output >2 mW/klm.

- high intensity discharge lamps not having lamp cap E27, E40, PGZ12.

As regards the last three exemptions, see remarks in par. 5.19.6. As regards blended lamps, stakeholders are invited to comment on the necessity to maintain the exemption.

For other exemptions from regulation 245/2009 see the Task 1 report or the regulation itself.

Directional lamps are exempted from regulation 1194/2012 if they are special purpose products, see the Task 1 report or the regulation itself.

5.18. High intensity discharge, sodium lamps

5.18.1. HPS, BC description

According to the definitions of regulation 245/2009: " 'High-pressure sodium (vapour) lamp' means a high intensity discharge lamp in which the light is produced mainly by radiation from sodium vapour operating at a partial pressure of the order of 10 kilopascals".

Low-pressure sodium (LPS) lamps are also included in this base case, even if they are not high-intensity discharge lamps [267]. However, although very efficient, they are hardly being used in new applications due to their very low colour rendering index, and for this reason they are not further considered in this study.

Most High-pressure sodium (HPS)-lamps operate on an external ballast and ignitor, of the magnetic or electronic type, and the majority is non-directional [268], emitting a yellow-orange light. Due to this coloured light, most HPS-lamps do not have good colour rendering properties and are therefore not suitable for indoor lighting or task lighting. Light colour can be adapted, and colour rendering can be improved, by mixing the sodium with mercury. The mercury helps add a blue spectrum light to the pure yellow of the sodium [269]. Lamp manufacturers also offer mercury-free versions [270], that have a lower efficacy and lumen maintenance. The efficacy of HPS-lamps depends strongly on power level and colour rendering properties, but in general it is high, typically above 100 lm/W, with 140 lm/W feasible at higher powers.

HPS-lamps (together with MH-lamps, see next paragraph) are the most frequently used lamps in outdoor industrial applications and street lighting. In addition some types of HPS-lamps are used as grow-lights in horticulture.

For a technical description of these lamps, see the 2007 VITO study on street lighting [271] and the CLASP 2013 study [272]. Considering the competition of MH-lamps and LED-lamps, the sales levels of HPS-lamps are stable or decreasing, and consequently hardly any investments are being made to further improve their efficacy.

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[267] Low Pressure Sodium lamps are monochromatic light sources with colour temperature of 1800 K. The 'white light definition' in EC regulation (244/2009) includes LPS lamps. In HPS lamps the spectral lines are broadened compared to LPS due to an increase in arc plasma pressure, see "J. de Groot, J. van Vliet (1986): 'The High-Pressure Sodium Lamp', ISBN 90 201 1902 8"

[268] Considering the light sources themselves, i.e. not considering the luminaire.

[269] http://www.edisontechcenter.org/SodiumLamps.html

[270] https://www.budgetlight.nl/philips-master-son-t-apia-plus-hg-free-150w-e40.html?gclid=CNTlyZyn9cQCFSLlwgodzUsAxg ; http://www.lighting.philips.com/main/prof/oem/hid-systems/high-pressure-sodium/master-son-t-apia-plus-hg-free/928199009830_EU/product

[271] Preparatory Studies for Eco-design requirements of EuPs, Final Report, Lot 9: Public Street lighting, Study for the European Commission DGTREN unit D3, contact Andras Toth, by VITO in cooperation with Laborelec and Kreios, January 2007, Contract TREN/D1/40-2005/LOT9/S07.56457, available through 'eup4light.net'

[272] CLASP (2013) Estimating potential additional energy savings from upcoming revisions to existing regulations under the ecodesign and energy labelling directives: a contribution to the evidence base. Available: http://www.eceee.org/all-news/press/2013/2013-02-19/eceee-clasp-report-estimating-potential

Since 2007, some improvements have been made on lifetime and lumen maintenance. Modern HPS-lamps with increased xenon-pressure are offering lifetimes of 24,000 hours with LSF and LLMF > 90%. These xenon filled HPS lamps have an external starting antenna and use bimetal to remove the antenna after ignition. More recent designs have integrated starting antennas on the ceramic arc tube itself [273], and/or use a ZrAl alloy getter to better maintain the vacuum [274]. As a consequence, the best HPS lamps on the market today have longer lifetime, lumen maintenance and slightly higher efficacy than the minimum stage 3 requirements and indicative benchmark (table 21) of regulation 245/2009.

Other important changes have been introduced on the ballast side. Compared to the lot 9 study on street lighting in 2007, many electronic ballasts with dimming function entered the market [275]. High pressure sodium lamps can easily be dimmed to 50% of their power, resulting in about 30% of light output. This can yield important energy savings when dimming street lights during hours of low traffic. Although the electronic ballast for HPS-lamps does not result in a higher lamp efficacy, it reduces the overall power losses for the system. The main advantages of electronic ballasts are: control of the light output independent from the line and lamp voltage, less harmonic current, and dimmability in some cases. The end-of-life of HPS lamps is known as 'cycling' [276], wherein the lamp voltage builds up until it becomes too high for the magnetic ballast to operate. In electronic ballasts this can be monitored and/or life can be extended. Fr details on this topic see the Lot 37 lighting systems study.

Non-directional HPS lamps are subject to regulation 245/2009 (as amended by regulation 347/2010). The efficacy requirements depend on the colour rendering properties (Ra), on the rated lamp power, and on the transparency of the lamp envelope (clear, non-clear). For clear lamps with Ra≤60, the required efficacy varies from 60 lm/W at 45 W lamp power to 135 lm/W at 255 W or higher [277]. For clear lamps with Ra>60, the requirement at the same maximum power is 85 lm/W [278] [279]. In addition regulation 245/2009 sets minimum LLMF and LSF requirements for HPS lamps [280]. These requirements are applicable since April 2012 [281]. For exemptions see par. 5.18.6.

Directional HPS-lamps are subject to regulation 1194/2012 that requires an EEI<0.5 starting from September 2014 (Stage 2) and EEI<0.36 from September 2016 (Stage 3). For examples of directional HPS-lamps, see [282].

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[273] http://www.havells-sylvania.com/nl_BE/products/0020693 or http://www.lighting.philips.com/main/prof/lamps/high-intensity-discharge-lamps/son-high-pressure-sodium/master-son-t-apia-plus-xtra#filters=

[274] http://www.lighting.philips.com/main/prof/lamps/high-intensity-discharge-lamps/son-high-pressure-sodium/master-son-t-apia-plus-hg-free

[275] http://www.harvardeng.com/productsoutdoor.html or http://www.tridonic.com/ae/products/electronic-hid-control-gear.asp

[276] http://en.wikipedia.org/wiki/Sodium-vapor_lamp

[277] See details in table 7 of regulation 245/2009.

[278] See details in table 8 of regulation 245/2009.

[279] Lamps with Tc ≥ 5000 K or equipped with a second lamp envelope shall fulfil at least 90 % of the applicable lamp efficacy requirements.

[280] See details in table 13 of regulation 245/2009 (as amended by regulation 347/2010).

[281] But until April 2015, retrofit HPS lamps operating on HPM-ballast were exempted from the Ra≤60 requirements.

[282] http://www.lamptech.co.uk/Spec%20Sheets/Reflux.htm or http://www.reflux.ru/ http://www.nfl-lighting.cz/en/lamps.htm (use as grow lights)

Ballasts for all HID-lamps (including HPS) are subject to regulation 245/2009. Minimum efficiency requirements for HID-ballasts are initially prescribed for Stage 2 (April 2012) and will be raised in Stage 3 (April 2017), see figure 7 of the Task 1 report [283].
The market is moving towards LED light sources to replace HPS-lamps and therefore it is unlikely that much effort will be done to improve HPS-ballast technology.

The average EU-28 characteristics for this base case are summarized in Table 45. They are based on the information presented in the Task 2 and 3 reports.

Table 45: Average EU-28 characteristics for the HPS base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	0	13.9	13.9	
Lifetime (yr)	(17.1)	3.0	3.0	
Stock (mln units)	0	42.2	42.2	
Capacity (lm)	(13300)	13300	13300	
Efficacy (lm/W)	(95)	95	95	
Power (W)	(140)	140	140	Exclusive ballast power
Ballast efficiency (%)	(83%)	83%	83%	Mainly magnetic
Burning Hours (h/a)	(700)	4000	4000	
Electricity rate (euros/kWh)	(0.191)	0.119	0.119	
Price (euros/unit)	(32.40)	27.00	27.00	
Installation cost (euros/unit)	(0.00)	9.25	9.25	253
Maintenance cost (euros/unit)	(0.00)	18.50	18.50	253

5.18.2. HPS, Improvement options

The following improvement / replacement options have been identified:

1) Substitute the HPS-lamp by an improved HPS-lamp, optionally also substituting the magnetic ballast by a (dimmable) electronic ballast. The improvements can regard lifetime (LSF), lumen maintenance (LLMF) and efficacy. Another option is to use mercury-free lamps, but with lower efficacy and lumen maintenance. For further information, see par. 5.18.3.

2) Substitute the HPS-lamp by a MH retrofit lamp. For the characteristics of the latter, see par. 5.19. MH-lamps have the advantage of offering white light with high CRI while HPS-lamps offer a yellow/orange light with low CRI. Some studies have shown that HPS-lamps need to produce up to 3.9 times the amount of lumens in order to equal the scotopic lighting benefits of higher CRI metal halide lamps [284]. This implies that MH-lamps can have lower lumen levels than the HPS-lamps they aim to substitute. However, attention also has to be paid to lumen

[283] See details in tables 15 and 16 of regulation 245/2009 (as amended by regulation 347/2010).
[284] http://www.ushio.com/products/generallighting/mh-ultraarc.php . Scotopic vision is the vision of the eye under low light conditions

maintenance and lifetime: MH-lamps can behave worse than HPS-lamps from these points of view.

3) Substitute the HPS-lamp by a LED retrofit lamp. For the characteristics of the latter, see par. 5.17.3. A simple one-to-one LED retrofit lamp should not be expected because:
   - HPS-luminaires are equipped with high voltage ignitors that should be removed.
   - Without modification, HPS-ballasts cannot be used to supply LED modules, they should be replaced by LED-drivers.
   - HPS-lamps and HPS-luminaire optics are very compact, and this will cause problems for LED cooling, in particular for higher-lumen lamps.

   As a consequence, a LED-retrofit solution with the associated additional work, should be carefully evaluated.

4) Substitute the HPS-luminaire by a LED luminaire. For the characteristics of the latter, see par. 5.17.4. Considering current trends in street lighting and considering the advantages of LED luminaires over LED retrofit lamps, this is expected to be a frequently used option, in particular for low wattage HPS-lamps at the end of the luminaire life time (30 years).

As regards the probability of the future use of the above options, the same remarks apply as made in par. 5.17.2 and 5.17.3 for HPM-lamps, with the difference that highly efficient HPS-lamps are still on the market while HPM-lamps are phased out.

5.18.3. HPS, BAT description, maintaining HPS-technology

Table 46 summarizes the minimum requirements of regulation 245/2009 and includes also the ‘indicative benchmark values’ (BAT(245/2009) from Annex V. In addition the current identified BAT (2015) is indicated. The efficacy of the latter is lower than the indicative benchmark values in the regulation, because the reference lamp technology presented in 2007 is not on the market anymore. The current benchmark values (BAT (2015)) are available from several manufacturers. In principle the 245/2009 benchmark values could still be achieved: they require an electronic ballast and an optimized discharge tube.

Lamp Wattage (Nominal) [W]	Efficacy clear lamps [lm/W]	Efficacy Not clear lamps [lm/W]	Efficacy BAT (245/2009) [lm/W]	Efficacy BAT (2015) [lm/W]	LLMF minimum (245/2009)	LSF minimum (245/2009)	LLMF BAT (2015) [lm/W]	LSF BAT (2015) [lm/W]
W≤45	≥60	≥60			>0,8@12000h	>0,9@12000h		
45<W≤55	≥80	≥70	≥91	87	>0,8@12000h	>0,9@12000h	>0,86@12000h	>0,99@12000h
55<W≤75	≥90	≥80	≥107	97	>0,8@12000h	>0,9@12000h	>0,86@12000h	>0,99@12000h
75<W≤105	≥100	≥95	≥110	107	>0,85@16000h	>0,9@16000h	>0,90@16000h	>0,99@16000h
105<W≤155	≥110	≥105	≥128	117	>0,85@16000h	>0,9@16000h	>0,90@16000h	>0,99@16000h
155<W≤255	≥125	≥115	≥138	133	>0,85@16000h	>0,9@16000h	>0,90@16000h	>0,99@16000h
255<W≤605	≥135	≥130		144	>0,85@16000h	>0,9@16000h	>0,90@16000h	>0,99@16000h

Table 46 Minimum requirements for High-Pressure Sodium lamps in regulation 245/2009 and identified BAT

5.18.4. HPS, BAT description, using LED-technology

See par. 5.17.3 (LED retrofit).

5.18.5. HPS, BNAT description

See par. 5.17.4 (LED luminaire).

5.18.6. HPS, Special cases and non-availability of improving substitutes

Non-directional HID-lamps with specific characteristics are excluded from regulation 245/2009, as amended by regulation 347/2010 (see par. 5.17.6 and 5.19.6), but these specific characteristics do not seem to be relevant for HPS-lamps.

Directional HPS-lamps are exempted from regulation 1194/2012 if they are special purpose products, see the Task 1 report or the regulation itself.

5.19. High intensity discharge, metal halide lamps

5.19.1. MH, BC description

According to the definitions of regulation 245/2009: " 'Metal halide lamp' means a high intensity discharge lamp in which the light is produced by radiation from a mixture of metallic vapour, metal halides and the products of the dissociation of metal halides".

As other HID-lamps, metal-halide light sources typically operate on external ballasts, are most non-directional, and used in industrial and commercial applications, street lighting and sports lighting. Different from sodium lamps they emit a white light, and compared to both sodium and mercury lamps they have better colour rendering properties, which makes them acceptable also for some indoor and task lighting applications. The maximum efficacy of MH-lamps is slightly lower than for HPS-lamps. At least until recently, MH-lamps were the only type of HID-lamp showing increasing sales, and consequently investments were still being made in their improvement.

A description of the HID-technology is included in the 2007 VITO study on street lighting [247] and its references. For a basic description of the MH-technology see [285]. For remarks on recent developments in MH-technology see the 2013 CLASP report [248] and the 2014 Omnibus study [156].

In recent years (2007-2013), the efficacy, colour rendering, and lifetime of MH-lamps has been improved, due to design optimisations in the arc tube, in the electrodes, and in the plasma [286].

As regards the <u>material for the arc tube</u>, two main versions of MH-lamps exist: <u>quartz and ceramic</u>. The more recent ceramic arc tube allows higher operating temperatures, which also implies higher efficacies, especially when combined with the 'unsaturated' working conditions, that avoid the presence of halide salts in the liquid phase, even when the lamp is dimming down to 50% of its rated power, see details in [248].

Considering that unsaturated ceramic arc tube MH-lamps have higher efficacies, it has been proposed [248] to raise the minimum efficacy requirements in the regulations (see below), thus effectively phasing-out the quartz versions. Stakeholders (LightingEurope, IALD) have warned against this, because in their opinion <u>the ceramic version cannot replace the quartz version in all applications</u>: the difference in size of light source area would compromise the optical performance of many fitting types [287].

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[285] http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/mwmhl/abstract.asp

[286] The mixture of gases in the arc tube.

[287] In its comments on Task reports 0-3 the IALD states: "The further proposals to remove the availability of quartz envelope Metal halide lamps in favour of ceramic envelope would compromise the optical performance of many

In addition to the above, the application of electronic control gear with dimming capabilities can further improve the system efficiency. Many of the newly introduced lamps were specifically designed to work on specified, electronic ballasts. The main advantages of electronic ballasts are: control of the light output independent from the line and lamp voltage, less harmonic current, and dimmability in some cases. Dimming of MH-lamps is typically limited to 50-100% light output and to 60-100% of the rated power [288] [289]. This can yield important energy savings when dimming street lights during hours of low traffic. Dimming at less than 60% of the power can result in colour shifting of the light.

Non-directional MH-lamps are subject to regulation 245/2009 (as amended by regulation 347/2010). Stage 2 (April 2012) specifies minimum efficacy requirements for MH-lamps with Ra≤80, varying from 60 to 85 lm/W, in function of the lamp power, and differentiating between clear and non-clear lamps [290]. In Stage 3 (April 2017) the minimum requirements are raised, varying from 65 to 90 lm/W, and extended to all MH-lamps, regardless of their colour rendering index [291] [292]. In addition regulation 245/2009 sets minimum LLMF and LSF requirements for MH-lamps [293]. For exemptions see par. 5.19.6.

Due to the technological progress in the period 2007-2013, the current state-of-the-art of MH-lamps is already well above the 2017 Stage 3 requirements of regulation 245/2009, see par. 5.19.3.

Directional MH-lamps are subject to regulation 1194/2012 that requires an EEI<0.5 starting from September 2014 (Stage 2) and EEI<0.36 from September 2016 (Stage 3). Directional MH-lamps do not seem to be widespread, but there are some on the market and they already meet the September 2016 efficacy requirement. The example found is a compact reflector lamp similar to a MR16-GU10, but using a GX10 cap to withstand the higher ignition voltages [294].

Ballasts for all HID-lamps (including MH) are subject to regulation 245/2009. Minimum efficiency requirements for HID-ballasts are initially prescribed for Stage 2 (April 2012) and will be raised in Stage 3 (April 2017), see figure 7 of the Task 1 report [295].

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fitting types due to the significantly larger light source area. Metal halide should be considered as an energy saving lamp as it can be a single, powered light source for a multitude of lighting fixtures as in the case of fibre optic applications (one light source lighting 10 fixtures, as an example). The study should include system scale assessments of the impact of removing these specific lamp types and the financial burden placed on the owners of the affected properties."

[288] http://www.isienergycontrols.com/wp-content/uploads/2011/05/NEMALSD14-2010Guidelines.pdf

[289] http://www.harvardeng.com/outdoorleafnut.html and http://www.lighting.philips.com.cn/pwc_li/cn_zh/subsites/oem/download/cosmopolis/cosmo_design-in_guide.pdf (see page 24)

[290] See details in table 8 of regulation 245/2009.

[291] See details in table 10 of regulation 245/2009.

[292] Lamps equipped with Tc ≥ 5000 K or with a second lamp envelope shall fulfil at least 90 % of the applicable lamp efficacy requirements.

[293] See details in table 14 of regulation 245/2009.

[294] http://www.havells-sylvania.com/en/products/0020270 This lamp can be computed to have an EEI=0.29 and thus meets the stage 3 requirements of regulation 1994/2012.

[295] See details in tables 15 and 16 of regulation 245/2009 (as amended by regulation 347/2010).

The market is moving towards LED light sources to replace HID lamps and therefore it is unlikely that much effort will be done for improving HID ballast technology compared to the state of art.

The average EU-28 characteristics for this base case are summarized in Table 47. They are based on the information presented in the Task 2 and 3 reports.

Table 47: Average EU-28 characteristics for the MH base case, reference year 2013. (Price information is in fixed 2010 euros, inclusive 20% VAT for the residential part)

Parameter	Residential	Non-Residential	All Sectors	Notes
Sales (mln units/yr)	0	16.4	16.4	
Lifetime (yr)	(11.4)	2.0	2.0	
Stock (mln units)	0	36.5	36.5	
Capacity (lm)	(13120)	13120	13120	
Efficacy (lm/W)	(82)	82	82	
Power (W)	(160)	160	160	Exclusive ballast power
Ballast efficiency (%)	(83%)	83%	83%	Mainly magnetic
Burning Hours (h/a)	(700)	4000	4000	
Electricity rate (euros/kWh)	(0.191)	0.119	0.119	
Price (euros/unit)	(32.40)	27.00	27.00	
Installation cost (euros/unit)	(0.00)	9.25	9.25	253
Maintenance cost (euros/unit)	(0.00)	12.33	12.33	253

5.19.2. MH, Improvement options

Some further improvement of MH-lamps might still be possible, but it is expected that most manufacturers will choose to invest in LED or OLED technology instead, and consequently future improvements will be limited and they are neglected for the purposes of this study. MH-lamps can of course be replaced by the same type, where possible substituting the magnetic ballast by an electronic one. Three improvement / replacement options have been identified:

1) Substitute the MH-lamp by an improved state-of-the art MH-lamp, possibly also substituting the magnetic ballast by an electronic ballast. In order to fully exploit the efficacy advantages of the improved MH-lamp, it would have to run on the existing control gear at a lower lamp power. On magnetic ballasts this would require a change in lamp voltage, but no retrofit MH-lamps with this feature could be found on the market (4/2015). The potential energy savings can be realized only if the ballast is also substituted, or using entirely new MH-luminaires. The relatively high cost of retrofitting and ballast or luminaire substitution is expected to orient more consumers towards dedicated LED luminaires that have several other benefits. Considering also the current trends in street lighting, this is therefore not expected to be a frequently used option. For further information on state-of-the-art MH-lamps, see par. 5.19.3.

2) Substitute the MH-lamp by a LED retrofit lamp. For the characteristics of LED retrofit lamps for HID-lamps, see par. 5.17.3. See also the comments made in par. 5.17.2 and 5.17.3.

3) Substitute the MH-lamp by a LED luminaire. For the characteristics of the latter, see par. 5.17.4. Considering current trends in street lighting and considering the advantages of LED luminaires over LED retrofit lamps, this is expected to be a frequently used option, in particular for low wattage MH-lamps at the end of the luminaire life time (30 years).

As regards the probability of the future use of the above options, the same remarks apply as made in par. 5.17.2 and 5.17.3 for HPM-lamps, with the difference that MH-lamps are still on the market while HPM-lamps are phased out.

5.19.3. MH, BAT description, maintaining MH-technology

As anticipated in par. 5.19.1, due to the technological progress in the period 2007-2013, the current state-of-the-art of MH-lamps is already well above the 2017 Stage 3 requirements of regulation 245/2009. This is illustrated in Table 48 and also confirmed in table 4-2 of the 2013 CLASP study [248].

New designs with elliptical or ball shaped ceramic discharge tubes are entering the market and are replacing previous tubular designs. The efficacy improvement seems to be more in the lower wattage range and for this type of lamp the dependency of efficacy on wattage is weaker than that expressed in table 15 of regulation 245/2009. Lamps with different caps, different colour rendering, and different efficacies, for specific purposes are available.

Table 48: Efficacies of MH-lamps existing on the market, compared to the minimum efficacies requested by regulation 245/2009 from April 2017. Today's MH-lamps already exceed the future requirements (Source: Omnibus study [156])

Metal-halide lamps existing on the market				Required efficacy (lm/W), regulation 245/2009, table 10, clear lamps, from April 2017
Lamp wattage (W)	CRI	CCT (K)	Efficacy (lm/W)	
20 (cap G8.5)	87	3000	102	≥ 70 lm/W (for power ≤ 55 W)
45	66	2800	110	
50	89	2800	104	
50	90	4200	100	
60	73	2700	120	≥ 80 lm/W (55 W ≤ power ≤ 75 W)
60	81	4000	107	
70	87	3000	105	
70	87	4200	101	
140	66	2800	118	≥ 85 lm/W (75 W ≤ power ≤ 255 W)
150	90	3000	100	
315	90	3100	115	≥ 90 lm/W (255 W ≤ power ≤ 405 W)
315	90	4200	109	

5.19.4. MH, BAT description, switching to LED technology

This is the same solution as described in par. 5.17.4 (LED luminaire).

5.19.5. MH, BNAT description

In general the BNAT solution for substitution of MH-lamps and -luminaires is to use dedicated LED luminaires. The future characteristics of these LED luminaires are expected to follow the trends outlined in chapter 2. See also comments regarding substitution of HID-lamps in par. 5.17.

5.19.6. MH, Special cases and non-availability of improving substitutes

Non-directional HID-lamps (including MH-lamps) with the following characteristics are excluded from regulation 245/2009, as amended by regulation 347/2010:

- high intensity discharge lamps with Tc > 7000 K. This exemption is understood to be relevant, for example, for MH lamps used in decorative applications such as outdoor façade lighting [296], and for high colour temperature aquarium lamps [297] that simulate the appearance of sunlight near the equator in ocean depths (blueish). The lumen scale used to express the amount of light perceived by the human eye, is a relative scale in favour of yellow/green light that 'underweights' blue light. As a consequence, blue light from HID-lamps with Tc>7000 K would not meet the efficacy criteria from the regulation, despite the fact that they are sold and useful in specific applications.

- high intensity discharge lamps having a specific effective UV output >2 mW/klm. Special MH lamps are used in industrial/medical UV curing applications [297]. They were not intended to be in the scope of regulation 245/2009, and excluded by this criterion.

- high intensity discharge lamps not having lamp cap E27, E40, PGZ12. White light HID-lamps frequently used in car headlights, shop lighting, and projectors have other (smaller) lamp caps. They were intended to be outside the scope of regulation 245/2009 and discriminated by this cap-criterion. As regards shop lighting, HID-lamps with other caps have come to the market after regulation 245/2009 was drafted, e.g. RX7s, GU6.5, G8, G12, G22, that are used for their compact size in low wattage lamps. These lamps have similar performance as their E27 equivalents and their exemption could therefore be reconsidered.

For other exemptions from regulation 245/2009 see the Task 1 report or the regulation itself.

Directional lamps are exempted from regulation 1194/2012 if they are special purpose products, see the Task 1 report or the regulation itself.

[296] http://www.venturelightingeurope.com/products/lamps-for-special-applications/designer-color-lamps.html
[297] http://www.ushio.com/products/aquarium/aqualite.php

6. Production, Distribution and End-of-Life

The major part of this chapter is dedicated to the bill-of-materials (BoM) for the various base cases (par. 6.3). This information will be used as input for the EcoReports, with the aim to estimate environmental impacts (see Task 5 report).

The BoM also includes packaging materials, while the EcoReports additionally requires the input of a gross product volume (for assembly, shipping, storage and retailing impact estimates). These topics are addressed in the paragraph on distribution and packaging (par. 6.2).

Par. 6.4 deals with the end-of-life phase of lighting products and focuses on the input required for the EcoReports. Additional information on the end-of-life of lighting products has been presented in the Task 3 report, chapter 6.

As regards the production phase (par. 6.1), only the production of LEDs is briefly addressed. This description does not enter into detail, as specific manufacturing process details are not required for the EcoReports.

6.1. LED production

Compared to other lamp technologies (see the 2007-2009 preparatory studies) the production of LED lighting products is relatively complex. The manufacturing process can be generally defined by a sequence of reasonably independent manufacturing steps, that togheter with the manufacturing equipment, materials, and testing equipment, form the manufacturing supply chain (Figure 43) [298]. It is common that the supply chain is distributed over different manufacturing sites. For example luminaire manufacturing can be done in Europe with LED packages sourced from Asia.

The typical LED manufacturing process starts with the substrate production. The substrate is the base material on which the p-n (and other) layers of the led chip/die are created using a process called epitaxy. As explained in par. 2.2.6, the substrate is not prepared for a single LED die, but as a larger wafer, and different materials can be used, each with its own manufacturing process details. As also pointed out in par. 2.2.6, in recent years an increase in wafer size from 2" to 6" has enabled a cost reduction and a production capacity increase.

An example of the materials and process steps involved in the production of a 3" sapphire substrate can be found in the 2012 US DoE life cycle analysis report [299]:

- Boule growth in reactor
- Core fabrication
- Wafer slicing
- Lapping and bevelling
- Polishing and chemical-mechanical planarization
- Geometrical and optical inspection
- Final cleaning

[298] DOE(2014): 'Manufacturing Roadmap Solid-State Lighting Research and Development Prepared for the US Department of Energy August 2014', Prepared by Bardsley Consulting, Navigant Consulting, SB Consulting, and SSLS, Inc, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf

[299] Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance, US DoE, June 2012 see in particular par. 5.2 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf

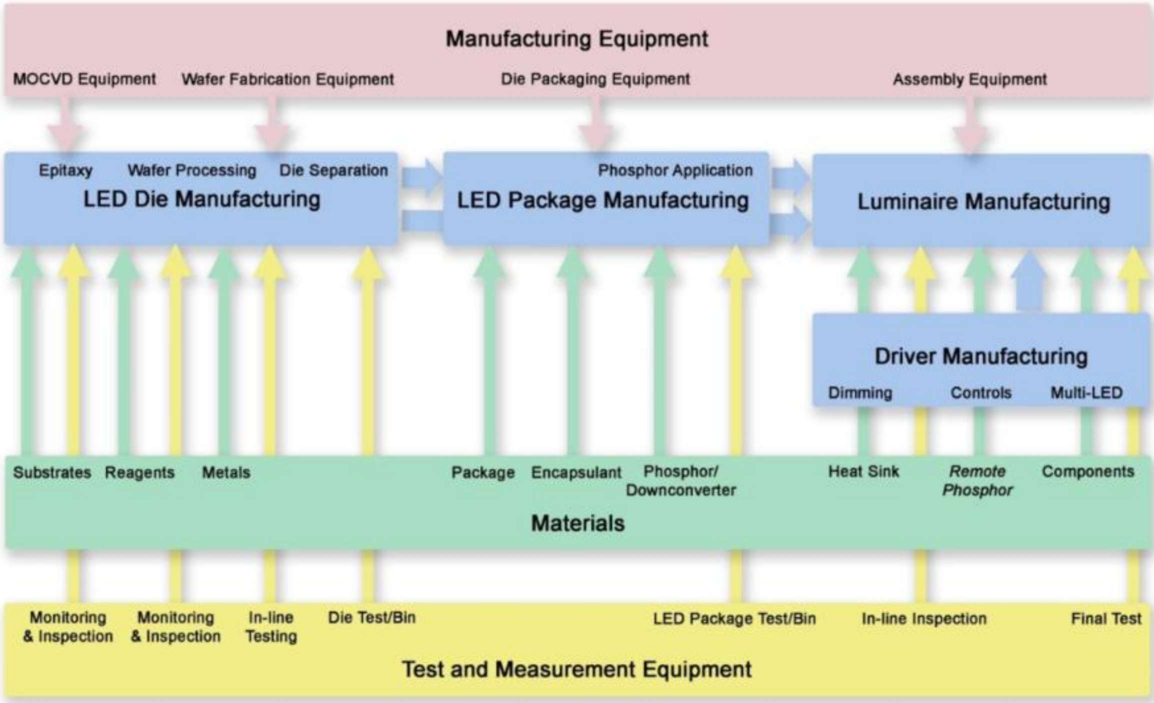

Figure 43 LED-Based SSL Manufacturing Supply Chain (source: US DoE 2014 [298])

During the epitaxy, the nucleation layer, n-type layer, active layers, and p-type layer are 'grown' upon the substrate. This occurs in a metal organic chemical vapour deposition (MOCVD) reactor, in a sequence of well-controlled process steps. Details for a gallium-nitride epitaxy are provided in [299].

Following the growth of the layers, the post-epitaxy steps involve e.g. wafer inspection, creation of the P-contacts, making the N-contact opening, realization of the GaN pattern, creation of the N-contacts, and back-grinding of the substrate. Each of these steps involves several sub-steps. For example, the US DoE LCA report [299] distinguishes 12 sub-steps for the creation of the N-contact alone.

At the end of this process, the individual dies, including their electrical contacts, are visible on the wafer. The substrate is separated from the LED dies, that are then cut (die singulation) and tested/binned according to their performance. At the end of this stage, the LED dies are ready to be packaged.

Note that the details of this process will differ per LED-die manufacturer, depending on the type of materials used and on the foreseen packaging method. E.g. in a flip-chip approach where the layers have been grown on a transparent sapphire substrate, it may not be necessary to remove the substrate (par. 2.6).

The manufacturing steps in the packaging phase heavily depend on the type of package. As explained in par. 2.6, considerable progress has been made in package design (and hence manufacturing) in recent years. The importance of this is illustrated by the cost breakdown for LED packages presented by US DoE in its 2014 manufacturing roadmap (Figure 44), showing that more than 50% of the costs derives from packaging activities.

Luminaire manufacturing and control gear manufacturing are not described here.

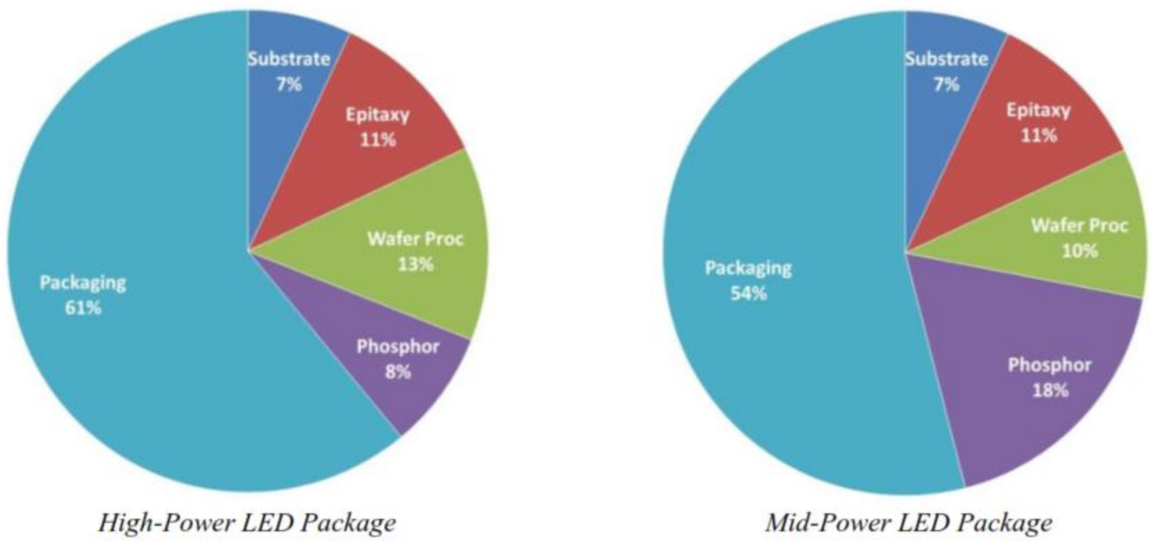

Figure 44 Typical cost breakdowns for high-power and mid-power LED packages (source: US DoE 2014, figure 1.5 [298])

As regards the European manufacturers involved in LED production, US DoE [298] mentions:

- Die manufacturing and LED package manufacturing: Osram Opto semiconductors, Optogan and Plessey semiconductors.
- Luminaire manufacturing: Philips, Osram Sylvania and Zumtobel.
- Equipment for epitaxial growth: Aixtron.
- Equipment for wafer processing: Oxford Inst. Plasma Tech, EV Group, SUSS Micro Tec, Logitech.
- Equipment for LED packaging: Besi.
- Equipment for luminaire assembly: ASM Siplace, Assembleon.
- Equipment for test and inspection: Laytec, Bede, Bruker, Instrument Systems, Cameca, SUSS Micro Tec, Ismeca.
- Substrates: Monocrystal, Ammono, St.Gobain, Soitec.
- Chemical reagents: Akzo Nobel, Linde Industrial Gases, Air Liquide.
- Packaging: Heraeus.
- Phosphors / Down-converters: Merck, Osram Opto Semiconductors.
- Encapsulation: Wacker Chemie.

For a list of American and Asian producers involved in LED manufacturing, see the reference.

6.2. Distribution and Packaging

Single light sources, or a few light sources together, are typically packaged in a box or in a blister.

The box material is usually paper, e.g. paperboard, cardboard or corrugated fibreboard, but versions in thermo-foldable plastic are also on the market [300]. The most common shape is a straight rectangular box, but a variety of other shapes exists. The boxes often have openings to display the product and these openings may be covered by transparent plastic.

Blisters are typically made from pre-formed plastic, often PET (polyethylene terephthalate), but paperboard versions also exist. A frequently encountered shape is a flat paperboard backside with a pre-formed transparent plastic front glued onto it.

The Western European market place typically prefers carton boxes, while Southern European countries are demanding the products in blister packaging. This led a designer working for Philips to come up with the Blister Box, consisting of a single piece of foldable, pre-thermoformed PET plastic [300]. On the contrary, Osram states to prefer cardboard boxes from recycled material, using blister packs containing PET only in 4% of the cases because retailers request it [301].

The main functions of the packaging are:

- to protect the fragile light sources during transport,
- to display the product information as required by the regulations,
- to attract the customer towards the product (marketing),
- to display the product in the retail store, usually standing or hanging.

The package shall have a low cost and preferably be eco-friendly, recyclable.

The combination of functions is challenging and has attracted many designers, leading to several design competitions and to a large variety of packages [302].

The above regards the primary packaging of light sources, i.e. the one typically seen by the consumer. These packages usually contain a single light source, or two or three at the most. For shipments from the manufacturing plants to wholesalers and retailers, several dozens of these primary packages are usually packed together in larger boxes of corrugated cardboard.

Packaging of light sources would probably deserve a separate study, but that is clearly beyond the scope of this preparatory study. Anyway, as regards resources, the

[300] http://www.blisternews.com/tag/philips-lighting/

[301] http://www.osram.com/osram_com/sustainability/environmental/sustainability-criteria/secondary-performance-indicators/packaging/index.jsp : For the majority of our products cardboard boxes are used for primary packaging and corrugated cardboard boxes for shipment packaging. The cardboard and paper used to produce these packaging components have a recycling quota between 70 and 90 %. Only 4 % of the products are sold in blister packs containing a small proportion of plastic as this packaging is requested by our retail customers. The plastic material used is PET (polyethylene terephthalate) which, in contrast to PVC, places a significantly smaller burden on the environment in terms of its manufacture and disposal. Packaging for internal transport during manufacturing is mostly multi-use packaging made from corrugated cardboard or plastic.

[302] http://inhabitat.com/student-designer-creates-more-sustainable-packaging-for-led-light-bulbs/
https://it.pinterest.com/aktono/light-bulb-packaging/
https://www.behance.net/collection/Light-Bulb-Packaging/8435073
http://cargocollective.com/search/light-bulb-packaging
http://www.sca.com/en/Media/News-features/2010/Sustainable-light-bulb-packaging-wins-SCA-Packaging-Design-Challenge/
http://www.alibaba.com/showroom/led-bulb-packaging.html
http://www.packagingoftheworld.com/2015/02/green-depot-eco-friendly-light-bulb_24.html

packaging is an important aspect because the weight of the packaging is often higher than the weight of the light source itself.

For the EcoReports that will be used in Tasks 5 and 6, two aspects of packaging are relevant: the bill-of-materials (type of packaging materials and their weights), and the gross per-lamp volume, that is used to compute the transport impacts.

Full packaging information is often not readily available from lamp datasheets, in particular as regards the difference between the net lamp weight and the gross lamp weight (inclusive packaging at all levels).

Interesting reference information on packaging was found on the ledzworld website [303] and is summarised in Table 49 (for a better understanding, see illustrations on the reference site). This information considers three levels of packaging. The first level is a box or blister that contains a single lamp. The second level, if present, is a corrugated fibreboard box that contains from 10 to 16 lamps with their primary packages. The final outer package is another corrugated fibreboard box that contains four secondary boxes or from 6 to 24 primary packages. Although the information regards LED lamps, it is considered to be an interesting reference for all light sources similar to the ones listed.

The following conclusions can be drawn from the table:

- For small light sources like MR16 and candle-lights, the (net) volume of a rectangular box enveloping the lamp is 0.12-0.19 dm^3.
- For medium size sources like LED bulbs and PAR20, the (net) volume of a rectangular box enveloping the lamp is 0.34-0.46 dm^3.
- For large sources like PAR30 and PAR38, the (net) volume of a rectangular box enveloping the lamp is 1-2 dm^3.
- For small and medium sized light sources with a primary package box, the <u>gross shipment volume per lamp can be 2 to 3 times higher than the net volume</u>. For large lamps this is around 1.5 times.
- Lamps using blisters as primary package can have a gross shipment volume that is from 5 to 9 times their net volume.

- The primary package weight is around 12-23 g for small lamps, 20-37 g for medium size lamps and 70 to 120 g for large lamps. Blisters tend to be heavier than boxes.
- The <u>total package weight per lamp</u> (including also the corresponding portion of secondary and tertiary packaging) is typically <u>2 to 3 times higher than the weight of the primary packaging</u>.

Figure 45 is based on the data in the table and provides the lamp packaging weight (kg) and lamp gross shipping volume (dm^3) in function of the net lamp volume (enveloping box, dm^3). This includes primary, secondary and outer packaging. It does not include shipping containers and pallets (assumed to be re-used) and enveloping plastic foils for boxes on the pallets (per-lamp contribution assumed negligible). These graphs will be used as an approximate reference to determine the corresponding input data for the EcoReports.

In addition to the packaging described above, it should be noted that on-line lamp sales are increasing. It is likely that this sales-channel will consume additional transport resources as compared to direct retail sales, and that additional packaging material will be used. As data lack on this issue, and the volumes and weights of Figure 45 seem rather high, it is assumed that the data of the figure also include this on-line-sales effect.

As regards the types of packaging material, taking into account that the secondary and outer boxes are in corrugated fibreboard, it is assumed that 90% of the weight is paper-based, and 10% PET.

Table 49: Information on lamp package weight and package volume from ledzworld[303]

	lamp				primary package			secondary package				outer package			totals		ratios	
lamp type	net lamp weight kg	lamp dimension H mm	lamp dimension W mm	Net lamp (box) volume dm3	Primary package type	Primary package weight kg	Primary package volume dm3	type	number of lamps in package	Secondary package weight kg	Secondary package volume dm3	number of lamps in package	Outer package weight kg	Outer package volume dm3	total package weight per lamp kg	total volume per lamp dm3	total package weight / primary package weight, per lamp	total package volume per lamp / ideal minimum volume per lamp
LED bulb	0.115	116	56	0.36	box	0.022	0.46	box	12	0.22	7.3	48	1.2	39	0.065	0.81	2.9	2.2
LED superior bulb	0.130	119	62	0.46	box	0.025	0.46	box	12	0.36	9.7	48	1.6	57	0.088	1.18	3.5	2.6
PAR20 downlighter	0.140	94	60	0.34	box	0.020	0.40	box	12	0.19	6.3	48	1.1	35	0.059	0.72	2.9	2.1
PAR16 spotlight	0.110	92	50	0.23	box	0.020	0.28	box	12	0.15	4.5	48	0.9	26	0.052	0.53	2.6	2.3
MR16 spotlight	0.043	50	49	0.12	box	0.012	0.16	box	10	0.10	2.4	40	0.6	14	0.037	0.35	3.0	2.9
PAR16 short spot	0.047	58	49	0.14	box	0.012	0.16	box	10	0.10	2.4	40	0.6	14	0.037	0.35	3.0	2.5
Candlelight	0.040	110	41	0.18	box	0.016	0.29	box	16	0.22	7.3	64	1.2	39	0.048	0.61	3.0	3.3
PAR30 spotlight	0.200	103	95	0.92	box	0.070	1.18	none				6	0.4	9	0.138	1.54	2.0	1.7
PAR38 spotlight	0.390	120	129	1.97	box	0.090	2.29	none				6	0.6	17	0.192	2.86	2.1	1.4
AR111 reflector	0.250	62	111	0.76	box	0.120	1.31	none				6	0.2	13	0.150	2.21	1.3	2.9
LED bulb 6.5W E27	0.118	116	56	0.36	blister	0.037	1.36	none				12	1.2	32	0.136	2.70	3.7	7.4
MR16 3W GU5.3	0.051	50	49	0.12	blister	0.022	0.82	none				24	0.6	21	0.047	0.87	2.1	7.3
MR16 4W GU10	0.052	49	58	0.16	blister	0.022	0.82	none				24	0.6	21	0.047	0.87	2.1	5.3
Candlelight 4W E14	0.047	112	41	0.19	blister	0.023	0.71	none				24	1.2	42	0.072	1.74	3.1	9.2

[303] http://ledzworld.com/color-box-carton-measurements/
http://ledzworld.com/tools-support/blister-pack-carton-measurements/

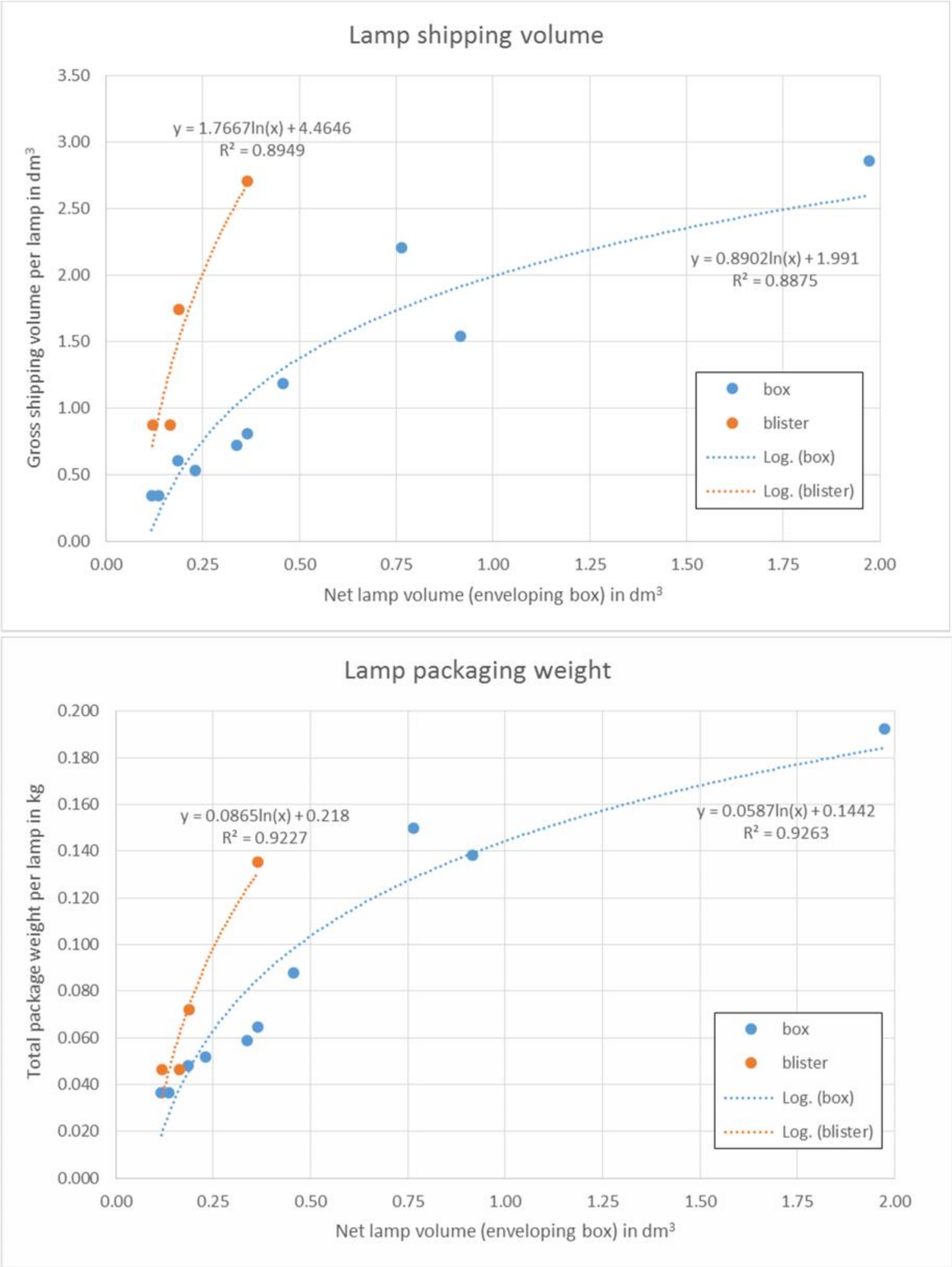

Figure 45: Lamp packaging weight (kg) and lamp gross shipping volume (dm^3) in function of the net lamp volume (enveloping box) (dm^3). Elaboration by VHK, based on data from ledzworld [303]. These graphs will be used as an approximate reference for input data of the EcoReports in Tasks 5 and 6. Data may not be valid for LFL, long CFLni, and similar lamps.

6.3. Bill-of-materials and weights

6.3.1. GLS X (non-reflector)

For non-reflector incandescent lamps (non-halogen), the most detailed BoM was found in a 2012 US DoE publication [304] for a 60W A19 lamp. The total weight of the lamp is reported there as 38 g. This total mass for the lamp is considered too high for use in this study, for the following reasons:

- In a survey of LCA-studies, Tähkämö [305] reports that weights varying from 23 to 38 g were used for 60 W GLS-lamp models.
- The Philips Standard 60W E27 220-240V A55 CL 1CT is reported to have a mass of only 25 g [306].
- The US DoE list of materials includes 7.3 g for oxygen gas as part of the lamp weight of 38 g. It has not been understood where this gas actually ends up inside the lamp; it will not be part of the gas filling.
- The GLS base case for which the BoM has to be made has an average power less than 60 W and also includes smaller lamps such as candle-shapes and P45 spheres, in part with the smaller E14 and B15 caps, so that the average weight will be considerably smaller than the 38 g assumed by US DoE.

As a compromise of all available data, a lamp weight of 25 g has been chosen, of which 89% is glass [307]. Other details of the BoM essentially derive from the US DoE reference, with some values slightly scaled to meet the 25 g total.

An average net lamp volume of 0.24 dm^3 has been assumed [308]. This leads to a total packaging weight per lamp of approximately 60 g, of which 90% paper-based and 10% PET. The derived gross shipping volume per lamp is 0.75 dm^3. This is inclusive secondary and tertiary packaging, see par. 6.2, Figure 45.

The bill-of-materials in EcoReport format is presented in Table 50.

Table 50: Bill-of-Materials for GLS-X (non-reflector) lamps

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Argon gas	0.137			
Aluminium	0.958	4-Non-ferro	27 -Al sheet/extrusion	
Brass	0.050	5-Coating	41 -Cu/Ni/Cr plating	
Resin Glue	1.292	2-TecPlastics	15 -Epoxy	
Solder paste	0.150	6-Electronics	53 -Solder SnAg4Cu0.5	
Glas bulb (Borosilicate)	18.783	7-Misc.	55 -Glass for lamps	
Getter (phosphoric acid)	0.002			
Glass Flare	1.748	7-Misc.	55 -Glass for lamps	

[304] Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance, US DoE, June 2012, for GLS data see par. 5.4 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf

[305] Leena Tähkämö, 2013, Life cycle assessment of light sources –Case studies and review of the analyses http://lib.tkk.fi/Diss/2013/isbn9789526052502/isbn9789526052502.pdf

[306] http://www.lighting.philips.com/main/prof/lamps/incandescent-lamps/standard-t-a-e-shape/standard-a-shape-clear/920054643302_EU/product

[307] Assumed glass fractions in various LCA studies for 60W GLS lamps vary from 70 to 94%, see reference of note 305, table 2.

[308] For comparison: a 60W GLS A-lamp has approximate dimensions 0.97*0.56*0.56 = 0.30 dm^3. As the base case also contains smaller candle- and sphere shapes, the same value of 0.24 dm^3 as used in the VITO 2009 study is taken.

Table 50: Bill-of-Materials for GLS-X (non-reflector) lamps				
Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Exhaust tube	1.804	7-Misc.	55 -Glass for lamps	
Lead wire	0.100	4-Non-ferro	30 -Cu wire	
Molybdenum support wire	0.013			
Filament - Tungsten	0.010			
Subtotal lamp	25.047			
packaging cardboard/paper	54.0	7-Misc.	57 -Cardboard	
packaging plastic	6.0	1-BlkPlastics	10 -PET	Yes

6.3.2. GLS R (reflector)

No specific information has been found regarding the BoM for GLS incandescent reflector lamps (non-halogen). As regards lamp weight and net dimensions, a 60 W R63 reflector lamp with E27 cap has been considered as representative for this base case.

Such a lamp has a typical length of 105 mm and a diameter of 63 mm [222] for a net volume of the enveloping box of 0.42 dm^3. This leads to a total packaging weight per lamp of approximately 90 g, of which 90% paper-based and 10% PET. The derived gross shipping volume per lamp is 1.2 dm^3. This is inclusive secondary and tertiary packaging, see par. par. 6.2, Figure 45.

The typical net weight of the lamp is around 30 g [309]. The same weight was used in the VITO 2009 study. Considering the lack of specific information, the same bill-of-materials is used as for non-reflector GLS lamps (previous paragraph), but scaling values to match the higher weights. No information was available as regards the type and (very small) weights of the materials used for the reflective layer, so this has been neglected in the BoM.

The bill-of-materials in EcoReport format is presented in Table 51.

Table 51: Bill-of-Materials for GLS-R (reflector) lamps				
Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Argon gas	0.164			
Aluminium	1.150	4-Non-ferro	27 -Al sheet/extrusion	
Brass	0.060	5-Coating	41 -Cu/Ni/Cr plating	
Resin Glue	1.550	2-TecPlastics	15 -Epoxy	
Solder paste	0.150	6-Electronics	53 -Solder SnAg4Cu0.5	
Glas bulb (Borosilicate)	22.540	7-Misc.	55 -Glass for lamps	
Getter (phosphoric acid)	0.002			
Glass Flare	2.097	7-Misc.	55 -Glass for lamps	
Exhaust tube	2.165	7-Misc.	55 -Glass for lamps	
Lead wire	0.120	4-Non-ferro	30 -Cu wire	
Molybdenum support wire	0.013			
Filament - Tungsten	0.010			
Subtotal lamp	30.021			
packaging cardboard/paper	81.0	7-Misc.	57 -Cardboard	
packaging plastic	9.0	1-BlkPlastics	10 -PET	Yes

[309] See for example: General Electric R63 reflector lamp TU§60R63/E27 230V GE 1/10/40 MIH, http://catalog.gelighting.com/lamp/incandescent/reflector/f=reflector-r63/p=91080/d=0/?r=emea

6.3.3. CFLi (integrated ballast)

For the determination of typical weight and dimensions, CFLi's ranging from 8W to 14W have been taken into account.

The typical lamp diameter (usually at the base) is 40-43 mm, but in the case of the presence of a second envelope (protective bulb hiding the arc tube) this can increase to around 60 mm (at the bulb). Lamp length varies between the models, also in function of lamp power, from 106 to 155 mm [310]. As an average for the base case, 45 mm diameter and 130 mm length have been assumed. This gives a net volume of the enveloping box of 0.26 dm^3, leading to a total packaging weight per lamp of approximately 60 g, of which 90% paper-based and 10% PET. The derived gross shipping volume per lamp is 0.75 dm^3. This is inclusive secondary and tertiary packaging, see par. 6.2, Figure 45.

Lamp net weight for the considered models varies from 48 g for a candle shape to 75 g for a lamp with protective bulb. For the base case an average of 60 g is considered.

Declared mercury content (by Osram and Philips) varies from 0.9 to 2.0 mg, with a value of 1.5 mg seeming to be typical. However, in most LCA's found in literature, 3 or 4 mg is used. Directive 2011/65/EU (RoHS2) sets a limit of 2.5 mg for CFL's < 30 W since 31 December 2012 [311]. A value of 2.0 mg has been used for the BoM, but older lamps are assumed to contain 3.5 mg.

The most detailed BoM was found in a 2012 US DoE publication [304] for a 15 W twisted CFLi with a total reported net lamp weight of 153 g. The 15 W power is too high as an average for our base case, and the lamp weight is very high as compared to other LCA's, where it varies from 46 to 109 g for 15 W lamps [305]. An additional problem is that the weight of the materials listed by US DoE sums up to only around 30 g, so 123 g are missing.

Welz et al [312] provide a BoM for an 11 W CFLi, modifying LightingEurope data [313], but the lamp weight is 111 g (Welz) or 120 g (LE), which is around twice the weight found in current manufacturers' catalogues for similar lamps.

Other sources of information that have been explored are:

- Navigant 2009 [314] (23 W CFLi, 92 g o/w 34 g glass, 44 g ballast)
- Chalmers University of Technology, Sweden 2011 [315] (Phosphor is estimated at 2.5% of the total weight, REE in Phosphor is 27.9%)
- Kaunas University of Technology, Lithuania 2012 [316] (15 W CFLi, 75 g o/w 22 g glass, 24 g copper (=ballast?))

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[310] http://download.p4c.philips.com/l4bt/3/348830/eco_home_348830_ffs_aen.pdf
http://www.osram.com/osram_com/products/lamps/compact-fluorescent-lamps/osram-duluxstar/index.jsp

[311] Task 1 report par. 5.1.14

[312] Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis, Tobias Welz, Roland Hischier, Lorenz M. Hilty, Environmental Impact Assessment Review, Volume 31, Issue 3, April 2011, Pages 334–343, http://www.sciencedirect.com/science/article/pii/S0195925510001149

[313] http://www.elcfed.org/2_lighting_composition.html

[314] Life Cycle Assessment of Ultra-Efficient Lamps, Navigant Consulting Europe research report for DEFRA, May 2009

[315] Sustainable processes development for recycling of fluorescent phosphorous powders – rare earths and mercury separation, Cristian Tunsu, Teodora Retegan, Christian Ekberg, Chalmers University of Technology, Gothenburg, Sweden, 2011, http://publications.lib.chalmers.se/records/fulltext/local_157270.pdf

[316] Life Cycle assessment of Compact and Incandescent Lamps: Comparative Analysis - Department of Environmental Engineering, Kaunas University of Technology, Lithuania (september 2012), http://www.google.it/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCEQFjAA&url=http%3A%2F%2Fwww.eejournal.ktu.lt%2Findex.php%2Ferem%2Farticle%2Fdownload%2F2425%2F1892&ei=2lcyVbCqEobiaNzsgOgL&usg=AFQjCNHti3hnPFcIF0zXiZitOPRkP_z6rA&sig2=sAVxNw2mbuzsU99eQp4YbA&bvm=bv.91071109,d.d2s

- Philips 2012 [317] (maximum weight % for phosphor, tin, indium, bismuth, mercury)

The BoM proposed for this study considers information from all sources and started from the survey provided by Tähkämö [305]:

- Glass content 30-73%, for this study 45% is chosen.
- Electronics content 14-31%, for this study 25% is chosen.
- Plastic content 16-38%, for this study 20% is chosen.
- Metal content 2-10%, , for this study 5% is chosen.

The remaining 5% is divided over phosphors, glues, gases, mercury, etc.

The bill-of-materials in EcoReport format is presented in Table 52.

Table 52: Bill-of-Materials for CFLi (integrated control gear)

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Glass Tube (Borosilicate)	27.000	7-Misc.	55 -Glass for lamps	
Plastic Base (PET or PVC)	12.000	1-BlkPlastics	10 -PET	
Ballast - electronic	14.600	6-Electronics	50 -PWB 1/2 lay 3.75kg/m2	
Ballast - electromagnetic	0.000	6-Electronics	45 -big caps & coils	
Resin glue / potting	1.700	2-TecPlastics	15 -Epoxy	
Solder paste	0.200	6-Electronics	53 -Solder SnAg4Cu0.5	
Cap, electrodes, other metal parts	2.200	4-Non-ferro	32 -CuZn38 cast	
Cap, electrodes, other metal parts	0.400	5-Coating	41 -Cu/Ni/Cr plating	
Phosphors (Yt oxide, Ba Aluminate, rare earths)	1.500			
Gases	0.400			
Mercury	0.003			
packaging cardboard/paper	54.000	7-Misc.	57 -Cardboard	
packaging plastic	6.000	1-BlkPlastics	10 -PET	Yes
Subtotal lamp	60.003			
packaging cardboard/paper	54.0	7-Misc.	57 -Cardboard	
packaging plastic	6.0	1-BlkPlastics	10 -PET	Yes

6.3.4. CFLni (without ballast)

No specific information has been found regarding the BoM for CFL’s with non-integrated ballast.

For the determination of typical weight and dimensions for this base case, CFLni’s ranging from 7W to 18W have been taken into account, with 2-pin or 4-pin base.

The lamp cross sectional dimensions have been found to vary from 22x35 mm to 43x46 mm. Lamp length depends on the power, and on the model, and varies from 110 to 236

[317] http://www.usa.lighting.philips.com/connect/tools_literature/downloads/CFL-i_Lamps_LMDS_CFI-08100B.pdf

mm for the models examined [318] [319]. As an approximate average, a cross section of 35x35 mm with a length of 150 mm has been assumed. This gives a net volume of the enveloping box of 0.20 dm^3, leading to a total packaging weight per lamp of approximately 50 g, of which 90% paper-based and 10% PET. The derived gross shipping volume per lamp is 0.50 dm^3. This is inclusive secondary and tertiary packaging, see par. 6.2, Figure 45.
Lamp net weight for the considered models varies from 22 g for a 7W lamp with 2G7 base to 73 g for a 18W lamp with 2G10 base. For the base case an average of 50 g is considered.

Declared mercury content (by Osram and Philips) varies from 1.4 to 3.0 mg, with a value of 1.8 mg seeming to be a representative average. However, it has been preferred to use the same 3 mg value as applied for CFLi.

By lack of specific information, the bill-of-materials for CFLni has been based on the one presented for CFLi, but removing ballast and cap, and scaling glass and plastic masses to obtain the desired total weight.
The bill-of-materials in EcoReport format is presented in Table 53.

Table 53: Bill-of-Materials for CFLni (non-integrated control gear)

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Glass Tube (Borosilicate)	34.000	7-Misc.	55 -Glass for lamps	
Plastic Base (PET or PVC)	11.300	1-BlkPlastics	10 -PET	
Resin glue / potting	1.000	2-TecPlastics	15 -Epoxy	
Solder paste	0.200	6-Electronics	53 -Solder SnAg4Cu0.5	
Electrodes, pins, other metal parts	1.000	4-Non-ferro	30 -Cu wire	
phosphors (Yttrium oxide, Barium Aluminate, rare earths)	2.000			
gases	0.500			
Mercury	0.003			
Subtotal lamp	50.003			
packaging cardboard/paper	45.0	7-Misc.	57 -Cardboard	
packaging plastic	5.0	1-BlkPlastics	10 -PET	Yes

[318] http://www.osram.com/osram_com/products/lamps/compact-fluorescent-lamps/osram-dulux-t/index.jsp
OSRAM DULUX T PLUS, two-pin GX24d, 13 W/830, 53 g net, 114x43x46, Hg 2.1 mg
OSRAM DULUX T/E PLUS, four pin GX24q, 13 W/827, 50 g net, 114x43x46, Hg 2.1 mg
OSRAM DULUX D, two-pin GX24d, 10 W/840, 36 g net, 110x35x35, Hg 1.4 m; 13 W/865, 44 g net, 140x35x38, Hg 2.5 mg; 18 W/827, 48 g net, 153x35x35, Hg 1.4 mg
OSRAM DULUX D/E, four pin GX24q, 10 W/830, 31 g net, 103x35x35, Hg 1.4 mg; 13 W/840, 40 g net, 131x35x35, Hg 1.4 mg; 18 W/865, 44 g net, 144x35x35, Hg 1.4 mg
OSRAM DULUX S, two pin G23, 7 W/840, 25 g net, 137x22x35, Hg 1.4 mg; 9 W/827, 29 g net, 167x22x35, Hg 1.4 mg; 11 W/830, 38 g net, 237x22x35, Hg 1.4 mg
OSRAM DULUX S, four pin 2G7, 7 W/827, 22 g net, 114x22x38, Hg 1.4 mg; , 9 W/830, 26 g net, 144x22x38, Hg 1.4 mg; 11 W/865, 35 g net, 220x22x38, Hg 3.0 mg
OSRAM DULUX L, four pin 2G11, 18 W/827, 55 g net, 217x28x44, Hg 2.1 mg
OSRAM DULUX F, four pin 2G10, 18 W/827, 73 g net, 122x24x85, Hg 2.5 mg

[319] http://www.lighting.philips.com/main/prof" \l "pfpath=0-EP01_GR-EP01LCFN_CA
MASTER PL-R Eco 4 pin GR14q, 14W 127x42; 17W 142x42, 1.4 mg Hg
MASTER PL-S 2 pin G23, 7W 135x30x15; 9W 167x30x15; 11W 236x30x15, 1.4 mg Hg
MASTER PL-S 4 pin 2G7, 7W 119x30x15; 9W 151x30x15; 11W 220x30x15, 1.4 mg Hg
MASTER PL-C 4 pin G24q, 10W 110x30x30; 13W 132x30x30; 18W 144x30x30, 1.4 mg Hg
MASTER PL-T 2 pin GX24-d, 13W 114x41x41; 18W 119x41x41; 26W 134x41x41, 1.4 mg Hg

6.3.5. LFL T8 tri-phosphor

The reference power (EU-28 average) for this base case is 30W, and this corresponds to tubes of 900 mm length. For these lamps, the following weight information has been found [320]:

- Net weight 131 g (GE [321])
- Net weight 160 g (Leboom [322])
- Gross weight including primary packaging 126 g (Osram [323])
- Gross weight including primary packaging 147 g (GE)
- Gross weight including shipment packaging 156 g (Osram)
- Gross weight including shipment packaging 162 g (Radium [324])
- Gross weight including shipment packaging 200 g (Leboom)

The 131 g net lamp weight from GE has been used for this base case. The total packaging weight per lamp is estimated to be 40 g (inclusive secondary and tertiary packaging) and this is all assumed to be paper-based material [325] [326].

Considering the 26 mm diameter of the T8 tubes, the net enveloping box volume for a 900 mm lamp is 0.61 dm^3. The gross shipping volume per lamp according to Radium is 0.85 dm^3, while Osram data would lead to 1.4 dm^3. The latter value would be in line with the data from par. 7.2, but is anyway judged as too high. A value of 1 dm^3 will be used in the EcoReports. For examples of LFL packaging, see [327].

The various sources (GE, Osram, Radium) report a mercury content per lamp between 2.5 and 3.3 mg. Where amalgams are used instead of liquid mercury, they can be Zn-Hg (50%-50%), Sn-Hg or, for special applications, contain In, Bi, Pb, and Ag [328]. Directive 2011/65/EU (RoHS2) sets a limit of 3.5 mg for LFL T8t since 31 December 2011 [329]. A value of 3.0 mg has been used for the BoM, but older lamps are assumed to contain 4 mg.

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[320] These data should be used with caution: weight data in the lamp documentation are not always clear (net weight or gross weight; what packaging is included) and in numerous occasions errors have been encountered.

[321] General Electric T8 @FT8/30W/830/GE/SL1/25, 30W, 895 mm, 131 g net, 147 g gross, 2.5 mg Hg, http://catalog.gelighting.com/lamp/linear-fluorescent/t8-tubes/d=0/?r=emea

[322] http://leboomzj.ecol.xyz/products/energy-saving-fluorescent/p440238/t8-triphosphor-fluorescent-lamp.html

[323] Osram Lumilux T8 L 30W/827, 895 mm, 2.5 mg Hg, 126 g 0.66 dm3 gross incl. sleeve, 156 g 1.4 dm3 gross incl. 1/25 of shipping box, http://www.osram.com/osram_com/products/lamps/fluorescent-lamps/fluorescent-lamps-t8/index.jsp

[324] Bonalux® NL-T8 30W/840/G13, 895 mm, 162 g 0.85 dm3 gross incl. 1/25 of shipping box, 2.5 mg Hg, http://www.radium.de/en/product-catalogue/fluorescent-lamps-t8

[325] This is considerably lower than what could be derived from par. 7.2, Figure 38, but the information there is not specific for LFL's. The impression is that blister-like packages in PET are hardly being used for LFL's. Additional weight for on-line sales as considered in par. 7.2 seems also less applicable to LFL's.

[326] If it is decided, in future, to increase the average power for this base case, the typical tube length would become 1200 mm (32W energy saver, or 36W standard), which is indicated in par. 5.4.1 as the most popular length. In that case the net tube weight would become 160-180 g.

[327] Some examples of LFL packaging
http://www.alibaba.com/product-detail/led-flourescent-T8-tube-with-Paper_1029626363.html
http://www.alibaba.com/product-detail/Linear-T8-Fluorescent-Lamp-Tube_227031951.html
http://creativecolordisplay.com/products/lamp-bulb-wrappers/
http://bestinpackaging.com/2014/09/29/whats-new-in-blisters-and-clamshells/

[328] http://www.aplmaterials.com/products/amalgams/fluorescent_products

[329] Task 1 report par. 5.1.14

Reference information regarding the bill-of-materials for LFL's is scarce. Tähkämö (2013) presents a BoM for a 49W T5 lamp [330], which is based on an ELC-publication [331] (not clear if this is for T8 or T5). Both sources consider a total lamp weight of 120 g of which 115 is glass. The large percentage of the glass tube in the total weight is confirmed by a Philips publication (96%) [332] and by the VITO 2007 study on office lighting (133 g glass on 140 g total lamp weight for a 36W T8 lamp).

As regards the phosphor, the same Philips publication [332] states that it is around 2.5% of the total weight. Around 28% of this weight consists of rare earth elements [333]. For the phosphor composition see also par. 2.3.3.

The electrode construction for a fluorescent lamp is complex [334], and limited information is available as regards the types of materials and their weights. Tungsten filaments are used, and their weight could be 10-20 mg [335]. These filaments are coated with a so called emission mix, which is a mixture of Barium- Strontium- and Calcium-Oxide (obtained from the carbonates of these materials) [334] [336]. The lead wires can be in dumet [337], which has a special composition involving copper, nickel, steel and a borated surface finish, that is studied to maintain a good sealing on glass.

The bill-of-materials in EcoReport format is presented in Table 54.

Table 54: Bill-of-Materials for LFL T8 tri-phosphor (without control gear). The same data are used for T8 halo-phosphor, except that phosphor composition is different.

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Glass-tube (soda-lime)	123.140	7-Misc.	55 -Glass for lamps	
Caps (aluminium)	3.000	4-Non-ferro	27 -Al sheet/extrusion	
Phosphor (tri-phospor)	3.275			
Resin glue / potting	0.500	2-TecPlastics	15 -Epoxy	
Electrode (tungsten)	0.020			
Electrode coating (BaO, SrO, CaO)	0.001			
Lead wires (dumet, Ni, Cu, Fe) and other metal parts	0.560	4-Non-ferro	30 -Cu wire	
Mercury (or amalgam, Hg, Zn, Sn, Bi, In, Pb, Ag))	0.003			
Noble gases (Ar, Kr, Ne, Xe)	0.500			
Subtotal lamp	131.000			
packaging cardboard/paper	40.0	7-Misc.	57 -Cardboard	

330 Leena Tähkämö, 2013, Life cycle assessment of light sources –Case studies and review of the analyses http://lib.tkk.fi/Diss/2013/isbn9789526052502/isbn9789526052502.pdf, see also: "Life cycle assessment of a fluorescent lamp luminaire used in industry – a case study", Leena Tähkämö et al, Lighting Res. Technol. 2014; Vol. 46: 453–464, http://lrt.sagepub.com/content/46/4/453.full.pdf

331 http://www.elcfed.org/2_lighting_composition.html

332 http://www.usa.lighting.philips.com/pwc_li/us_en/connect/tools_literature/downloads/Fluorescent-T8-Lamps-LMDS-TL8-13100.pdf

333 Sustainable processes development for recycling of fluorescent phosphorous powders – rare earths and mercury separation, Cristian Tunsu, Teodora Retegan, Christian Ekberg, Chalmers University of Technology, Gothenburg, Sweden, 2011, http://publications.lib.chalmers.se/records/fulltext/local_157270.pdf

334 See for example: http://www.osram.com/media/resource/HIRES/349830/7129720/single-and-double-capped-fluorescent-lamps-english-part-1.pdf , pages 57 and 154

335 http://www.itia.info/an-element-of-lighting.html . The mass of 10-20 mg is reported for CFL's, but it is not expected to be less in LFL's.

336 In other sources zirconium oxide (ZrO) and Silicon Carbide (SiC) are also mentioned as materials for coating of the electrodes (LCA of ultra-efficient lamps, Navigant 2009)

337 http://www.dumet.net/

6.3.6. LFL T8 halo-phosphor

No specific information is available regarding the bill-of-materials for LFL T8 halo-phosphor lamps. Consequently the same BoM is used as presented in Table 54, but:

- The composition of the phosphor differs, see par. 2.3.3 and [338], containing antimony (Sb) but not containing rare earth elements. A mass of 2.3 g Sb per kg phosphor powder is assumed [339], which implies (2.3*1000)*(3.275/1000) = 7 mg Sb per lamp.
- The allowed mercury content of halo-phosphor lamps under the new Directive 2011/65/EU (RoHS2) is zero. In fact, only old lamps still exist, and it is assumed that these have a mercury content below the 10 mg limit of the previous Directive 2002/95/EC (RoHS): 8 mg has been used in the BoM.

6.3.7. LFL T12

No specific information is available regarding the bill-of-materials for LFL T12. The same BoM is used as for LFL T8h, but scaling values in function of the difference in diameter.

The bill-of-materials in EcoReport format is presented in Table 55.

Table 55: Bill-of-Materials for LFL T8 tri-phosphor (without control gear). The same data are used for T8 halo-phosphor, except that phosphor composition is different.

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Glass-tube (soda-lime)	184.710	7-Misc.	55 -Glass for lamps	
Caps (aluminium)	5.625	4-Non-ferro	27 -Al sheet/extrusion	
Phosphor (halo-phosphor)	4.913			
Resin glue / potting	0.750	2-TecPlastics	15 -Epoxy	
Electrode (tungsten)	0.020			
Electrode coating (BaO, SrO, CaO)	0.001			
Lead wires (dumet, Ni, Cu, Fe) and other metal parts	0.560	4-Non-ferro	30 -Cu wire	
Mercury	0.008			
Noble gases (Ar, Kr)	1.125			
Subtotal lamp	197.712			
packaging cardboard/paper	60.0	7-Misc.	57 -Cardboard	

6.3.8. LFL T5

The reference power (EU-28 average) for this base case is 25W. This does not correspond to a precise tube length (and corresponding weight), as illustrated by the following data:

- Osram Lumilux T5 HO ES 20W, tube length: 549 mm [340]
- Osram Lumilux T5 HO 24W, tube length: 549 mm
- Philips HO Eco 20W, tube length: 549 mm [341]

[338] https://www.electrochem.org/dl/interface/sum/sum98/IF6-98-Page28-31.pdf
[339] http://www.epa.gov/ttncatc1/dir1/mercury.txt
[340] http://www.osram.com/osram_com/products/lamps/fluorescent-lamps/fluorescent-lamps-t5/index.jsp
[341] http://download.p4c.philips.com/l4bt/3/310750/master_tl5_high_efficiency_eco_310750_ffs_aen.pdf
http://download.p4c.philips.com/l4bt/3/322859/master_tl5_high_output_eco_322859_ffs_aen.pdf

- Bonalux NL-T5 24W, tube length: 549 mm [342]
- GE T5 HO LongLast 24W, tube length: 549 mm [343]
- Osram Lumilux T5 HO ES 34W, tube length: 849 mm
- Philips HE Eco 19W, tube length: 849 mm
- Philips HO Eco 34W, tube length: 849 mm
- Bonalux NL-T5 21W, tube length: 849 mm
- Bonalux NL-T5 39W, tube length: 849 mm
- Osram Lumilux T5 HE ES 25W, tube length: 1149 mm
- Osram Lumilux T5 HE 28W, tube length: 1149 mm
- Philips HE Eco 28W, tube length: 1149 mm
- Bonalux NL-T5 28W, tube length: 1149 mm
- GE T5 Watt-Miser 26W, tube length: 1150 mm
- GE T5 HE LongLast 28W, tube length: 1150 mm

A 25W LFL T5 can have a tube length ranging from slightly above 550 mm to 1150 mm. As a compromise, a length of 850 mm is considered as the average for the base case.
For this tube length, the following weight information has been found:

- Net weight 77 g (GE)
- Net weight 86 g (Osram)
- Gross weight including primary packaging 100 g (GE)
- Gross weight including primary packaging 82-92 g (Osram)
- Gross weight including shipment packaging 105-107 g (Osram)
- Gross weight including shipment packaging 120 g (Radium)

On the basis of this information, a net lamp weight of 80 g has been used. The total package weight is taken to be 30 g (inclusive secondary and tertiary packaging) and this is all assumed to be paper-based material [344] [345].

Considering the 16 mm diameter of the T5 tubes, the net enveloping box volume for a 850 mm lamp is 0.22 dm^3. The gross shipping volume per lamp according to Radium is 0.44 dm^3, while Osram data would lead to 0.38-0.44 dm^3. A value of 0.44 dm^3 will be used in the EcoReports.

Osram, Philips and Radium report a mercury content per lamp between 1.4 and 1.9 mg. GE reports a slightly higher value: 2.5 mg. Directive 2011/65/EU (RoHS2) sets a limit of 3.0 mg for LFL T5 since 31 December 2011 [346]. A value of 2.0 mg has been used for the BoM, but older lamps are assumed to contain 3.0 mg. Where amalgams are used instead of liquid mercury, they can be Zn-Hg (50%-50%), Sn-Hg or, for special applications, contain In, Bi, Pb, and Ag [347].

Reference information regarding the bill-of-materials is the same as reported in par. 6.3.5 for LFL T8t, showing that glass accounts for more than 95% of the weight. The

[342] http://www.radium.de/en/product-catalogue/fluorescent-lamps-t5
[343] http://catalog.gelighting.com/lamp/linear-fluorescent/t5-tubes-long/d=0/?r=emea
[344] This is considerably lower than what could be derived from par. 7.2, Figure 38, but the information there is not specific for LFL's. The impression is that blister-like packages in PET are hardly being used for LFL's. Additional weight for on-line sales as considered in par. 7.2 seems also less applicable to LFL's.
[345] If it is decided, in future, to increase the average power for this base case, the typical tube length would become 1200 mm (28W HE), which is indicated in par. 5.4.1 as the most popular length. In that case the net tube weight would become 100-110 g.
[346] Task 1 report par. 5.1.14
[347] http://www.aplmaterials.com/products/amalgams/fluorescent_products

VITO 2007 study on office lighting considered a mass of 105 g of which 100 g glass, for a 28W LFL T5.

As regards the phosphor and the electrode construction, the same remarks apply as in par. 6.3.5.
The bill-of-materials in EcoReport format is presented in Table 56.

Table 56: Bill-of-Materials for LFL T5 (without control gear).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Glass-tube (soda-lime)	75.200	7-Misc.	55 -Glass for lamps	
Caps (aluminium)	1.723	4-Non-ferro	27 -Al sheet/extrusion	
Phosphor (tri-phosphor)	2.000			
Resin glue / potting	0.300	2-TecPlastics	15 -Epoxy	
Electrode (tungsten)	0.020			
Electrode coating (BaO, SrO, CaO)	0.001			
Lead wires (dumet, Ni, Cu, Fe) and other metal parts	0.560	4-Non-ferro	30 -Cu wire	
Mercury (or amalgam, Hg, Zn, Sn, Bi, In, Pb, Ag))	0.002			
Noble gases (Ar, Kr, Ne, Xe)	0.195			
Subtotal lamp	80.002			
packaging cardboard/paper	30.0	7-Misc.	57 -Cardboard	

6.3.9. LFL X (T5 4-13W mini and other special)

This base case contains various types of lamps and consequently it is not straightforward to define a BoM. As the base case is of minor importance, it is assumed that a miniature LFL T5 of 13 W can be a reasonable representative.

From data in the GE lamp catalogue [348] it can be derived that the typical lamp length is 517 mm with a net weight of 47 g and a gross weight of 53 g (probably including primary packaging only). The total package weight is taken to be 20 g (inclusive secondary and tertiary packaging) and this is all assumed to be paper-based material.

Considering the 16 mm diameter of the T5 tubes, the net enveloping box volume for a 517 mm lamp is 0.13 dm^3. The gross shipping volume per lamp is assumed to be approximately double: a value of 0.26 dm^3 will be used in the EcoReports.

The same bill-of-materials as for LFL T5 is used, but scaling values considering the difference in tube length (517/850) where applicable.
The bill-of-materials in EcoReport format is presented in Table 57.

Table 57: Bill-of-Materials for LFL X (without control gear).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Glass-tube (soda-lime)	43.0593	7-Misc.	55 -Glass for lamps	
Caps (aluminium)	1.7234	4-Non-ferro	27 -Al sheet/extrusion	
Phosphor (tri-phosphor)	1.2165			

[348] http://catalog.gelighting.com/lamp/linear-fluorescent/t5-tubes-short/d=0/?r=emea, T5 Miniature – Standard, F13W/29/T5/GE/SL 1/25 MIC and T5 Miniature - Triphosphor, F13W/827/T5/GE/SL 1/25 MIC

Table 57: Bill-of-Materials for LFL X (without control gear).				
Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Resin glue / potting	0.3000	2-TecPlastics	15 -Epoxy	
Electrode (tungsten)	0.0200			
Electrode coating (BaO, SrO, CaO)	0.0010			
Lead wires (dumet, Ni, Cu, Fe) and other metal parts	0.5600	4-Non-ferro	30 -Cu wire	
Mercury (or amalgam, Hg, Zn, Sn, Bi, In, Pb, Ag))	0.0020			
Noble gases (Ar, Kr, Ne, Xe)	0.1188			
Subtotal lamp	47.001			
packaging cardboard/paper	20.0	7-Misc.	57 -Cardboard	

6.3.10. HPM (high-pressure mercury lamps)

The reference power (EU-28 average) for this base case is 250W. Lamps of this power have the following approximate characteristics [349]:

- Net weight 160 g.
- Gross weight 248 g (shipping box 2980 g / 12 lamps)
- Diameter 91 mm; length 211-230 mm, net volume 1.9 dm^3.
- Gross shipping volume 2.5 dm^3 (shipping box 30.4 dm^3 / 12 lamps).
- Mercury content 38-39 mg / lamp.

The only available reference for the BoM of these lamps is the VITO 2007 study on street lighting, where data from lamp manufacturers were obtained for a 125W lamp (total 71g) and a 400W lamp (total 229 g). These data have been interpolated and scaled to obtain those for the 250 W (total 160 g) lamp.

The bill-of-materials in EcoReport format is presented in Table 58.

Table 58: Bill-of-Materials for HPM (without control gear).				
Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Outer bulb, lead-free glass	114.855	7-Misc.	55 -Glass for lamps	
Stem tube, lead-free glass	10.012	7-Misc.	55 -Glass for lamps	
Lead-in (Ni, Fe, Cu, W)	2.706	4-Non-ferro	30 -Cu wire	
Coating (Yt,V,P&B oxides)	0.303	5-Coating	40 -powder coating	
Resistor (MgO,Ni,Cu,Mo)	0.994	4-Non-ferro	30 -Cu wire	
Filling gas (Ar, Ne)	0.000			
Envelope (quartz glass)	8.948	7-Misc.	55 -Glass for lamps	
Lead-in (Molybdene)	0.028	4-Non-ferro	30 -Cu wire	
Electrode&Emittor (Tungsten&Ba/Ca/Yt oxide)	0.479	4-Non-ferro	30 -Cu wire	
Filling, mercury	0.038			
Cap, brass and glass-frit	13.026	4-Non-ferro	32 -CuZn38 cast	
Solder, Sn,Pb,Sb	8.565	6-Electronics	53 -Solder SnAg4Cu0.5	
Subtotal lamp	159.954			
packaging cardboard/paper	90.0	7-Misc.	57 -Cardboard	

[349] http://www.osram.com/osram_com/products/lamps/high-intensity-discharge-lamps/mercury-vapor-lamps-for-open-and-enclosed-luminaires/hql/index.jsp
http://download.p4c.philips.com/l4bt/3/332443/mercury_vapor_standard_332443_ffs_aen.pdf
http://www.havells-sylvania.com/en_GB/products/0020429

6.3.11. HPS (high-pressure sodium lamps)

The reference power (EU-28 average) for this base case is 140W. There are elliptical-shaped or tubular-shaped lamps with this power (150W used as reference), with slightly different dimensions and weights [350].

For the tubular shape:

- Net weight 120-150 g
- Gross weight 180-210 g (including portion of shipping box)
- Diameter 47 mm; length 209-226 mm, net volume 0.47 dm^3.
- Gross shipping volume 1.4 dm^3 (shipping box 17 dm^3 / 12 lamps).
- Mercury content 13-20 mg / lamp.

For the elliptical shape:

- Net weight 150-200 g
- Gross weight 200-260 g (including portion of shipping box)
- Diameter 91 mm; length 226 mm, net volume 1.9 dm^3.
- Gross shipping volume 3 dm^3 (shipping box 36 dm^3 / 12 lamps).
- Mercury content 13-24 mg / lamp.

An average net lamp weight of 158 g containing 20 mg mercury has been used in the BoM, which are the same data used in the 2007 VITO study on street lighting. The package weight has been taken 60 g, assumed to be all paper-based material.

The main reference for the BoM of these lamps is the same 2007 VITO study on street lighting, where data from lamp manufacturers were obtained for a 150W lamp (total 158 g). These data are very similar to those in an ELC publication [351] and most likely have the same origin.

The bill-of-materials in EcoReport format is presented in Table 59.

Table 59: Bill-of-Materials for HPS (without control gear).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Envelope_Glass	96.550	7-Misc.	55 -Glass for lamps	
Stem tube_Glass	10.390	7-Misc.	55 -Glass for lamps	
Lead wires_Low carbon steel	5.470	3-Ferro	26 -Stainless 18/8 coil	
Tube_Si, B, Al, Na, K, Mg, Ca, Ba, -oxides	3.200	5-Coating	41 -Cu/Ni/Cr plating	
Getter_Zr, Al, Fe	0.380	4-Non-ferro	28 -Al diecast	
Burner_PCA (Poly Crystallyne Aluminium Oxide)	6.750	4-Non-ferro	27 -Al sheet/extrusion	

[350] http://www.osram.com/osram_com/products/lamps/high-intensity-discharge-lamps/high-pressure-sodium-vapor-lamps-for-open-and-enclosed-luminaires/vialox-nav-e/index.jsp
http://www.osram.com/osram_com/products/lamps/high-intensity-discharge-lamps/high-pressure-sodium-vapor-lamps-for-open-and-enclosed-luminaires/vialox-nav-t/index.jsp
http://download.p4c.philips.com/l4bt/3/344246/master_son_apia_plus_xtra_344246_ffs_aen.pdf
http://download.p4c.philips.com/l4bt/3/322832/son-t_322832_ffs_aen.pdf
http://www.havells-sylvania.com/en_GB/products/0020740
http://www.havells-sylvania.com/en_GB/products/0020739
http://catalog.gelighting.com/lamp/high-intensity-discharge/high-pressure-sodium-lamps/f=lucalox-xo-elliptical-diffuse/p=93380/d=0/?r=emea
http://catalog.gelighting.com/lamp/high-intensity-discharge/high-pressure-sodium-lamps/f=lucalox-xo-tubular-clear/p=93377/d=0/?r=emea

[351] http://www.elcfed.org/2_lighting_composition.html

Table 59: Bill-of-Materials for HPS (without control gear).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Burner_Amalgam_Hg, Na	0.020			
Burner_Electrode&Emittor_Tungsten &Ba,Y,W-oxides	0.790	4-Non-ferro	30 -Cu wire	
Burner_Frit ring_Ca, Ba, Al-oxides	0.050			
Burner_Niobium Tube	1.450			
Cap E40_Brass and glass-frit	25.690	4-Non-ferro	32 -CuZn38 cast	
Cap E40_Solder_Sn, Pb, Sb	4.100	6-Electronics	53 -Solder SnAg4Cu0.5	
Cap E40_Capping cement_CaCO3	2.920			
Subtotal lamp	157.760			
packaging cardboard/paper	60.0	7-Misc.	57 -Cardboard	

6.3.12. MH (metal halide lamps)

The reference power (EU-28 average) for this base case is 160W. There is a wide variety of MH-lamps with approximately this power, with different shapes and caps, and with considerable differences in volume, weight and mercury content [352] [353]:

Tubular shape with G12 cap:

- Net weight 31-34 g
- Gross weight 47-113 g (including portion of shipping box)
- Diameter 20-25 mm; length 84-105 mm, net volume 0.048 dm^3.
- Gross shipping volume 0.27-0.33 dm^3 (shipping box 3.2-4.0 dm^3 / 12 lamps).
- Mercury content 8-32 mg / lamp.

Tubular shape with RX7s cap:

- Net weight 17-74 g
- Gross weight 42-92 g (including portion of shipping box)
- Diameter 23-25 mm; length 135-138 mm, net volume 0.086 dm^3.
- Gross shipping volume 0.25-0.37 dm^3 (shipping box 3.0-4.5 dm^3 / 12 lamps).
- Mercury content 11-24 mg / lamp.

Tubular shape with E27 or E40 cap:

- Net weight 110-150 g
- Gross weight 189-222 g (including portion of shipping box)
- Diameter 47-48 mm; length 207-211 mm, net volume 0.48 dm^3.
- Gross shipping volume 1.4 dm^3 (shipping box 17.3 dm^3 / 12 lamps).
- Mercury content 4-19 mg / lamp.

Elliptic bulb shape with E27 cap:

- Net weight 79-120 g
- Gross weight 95-224 g (including portion of shipping box)
- Diameter 54-55 mm; length 137-142 mm, net volume 0.42 dm^3.
- Gross shipping volume 1.7 dm^3 (shipping box 19.4-21.3 dm^3 / 12 lamps).
- Mercury content 9-27 mg / lamp.

As regards references for the BoM:

[352] http://www.osram.com/osram_com/products/lamps/high-intensity-discharge-lamps/index.jsp
http://catalog.gelighting.com/lamp/high-intensity-discharge/metal-halide-lamps
http://www.havells-sylvania.com/en_GB/products/category/light-sources/hid
http://www.lighting.philips.com/main/prof#pfpath=0-EP01_GR-EP01LHID_CA
[353] Most of the listed data are for 150W lamps.

- The VITO 2007 street lighting study considered a 70W lamp of total 41 g of which 20 g is glass, containing 2 mg mercury [354].
- An ELC publication considered a 400W lamp of total 240 g of which 195 g is glass [355].
- A 2009 Navigant / DEFRA research considered a 20W lamp of 100 g of which 60 g is glass, containing 6 mg mercury [356].

Considering all available information, for this study a net lamp weight of 110 g has been estimated, of which approximately 70% glass. Average packaging weight is taken to be 50 g (values found vary from 16 to 120 g), and all is assumed to be paper-based material.

The gross per-lamp shipping volume for input in the EcoReports is taken as 1 dm^3 (varies from about 0.3 dm^3 for small lamps to about 1.5 dm^3 for larger lamps).

As regards mercury content, the declared values vary from 2 mg [357] to 32 mg per lamp. Metal halide lamps are exempted from the RoHS2 directive, so there is no mercury limit. An average of 10 mg mercury per lamp has been assumed.

The bill-of-materials in EcoReport format is presented in Table 60.

Table 60: Bill-of-Materials for MH-lamps (without control gear).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
BULB_Envelope_Glass	69.300	7-Misc.	55 -Glass for lamps	
BULB_Stem tube_Glass	7.600	7-Misc.	55 -Glass for lamps	
Lead wires_Low carbon steel / Mo	3.647	3-Ferro	26 -Stainless 18/8 coil	
BULB_Tube_Si, B, Al, Na, K, Mg, Ca, Ba, -oxides	2.133	5-Coating	41 -Cu/Ni/Cr plating	
BULB_Getter_Zr, Al, Fe	0.253	4-Non-ferro	28 -Al diecast	
BURNER_PCA (Poly Crystallyne Aluminium Oxide)	9.000	4-Non-ferro	27 -Al sheet/extrusion	
BURNER_Metal filling_Hg	0.010			
BURNER_Gas_ArKr	0.000			
Salt mix, including Tl, rare earths	0.004			
BURNER_Electrode_NbZr	0.267	4-Non-ferro	30 -Cu wire	
BURNER_Frit ring_AlDySi	0.013	4-Non-ferro	27 -Al sheet/extrusion	
BURNER_Niobium pen	0.307			
Cap_Brass and glass-frit	14.000	4-Non-ferro	32 -CuZn38 cast	
Cap_Solder_Sn, Pb, Sb	2.000	6-Electronics	53 -Solder SnAg4Cu0.5	
Capping cement_CaCO3	1.500			
Subtotal lamp	110.034			
packaging cardboard/paper	50.000	7-Misc.	57 -Cardboard	

[354] Preparatory Studies for Eco-design requirements of EuPs, Final Report, Lot 9: Public Street lighting, Study for the European Commission DGTREN unit D3, contact Andras Toth, by VITO in cooperation with Laborelec and Kreios, January 2007, Contract TREN/D1/40-2005/LOT9/S07.56457, available through 'eup4light.net', table 45

[355] http://www.elcfed.org/2_lighting_composition.html

[356] Life Cycle Assessment of Ultra-Efficient Lamps, Navigant Consulting Europe research report for DEFRA, May 2009

[357] http://download.p4c.philips.com/l4bt/3/322871/master_cosmowhite_cpo-tw__cpo-tw_322871_ffs_aen.pdf

6.3.13. HL MV E (substitute for GLS and reflector, with E-cap)

The reference power for these lamps is 36 W. The most detailed reference for a bill-of-materials is from Osram [358] and shows a total net weight of 24.2 g (of which 86% glass) for a 42W, 630 lm lamp with E27 cap.

This weight is more or less consistent with the 28-34 g (inclusive primary packaging) declared for 30W and 46W halogen A-bulbs in the lamp catalogue [359].

The net weight is also close to the 25-30 g of the GLS-lamps (par. 6.3.1, 6.3.2), which seems reasonable.

The gross lamp mass (including primary carton box or blister and portion of the shipping box) is 34-66 g according to the catalogue [359]. This implies a packaging weight of 10-42 g. However, for consistency with the GLS-lamps a packaging mass of 60 g is assumed, of which 90% paper-based material and 10% PET (see also par. 6.2).

For the 30W and 46W halogen A-bulbs, the gross lamp shipping volume in the Osram catalogue [359] varies from 0.28 to 0.9 dm^3 (net enveloping box volume for the 97x55 mm lamps is 0.29 dm^3). For consistency with the GLS-values, 0.75 dm^3 is used.

The bill-of-materials in EcoReport format is presented in Table 61.

Table 61: Bill-of-Materials for MV HL E-lamps.

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Outer bulb, lead-free glass	14.740	7-Misc.	55 -Glass for lamps	
Flare, lead-free glass (SiO_2, BaO)	1.140	7-Misc.	55 -Glass for lamps	
Burner bulb (glass, SiO_2)	2.850	7-Misc.	55 -Glass for lamps	
Exhaust tube, lead-free glass (SiO_2, BaO)	0.470	7-Misc.	55 -Glass for lamps	
Filament (tungsten)	0.003			
Lead wires (dumet, FeNi42Cu)	0.050	3-Ferro	26 -Stainless 18/8 coil	
Pins (molybdenum)	0.050			
Clip (1.4310, Fe)	0.320	3-Ferro	26 -Stainless 18/8 coil	
Cap, shell (Al)	1.170	4-Non-ferro	27 -Al sheet/extrusion	
Cap, shell (Cu, Zn, plating)	0.120	5-Coating	41 -Cu/Ni/Cr plating	
Cap, insulator (glass)	1.610	7-Misc.	55 -Glass for lamps	
Cement ($CaCO_3$)	1.450			
Soft solder (Sn)	0.200	6-Electronics	53 -Solder SnAg4Cu0.5	
Gas fillings	0.040			
Subtotal lamp	24.213			
packaging cardboard/paper	54.000	7-Misc.	57 -Cardboard	
packaging plastic	6.0	1-BlkPlastics	10 -PET	Yes

[358] http://www.osram.com/osram_com/sustainability/environmental/product-lifecycle-management/lca-of-a-halogen-lamp/index.jsp and http://www.osram.com/media/resource/HIRES/333051/82511/osram-material-declaration-sheet_hal.pdf

[359] http://www.osram.com/osram_com/products/lamps/halogen-lamps/halogen-classic/classic-superstar-a/index.jsp

6.3.14. HL MV X (PAR 16/20/25/30 Hard glass reflectors, GU10 etc.)

This base case collects 'other mains-voltage halogen lamps' and is therefore heterogeneous by definition, but it is expected to contain mainly directional lamps with a GU10 or GZ10 cap [360]. The reference power for these lamps is 35 W.

Based on the database used for the MV DLS Market Study [361], taking into account GU10 halogen lamps with powers between 25 and 42W, the average net weight of these lamps is 45 g. This might be slightly overestimated because the weights of some lamps in the database include the primary packaging weight.

The VITO 2009 Lot19 study used a net weight of 37.5 g of which 36 g for glass and 1.5 g for the connector pins.

As a compromise, and in absence of other data, a net weight of 40 g is used.

The BoM used in this study is largely based on the one used for MV HL E in the previous paragraph, maintaining the masses for the 'heart' of the lamp, substituting the E-cap by a GU10 cap, and adapting the glass weight such that the desired total weight is obtained.

The GU10 lamps have typical dimensions of 55x50 mm (length x diameter) and are thus considerably smaller than the MV HL E lamps discussed in the previous paragraph. Packaging weight is therefore estimated as 40 g (instead of 60 g) and gross shipping volume as 0.4 dm^3 (instead of 0.75 dm^3).

The bill-of-materials in EcoReport format is presented in Table 62.

Table 62: Bill-of-Materials for MV HL X-lamps.

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Outer bulb, lead-free glass	32.700	7-Misc.	55 -Glass for lamps	
Flare, lead-free glass (SiO2, BaO)	1.140	7-Misc.	55 -Glass for lamps	
Burner bulb (glass, SiO2)	2.850	7-Misc.	55 -Glass for lamps	
Exhaust tube, lead-free glass (SiO2, BaO)	0.470	7-Misc.	55 -Glass for lamps	
Filament (tungsten)	0.003			
Lead wires (dumet, FeNi42Cu)	0.050	3-Ferro	26 -Stainless 18/8 coil	
Pins (molybdenum)	0.050			
Reflector coating	0.000			
Connector pins	1.500	4-Non-ferro	30 -Cu wire	
Cement (CaCO3)	1.000			
Soft solder (Sn)	0.200	6-Electronics	53 -Solder SnAg4Cu0.5	
Gas fillings	0.040			
Subtotal lamp	40.003			
packaging cardboard/paper	36.000	7-Misc.	57 -Cardboard	
packaging plastic	4.0	1-BlkPlastics	10 -PET	Yes

[360] As regards PAR-lamps with E-caps, it is uncertain if their sales quantities have been counted in the HL MV E group or in the HL MV X group. At the data origin this depends on how lamp manufacturers accounted this in their data supply to LightingEurope.

[361] Market assessment on directional mains voltage filament lamps related to stage 3 of Commission Regulation (EU) No. 1194/2012, VHK for the European Commission, April 2015.

6.3.15. HL MV L (R7s)

The reference power for these lamps is 250 W. They typically have a diameter of 8-12 mm and a length of 114-120 mm [362]. Net weight declarations vary from 7 to 10 g. Weights inclusive primary packaging from 15 to 21 g. The gross shipping volume per lamp can be estimated as 0.27 dm^3.

There is no reference information as regards the BoM for these lamps, so it has been based on the one for other halogen lamps, taking into account a net weight of 10 g, a packaging weight of 20 g (inclusive shipment packaging), the absence of an outer glass bulb, and the considerably longer filament. No information could be found regarding the type of material used for the end caps of the lamp; this has been assumed to be glass as well.

The bill-of-materials in EcoReport format is presented in Table 63.

Table 63: Bill-of-Materials for MV HL L-lamps (linear R7s).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Tube glass	6.000	7-Misc.	55 -Glass for lamps	
Caps, glass	3.000	7-Misc.	55 -Glass for lamps	
Filament (tungsten)	0.020			
Lead wires (dumet, FeNi42Cu)	0.050	3-Ferro	26 -Stainless 18/8 coil	
Foils (molybdenum)	0.250			
Support wires (molybdenum)	0.050			
Caps, contacts (Al)	0.250	4-Non-ferro	27 -Al sheet/extrusion	
Caps, plating (Cu, Zn)	0.050	5-Coating	41 -Cu/Ni/Cr plating	
Cement (CaCO3)	0.250			
Soft solder (Sn)	0.050	6-Electronics	53 -Solder SnAg4Cu0.5	
Gas fillings	0.030			
Subtotal lamp	10.000			
packaging cardboard/paper	18.000	7-Misc.	57 -Cardboard	
packaging plastic	2.0	1-BlkPlastics	10 -PET	Yes

6.3.16. HL MV C (G9)

The reference power for these lamps is 35 W. They typically have a diameter of 13-14 mm and a length of 43-44 mm [363]. Net weight declaration is around 4 g. Weights inclusive primary packaging range from 6 to 14 g; inclusive shipment packaging from 12 to 22 g. The gross shipping volume per lamp can be estimated as 0.15-0.3 dm^3.

Measurements by the study team resulted in a total mass of 3.56 g (matches declared 4 g), of which 3.44 g for glass.

There is no reference information as regards the BoM for these lamps, so it has been based on those for other halogen lamps, taking into account a net weight of 3.56 g and a packaging weight of 15 g (inclusive shipment packaging).

[362] http://www.osram.com/osram_com/products/lamps/halogen-lamps/haloline/haloline-superstar/index.jsp
http://download.p4c.philips.com/l4bt/3/323050/plusline_es_small_323050_ffs_aen.pdf
http://www.havells-sylvania.com/en_GB/products/0021717
http://catalog.gelighting.com/lamp/halogen/halogen-linear/f=halogen-linear/p=64968/d=0/?r=emea

[363] http://www.osram.com/osram_com/products/lamps/halogen-lamps/halopin/halopin-superstar/index.jsp
http://catalog.gelighting.com/lamp/halogen/halogen-capsule/f=g9-mains-voltage/p=97278/d=0/?r=emea
http://www.havells-sylvania.com/en_GB/products/0023752

The bill-of-materials in EcoReport format is presented in Table 64Table 63.

Table 64: Bill-of-Materials for MV HL C-lamps (capsule G9).				
Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Tube glass	3.440	7-Misc.	55 -Glass for lamps	
Filament (tungsten)	0.003			
Lead wires (dumet, FeNi42Cu)	0.020	3-Ferro	26 -Stainless 18/8 coil	
Foils (molybdenum)	0.055			
Contact wires	0.040	4-Non-ferro	30 -Cu wire	
Soft solder (Sn)	0.001	6-Electronics	53 -Solder SnAg4Cu0.5	
Gas fillings	0.001			
Subtotal lamp	3.560			
packaging cardboard/paper	13.500	7-Misc.	57 -Cardboard	
packaging plastic	1.5	1-BlkPlastics	10 -PET	Yes

6.3.17. HL LV C (G4, GY6.35)

The reference power for these lamps is 35 W. Lamps with this power typically have a GY6.35 cap, diameter of 10.5-12 mm and length 44 mm [364]. Net weight declarations vary from 2 to 12 g, but probably the lower value is more correct. Weights inclusive primary packaging range from 4 to 16 g; inclusive shipment packaging from 6 to 20 g. The gross shipping volume per lamp is reported as 0.05-0.32 dm^3.

By lack of reference information, the same BoM is used as for the MV G9 capsules, but using 2/3 of the glass weight.

The bill-of-materials in EcoReport format is presented in Table 65Table 63.

Table 65: Bill-of-Materials for LV HL C-lamps (capsule G4, GY6.35) (without transformer).				
Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Tube glass	2.293	7-Misc.	55 -Glass for lamps	
Filament (tungsten)	0.003			
Lead wires (dumet, FeNi42Cu)	0.020	3-Ferro	26 -Stainless 18/8 coil	
Foils (molybdenum)	0.055			
Contact wires	0.040	4-Non-ferro	30 -Cu wire	
Soft solder (Sn)	0.001	6-Electronics	53 -Solder SnAg4Cu0.5	
Gas fillings	0.001			
Subtotal lamp	2.413			
packaging cardboard/paper	13.500	7-Misc.	57 -Cardboard	
packaging plastic	1.5	1-BlkPlastics	10 -PET	Yes

[364] http://catalog.gelighting.com/lamp/halogen/halogen-capsule/f=low-voltage-capsule-axial-filament/p=35699/d=0/?r=emea
http://www.osram.com/osram_com/products/lamps/halogen-lamps/halostar/index.jsp

6.3.18. HL LV R (MR16 with GU5.3 cap)

The reference power for these lamps is 35 W. There are three main lamp shapes with this power [365]:

- MR11 with GU4 cap, 41x35 mm, 12-35 g net weight, 16-46 gross weight,
- MR16 with GU5.3 cap, 46x51 mm, open or closed model, 15-38 g net weight, 45-52 gross weight (including primary packaging).
- AR111 with G5.3 cap, 67x111 mm, 50 g net weight, 94 g gross weight.

The largest group are expected to be the MR16 lamps, and the lower MR11 weights could compensate the higher AR111 weights.
The VITO 2009 study used a total lamp weight of 30 g of which 29 g for glass. This seems a reasonable estimate. In absence of other reference information, the BoM for these LV reflector lamps has been compiled considering the BoMs for the LV capsules and for the MV reflector lamps, adapting the outer bulb glass weight to obtain a total lamp net weight of 30 g.

The bill-of-materials in EcoReport format is presented in Table 66.

Table 66: Bill-of-Materials for HL LV R-lamps (LV reflectors)(without transformer).

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Outer bulb, lead-free glass	26.750	7-Misc.	55 -Glass for lamps	
Inner capsule, glass	2.290	7-Misc.	55 -Glass for lamps	
Filament (tungsten)	0.003			
Lead wires (dumet, FeNi42Cu)	0.022	3-Ferro	26 -Stainless 18/8 coil	
Foils (molybdenum)	0.055			
Reflector coating	0.000			
Connector pins	0.500	4-Non-ferro	30 -Cu wire	
Cement (CaCO3)	0.250			
Soft solder (Sn)	0.100	6-Electronics	53 -Solder SnAg4Cu0.5	
Gas fillings	0.030			
Subtotal lamp	30.000			
packaging cardboard/paper	27.000	7-Misc.	57 -Cardboard	
packaging plastic	3.000	1-BlkPlastics	10 -PET	Yes

6.3.19. LED retrofit lamps

This base case intends to cover all LED retrofit lamps. In the modelling, these LED lamps will substitute less efficient non-LED lamps (from the other base cases, with known average lumens) on the basis of an approximate lumen equivalence. The basic idea is therefore to develop a bill-of-materials for LED retrofit lamps per unit of lumen, i.e. per 1000 lm (klm). Such a BoM could then be scaled in function of the lumens of the lamp that is being substituted.
Due to the variety of LED lamp models, due to the fast technological developments, and due to the variety of materials used, the development of a bill-of-material for a LED lamp is a real challenge.

365 http://www.osram.com/osram_com/products/lamps/halogen-lamps/decostar/index.jsp
http://catalog.gelighting.com/lamp/halogen/halogen-reflector-low-voltage/d=0/?r=emea

Lamp weight per kilo-lumen

The first aspect that was examined is the lamp weight per kilo-lumen.

The database used for the market assessment on mains-voltage directional lamps [222] contains 341 directional LED lamps with lamp weight data. The bottom part of Figure 46 shows the lamp weight in grams/klm in function of the lamp lumens. The top part of the same figure shows the number of lamps within a given grams/klm interval.

For the 122 lamps with E14 or E27 cap, weights range from 88 to 881 g/klm with an average of 251 g/klm. For the 219 lamps with GU10 cap, values range from 80 to 600 g/klm with an average of 217 g/klm. The median of all lamps is approximately 225 g/klm.

These data are for directional lamps, where the luminous flux is measured in a 90° or 120° cone, while for the modelling in this study the full luminous flux will be used. In addition, some of the declared lamp weights include packaging weight. From catalogue data that report both the total luminous flux and the cone flux, it can be estimated that the former is approximately 20% higher. Consequently it is estimated that 185 g/klm could be a reasonable average for directional LED lamps.

A similar research was conducted for LED retrofit lamps for classic NDLS bulbs. This survey is shown in Table 67. The average value of 25 lamp models is 173 g/klm and consequently close to the value derived for the directional lamps.

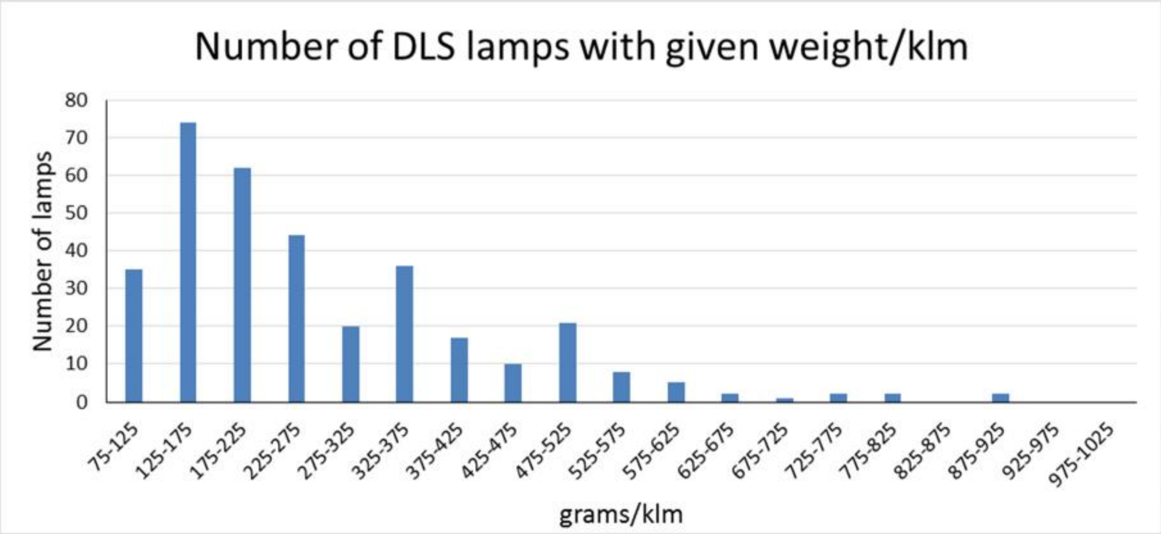
There is a considerable spread in values however, from 58 to 332 g/klm. In part this is caused by the quality of the data (suspect errors) [366], but it is also due to technological progress, more lumens being recently provided with the same or lower lamp weight. An example is the disappearance of heat sinks: a recent LED filament lamp (without heat sink) was weighed by the study team and has only 58 g/klm.

Another source of variation is that often the same bulb shape is used for lamps with different lumen outputs, probably varying only the number of LEDs inside (e.g. the 7W and 11W dimmable GE-lamps, with 470 and 810 lm, but with the same lamp weight).

For LED retrofit tubes that replace LFL-T8, a slightly lower weight of 134 g/klm was found (Table 68).

Considering all available data, an average weight of 150 g/klm was used for the BoM.

[366] Lamp weight data are not supplied by all manufacturers, and they are not available for all models. Osram does not provide net lamp weights, but has detailed data as regards primary packaging weight and total shipping weight. The reported Osram data include primary packaging (carton box or blister). GE provides a net and gross lamp weight, but it is not clear exactly what is included in the gross weight. A complication is that there seem to be a lot of errors in the weight data and packaging volumes.



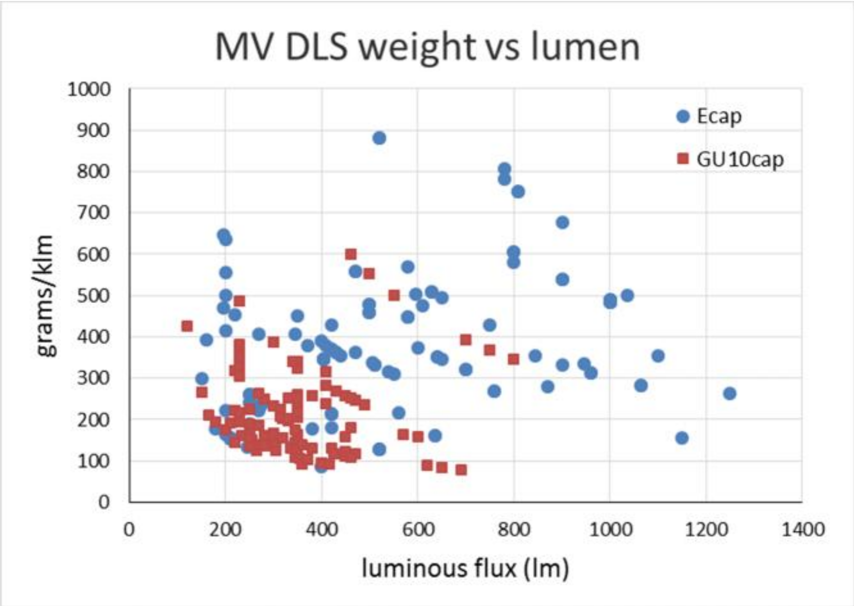


Figure 46 Top: Distribution of the lamp weight in grams/klm for directional LED lamps that are retrofits for mains-voltage directional filament lamps. Bottom: grams/klm in function of lamp lumen, for the same LED lamps. Blue dots are for lamps with E14 or E27 cap (total 122); Red squares are for lamps with GU10 cap (total 219). (Source: database for MV DLS market assessment [222])

Table 67 Lamp weights per kilo-lumen for classic LED bulbs, retrofits for non-directional halogen or GLS lamps (Source: compiled by VHK from catalogue data [367]; LED filament lamp weighed by study team)

	W	lm	CCT (K)	L (mm)	D(mm)	M (g)	g / klm
osram parathom	12	810		116	62	196	242
osram parathom	6	470		97	55	140	298
osram parathom	10	806		107	60	151	187
osram parathom	12	1060		115	60	175	165
osram parathom	4	250		82	43	61	244
osram candle	4	250		102	38	74	296
GE	7	400	2700	108	60	111	278
GE	7	500	6500	108	60	111	222
GE	7	470	2700	109	62	156	332
GE	7	600	6500	109	62	64	107
GE	10	810	2700	109	62	156	193
GE	10	1000	6500	109	62	112	112
GE	13	1055	2700	140	68	64	61
GE	13	1300	6500	141	68	156	120
GE	16	1300	2700	140	68	156	120
GE	16	1650	6500	141	68	156	95
GE energy smart, dimmable	7	470	2700	109	60	110	234
GE energy smart, dimmable	11	810	2700	109	60	110	136
GE energy smart, dimmable	14	1100	2700	108	62	150	136
Megaman LED classic	3.5	250	all	104	55	53	212
Megaman LED classic	5	400	all	93	45	42	105
Megaman LED classic	5	400	all	104	55	59	148
Megaman LED classic	7.5	600	all	115	60	67	112
Megaman LED classic	9.5	810	all	115	60	97	120
Calex LED filament lamp	6	600	2700			34.5	58
Average of all models							173

Table 68 Lamp weights per kilo-lumen for LED retrofit tubes for LFL-T8 (Source: compiled by VHK from catalogue data [368])

	W	lm	CCT (K)	L (mm)	D(mm)	M (g)	g / klm
megaman LED T8	33	2700	3000	1212	28	398	147
megaman LED T8	33	2970	4000	1212	28	398	134
megaman LED T8	25	2400	4000	1513	28	422	176
megaman LED T8	17	1350	3000	602	28	207	153
megaman LED T8	17	1480	4000	602	28	207	140
megaman LED T8	22	2000	3000	1513	28	184	92
megaman LED T8	22	2200	6500	1513	28	184	84
megaman LED T8	18	1600	3000	1212	28	190	119
megaman LED T8	18	1750	6500	1212	28	190	109
megaman LED T8	24.5	2400	3000	1513	28	394	164
megaman LED T8	24.5	2600	4000	1513	28	394	152
Average of all models							134

[367] http://www.osram.com/osram_com/products/lamps/led-lamps/parathom-ledotron/parathom-ledotron-classic-a/index.jsp
http://www.osram.com/osram_com/products/lamps/led-lamps/consumer-led-lamps-with-classic-bulbs/led-star-classic-a/index.jsp
http://www.osram.com/osram_com/products/lamps/led-lamps/parathom-ledotron/parathom-ledotron-classic-p/index.jsp
http://www.osram.com/osram_com/products/lamps/led-lamps/parathom-ledotron/parathom-ledotron-classic-b/index.js
http://catalog.gelighting.com/lamp/led-lamps/gls-bulb/f=ge-start-gls/d=0/?r=emea
http://catalog.gelighting.com/lamp/led-lamps/gls-bulb/f=ge-energy-smart-gls-dimmable/d=0/?r=emea
http://www.megaman.cc/products/led/led-classic
[368] http://www.megaman.cc/products/led/led-t8/LT0133/?voltage=220v

Types of materials and weight distribution for a LED package

Table 69 shows an example of a material breakdown for a white LED SMD package. Even if this is only one of the numerous possible LED package designs, it gives a good general idea of the types of materials involved and of their relative masses.

The total package mass is small: 0.15 g. The mass of the LED-die is less than 1% of the package mass. The major mass components are: electrical contacts (39%), housing (33%), heat sink (16%) and lens (11%).

Within the die mass of 1.05 mg, 77% is for the carrier material (indicated as germanium in the table, but could also be sapphire or silicon for example). Only 3% of the die is semiconductor material, of which 83% is gallium (0.03 mg per die).

The last three columns of the table give the masses in mg for 13.3 dies, which is approximately the quantity needed to obtain a 1000 lm light source [369].

For comparison: the study team measured the weight of the filaments in a recent LED filament lamp as 0.9 g. This lamp contained 8 filaments, mounting 24 dies each, resulting in a mass per die of 4.7 mg.

Table 69 Example of a material breakdown for a LED package: Osram Golden Dragon white LED SMD [369]. (Source for data: Ökopol 2013, table 7 [370]).

	mg	%	mg	%	mg	%	mg / klm		
Entire LED package	151.154	100.0%							
Anode/Cathode/Frame (Copper)	58.979	39.02%					786.4		
Housing, Poly Pthalamide + TiO2, glass fibre	50.000	33.08%					666.7		
Heat sink, Al2O3, AlN	24.150	15.98%					322.0		
Lens, Si-polymer	16.764	11.09%					223.5		
LED die	1.047	0.69%					14.0		
Carrier (150 micron) (Ge)			0.808	77.1%				10.8	
Phosphor (30 micron)			0.141	13.5%				1.9	
Yttrium					0.063	44.7%			0.8
Aluminium					0.032	22.7%			0.4
Oxygen					0.046	32.6%			0.6
Cerium					0.000	0.0%			0.0
Metals (3.5 micron)			0.068	6.5%				0.9	
Gold					0.056	82.1%			0.7
Silver					0.011	16.3%			0.1
Al, Ti, Ni					0.001	1.6%			0.0
Semiconductor (5 micron)			0.031	3.0%				0.4	
Gallium					0.026	83.2%			0.3
Indium					0.000	0.0%			0.0
Nitrogen					0.005	16.8%			0.1
Mg, Si					0.000	0.0%			0.0
Bonding wire (gold)	0.151	0.10%					2.0		
ESD-diode (Si)	0.063	0.04%					0.8		

[369] http://www.osram-os.com/Graphics/XPic3/00146543_0.pdf/LCW%20W5SM%20-%20Golden%20DRAGON.pdf
Dimensions (indicative): 6x7 mm (incl. leads 11 mm) thick 1.8 mm, LED die 1x1 mm.
Characteristics (typical): 3.2V, 350 mA, 1.12W, 75 lm (45-112 depending on bin, @350mA, 25˚C), 25 cd, 13.3 dies/klm

[370] EXPERTISE LEUCHTDIODEN, UMWELT-, GESUNDHEITS- UND VERBRAUCHERRELEVANTE ASPEKTE VON LEUCHTMITTELN AUF BASIS VON LED, August 2013, Ökopol – Institut für Ökologie und Politik, (in German, with English summary) http://www.oekopol.de/archiv/material/551_1_Oekopol_LED_Endbericht_Aug%202013.pdf.

Another example of the material composition of a LED package, normalized to a die-size of 1 mm^2, is provided in a 2012 Cyc-led publication [373], see Table 70. Some of the listed materials are classified in the European Union as critical raw materials [371] [372]. The list of masses sums up to 3.2 mg/mm^2, but it is not clear if they can be summed, i.e. some seem to be alternative solutions rather than materials being used together. In addition, elements like housing, heat sink and lens seem to be missing.

Table 70 Material composition of LED packages normalized to 1 mm^2. (Source Cyc-led [373])

	Description	Elements	Thickness	mass percentage	density	Mass per 1 mm^2 of die
		[PSE]	[µm]	[%vol]	[g/cm^3]	[$\mu g/mm^2$]
Interconnection technologies	SnAg soldering	Ag	70	3.5	11.49	28
	Ag sintering	Ag	80	95	11.49	873
	AuSn soldering	Au	30	90	19.32	522
	Ag conductive adhesive	Ag	30	80	11.49	276
	CuSn TLPS	Cu	80	60	8.92	428
	Au TC-Bond	Au	35	40	19.32	270
	Au wire bond	Au	32	3	19.32	19
Phosphor	YAG:Ce	Ce	100[1]	0.5	6.773	3
	YAG:Ce	Y	100[1]	20	4.472	89
	TAG:Ce	Tb	100[1]	20	8.253	165
	LuAG:Ce	Lu	100[1]	20	9.84	197
	ortho-silcate	Eu	100[1]	0.5	5.245	3
	ortho-silcate	Ce	100[1]	1.25	6.773	8
die material	GaAs (bulk)	Ga	100[1]	50	5.904	295
	GaAs (thin film)	Ga	5	50	5.904	15
	GaN (thin film)	Ga	5	50	5.904	15
	InGaN	Ga	5	25	5.904	7
	InGaN	In	5	25	7.31	9

[1] Based on die level; 10 to 15 times the amount is needed on package level and 8000 time the amount on lamp level for a lamp with 5 cm diameter.

[371] COM(2014) 297 final On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative.

[372] http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/crm-report-on-critical-raw-materials_en.pdf

[373] Cycled, Cycling resources embedded in systems containing Light Emitting Diodes, Categorization of LED products, April 2012, table 4-3, http://www.cyc-led.eu/Files/CycLED_D2_1_120507.pdf

Types of materials and weight distribution for a LED retrofit lamp

As regards the bill-of-materials for LED retrofit lamps, the following references have been examined:

- VITO 2015, weight measurements on a LED filament lamp [374].
- Ökopol 2013 [375], LED retrofit lamps with E27 cap.
- US DoE 2012, LCA part 1 and 2 [376], Philips Endura lamp.
- IEA 4E 2014 [377], generic distribution of LED lamp materials.
- Osram 2009 [378], Parathom classic A.
- Hendrickson et al [379], weight measurements on three types of LED lamps.
- Navigant / DEFRA 2009 [380], focuses on LED luminaires, but some indications for lamps.
- Leena Tähkämö 2013 [381], references to other studies and LED downlighting luminaire.
- Hartley et al 2009 [382], weight breakdown for LED luminaires.
- Principi et all [383], downlighting luminaires with 2000 lm LED lamp.

The information regarding LED retrofit lamps from the above cited sources has been summarized in Table 71. Total lamp weights range from 35 to 284 g. The largest weight components are typically the heat sink and the control gear. For both of these components there can be a large difference between recent and older LED lamps. Note e.g. that the 2015 LED filament lamp weighed by VITO does not have a heat sink and that the electronics mass is only 2.2 g (6%). The 2009 Parathom classic A LED lamp has a heat sink that accounts for 41% of the weight and electronics weigh 28 g (16%).

[374] Calex LED volglas Filament Standaardlamp 240V 6W 600lm E27 A60, Helder 2700K

[375] See footnote 323, in particular tables 5 and 9. The lamp of table 5 is the same lamp as Hendrickson et al lamp 1.

[376] Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 1: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps, US DoE, February 2012, updated August 2012, in particular table 4.2, which is the same lamp as Hendrickson et al lamp 3, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf
and
Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance, US DoE, June 2012, in particular table 5-9, for the Philips Endura lamp, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf

[377] Solid State Lighting Annex: Life Cycle Assessment of Solid Stae Lighting, final report, IEA 4E September 2014, in particular figure 2-5, http://ssl.iea-4e.org/files/otherfiles/0000/0068/IEA_4E_SSL_Report_on_LCA.pdf

[378] http://www.osram.com/osram_com/sustainability/environmental/product-lifecycle-management/lca-of-an-led-lamp/index.jsp and http://www.osram.com/media/resource/HIRES/333052/94307/osram-material-declaration-sheet_led.pdf

[379] "Reducing environmental burdens of sold-state lighting through end-of-life design", C. T. Hendrickson, D. H. Matthews, M. Ashe, P. Jaramillo and F.C. McMichael, Environmental Research Letters, no. 5, 2010. DOI: 10.1088/1748-9326/5/1/014016, http://iopscience.iop.org/1748-9326/5/1/014016/pdf/1748-9326_5_1_014016.pdf

[380] Life Cycle Assessment of Ultra-Efficient Lamps, Navigant Consulting Europe research report for DEFRA, May 2009, http://randd.defra.gov.uk/Document.aspx?Document=EV0429_8060_FRP.pdf

[381] Life cycle assessment of light sources - Case studies and review of the analyses, Leena Tähkämö 2013, tables 4 and 6, http://lib.tkk.fi/Diss/2013/isbn9789526052502/isbn9789526052502.pdf

[382] Life Cycle Assessment of Streetlight Technologies, Mascaro Center for Sustainable Innovation , Douglas Hartley, Cassie Jurgens, Eric Zatcoff, University of Pittsburgh, July 2009, http://www.pitt.edu/news2010/streetlight_report.pdf

[383] A comparative life cycle assessment of luminaires for general lighting for the office e compact fluorescent (CFL) vs Light Emitting Diode (LED) e a case study, Paolo Principi, Roberto Fioretti (Università Politecnica delle Marche), Journal of Cleaner Production 83 (2014) 96-107, http://www.sciencedirect.com/science/article/pii/S0959652614007392

Table 71 Reference information for the bill-of-materials of LED retrofit lamps. Elaboration by the study team of data in the references (see text)

Description	VITO 2015, own measurements, LED Filament lamp		Oekopol, 2013, E27 reference lamp		Oekopol, 2013 and Hendrickson 2010 lamp 1, E27 lamp		US DoE 2012, part 1, and Hendrickson 2010 lamp 3		US DoE 2012, part 2, Philips Endura		IEA 4E, 2014, generic		Osram, 2009, Parathom Classic A		Hendrickson, 2010 Lamp 2		Defra, 2009, LEDi	
Power (W)	6		10		n/a		12.5		12.5		n/a		8		n/a		12	
Capacity (lm)	600		650		n/a		800		812		n/a		345		n/a		720	
	g	%	g	%	g	%	g	%	g	%	g	%	g	%	g	%	g	%
Lens or Bulb (glass)	20.0	58%	10.0	4%	21.8	9%	10.7	13%			14.0	7%					21.0	9%
Lens or Bulb (plastic, PC)			10.0	4%					12.1	7%			13.0	7%	22.6	8%		
LED (filament, die, array)	0.9	3%	2.0	1%	1.5	1%	1.5	2%	2.0	1%			1.5	1%	3.0	1%	19.0	8%
Heat sink (aluminium)			140.0	57%	156.4	63%	36.9	45%	68.2	39%	100.0	49%	71.0	41%	134.9	48%	100.0	42%
Heat sink (local, copper)			20.0	8%	28.2	11%					20.0	10%			20.0	7%		
Control gear (electronics, PCB)	2.2	6%	9.9	4%	6.1	2%	10.6	13%	27.0	15%	20.0	10%	28.0	16%	6.7	2%	72.0	30%
Cap / Fitting / Electrical contact	7.0	20%	9.0	4%	9.1	4%	12.2	15%	6.7	4%			7.0	4%	8.6	3%	3.5	1%
Housing/Base (porcelain, glass)	1.5	4%	20.0	8%	19.7	8%			20.0	11%			4.3	2%			6.0	3%
Housing/Base (plastic, acrylic, PC)	1.5	4%	10.0	4%	4.0	2%	10.8	13%	20.0	11%	21.0	10%	10.0	6%	75.9	27%	16.0	7%
Housing/Base (potting resin)	1.5	4%	10.0	4%					4.5	3%	21.0	10%	40.0	23%	6.8	2%		
Other metals (ferrous)									4.0	2%	5.0	2%	0.3	0%				
Other metals (non-ferrous)			5.0	2%					11.2	6%	5.0	2%			3.5	1%		
Solder paste									0.3	0%							0.2	0%
Total lamp weight (g)	35	100%	246	100%	247	100%	83	100%	176	100%	206	100%	175	100%	282	100%	238	100%
Total lamp weight (g/klm)	58		378				103		217				508				330	

For the six references where luminous flux information is available, the masses from Table 71 have been scaled to g/klm (Table 72). These masses have been summed per component/type-of-material and percentages of total mass have been determined. The component masses to be used as BoM-input in the EcoReport have been computed by taking the corresponding percentage of the total target mass of 150 g/klm for the LED retrofit lamp. The resulting BoM in EcoReport format is shown in Table 73.

Table 72 Component masses in g/klm for six reference LED retrofit lamps, sum of these masses, percentages of total mass, and derived component masses for the target lamp with 150 g/klm. The latter values are used as BoM-input for the EcoReport.

Description	VITO 2015	Oekopol 2013	US DoE 2012 (1)	US DoE 2012 (2)	Osram 2009	Defra 2009		sum	%	g/klm
Lens or Bulb (glass)	33.4	15.4	13.4	0.0	0.0	29.2		91.3	5.7%	8.6
Lens or Bulb (plastic, PC)	0.0	15.4	0.0	14.9	37.7	0.0		68.0	4.3%	6.4
LED (filament, die, array)	1.5	3.1	1.9	2.5	4.3	26.4		39.6	2.5%	3.7
Heat sink (aluminium)	0.0	215.4	46.1	84.0	205.8	138.9		690.2	43.3%	65.0
Heat sink (local, copper)	0.0	30.8	0.0	0.0	0.0	0.0		30.8	1.9%	2.9
Control gear (electronics, PCB)	3.6	15.2	13.3	33.3	81.2	100.0		246.6	15.5%	23.2
Cap / Fitting / Electrical contact	11.6	13.8	15.3	8.2	20.3	4.9		74.1	4.6%	7.0
Housing/Base (porcelain, glass)	2.5	30.8	0.0	24.6	12.5	8.3		78.7	4.9%	7.4
Housing/Base (plastic, acrylic, PC)	2.5	15.4	13.5	24.6	29.1	22.2		107.3	6.7%	10.1
Housing/Base (potting resin)	2.5	15.4	0.0	5.5	115.9	0.0		139.4	8.7%	13.1
Other metals (ferrous)	0.0	0.0	0.0	4.9	0.8	0.0		5.7	0.4%	0.5
Other metals (non-ferrous)	0.0	7.7	0.0	13.9	0.0	0.0		21.5	1.4%	2.0
Solder paste	0.0	0.0	0.0	0.4	0.0	0.3		0.6	0.0%	0.1
sum	57.5	378.3	103.4	216.7	507.6	330.1		1593.7	100%	150

Table 73: Bill-of-Materials for a 1000 lm LED retrofit lamp with integrated control gear.

Material	Weight (g)	EcoReport Category	EcoReport Material or process	recycling
Lens or Bulb (glass)	8.592	7-Misc.	55 -Glass for lamps	
Lens or Bulb (plastic, PC)	6.397	2-TecPlastics	13 -PC	Yes
LED (filament, die, array)	3.728	6-Electronics	49 -SMD/ LED's avg.	
Heat sink (aluminium)	64.961	4-Non-ferro	28 -Al diecast	
Heat sink (local, copper)	2.896	4-Non-ferro	32 -CuZn38 cast	
Control gear (electronics, PCB)	23.206	6-Electronics	50 -PWB 1/2 lay 3.75kg/m2	
Cap / Fitting / Electrical contact	6.970	4-Non-ferro	31 -Cu tube/sheet	
Housing/Base (porcelain, glass)	7.405	7-Misc.	55 -Glass for lamps	
Housing/Base (plastic, acrylic, PC)	10.099	2-TecPlastics	13 -PC	Yes
Housing/Base (potting resin)	13.116	2-TecPlastics	15 -Epoxy	
Other metals (ferrous)	0.540	3-Ferro	24 -Cast iron	
Other metals (non-ferrous)	2.028	4-Non-ferro	27 -Al sheet/extrusion	
Solder paste	0.061	6-Electronics	53 -Solder SnAg4Cu0.5	
Subtotal lamp	150.000			
packaging cardboard/paper	36.000	7-Misc.	57 -Cardboard	
packaging plastic	4.000	1-BlkPlastics	10 -PET	Yes

6.4. End-of-Life

For additional information see also the Task 3 report, chapter 6.

Incandescent lamps (GLS) and halogen lamps are normally not separately collected and recycled. It is therefore assumed in the EcoReport inputs that these lamps will end up in an incinerator or a landfill as mixed domestic waste.

As regards discharge lamps (CFL, LFL, HID), the information from the Task 3 report is used, i.e. 30% is collected of which 80% is recycled. Recycling plants are available that process fluorescent powder (rare earth materials), mercury, lamp glass and other metals [384] [385]. Consequently, it is assumed in the EcoReports that 80%*30%=24% is recycled and 76% ends up in an incinerator or a landfill as mixed domestic waste.

LED lighting products have only recently been introduced on the market and they have a long lifetime, so there are no significant waste volumes yet. In principle they have to be separately collected, just as all other products under the WEEE directive (Task 3 report), but no specific data on collection and recycling percentages are available.

Some organisations for the collection and recycling of discharge lamps also process LED lamps [386]. In addition LED lamps would enter the collection and processing schemes for other electronic and electrical products such as mobile phones, computers, monitors, television sets, etc.

For the moment, for the modelling in the EcoReport, the same percentages are assumed as for the discharge lamps.

For future policy scenarios it might be important to recycle more critical raw materials. This could be an opportunity for high-tech SME's [387].

As regards packaging materials, according to Eurostat in 2012 in the EU-28, 64.6% of the package waste was recycled [388]. This percentage will be assumed in the EcoReports.

[384] http://www.zvei.org/Publikationen/Collection-and-Recyccling-Discharge-Lamps.pdf

[385] Sustainable processes development for recycling of fluorescent phosphorous powders – rare earths and mercury separation, literature report, Cristian Tunsu, Teodora retegan, Christian Ekberg, Gothenburg, Sweden, 2011, http://publications.lib.chalmers.se/records/fulltext/local_157270.pdf

[386] http://www.gelighting.com/LightingWeb/emea/resources/environmental-center/WEEE.jsp

[387] Recovery of Rare earths from Electronic Wastes: An Opportunity for High-Tech SME's, February 2015 Study for the ITRE Committee, IP/A/ITRE/2014-09, PE 518.77 http://www.europarl.europa.eu/RegData/etudes/STUD/2015/518777/IPOL_STU%282015%29518777_EN.pdf

[388] http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=ten00063

References

See footnotes in text

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Acronyms

a	Annum, year
ANSI	American National Standards Institute
BAT	Best Available Technology
BAU	Business As Usual
BC	Base Case (as used in MEErP)
BEF	Ballast Efficacy Rating
BGF	Ballast Gain Factor (due to dimming)
BLE	Ballast Luminous Efficiency
BMF	Ballast Maintenance Factor
bn / bln	Billion (10^9)
BNAT	Best Not (yet) Available Technology
BOM	Bill Of Materials
CCFL	Cold-Cathode Fluorescent Lamp
CCR	Constant Current Regulator
CCT	Correlated Colour Temperature
cd	candela
CDR	Commission Delegated Regulation
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CIE	International Commission on Illumination
CFL	Compact fluorescent lamps
CFLi	CFL with integrated ballast
CFLni	CFL without integrated ballast

CISPR	Comité International Spécial des Perturbations Radioélectriques
CN / CN8	Combined Nomenclature (coding)
cm-LED	Colour-Mixed LED
cor	corrected
CRI	Colour Rendering Index
DLS	Directional light sources
DEFRA	UK Department for Environment, Food and Rural Affairs
E14, E27	Screw-type lamp caps for general purpose lamp
EC	European Commission
ECEEE	European Council for an Energy Efficient Economy
ECG	Electronic Control Gear
ECO	Scenario considering ecodesign or energy labelling measures
ED	Ecodesign / Ecodesign Directive
EEI	Energy Efficiency Index
ELC	European association of lighting manufacturers, now part of LightingEurope
ELD	Energy Labelling Directive
ELV	Extra Low Voltage
EMC	Electro-Magnetic Compatibility
EMI	Electromagnetic Interference
EoL	End-of-Life
EQE	External Quantum Efficiency
ErP	Energy related Product
ESL	Electron Stimulated Luminescence
ESO	European Standardisation Organisation
EU	European Union
FIPEL	Field-Induced Polymer Electroluminescent Lighting
FU	Functional Unit
G4, GY6.35	Low-voltage halogen lamp types, 2 pin cap, single ended
G9	Mains-voltage halogen lamp, 2-pin cap, single ended
GaN	Gallium Nitride
GLS	General Lighting Service (a.k.a. incandescent lamp)
h	Hour
HE	High efficiency
HF	High Frequency
Hg	Mercury
HID	High-Intensity Discharge
HL	Halogen
HO	High output
HPM	High-Pressure Mercury
HPS	High-Pressure Sodium
HS	Harmonised System (coding)

HW	High Wattage
Hz	Hertz
IEC	International Electrotechnical Commission
IES / IESNA	Illuminating Engineering Society (of North America)
ILCOS	International Lamp COding System
ILV	International Lighting Vocabulary
IQE	Internal Quantum Efficiency
IR, IRC	Infrared, Infrared coating
IR	Incandescent Reflector Lamp
ISA	International Solid State Lighting Alliance
ISO	International Organization for Standardisation
klm	Kilo lumen (see lm)
LBS	Lampen-Bezeichnungs-System
LCC	Life Cycle Cost
LE	LightingEurope (lighting manufacturers association)
LED	Light Emitting Diode
LENI	Lighting Energy Numerical Indicator
LER (1)	Luminaire Efficacy Rating
LER (2)	Luminous Efficacy of Radiation ($lm/W_{optical}$ for LED package)
LFL	Linear Fluorescent Lamp
LLCC	Least Life Cycle Cost
LLE	LED Light Engine
LLMF	Lamp Lumen Maintenance Factor
lm, Φ	Lumen, unit of luminous flux Φ
LMF	Luminaire Maintenance Factor
LOR	Light Output Ratio
LPD	Lighting Power Density [$W/(m^2.lx)$] (Pr EN 13201-5)
LPS	Low-Pressure Sodium lamp
LV	Low Voltage (typical 12V)
LW	Low Wattage
L70	Lifetime, lumen output decreased to 70% of original value
max	maximum
MELISA	Model for European Light Sources Analysis
MEErP	Methodology for Ecodesign of Energy-related Products
MEPS	Minimum Efficacy Performance Standard
MF	Maintenance Factor
MH	Metal Halide
min	minimum
mn / mln	Million (10^6)
MOCVD	Metal Oxide Chemical Vapour Deposition
Mt	Mega tonnes (10^9 kg)
MV	Mains Voltage (typical 230V)

MYPP	Multi-Year Program Plan (from US Doe)
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne (coding)
NDLS	Non-directional light sources
nec	Not elsewhere classified
NEMA	National Electrical Manufacturers Association
OJ	Official Journal of the European Union
OLED	Organic Light Emitting Diode
P	Rated power
par	paragraph
PCE	Power Conversion Efficiency (of a LED package)
pc-LED	Phosphor-Converted LED
PFC	Power Factor Corrector
ProdCom	PRODuction COMmunautaire (coding)
PSS	Patterned Sapphire Substrate
PWM	Pulse-Width Modulation
-R	Reflector
R	Electrical Resistance
R7s	Mains voltage linear halogen lamp, double ended
R9	Saturated red colour used as rendering reference
Ra	Colour rendering index, unit
REE	Rare Earth Element
rf	Retrofit
ref	reference
RGB	Red Green Blue
s	Second (as unit for time)
SCHER	Scientific Committee on Health and Environmental Risks
SCENHIR	Scientific Committee on Emerging and Newly Identified Health Risks
Si	Silicon
SPL	Special Purpose Lamp
SPP	Special Purpose Product
sr	steradian
SSL	Solid State Lighting
sWLED	Solid State White Light Emitting Diode
TBC	To Be Confirmed
TBW	To Be Written / To Be Worked
TC	Technical Committee
TFFC	Thin-Film Flip-Chip LED package architecture
TLA	Temporal Light Artefacts
TWh	Tera Watt hour (10^12)
UF	Utilisation Factor
UK	United Kingdom

ULOR	Upward Light Output Ratio
US(A)	United States of America
UV	Ultraviolet (subtypes UVA, UVB, UVC)
UVA	near UV-Black Light, 315-400 nm
UVB	middle UV-Erythemal, 280-315 nm
UVC	far UV-Germicidal, 100-280 nm
V	Volt
VHK	Van Holsteijn en Kemna
VITO	Vlaamse Instelling voor Technologisch Onderzoek
W	Watt
WLED	White Light Emitting Diode
YAG	Yttrium Aluminium Garnet (light converting phosphor)
yr	year

Annex A Statement of contractor on right to delivered result

I, Dirk Fransaer, representing the “Consortium of VITO NV, VHK BV, Viegand & MaagØe ApS, Wuppertal Institute for Climate, Environment and Energy GmbH, and ARMINES”, party to the contract ‘Preparatory Study on Lighting Systems for Ecodesign and/or Energy Labelling Requirements (‘Lot 8/9/19’), specific contract No. ENER/C3/2012-418 LOT1/07/SI2.668526 implementing framework contract No. ENER/C3/2012-418-Lot 1’, warrant that the Contractor holds full right to the delivered Task 4 report of the ‘Preparatory Study on Lighting Systems for Ecodesign and/or Energy Labelling Requirements (‘Lot 8/9/19’)’, which is free of any claims, including claim of the creators who transferred all their rights and will be paid as agreed within 30 days from the receipt of confirmation of acceptance of work.

Mol, Belgium,
Date:
Signature:

Dirk Fransaer
Managing Director VITO NV

Annex B Description of MEErP Task 4

The MEErP [389] prescribes the following topics to be addressed in Task 4, Technologies:

Identify, retrieve and analyse data, report on

Technical product description

illustrated with data on performance, price, resources/emissions impact of

4.1.1 Existing products (working towards definition of Base Cases)

4.1.2 Products with standard improvement (design) options

4.1.3 Best Available Technology BAT (best of products on the market)

4.1.4 Best Not yet Available Technology BNAT (best of products in field tests, labs, etc.)

Production, distribution and end-of-life

specifically regarding

4.2.1 Product weight and Bills-of-Materials (BOMs), preferably in EcoReport format (see Task 5)

4.2.2 Assessment of the primary scrap production during sheet metal manufacturing

4.2.3 Packaging materials

4.2.4 Volume and weight of the packaged product

4.2.5 Actual means of transport employed in shipment of components, sub-assemblies and finished products

4.2.6 Materials flow and collection effort at end-of-life (secondary waste), to landfill/ incineration/ recycling/ re-use (industry perspective)

4.2.7 Technical product life (time-to-failure of critical parts)

Recommendations

for

4.3.1 refined product scope from the technical perspective (e.g. exclude special applications for niche markets)

4.3.2 barriers and opportunities for Ecodesign from a technical perspective

4.3.3 the typical design cycle for this product and thus approximately appropriate timing of measures

Technical product description (from MEErP par.4.1):

Task 4.1 has a dual purpose: capacity building for the policy makers/ stakeholders and a first assessment, as a predecessor of the modelling work in Task 6, of a number of anchor points:

- Base case (BC), representing the average product on the market in terms of resources, efficiency, emissions and functional performance (see MEErP par. 4.1.2);
- Least Life Cycle Cost point (LLCC), representing the product with lower resources use and emissions than the Base case at the lowest life cycle costs (see MEErP par. 4.1.3);

[389] MEErP 2011, Methodology for Ecodesign of Energy-related Products, part 1: Methods and part 2: Environmental policies and data, René Kemna (VHK) November 28th 2011

- A ‘break-even’ point (BE), representing a product with lower resources use and emissions than the Base case but at the same life cycle costs (see MEErP par. 4.1.4);
- Best Available Technology point (BAT), representing the best commercially available product with the lowest resources use and/or emissions (see MEErP par. 4.1.5);
- Best Not yet Available Technology point (BNAT), representing an experimentally proven technology that is not yet brought to market, e.g. it is still at the stage of field-tests or official approval.(see MEErP par. 4.1.6)