Chapter 5: Lighting technologies

Topics covered

5 Lighting technologies

5.1 Introduction

Artificial lighting is being used more and more in the world. The usage is quite non-homogeneous. In developing countries, we can still find a widespread use of fuel based lighting but nowadays the situation is changing and the demand for electric based lighting is growing. Electric lighting consumes about 19% of the world total electricity use. So, we should remember and consider that the improvement in energy efficient lighting will also be helpful for the progress in developing countries. Every change in technologies, in customers' consumption behaviour, even in lifestyle, has influences on global energy consumption and indirectly, on environment. Therefore, energy saving in lighting, and the methods of achieving this goal should be considered at different levels (state, region, town, enterprise) and by supranational organisations, too.

People stay in indoor environment for most of the day. Characteristics of light in indoor environment are much different than that of natural outdoor environment. On the other hand people do not stop activities after sunset. The artificial lighting has therefore impact on their well-being (see also the visual and non-visual aspects of light in Chapter 3). The needed artificial light has to be provided in energy efficient and environmentally conscious way. It is important to search for the technological solutions which meet human needs with the lowest impact on the environment during operation, when most of the impacts take place. The environmental impacts also include production and disposal of lamps, and related materials.

Artificial lighting is based on systems: lamps, ballasts, starters, luminaires and controls. Ballasts are needed for discharge lamps to connect the lamp to the mains. Lamps, ballasts and starters are mounted in the luminaire with the wiring and lamp bases, reflectors distribute and redirect the light emitted from the lamp and louvers shield the user from glare. Control systems interact with the building where they are installed. This means that the spider net of interactions and impacts is related with the architecture of the building (shape, space orientation etc. have influence for daylight contribution), with the supply network and with the different equipment installed, e.g. the heating, ventilation, cooling or electronic devices. Last, but not least, lighting systems are made for human beings who have individual needs and behaviours. User habits can be supported by automatic controls (for example, occupancy sensors), but the user habits cannot be overridden, and here education plays a major role. First of all, the perfect lighting system offering the best solution for every application does not exist. Every technology, including the more innovative and trendy ones, has its own limitations and its full potential is mainly related to specific application field.

Furthermore, the best lamp, if used with poor or incompatible luminaire or ballast, loses most of its advantages. Combining good lamp, ballast and luminaire in a wrong installation may not meet the user needs or provide lighting service in an inefficient way. Combination of a good lighting system in a well designed installation takes strong advantage from control devices, to drive the lighting system according to, for instance, on daylight availability and occupancy. In the case of new buildings the integration of daylight is important in order to reduce the energy consumption.

To summarize, energy savings / efficiency and economics are dependent on:

- Improvement of lighting technologies
- Making better use of available cost-effective and energy efficient lighting technologies
- Lighting design (identify needs, avoid misuses, proper interaction of technologies, automatic controls, daylight integration)
- Building design (daylight integration and architecture)
- Knowledge dissemination to final users
- Knowledge dissemination to operators (designers, sellers, decision makers)
- Reduction of resources by recycling and proper disposal, size reduction, using less aluminium, mercury, etc.
- Life Cycle Cost Assessment LCCA

In this chapter an overview is given for the current technologies of light sources, luminaries, and ballasts. Their potential is illustrated and the trends of the most promising ones are described. Integral lighting systems utilizing daylight together with electrical lighting systems and its control are also presented.

5.2 Light sources

5.2.1 Overview

Following characteristics are to be considered when choosing a lamp for an application.

a. Luminous efficacy
    - Luminous flux
    - Lamp power and ballast losses

b. Lamp life
    - Lumen depreciation during burning hours
    - Mortality

c. Quality of light
    - Spectrum
    - Correlated color temperature (CCT)
    - Color rendering index (CRI)

d. Effect of ambient circumstances
    - Voltage variations
    - Ambient temperature
    - Switching frequency
    - Burning position
    - Switch-on and restrike time
    - Vibration

e. Luminaire
    - Lamp size, weight and shape
    - Luminance
    - Auxiliaries needed (ballast, starter, etc.)
    - Total luminous flux
    - Directionality of the light, size of the luminous element

f. Purchase and operation costs
    - Lamp price
    - Lamp life
    - Luminous efficacy

- — Lamp replacement (relamping) costs
- — Electricity price and burning hours are not lamp characteristics, but have an effect on operation costs.

The diagram below shows the main lamp types for general lighting:

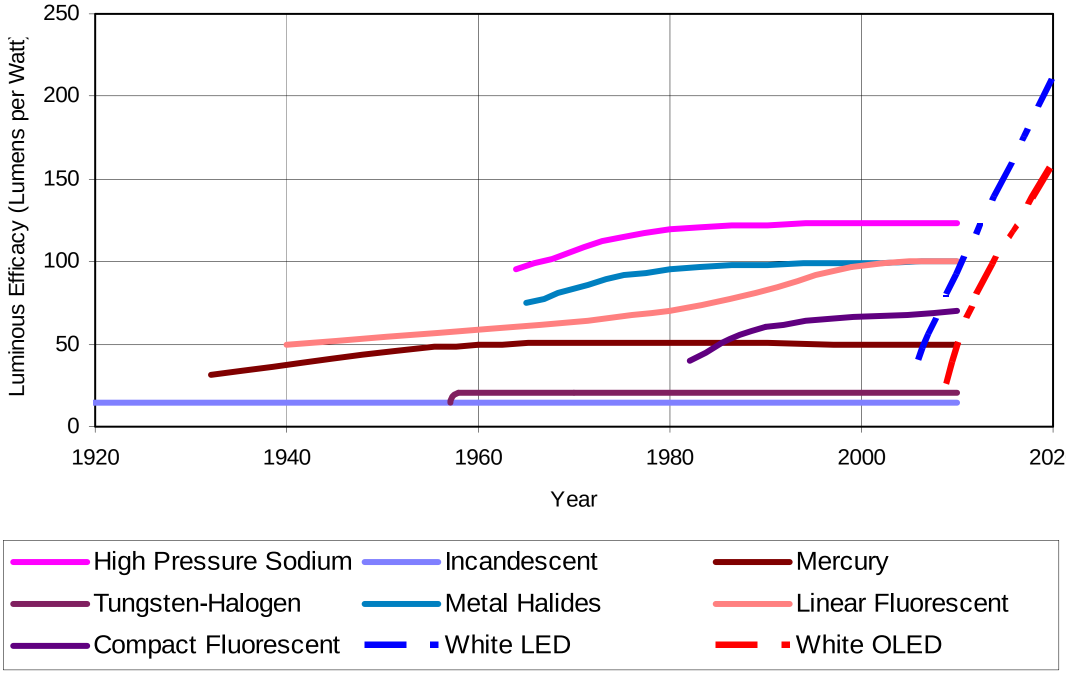


Figure 5-1. *The development of luminous efficacies of light sources.(Krames 2007, DOE 2010)*

Table 5-1. compares the main lamp types and gives the first indication of possible application fields.

Table 5-1. *Lamp types and their typical characteristics.*

Lamp type	Characteristics							
	Luminous efficacy (lm/W)	Lamp life h	Dimming control	Re-strike time	CRI	Cost of installation	Cost of operation	Applications
GLS	5-15	1000	excellent	prompt	very good	low	very high	general lighting
Tungsten halogen	12-35	2000-4000	excellent	prompt	very good	low	high	general lighting
Mercury vapour	40-60	12000	not possible	2-5 min	poor to good	moderate	moderate	outdoor lighting
CFL	40-65	6000-12000	with special lamps	prompt	good	low	low	general lighting
Fluorescent lamp	50-100	10000-16000	good	prompt	good	low	low	general lighting
Induction lamp	60-80	60000-100000	not possible	prompt	good	high	low	places where access for maintenance is difficult
Metal halide	50-100	6000-12000	possible but not practical	5-10 min	good	high	low	shopping malls, commercial buildings
High pressure sodium (standard)	80-100	12000-16000	possible but not practical	2-5 min	fair	high	low	Outdoor, streets lighting, warehouse
High pressure sodium (colour improved)	40-60	6000-10000	possible but not practical	2-6 min	good	high	low	outdoor, commercial interior lighting
LEDs	20-120	20000-100000	excellent	prompt	good	high	low	all in near future

5.2.2 *Lamps in use*

Van Tichelen *et al.* (2004) have given estimation of the total lamp sales in 2004 in European member countries (EU-25). However, annual sales do not give the total amount of light spots in use. For example, the lamp life of T8 lamps is 12 000 hours on the average and yearly burning hours in office use can be 2500 hours. Thus, the amount of lamps in use (light spots in Table 5-2) is almost fivefold (12000/2500 = 4.8). Energy used by the lamps can be calculated using the calculated amount of light spots, the annual burning hours, and average power of the lamp. In Table 5-2, the average lamp power including ballast losses has been estimated. The amount of light that lamps produce annually can be calculated using the average luminous efficacy. This, again, is not a known figure since it also depends on the power of the lamp, the ballast (magnetic or electronic) and the spectrum of the lamp.

Table 5-2. *Estimated total lamp sales in EU-25 on 2004 and calculated amount of light spots, energy consumption and amount of light. NOTE: Figures are based on assumptions on lamp power, efficacy, lamp life and burning hours.*

Lamp type	Sales		Light spots S*(T/t)		Energy LS*P*t		Quantity LS*P*η*t		Lamp power	Burning hours	Luminous efficacy	Lamp life
	Mpcs S	%	Mpcs LS	%	TWh W	%	Glmh Q	%	W P	t h	lm/w η	h T
GLS	1 225	68	1 225	37	74	25	735	4	60	1 000	10	1 000
Halogen	143	8	143	4	9	3	103	1	40	1 500	12	1 500
T12	14	1	68	2	8	3	510	3	50	2 500	60	12 000
T8	238	13	1 144	34	126	42	9 436	58	44	2 500	75	12 000
T5	12	1	78	2	6	2	528	3	32	2 500	85	16 000
CFL	108	6	433	13	10	3	572	3	11	2 000	60	8 000
OtherFL	33	2	159	5	17	6	1 047	6	44	2 500	60	12 000
Mercury	8	0	24	1	13	4	667	4	140	4 000	50	12 000
HPS	11	1	33	1	23	8	1 845	11	175	4 000	80	12 000
MH	11	1	27	1	13	4	900	6	120	4 000	70	10 000
All	1 804	100	3 333	100	299	100	16 343	100				

GLS = General lighting service lamp
Halogen = Tungsten halogen lamp
T12, T8, T5 = Long fluorescent lamps
Other FL = other fluorescent lamps
Mercury = mercury lamps
HPS = High pressure sodium lamps
MH = Metal halide lamps

Sales, S [Mpcs, million pieces]
Lamp power, P [W]
Burning hours, t [h]
Luminous efficacy, η [lm/W]
Lamp life, T [h]
Light spots, LS = S *x* (T/t) [Mpcs]
Energy, W = LS *x* P *x* tu [TWh]
Quantity of light, Q = W*x* η = LS *x* P *x* tu *x* η [Glmh]

The data of Table 5-2 is depicted in Figure 5-2. Two thirds of the lamps sold are incandescent lamps. Incandescent lamps cover about 37% of the light spots and they use about 25% of all the electricity used for lighting in EU-25 area. However, they produce only 4% of the light. With T8 lamps the trend is opposite, their share 13% of the sales, 34% of the light spots, 42% of the energy consumption, and they produce 58% of the light. According to Table 5-2, electricity can be saved by replacing incandescent lamps with more energy efficient lamps. Other inefficient light sources are T12-lamps (3% of energy) and mercury lamps (4% of energy).

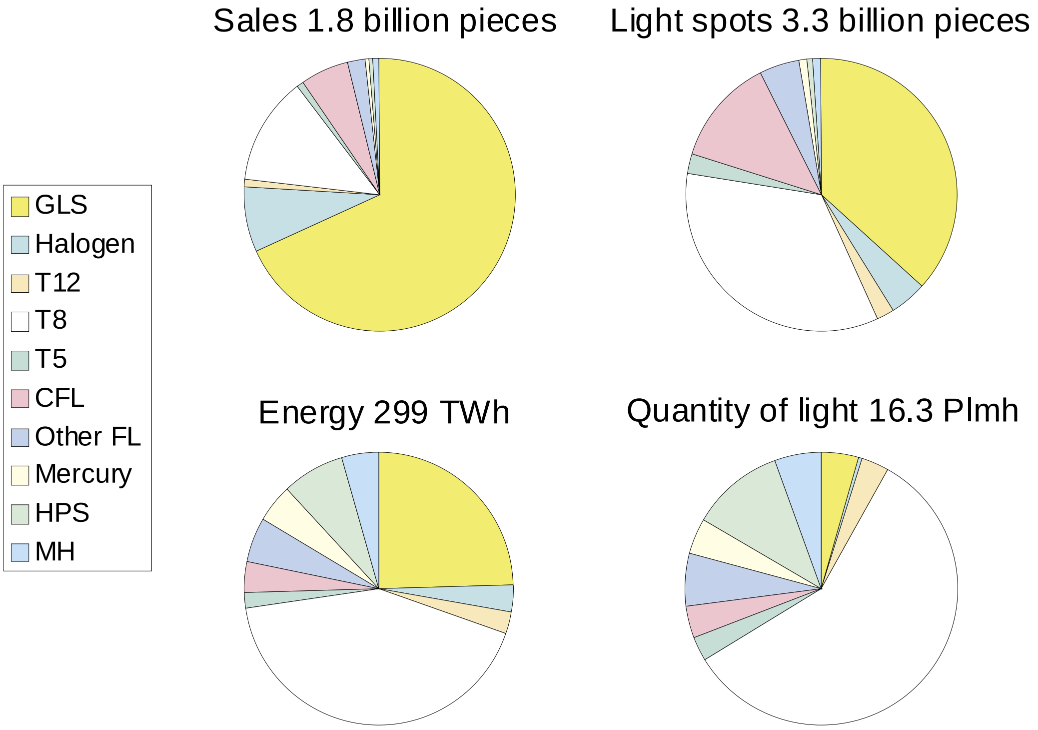


Figure 5-2. *EU-25 lamp sales on 2004. From the estimated lamp sales the amount of light spots in use, the energy lamps are using and the amount of light they are producing has been calculated. Assumptions of the average lamp power with ballast losses, annual burning hours, luminous efficacy and lamp life has been made.*

T12-lamps and mercury lamps can be replaced with T8-lamps and high pressure sodium lamps, respectively. In lighting renovation T12 luminaires should be replaced with T5-luminaires. Also new alternatives for the most energy consuming light source, T8-lamp, has to be found. According to Table 5-2, the average luminous efficacy of T8-lamps with ballast losses is 75 lm/W. At the moment T5-lamp with electronic ballast is more efficient. In the future LEDs will be the most efficient light source with the potential luminous efficacy reaching 200 lm/W.

5.2.3 Lamps

Incandescent lamp

In incandescent lamp, which is also called General Lighting Service Lamp (GLS), light is produced by leading current through a tungsten wire. The working temperature of tungsten filaments in incandescent lamps is about 2700 K. Therefore the main emission occurs in the infrared region. The typical luminous efficacy of different types of incandescent lamps is in the range between 5 and 15 lm/W.

Advantages of incandescent lamps:

- inexpensive
- easy to use, small and does not need auxiliary equipment
- easy to dim by changing the voltage
- excellent color rendering properties
- directly work at power supplies with fixed voltage
- free of toxic components
- instant switching

Disadvantages of incandescent lamps:

- short lamp life (1000 h)
- low luminous efficacy
- heat generation is high
- lamp life and other characteristics are strongly dependent on the supply voltage
- the total costs are high due to high operation costs.

The traditional incandescent lamps will be progressively replaced with more efficient light sources. For example, in Europe the Regulation 244/2009 is driving this process (EC 244/2009) (see also Chapter 4).

Tungsten halogen lamp

Tungsten halogen lamps are derived from incandescent lamps. Inside the bulb, halogen gas limits the evaporation of the filament, and redeposits the evaporated tungsten back to the filament through the so called halogen cycle. Compared to incandescent lamp the operating temperature is higher, and consequently the color temperature is also higher, which means that the light is whiter. Color rendering index is close to 100 as with incandescent lamps. Also, lumen depreciation is negligible. Their lifetime spans from 2000 to 4000 hours, and luminous efficacy is 12-35 lm/W.

Halogen lamps are available in a wide range of models, shapes (from small capsules to linear double ended lamps), with or without reflectors. There are reflectors designed to redirect forward only the visible light, allowing infrared radiation to escape from the back of the lamp. There are halogen lamps available for mains voltages or low voltages (6-24V), the latter needing a step-down transformer. Low voltage lamps have better luminous efficacy and longer lamp life than the high voltage lamps, but the transformer implicates energy losses in itself.

The latest progress in halogen lamps has been reached by introducing selective-IR-mirror-coatings in the bulb. The infrared coating redirects infrared radiations back to the filament. This increases the luminous efficacy by 40–60% compared to other designs and lamp life is up to 4000 hours.

Advantages of tungsten halogen lamps:

- small size
- directional light with some models (narrow beams)
- low-voltage alternatives
- easy to dim
- instant switching and full light output
- excellent color rendering properties

Disadvantages of tungsten halogen lamps

- low luminous efficacy
- surface temperature is high
- lamp life and other characteristics are strongly dependent on the supply voltage

Tips

Consider the choice of a halogen lamp if you need:

- instant switch on and instant full light
- excellent color rendering
- easy dimming
- frequent switching and, or short on-period

- directional light
- compact size of the light source.

Fluorescent lamps

A fluorescent lamp is a low-pressure gas discharge light source, in which light is produced predominantly by fluorescent powders activated by ultraviolet radiation generated by discharge in mercury. The lamp, usually in the form of a long tubular bulb with an electrode at each end, contains mercury vapour at low pressure with a small amount of inert gas for starting. The majority of the emission (95%) takes place in the ultraviolet (UV) region and the wavelengths of the main emission peaks are 254 nm and 185 nm. Hence, the UV radiation is converted into light by a phosphor layer on the inside of the tube. Since one UV-photon generates only one visible photon, 65% of the initial photon energy is lost as dissipation heat. On the other hand, the final spectral distribution of emitted light can be varied by different combinations of phosphors. Correlated color temperatures (CCT) vary from 2700 K (warm white) and 6500 K (daylight) up to 17 000 K and color rendering indices (CRI) from 50 to 95 are available. The luminous efficacy of the latest T5 fluorescent lamp is up to 100 lm/W (without ballast losses). Dimming is possible down to 1% of the normal luminous flux, and with special high voltage pulse circuits down to 0.01%.

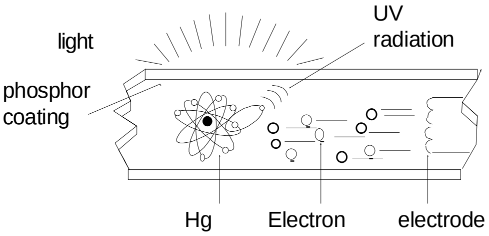


Figure 5-3. *Operation principle of a fluorescent lamp.*

Fluorescent lamps display negative voltage-current characteristics, requiring a device to limit the lamp current. Otherwise the ever-increasing current would destroy the lamp. Pure magnetic (inductive) ballast needs an additional starting element such as a glow switch. Electronic control gear incorporates all the equipment necessary for starting and operating a fluorescent lamp. Compared to conventional magnetic ballasts which operate lamps at a line frequency of 50 Hz (or 60 Hz), electronic ballasts generate high frequency currents, most commonly in the range of 25-50 kHz. High frequency operation reduces the ballast losses and also makes the discharge itself more effective. Other advantages of the electronic ballasts are that the light is flicker-free and there is the opportunity of using dimming devices.

Advantages of fluorescent lamps

- inexpensive
- good luminous efficacy
- long lamp life, 10 000 – 16 000 h
- large variety of CCT and CRI

Disadvantages of fluorescent lamps

- ambient temperature affects the switch-on and light output
- need of auxiliary ballast and starter or electronic ballast
- light output depreciates with age
- contain mercury
- short burning cycles shorten lamp life

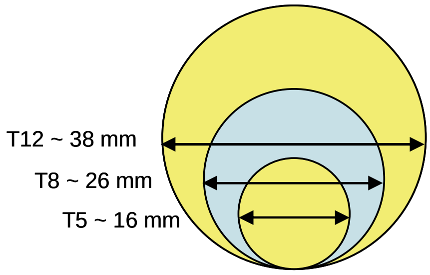


Figure 5-4. *Comparison of tube diameter of different fluorescent lamps.*

The linear fluorescent lamps have enhanced their performance and efficacy with time. From the old, bulky T12, passing through T8, to the present T5 lamps not only the diameter is reduced. The T5 has a very good luminous efficacy (100 lm/W), the same lamp surface luminance for different lamp powers (some lamps), and optimal operating point at higher ambient temperature. T5 lamps are shorter than the correspondent T8 lamps, and they need electronic ballasts. Dedicated luminaries for T5 lamps may reach a better light output ratio (LOR), as the lamp diameter is smaller thus allowing the light to be redirected in a more effective way.

The performance of a fluorescent lamp is sensitive to the ambient temperature. T5 lamps perform best at the ambient temperature of 35°C, and T8 lamps at 25°C. A temperature of 35°C inside the luminaire is more realistic for indoor installations. There are also amalgam lamps whose performance varies less with the temperature.

Tips

— Ideal for general lighting in most working places (including shops, hospitals, open spaces, etc.), but also in some residential applications
— The choice of the lamp is always related to the application. Always consider the correlated color temperature and the color rendering index.
— Halophosphate lamps have very poor light quality and will become obsolete. (Fluorescent lamps without integrated ballast shall have a color rendering index of at least 80 (EC 245/2009)
— The five-phosphor lamps, with their excellent color rendering, are particularly suitable in art galleries, shops, and museums but have lower luminous efficacy than the corresponding triphosphor lamps.
— By using lamps of different CCT in the same luminaire and proper dimming, it is possible to have dynamic light, where the color is selected by the user by reproducing preset cycles (e.g. during day)
— Correct disposal of these light sources, which contain mercury, is very important
— As some T5 lamp types have the same luminance for different powers, it is very easy to build "continuous lines".
—

Compact fluorescent lamps (CFL)

The CFL is a compact variant of the fluorescent lamp. The overall length is shortened and the tubular discharge tube is often folded into two to six fingers or a spiral. For a direct replacement of tungsten filament lamps, such compact lamps are equipped with internal ballasts and screw or bayonet caps. There are also pin base CFLs, which need an external ballast and starter for operation. The luminous efficacy of CFL is about four times higher than that of incandescent lamps. Therefore, it is possible to save energy and costs in lighting by replacing incandescent lamps with CFLs.

Today, CFLs are available with:

— different shapes, with bare tubes or with an external envelope (look alike for incandescent lamp)

- different CCT (warm white, cool white)
- instant ignition (some)
- diminished sensitivity to rapid cycles
- dimmable (some)

Advantages of compact fluorescent lamps

- good luminous efficacy
- long lamp life (6000-12 000 h)
- the reduced cooling loads when replacing incandescent lamps

Disadvantages of compact fluorescent lamps

- expensive
- E-27 based are not dimmable (apart from special models)
- light output depreciates with age
- short burning cycles shorten lamp life
- the current waveform of CFLs with internal electronic ballast is distorted
- contain mercury

Figure 5-5. *Different types of Compact fluorescent lamps.*

Tips

- The advantage of pin base lamps is that it is possible to replace the burnt lamp while keeping the ballast in place
- A physical limit of the CFLs is that a really instant ignition is incompatible with long life
- CFLs are ideal for situations in which long burning times are expected
- Care should be taken in the choice of the proper luminaire. It is very easy to unscrew a traditional incandescent lamp and replace it with a screw based CFL, but the result may be unsatisfying. This is because how the light is distributed around the CFL is very different compared to traditional incandescent lamps.

High Intensity Discharge lamps (High Pressure)

Without any temperature limitations (e.g. melting point of tungsten) it is possible to use gas discharges (plasmas) to generate optical radiation. Unlike thermal solid sources with continuous spectral emission, radiation from the gas discharge occurs predominantly in form of single spectral lines. These lines may be used directly or after spectral conversion by phosphors for emission of light. Discharge lamps generate light of different color quality, according to how the spectral lines are distributed in the visible range. To prevent runaway current and ensure stable operation from a constant voltage supply, the negative current-voltage characteristics of gas discharge lamps must be counterbalanced by a circuit element such as conventional magnetic or electronic ballasts. In all cases, higher voltages are needed for igniting the discharge.

The power conversion per unit volume in high pressure arc discharge lamps is 100 to 1000 times higher than that of low pressure lamps, which leads to considerable thermal loadings on the discharge tube walls. The wall temperatures may be in the region of 1000°C. The discharge tubes are typically made of quartz or PCA (polycrystalline sintered alumina: Al_2O_3). The arc discharge is provided with electrical power via tungsten pin electrodes. In most cases the main constituent of the plasma is mercury. To reach operating pressures of 1-10 bars, the vaporization of filling materials requires a warm-up time of up to 5 minutes after ignition. For starting high pressure lamps (except mercury lamps) superimposed pulses of some kVs from external ignition circuits or internal ferroelectric capacitors are used. An immediate re-start after short power break demands voltages of more than 20 kV. Many types of high pressure discharge lamps can not be dimmed, others only in a power range of 50% to 100%.

Mercury Lamps

In mercury lamp light is produced with electric current passing through mercury vapour. An arc discharge in mercury vapour at a pressure of about 2 bars emits five strong spectral lines in the visible wavelengths at 404.7 nm, 435.8 nm, 546.1 nm, 577 nm and 579 nm. The red-gap is filled up by a phosphor-layer at the outer bulb. Typical values of these lamps are luminous efficacy 40-60 lm/W, CRI between 40 and 60 and CCT 4000 K. The lamp life is 12 000 h.

Mercury lamps will be banned from European market after 2015. (EC 245/2009)

Metal halide lamps

To increase the luminous efficacy and CRI of mercury high pressure lamps, it is useful to add mixtures of metal components to the filling of the discharge tube. These additives emit their own line spectra in the arc discharge, leading to an enormous diversity of light color. For sufficient vapour pressure, it is better to use metal halides (compounds with iodine or bromine) instead of elemental metals. When the vapour enters the high temperature region of the discharge, molecules dissociate, metal atoms are excited and radiation is emitted.

The applications of metal halide lamps reach from electric torches (10 W miniature variants) to diverse purposes in indoor and outdoor lighting (wattages up to 20 kW). The lamps are available with luminous efficacy typically from 50 to 100 lm/W, CCT value from 3000 to 6000 K and CRI from 70 to over 90. The lamp life is typically from 6000 h to 12 000 h.

Advantages of metal halide lamps

- Good luminous efficacy

- Alternatives with good color rendering available
- Different color temperatures available.

Disadvantages of metal halide lamps

- Expensive
- Starting and re-starting time 2-5 min
- Differences in CCT between individual lamps and changes of CCT during burning hours. These differences are much reduced with ceramic metal halide lamps.

Figure 5-6. *Metal halide lamps, nominal power from left 150 W, 400 W, 75 W and 70 W.*

High pressure sodium lamps

In a high pressure sodium lamp light is produced by sodium vapour, the gas pressure being about 15 kPa. The golden-yellowish emission spectrum applies to wide parts of the visible area. The CRI is low (≈ 20), but the luminous efficacy is high. The most common application today is in street and road lighting. Luminous efficacy of the lamps is 80-100 lm/W, and lamp life is 12 000 h (16 000 h). The CCT is 2000 K.

An improvement of the CRI is possible by pulse operation or elevated pressure but this reduces the luminous efficacy. Color improved high pressure sodium lamps have CRI of about 65 and white high pressure sodium lamps of more than 80. Their CCT is 2200 and 2700, respectively.

Advantages of high pressure sodium lamp

- very good luminous efficacy
- long lamp life (12 000 h or 16 000 h)
- high luminous flux from one unit for street and area lighting

Disadvantages of high pressure sodium lamp

- low CCT, about 2200 K
- low CRI, about 20 (color improved 65, white 80)
- starting and re-starting time 2-5 min

Figure 5-7. *High pressure sodium lamps, elliptical bulb 100 W and 250 W, tubular bulb 250 W and white high pressure sodium 100 W.*

Electrodeless lamps

The burning time of discharge lamps is normally limited by abrasion of electrodes. It is possible to avoid this by feeding electrical power into the discharge inductively or capacitively. Although the principles of electrodeless lamp have been understood for over a hundred years, electrodeless lamps were not introduced into the commercial market until the past decades. The main reasons were the lack of reliable and low cost electronics, and avoidance of electromagnetic interferences. With the great development in electronics and consequently introduction of electronic ballasts, the electrodeless lamp has become ready to be introduced to commercial market for the general purpose lighting.

Induction lamp

The induction electrode-less fluorescent lamp is fundamentally different from the traditional discharge lamps, which employ electrodes as electron source. The operating frequency of induction lamp is usually in the range of hundreds of kHz to tens of MHz. A special generator or ballast is needed to provide high frequency power. Without electrodes, energy coupling coils are needed for the energy coupling into the plasma. A long lamp life and good lumen maintenance can be achieved with these lamps because of the absence of electrodes. The filling of the discharge vessel consists of mercury (amalgam) and low pressure krypton. Like in fluorescent lamps, the primary emission (in UV-region) is transformed with a phosphor coating into visible radiation. Typical parameters are: lamp wattages 55-165 W, luminous efficacy of systems 60-80 lm/W, CCT 2700-4000 K, CRI 80. The long lamp life of even 100 000 h is useful for applications in inaccessible locations (road tunnels, factory halls).

Compact fluorescent lamps (electrodeless)

Some models of CFLs are electrodeless lamps. Their advantages over common CFLs are instant switching and good performance with switching cycles.

5.2.4 Auxiliaries

Energy efficiency of the lighting system depends not only to the luminous efficacy of lamps but also on the efficiency of the auxiliary equipment. This equipment include ballasts, starters, dimmers and transformers.

Ballasts

Ballast providing a controlled current to the lamps is an essential component of any discharge lighting system. The amount of energy lost in the ballasts can be reduced considerably by using efficient ballasts. European Directive 2000/55/EC divides ballasts into six categories shown in the Table 5-3. Several types of ballasts are excluded from the directive:

- ballasts integrated in lamps,
- ballasts designed specifically for luminaries to be mounted in furniture and which form a non-replaceable part of the luminaries and which cannot be tested separately from the luminaries,
- ballasts to be exported from the Community, either as a single component or incorporated in luminaries.

Table 5-3. *Ballast Categories.* (EC 55/2000)

Category	Description
1	Ballast for linear lamp type
2	Ballast for compact 2 tubes lamp type
3	Ballast for compact 4 tubes flat lamp type
4	Ballast for compact 4 tubes lamp type
5	Ballast for compact 6 tubes lamp type
6	Ballast for compact 2 D lamp type

The purpose of the directive is to achieve cost-effective energy savings in fluorescent lighting, which would not otherwise be achieved with other measures. Therefore, the maximum input powers of ballast-lamp circuits are given in Annex III of the ballast Directive (EC 55/2000). Manufacturers of ballasts are responsible for establishing the power consumption of each ballasts according to the procedures specified in the European Standard EN 50294 (EN 1998).

Table 5-4. *Examples of the maximum input power of ballast-lamp circuits (phase two).* (EC 55/2000)

Ballast category	Lamp power		Maximum input power of ballast-lamp
	50 Hz	HF	
1	15 W 70 W	13,5 W 60 W	23 W 80 W
2	18 W 36 W	16 W 32 W	26 W 43 W
5	18 W 26 W	16 W 24 W	26 W 34 W
6	10 W 38 W	9 W 34 W	16 W 45 W

The Directive 2000/55/EC aims at reducing the energy consumption of ballasts for fluorescent lamps by moving gradually away from the less efficient ballasts towards more efficient ones. The ballast, however, is only one part of the energy consumption equation. The energy efficiency of fluorescent lamps lighting systems depends on the combination of the ballast and the lamp. As a consequence, the Federation of National Manufacturers Associations for Luminaries and Electrotechnical Components for Luminaries in the European Union (CELMA) has found it necessary to develop a ballast classification system based on this combination (CELMA 2007)

The European Ballasts manufacturers, represented in CELMA, have adopted the scheme of classification of ballasts defined by CELMA since 1999. As a consequence, all ballasts falling under the scope of the 2000/55/EC Directive are marked with the pertinent Energy Efficiency Index EEI (voluntary) printed in the label or stated in the data sheets.

There are seven classes of efficiency. Every class is defined by a limiting value of the total input power related to the corresponding ballast lumen factor BLF (1.00 for high frequency operated ballasts and 0.95 for magnetic ballasts). The classes are listed bellow:

- Class D: magnetic ballasts with very high losses (discontinued since 2002)
- Class C: magnetic ballasts with moderate losses (discontinued since 2005)
- Class B2: magnetic ballasts with low losses
- Class B1: magnetic ballasts with very low losses
- Class A3: electronic ballasts
- Class A2: electronic ballasts with reduced losses
- Class A1: dimmable electronic ballasts

Dimmable ballasts are classified as A1 if they fulfil the following requirements:

- At 100% light output setting the ballast fulfils at least the demands belonging to A3
- At 25% light output the total input power is equal to or less than 50% of the power at the 100% light output
- The ballast must be able to reduce the light output to 10% or less of the maximum light output

Electronic ballasts complying with CELMA energy efficiency scheme classes A1 and A2 are the major power savers. They can even reduce the power consumption of ballast-lamp circuits to less than the rated power of the lamp at 50Hz. This is caused by the increased lamp efficiency at high frequencies (>20 kHz), leading to about 10% reduction of lamp power and a decrease of the ballast losses.

The European Standard EN 50294 (EN 1998) defines the measuring methods for the total input power of the ballast-lamp system. On the basis of this standard CELMA has defined energy classes and limit values for the ballast-lamp combination of the most common fluorescent lamps (details are given in annexes to the CELMA guide (CELMA 2007) – an example of class description in Table 5-5. The EEI system comprises the following lamp types:

- Tubular fluorescent lamps T8
- Compact fluorescent lamps TC-L
- Compact fluorescent lamps TC-D
- Compact fluorescent lamps TC-T
- Compact fluorescent lamps TC-DD

Table 5-5. *An example of the EEI class description system power.*(CELMA 2007)

Lamp type	Lamp power		Class						
	50Hz	HF	A1[x]	A2	A3	B1	B2	C	D
T8	15 W	13,5 W	9 W	16 W	18 W	21W	23 W	25 W	>25 W
	70 W	60 W	36 W	68 W	72 W	77 W	80 W	83 W	>83 W

[x] at 25% light output

Comparison of the electro-magnetic-ballasts and electronic ballasts

Electro-magnetic ballast produces a number of negative side-effects, such as:

- They operate at the 50 or 60Hz frequency of the AC voltage. This means that each lamp switches on and off 100 or 120 times per second, resulting in a possibly perceptible flicker and a noticeable hum,
- Operating at 50 or 60 Hz may cause a stroboscopic effect with rotating machinery at speeds that are a multiples of those frequencies,
- They can give off excessive EMF (Electro-Magnetic Fields).

Advantages of the electronic ballasts:

- They operate at about 25 kHz. High frequency operation eliminates flicker and hum, removing any associated health concerns.
- They are lightweight
- They generate very little heat
- They have better energy efficiency using 25-30% less energy.
- They can be built dimmable, enabling users to adjust light levels to personal needs resulting in energy savings.

The positive features of electromagnetic ballasts are that they are very robust and have long lifetime. The material recovery from them in the end-of-life is relatively easy and valuable metals can be recycled, while electronic ballasts are more difficult to recycle.

Transformers

Halogen lamps are available with low voltage ratings. A transformer is needed to provide voltage supply from either 110 V AC or 230 V AC mains to the lamps. Transformers are generally available with power ratings from 50 to 300 W. The transformer used in a low voltage lighting system may be either electronic or magnetic. The *electronic* transformer ET represents an alternative means of power conversion to the more standard iron core, bulky and heavy transformer operating at 50/60 Hz. The advantages of the electronic transformer compared with the classical solution are

(Radiolocman 2007):

- The output power from the electronic transformer to the lamp can be varied, thus dimming control can be added.
- It is possible to include protection against short circuit of the lamp filament.
- Weight can be reduced and the construction made more compact.
- Acoustic noise (mains hum) is eliminated.

The topology of the transformer circuit is the classic half-bridge. The control circuit could be realised using an IC (fixing the operating frequency), but there is a more economical solution (Radiolocman 2007, Fichera and Scollo 1999) which consists of a self-oscillating circuit where the two transistors are driven in opposing phase by feedback from the output circuit. As the capacitor at the input of the circuit is relatively small, there is little deformation of the input current waveform. However, this type of circuit generates a certain amount of electro-magnetic interference, due to the high frequency source that feeds the resonant network. Thus, a suitable filter must be inserted in the circuit before the rectifier bridge to prevent this interference being fed back to the mains. Another solution (Liang *et al.* 2006) might be piezoelectric ceramic transformer. This is a new kind of electronic transformer which has low electromagnetic interference, high power density, high transfer efficiency. It is small in size and light in weight and makes no noise.

The disadvantage of these transformers is that their lamp currents are rectangular in shape, leading to generation of high electromagnetic noise and increased transformer core losses. The new constructions solve these problems. An example of such solution is an electronic transformer using class-D zero-voltage-switching (ZVS) inverter (Jirasereeamornkul *et al.* 2003) giving near sinusoidal lamp current. The experimental results from a 50 W/12 V prototype show that efficiency is greater than 92% with unity power factor. Moreover, the dimming possibility and controlled starting current can be achieved by simply increasing the switching frequency without increasing the switching losses. The wattage rating (Farin 2008) of the electronic transformer or of the toroidal magnetic transformer should always be equal to or greater than the total wattage of the lighting system, but if a conventional EI magnetic transformer (transformer with a magnetic core shaped like the letters E and I) is used, then the maximum wattage of the lighting system may be equal to but not greater than 80% of the wattage rating of the conventional EI magnetic transformer.

Transformers usually have a minimum wattage (Farin 2008) which they must power before they work. For example, it is not uncommon for a 60 W electronic transformer to require there to be at least 10 W of lighting load and if there is only 5 watts of lighting load connected, the lighting system will not work. Low voltage lighting systems require thicker wires due to higher currents. For example, a 300 W lighting system operating at 12 V uses a 25 A current on the low-voltage side of the transformer, whereas this same transformer may be powered by 230 V and 1.3 A current on the line voltage side of the transformer.

An AC (alternating current) electronic transformer should not be placed further than 3 m (10 feet) from the lighting system in order to avoid lower voltages (voltage drop) and consequently lower luminous flux. Also, the longer the distance from the AC electronic transformer to the lighting system, the greater the chance that it might create radio frequency interference (RFI) with other electronic components in the area. A DC (direct current) electronic transformer may be placed up to about 16 m (50 feet) from the lighting system. The DC output significantly reduces radio frequency interference (RFI) and virtually eliminates the possibility of voltage drop (the drop in voltage over a long circuit).

Starters

Starters are used in several types of fluorescent lamps. When voltage is applied to the fluorescent lamp, the starter (which is a timed switch) allows current to flow through the filaments at the ends of the tube. The current causes the starter's contacts to heat up and open, thus interrupting the flow of current. The lamp is then switched on. Since the arc discharge has low resistance (in fact negative voltage-current characteristics), the ballast serves as a current limiter. Preheat fluorescent lamps use a combination of filament/cathode at each end of the lamp in conjunction with a mechanical or automatic switch that initially connects the filaments in series with the ballast and thereby preheat the filaments prior to striking the arc. These systems are standard equipment in countries with voltage level of 230 V (and in countries with voltage level 110 V with lamps up to about 30 watts), and generally use a glow starter. Electronic starters are also sometimes used with these electromagnetic ballasts.

The automatic glow starter consists of a small gas-discharge tube, containing neon and/or argon and fitted with a bi-metallic electrode. When starting the lamp, a glow discharge will appear over the electrodes of the starter. This glow discharge will heat the gas in the starter and cause the bi-metallic electrode to bend towards the other electrode. When the electrodes touch, the two filaments of the fluorescent lamp and the ballast will effectively be switched in series to the supply voltage. This causes the filaments to glow and emit electrons into the gas column. In the starter's tube, the touching electrodes have stopped the glow discharge, causing the gas to cool down again. The starter additionally has a capacitor wired in parallel to its gas-discharge tube, in order to prolong the electrode life. While all starters are physically interchangeable, the wattage rating of the starter should be matched to the wattage rating of the fluorescent tubes for reliable operation and long life. The tube strike is reliable in these systems, but glow starters will often cycle a few times before letting the tube stay lit, which causes undesirable flashing during starting.

If the tube fails to strike or strikes but then extinguishes, the starting sequence is repeated. With automated starters such as glow starters, a failing tube will cycle endlessly, flashing as the lamp quickly goes out because emission is insufficient to keep the lamp current high enough to keep the glow starter open. This causes flickering, and runs the ballast at above design temperature. Some more advanced starters time out in this situation and do not attempt repeated starts until power is reset. In some cases, a high voltage is applied directly. Instant start fluorescent tubes simply use a high enough voltage to break down the gas and mercury column and thereby start arc conduction. These tubes can be identified by a single pin at each end of the tube. Low-cost lamps with integrated electronic ballast use this mode even if it reduces lamps life. The rapid start ballast designs provide filament power windings within the ballast. They rapidly and continuously warm the filaments/cathodes using low-voltage AC. No inductive voltage spike is produced for starting, so the lamps must be mounted near a grounded (earthed) reflector to allow the glow discharge to propagate through the tube and initiate the arc discharge. In some lamps a *starting aid* strip of grounded metal is attached to the outside of the lamp glass.

Dimming

Dimmers are devices used to vary the luminous flux of incandescent lamps. By adjusting the root mean square (RMS) voltage and hence the mean power to the lamp it is possible to vary the intensity of the light output. Small domestic dimmers are generally manually controlled, although remote control systems are available.

Modern dimmers are built from silicon-controlled rectifiers (SCR) instead of potentiometers or variable resistors because they have higher efficiency. A variable resistor would dissipate power by heat (efficiency as low as 0.5). Theoretically a silicon-controlled rectifier dimmer does not heat up, but by switching on and off 100/120 times a second, it is not 100% efficient. Dimming light output to 25%, reduces electricity consumption only 20%, because of the losses in the rectifier. Using CFLs in dimmer circuit can cause problems for CFLs, which are not designed for this additional turning on and off of a switch 100/120 times per second.

Fluorescent lamp luminaires cannot be connected to the same dimmer switch used for incandescent lamps. There are two reasons for this, the first is that the waveform of the voltage of a standard phase-control dimmer interacts badly with many types of ballast, and the second is that it becomes difficult to sustain an arc in the fluorescent tube at low power levels. Dimming installations require 4-pin fluorescent lamps and compatible dimming ballasts. These systems keep the cathodes of the fluorescent tube fully heated even though the arc current is reduced. There are CFLs available that work also in a dimmer circuit. These CFLs have 4 pins in the lamp base.

5.3 Solid-state lighting

5.3.1 Light-emitting diodes (LEDs)

Solid-state lighting (SSL) is commonly referring to lighting with light-emitting diodes (LED), organic light-emitting diodes (OLED) and light-emitting polymers (LEP). At the moment there is still no official definition for solid-state lighting, the expression “solid-state” refers to the semiconductor crystal where charge carriers (electrons and holes) are flowing and originate photons (i.e., light) after radiative recombinations.

Operation principle and light generation

An LED is a *p-n* junction semiconductor which emits light spontaneously directly from an external electric field (electroluminescence effect). LEDs work similarly to a semiconductor diode, allowing current flow in one direction only. The diode structure is formed by bringing *p*- and *n*-type semiconductor materials together in order to form a *p-n* junction. P-type material is obtained by doping an intrinsic semiconductor material with acceptor impurities resulting in an excess of positive charges (holes). To produce an N-type semiconductor, donor impurities are used to create an excess of negative charges (electrons). The *p* and *n* materials will naturally form a depletion region at the junction, which is composed of ionized acceptors in the *p*-side and ionized donors in the *n*-side forming a potential barrier at the junction. The applied external electric field across the junction will allow electrons in the conduction band, which are more mobile carriers than holes, to gain enough energy to cross the gap and recombine with holes on the other side of the junction emitting a photon as a result of the decrease in energy from the conduction to the valence band (radiative recombination).

Although radiative transitions can also occur in indirect bandgap semiconductors, their probability is significantly lower than in direct bandgap semiconductors. Radiative recombinations are characteristic for direct bandgap semiconductors. Therefore, direct bandgap semiconductor alloys are commonly used in optoelectronic devices such as LEDs, where the highest radiative recombination rates are a desirable feature. Examples of direct bandgap semiconductors that have bandgap energies within the visible spectrum are binary alloys composed of elements in the groups III and V of the periodic table (e.g., InP, GaAs, InN, GaN, and AlN). The present high-brightness LED-industry is based on ternary and quaternary alloys containing a mixture of aluminum (Al), gallium (Ga), and/or indium (In) cations and either one of arsenic (As), phosphorus (P), or nitrogen (N) anions. The three main relevant material systems for LEDs are AlGaAs, AlGaInP, and AlInGaN. For each of these systems bandgap engineering is used during the epitaxial growth of the semiconductor wafers to create heterostructures that are required for high levels of carrier injection and efficient radiative recombination. (Žukauskas, Shur et al. 2002)

Theoretically, it is possible that all free electrons injected into the active region of recombine to create a photon. This suggests the high energy efficiency potential of LEDs. This energy efficiency potential is referred to as radiant or wall-plug efficiency η_e, and defined as the ratio between the total emitted radiated power and the total power drawn from the power source. The radiant or wall-plug efficiency of an LED depends on several internal mechanisms regulating light generation and emission processes in the semiconductor and LED package. These mechanisms are commonly characterised by their efficiencies, commonly referred to as feeding efficiency η_f, external quantum efficiency η_{ext}, injection efficiency η_{inj}, radiative efficiency or internal quantum efficiency η_{rad} and optical efficiency or light-extraction efficiency η_{opt}. (Žukauskas, Shur et al. 2002).

$$\eta_e = \eta_{ext} \times \eta_f \tag{5-1}$$

$$\eta_f = h\upsilon/qV \tag{5-2}$$

$$\eta_{ext} = \eta_{inj} \times \eta_{rad} \times \eta_{opt} \tag{5-3}$$

Luminous efficacy η_υ is obtained by multiplying the radiant efficiency with the luminous coefficient K_m.

$$\eta_\upsilon = \eta_e \times K_m \tag{5-4}$$

The best red AlInGaP LED and blue InGaN LEDs can have internal quantum efficiencies reaching almost 100% and 50%, respectively (Steigerwald, Bhat et al. 2002). To achieve external quantum efficiencies of such magnitudes, the light extraction has to be improved. One of the main challenges faced by the industry to allow the more photons to escape from the LED chip without getting absorbed by the surrounding structure (i.e., extraction efficiency) (Navigant Consulting Inc., Radcliffe Advisors et al. 2009).

The history of commercially available LEDs started in the early 1960`s with the first red LED with peak emission at 650 nm (Holonyak, Bevacqua 1962). The semiconductor material utilised was GaAsP (Gallium Arsenide Phosphide). The typical power consumption of these red LEDs would be typically around 0.1 W, emitting 0.01 lm resulting in 0.1 lm/W luminous efficacy (Humphreys 2008). The price was 260 $ and price per lumen around 26000 $. Since then, the LEDs have developed fast over the past four decades. Modern LED components cover peak wavelength regions from the ultraviolet to the infrared region. AlInGaP are today the chosen semiconductor material system to realise LEDs with spectral emission from red to yellow region of the visible spectrum. AlInGaN materials usually cover the wavelength region between green and ultraviolet. Colored LEDs are characterised by narrow spectral emission profiles. This characteristic is defined by the full spectral bandwidth at half magnitude (FWHM) usually around 15 nm to 60 nm (Žukauskas, Shur et al. 2002).

White LEDs can be realised by mixing the emission of different colored LEDs or by the utilisation of phosphors. Phosphor-converted white LEDs are usually based on blue or ultraviolet LEDs. The white light results from the combination of the primary blue or ultraviolet emission and the partially downward-converted emission created by specific phosphor layer or layers located over the semiconductor chip. (Kim, Jeon et al. 2004, Nakamura, Fasol 1997)

Depending on the properties of the phosphor layer or layers utilised, white light of different qualities can be realised. The typical spectrum for phosphor-converted warm- and cool-white LEDs at CCTs of 3000K and 7000K, respectively are shown in the Figure 5-8.

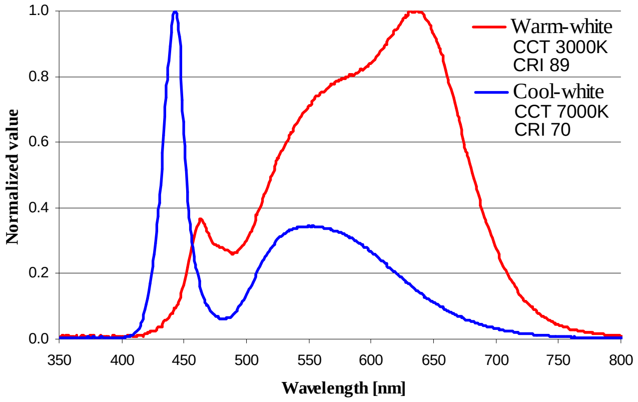


Figure 5-8. *Typical spectral power distribution curves for phosphor-converted warm- and cool-white LEDs at 3000K and 7000K CCT, respectively.*

Color-mixing by combining the emission of different colored LEDs is another approach to provide white light. Usually only two colored LEDs are needed to produce white light. However, to achieve high color rendering properties, at least three colored LEDs are usually required. Figure 5-9 represents the main approaches to create white light.

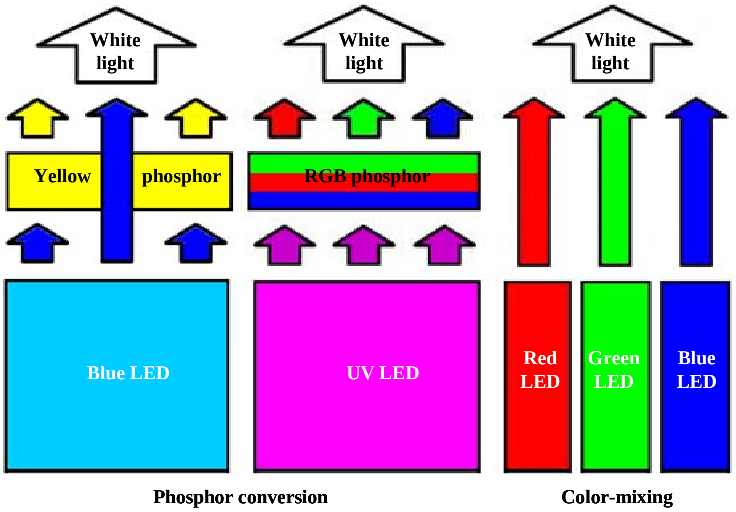


Figure 5-9. *Schematic representation of the two main approaches to create white light using LEDs.*

LED characterization

Optoelectronic devices such as LEDs are commonly characterised by optical, electrical and thermal parameters as schematically shown in Figure 5-10.

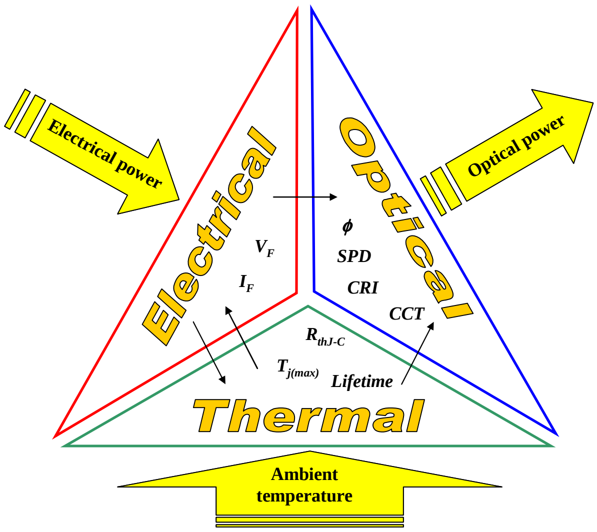


Figure 5-10. *Schematic representation of the main parameters and interactions, which characterise the operation of a LED.*

Electrically, an LED is characterised by its forward current (I_F) and forward voltage (V_F). Due to their typical I-V curve, representing the forward current as a function of the forward voltage, LEDs are called current-controlled devices. Along with the I-V curve, LED manufacturers provide the nominal and maximum forward currents and voltages of the devices in their datasheets.

Several parameters are used to characterise LEDs optically. The main parameters depending on the LED type (i.e., colored or white LED) are the spectral power distribution (SPD), spatial light distribution, viewing angle, color rendering index (CRI), correlated color temperature (CCT), peak wavelength, dominant wavelength, luminous flux, luminous intensity and luminous efficacy. The electrical and optical performance of an LED is interrelated with its thermal characteristics. Due to the inefficiencies resulting from the imperfections in the semiconductor and in the LED package structure heat losses are generated. These losses have to be removed from the device in order to keep the *p-n* junction operation temperature below the maximum allowed value and avoid premature or catastrophic failure of the device. The heat losses are firstly conducted to the exterior of the LED package throughout an included heat slug. Next, the heat is realised to the ambient throughout convention and radiation. In some applications the utilisation of an exterior cooling system such as a heatsink is required to facilitate the released of the heat to the ambient. Thus, the main parameter characterising the thermal performance of an LED is the thermal resistance between the *p-n* junction and the soldering-point. The variation of *p-n* junction temperature of the LED influences the optical and electrical properties.

Other important parameters characterising LED operation are the temperature coefficient of the forward voltage and the dominant wavelength temperature coefficient, given respectively by mV/°C and nm/°C. These coefficients show the interdependence between optical, thermal and electrical parameters. These parameters are responsible for optical and spectral dissimilarities between different LED types. AlInGaP LEDs (e.g., red, amber and yellow) are more sensitive to junction temperature variations than InGaN-based LEDs (e.g., blue, cyan, green and phosphor-converted white). These thermal behaviour dissimilarities are represented in Figure 5-11.

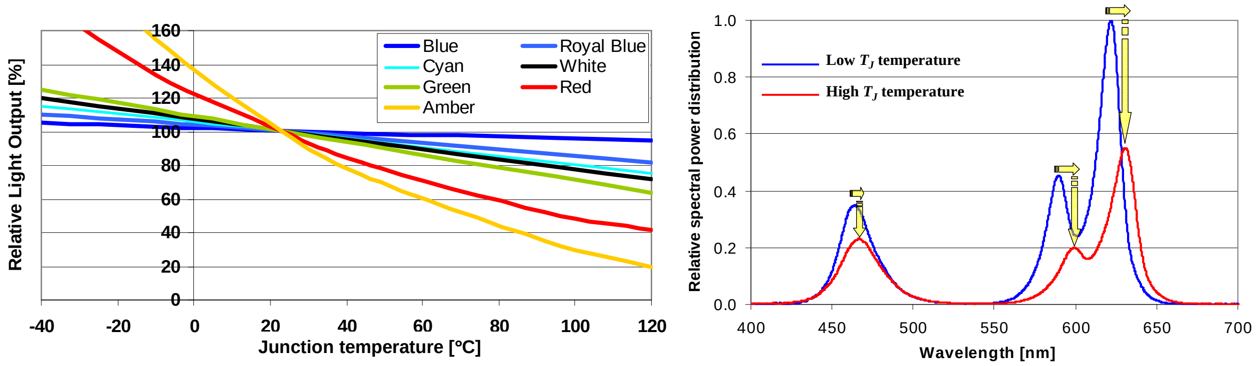
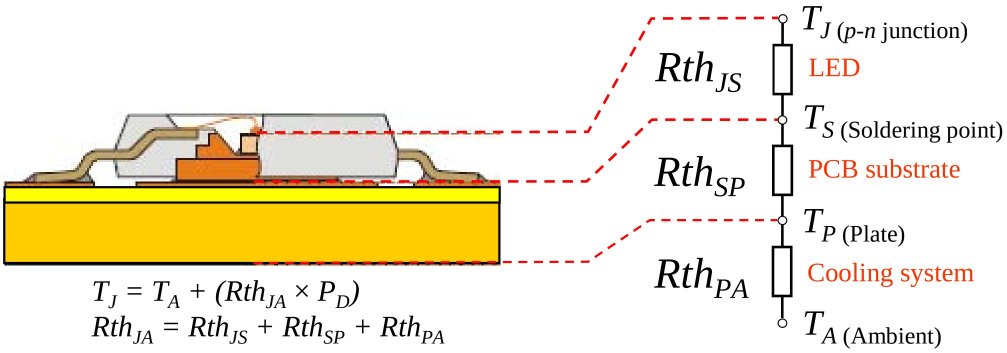


Figure 5-11. *Influence of the junction temperature (T_J) on the light output and spectral power distribution of AlInGaP and InGaN-based LEDs.*

The operation temperature of the *p-n* junction influences the optical and electrical characteristics of an LED. Therefore thermal management is an important aspect to be taken into account at an early design stage of LED engines. An LED is often mounted on circuit board which is attached to a heatsink. The simplified thermal model circuit and the main equations are shown in Figure 5-12., where Rth_{JA}, Rth_{JS}, Rth_{SP}, Rth_{PA} represent the thermal resistances between *p-n* junction and the ambient, *p-n* junction and soldering point, soldering point and plate, plate and ambient, respectively, An LED luminaire will need, also, external optics and a driver.



$$T_J = T_A + (Rth_{JA} \times P_D)$$
$$Rth_{JA} = Rth_{JS} + Rth_{SP} + Rth_{PA}$$

Figure 5-12. *Simplified thermal model circuit of a LED placed on a PCB.*

The conversion efficiencies of incandescent and fluorescent lamps are limited by fundamental laws of physics. A black body radiator with a temperature of 2800 K radiates most of its energy in the infrared part of the spectrum. Therefore, only about 5% of the radiation of an incandescent lamp is emitted in the visible spectrum. Mercury discharge of a fluorescent lamp occurs mainly at a UV-wavelength of 254 nm. When UV-radiation is converted into light with fluorescent powder, more than a half of the energy is lost. A fluorescent lamp can convert approximately 25% of the electrical energy into radiant energy in the visible spectrum.

LED technology on the other hand does not have to fight the fundamental laws of physics in a similar fashion as the phosphor conversion in fluorescent lamps. Theoretically, it can achieve a conversion efficiency of 100%. The luminous efficacy of a white light LED depends on the desired wavelengths and color rendering index (CRI). Zukauskas *et al.* (2002) have calculated the optimal boundaries for white light using two, three, four and five LEDs:

— η_v 430 lm/W and CRI 3 using two LEDs
— η_v 366 lm/W and CRI 85 using three LEDs
— η_v 332 lm/W and CRI 98 using four LEDs

- η_v 324 lm/W and CRI 99 using five LEDs

Luminous efficacy of 400 lm/W is reachable with three LEDs, but in that case the CRI will remain under 50. Zukauskas *et al.* (2008) have also shown that using phosphor-converted white LEDs good color rendering can be attained at different color temperatures, while maintaining luminous efficacies relatively high (i.e., 250 to 280 lm/W). Future lighting systems will require more intelligent features. In this regard LED-based lighting systems have an important advantage due to their easy controllability. Intelligent features combined with the inherent high energy-saving potential of LEDs will be an unbeatable combination in a wide range of applications.

Advantages of LEDs:

- Small size (heat sink can be large)
- Physically robust
- Long lifetime expectancy (with proper thermal management)
- Switching has no effect on life, very short rise time
- Contains no mercury
- Excellent low ambient temperature operation
- High luminous efficacy (LEDs are developing fast and their range of luminous efficacies is wide)
- New luminaire design possibilities
- Possibility to change colors
- No optical heat on radiation

Disadvantages of LEDs:

- High price
- Low luminous flux / package
- CRI can be low
- Risk of glare due to high output with small lamp size
- Need for thermal management
- Lack of standardisation

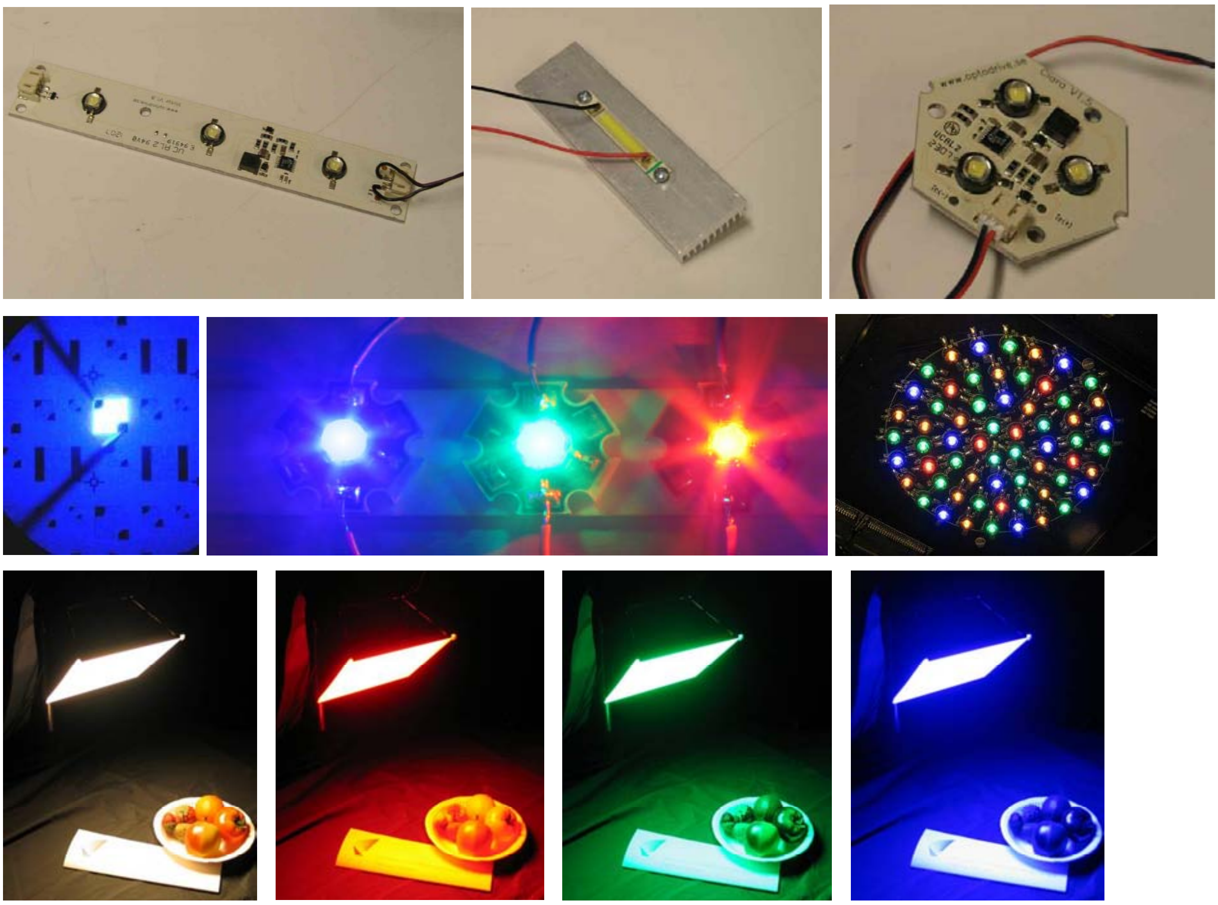


Figure 5-13. *Examples of LEDs and LED modules.*

5.3.2 OLEDs - Organic light-emitting diodes

Similarly to inorganic light-emitting diode, the organic light-emitting diode (OLED) promises highly efficient large area light sources.

Recent developments have reported luminous efficacies of 90 lm/W at luminances of 1000 cd/m^2 with improved OLED structure combining a carefully chosen emitter layer with high-refractive-index substrates and outcoupling structure (Reineke, Lindner et al. 2009). This efficacy level is already very close to that of fluorescent lamps which are the current benchmark for efficient and high quality white light sources used in general lighting.

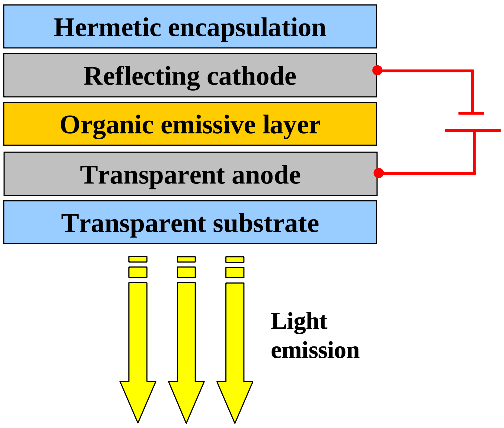


Figure 5-14. *Generic structure representation of an OLED.*

The basic materials of OLEDs are products of carbon chemistry. Typically an OLED is composed by one or several organic emissive materials sandwiched between two metal contacts (cathode and anode) as shown in Figure 5-14. One of these contacts has to be transparent while the other has reflective properties. Multi-layer-structures are deposited onto transparent substrates like glass or polycarbonate. Another essential difference is that the conduction properties of the materials do not depend on doping as inorganic LEDs, but are instead inherent characteristics of the organic molecule. White OLEDs have been made by piling three thin layers, emitting the red, green and blue light respectively. The special characteristics of OLEDs are:

- Light emission from large areas
- Simplicity of processing techniques
- Limited luminances (e.g. 1000 cd/m^2)

Applications range from lighting to flat-panel displays with high resolution. Transparent variants (TOLEDs) may be integrated into car windshields or similar equipment to combine window and display functions.

OLEDs are extremely thin with no restrictions on the size or shape. The main advantages of OLED technology are the simplicity of processing techniques, the availability of a wide range of organic luminescent materials and emitted colors, and the possibility of producing large and flexible surfaces. OLED technology has three specific characteristics: transparency, flexibility and white-light emission.

The energy efficiency potential of OLEDs is equally high as with inorganic LED technology. Both technologies share similar problems such as the relatively low external quantum efficiency. Theoretically, internal quantum efficiencies close to 100% are achievable by using phosphors. However, to produce highly efficient devices, the external quantum efficiency has to be increased by helping a larger fraction of the internally produced photons to escape to the exterior of the device.

5.3.3 LED drivers

LEDs are making their entrance into the lighting field using modern high-efficiency semiconductor material compounds and structures. Solid-state lighting (SSL), offers new possibilities and advantages for the end-user. By using appropriate drivers, control strategy and LEDs, the qualitative and quantitative aspects of the light can be fully controlled. Electronic drivers are indispensable components for most LED systems and installations. As LED technology evolves, the possibilities for new and more intelligent products increase the demand for more specific features from the LED drivers.

The LED chip has a maximum current density that should not be exceeded to avoid premature failure. The cheapest and most basic way to drive LEDs is to use a constant voltage power supply and a resistor in series with the LED to limit the current flowing through it. The selected resistance depends on the magnitude of the voltage source (V_{IN}), on the value of the LED’s forward voltage and the forward current of the LED. However, the use of limiting resistors is not desirable in applications where reliability, accurate control and electrical efficiency are desired features. In applications presenting small variations in the DC supply voltage, the LED current will vary considerably resulting in some cases in premature failure of the device.

Linear power supply (LPS) is an economical, simple and reliable way of driving LEDs. LPSs are based on either integrated circuit (IC) linear regulator or on bipolar junction or field effect transistors operating in the linear region. The operation in the linear region is comparable to the voltage-current characteristic of a resistor. The simplest linear voltage regulator can be made from a Zener diode operating in its breakdown region. Typical DC/DC circuit stages of linear voltage and current regulators are based on a commercially available 3-terminal adjustable ICs. LPSs are known for their very low electromagnetic interference (EMI). Therefore, they do not require additional filters. The low output ripple, excellent line and load regulation and fast response times are also important features. The main drawback is the heat loss mainly due to the operation of the linear regulator and the resistors used in the voltage divider network. Off-line AC/DC linear power supplies generally use transformers at the input stage followed by the rectification and filtering stages. The final stage includes a linear regulator which is the key component in this type of power supplies. Typical efficiency values range from 40% to 55%, resulting in low power density and bulky structure in most of the cases.

Switched-mode power supplies (SMPS) lack the main drawbacks of linear power supplies and are therefore the main solution to drive LEDs. Because LEDs are DC components, just DC/DC and AC/DC SMPS types are considered here. Efficiency (typically between 60 and 95%), controllability, small size and low weight are their main advantages over the linear power supplies. An SMPS can provide, if necessary, high currents (e.g., more than 30A) at very low voltages (e.g., 3V). Equivalent LPSs would be bulkier and heavier. The main component of an SMPS is the power switch. The power switch is basically a transistor that is used as an on/off switch. Typically, a power switch should have low internal resistance during the conduction time (i.e., on-time) and high switching speed capability. The main losses are due to switching and internal switch resistance during the on-time.

In applications where the load voltage is higher than the supply voltage, Boost DC/DC converters offer a simple and effective solution. Boost LED drivers are often required when a string of several series-connected LEDs are driven. In general, the boost configuration provides greater efficiency because of smaller duty cycle for a given output voltage. Also, the conduction losses in the inductor and other components are smaller. Buck, Buck-Boost, Cuk and Boost, are probably the most common topologies found in SMTP LED drivers. Other topologies that allow isolated operation such as Flyback and SEPIC (Single-Ended Primary Inductance Converter) are also used.

DC/DC Buck converters can provide simplicity, low cost and easy control. However, Buck-Boost can be a more versatile solution when the input voltage range overlaps the required output voltage. SEPIC and Flyback topologies are useful in applications where the output voltage falls between the minimum and maximum input voltage. Additionally, they provide full isolation between the input and output stages. Though SEPIC topology outperforms an equivalent Flyback topology in terms of efficiency and EMI, Flyback topology continues to be the most commonly used. One of the reasons for this is the larger coupled-inductor size required by the SEPIC topology for operation in continuous-current mode (CCM) at light loads.

The selection of the most appropriate topology to drive LEDs depends on the application requirements (e.g., operation environment conditions, system input voltage, LEDs’ forward voltage, number of LEDs and circuit array), standards and specifications. LED drivers intended for use in commercial aircrafts or cars will have to be designed according to specific standards and requirements. To respond to the demanding application features and requirements, practical implementations make use of ICs or Application-Specific Integrated Circuits (ASIC) as switch regulators or controllers.

5.3.4 LED dimming and control

LEDs allow spectral, spatial and temporal control of the light emitted. These features have been unobtainable with conventional light sources. Consequently, the emerging applications are bringing important benefits to the lighting field. A majority of these applications require special control features just achievable with intelligent batteries or drivers. Intelligent drivers are usually based on ASICs switching microcontrollers which include programmable flash memory (EEPROMs), several on-chip Pulse-Width Modulation (PWM) controllers, ADCs (analogue-to-digital converter) and DACs (digital-to-analogue converter) channels.

Microcontroller-based LED drivers bring additional benefits such as operational flexibility, efficiency, reliability, controllability and intelligence to the system. Microcontroller ICs provide a long list of useful features such as built-in soft-start, multi-channel from 8- to 64-bit DAC/ADC, programmable input startup voltage, programmable output current range, shutdown mode, wide-input-voltage range and short-circuit protection. The features also include thermal shutdown, multi-PWM channels, possibility of synchronization with external clock, built-in switches, RAM, ROM, and programmable flash memory (EEPROM) throughout serial USART (Universal Serial Asynchronous Receiver-Transmitter). In programmable microcontroller-based LED drivers the processing speed is probably one of the most important aspects to be considered. The microcontroller speed can limit the maximum switching speed and data acquisition in applications processing information in real-time. The reason is related to the full-cycle analyses of instructions and the reading of variables. The reading speed is given by Million of Instructions per Second (MIPS) is a value provided in the datasheet.

In many LED applications, accurate and versatile dimming of the light output is required. In applications such as LCD backlighting, dimming provides brightness and contrast adjustment. Dimming ratio or resolution is of paramount importance, especially at low brightness levels where the human eye perceives very small variations in the light output. The LED is a current-driven device whose light output and brightness are proportional to its forward current. Therefore, the two most common ways of dimming LEDs utilize DC-current control. One of the easiest implementations makes use of a variable resistor to control the LED’s forward current. This technique is commonly known as analogue dimming. However, voltage variations, power waste on the variable resistor and color shift, make the analogue dimming method not suitable for more demanding applications.

An alternative solution to analogue dimming is digital dimming which uses PWM of the forward current. Dimming a LED digitally reduces significantly the color shift associated with analogue dimming. Moreover, a LED achieves its best efficiency when driven at typical forward current level specified by the manufacturer. Another advantage of PWM dimming over analogue dimming is that a wider dimming range is possible. Ideally, with PWM dimming the LED current always stays at nominal value during the on-time defined by the duty cycle. By changing the duty cycle of the PWM signal, the average LED current changes proportionally. The selected PWM frequency should be high enough to reduce or completely remove flickering. Switching frequencies below 20 kHz might result in acoustic noise, and below 100 Hz are likely to cause visible flicker. Therefore, special care has to be taken during the selection of the operational switching frequency. However, a trade-off has to be established between the output ripple, the PWM resolution, the switching frequency and the size of the inductor in order to optimize the overall operational performance of a LED driver. High switching frequency will require a small inductor size but the PWM resolution will stay low. Low PWM resolution results in low control accuracy and high output ripple.

In general, SMPS for LEDs operate in continuous conduction mode (CCM) avoiding discontinuous conduction mode (DCM). The transition between the two modes defines the minimum duty cycle value. The minimum duty cycle is a critical aspect in terms of dimming resolution. Lighting control protocols such as Digital Addressable Lighting Interface (DALI) and DMX512 use 256-step dimming resolution. Such dimming resolution can be achieved with an 8-bit microcontroller. In applications requiring high-dimming resolution such as in Digital Lighting Processing (DLP) and Liquid Crystal Display (LCD) -based televisions, 4000 dimming steps or more are required. In RGB LED displays sophisticated LED drivers are required to provide a high number of brightness levels. The number of reproducible colors in the display is proportional to the number of brightness levels available for each of the RGB LEDs that make up a single pixel in the overall display.

For instance, in a 12-bit microcontroller-driven RGB LED, one pixel is capable of reproducing 68.7 billion colors. High-dimming resolution is required especially at low brightness levels where the driver’s output current is low. In order to avoid DCM a lower switching frequency has to be used. That way the output ripple, the electrical stress on the switch and the low efficiency associated with DCM can be avoided. Ideally the PWM frequency should be chosen low enough to ensure that the current regulation circuit has enough time to stabilize during the PWM on-time. The maximum PWM frequency depends on the power-supply startup and response times. Last but not least, the current linearity with duty cycle variation should be taken into account when selecting the switching frequency.

The manufacturers of LED systems want to make full use of the great potential and characteristics offered by LEDs. Thus, the optimization of the overall system performance is always an aspect to be considered. Electronic drivers are important components in a majority of LED-based systems. Relatively small improvements on the driver efficiency often result in big improvements in the system level efficiency. In order not to misuse one of the great advantages of LEDs, their high potential efficiency, the drivers should perform accordingly. In applications involving power LEDs, the best efficiency performance is normally achieved with SMPS. SMPS are an ideal solution when small size, light weight and efficient drivers are required. The most appropriate topologies are selected based on the type of LED clusters to be driven and on their operational requirements. IC switching regulators, microcontrollers or programmable microcontrollers are often being used in LED drivers. Microcontroller-based LED drivers are commonly used in applications where optical or thermal control feedback loops are needed. In most cases, this also requires a high level of integration by combining optoelectronics with controller and driver circuitry. This can result in cost savings and reduction of the size of the product. In some cases this might also result in a more complex design affecting other properties such as the product lifetime. With adequate thermal management of LEDs, it is possible to reach lifetime expectancies close to 100000 hours equivalent to 11 years of continuous operation. Ideally, on-board or integrated drivers should be able to match the lifetime performance of LEDs. Digitally controlled SMPS are and will be indispensable components of intelligent LED systems. However, the utilisation of digitally managed SMPS for LED driving have some limitations that need to be dealt with. Among them are the processing speed, inductor size, dimming resolution, communication capability with other lighting industry standards and driving capability for multiple outputs and/or LED strings. The power rating is also a limiting factor when ICs with internal switch are used.

In conclusion, the inconveniences associated with the utilization of electronic drivers are mainly related to the reduction of system reliability, increase in EMI, introduction of inefficiencies and increase of size. The utilization of AC LEDs may address the previous limitations at system level and ease the adoption of SSL. Besides reducing the system driving complexity, AC LEDs may also minimize the complexities associated with DC current control. Additionally, system cost reductions are also likely. The current and future demand for high-end LED drivers has been fuelled by the competition between LED OEM and systems manufacturers. The current and future trend is to include power conversion, control and intelligence properties within a small number of chips using the lowest number of external components. Consequently, the required PCB size is reduced, resulting in better reliability and allowing more compact, efficient and low-cost power supplies. Compact designs are usually possible with high switching frequencies due to smaller physical size of inductors and capacitors required. Because the main advantages of LEDs over conventional light sources should not be misused, digitally managed power supplies may be the best solution to drive a broad range of LED systems both now and in the future.

5.3.5 LED roadmaps

The high energy-efficiency potential has been one of the main drivers for the fast technological development of LEDs during the last three decades. Currently, the main R&D trends in the LED technology have been the improvement of the efficiency and increase of light output. The acceptance of solid-state lighting in niche applications such as horticultural lighting depends on future improvements in conversion efficiency and light output per package. The trend in LED light output and light cost is continuing to follow the Haitz's law, according to which the evolution of red LEDs in terms of light output increase by a factor of 20 per decade, while the costs decrease by a factor of 10 (Haitz, Kish et al. 1999).

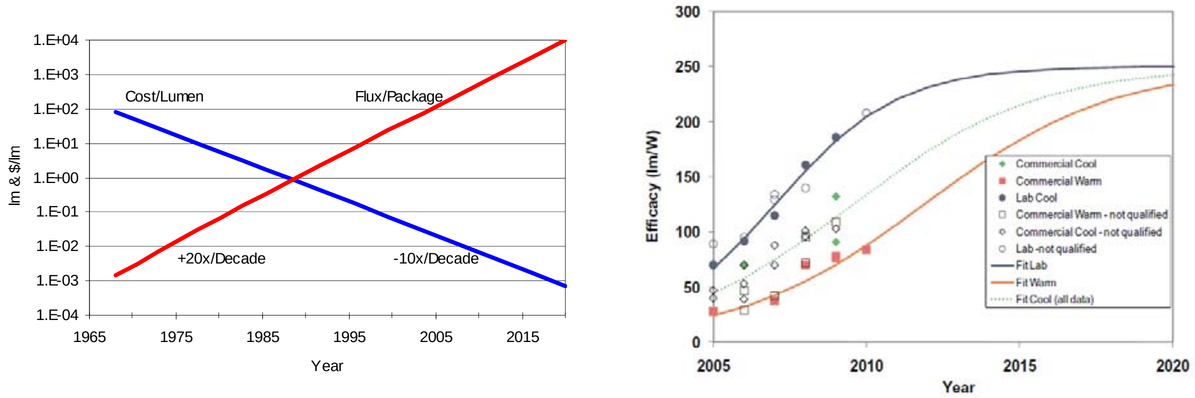


Figure 5-15. *Evolution of the light output per LED package, cost per lumen (left); and white light LED package efficacy targets (right). (DOE 2010, Haitz, Kish et al. 1999)*

The luminous efficacy projections shown above for cool white LEDs assume CRI between 70 and 80 at CCT located between 4746K and 7040K. The maximum expected efficacy for phosphor converted cool-white LEDs with these characteristics is expected to clear surpass 200lm/W by the year 2015. The luminous efficacy projections for warm white LEDs white expect values above 180lm/W. (DOE 2010)

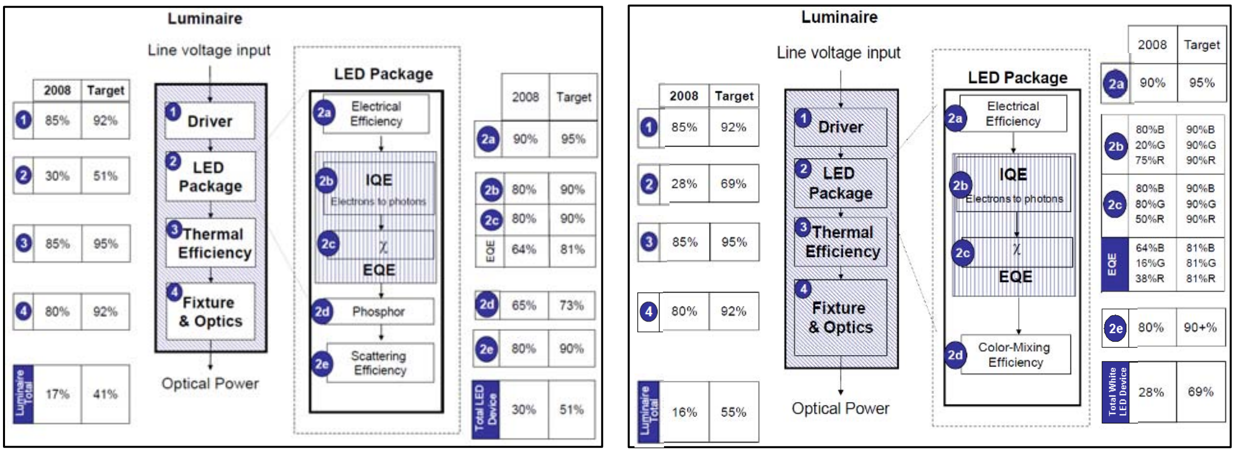


Figure 5-16. *Targeted luminaire efficiencies at steady-state operation of LED luminaires composed of phosphor-converted white LED (left) and color LEDs (right).* (Navigant Consulting Inc., Radcliffe Advisors et al. 2009)

The main future developments at LED luminaire level are expected to be on external quantum efficiency of the LED device followed by improvements of luminaire and optics efficiency. Producing white light using color-mixing gives the highest energy-efficiency potential at a system level in comparison to luminaires using phosphor-converted white LEDs. An RGB LED luminaire will be able to convert 55% of its input power into radiant power while a luminaire using white LEDs will only convert 41% (Navigant Consulting Inc., Radcliffe Advisors et al. 2009).

5.4 Trends in the future in light sources

Currently there is a global trend to phase out inefficient light sources from the market through legislation and voluntary measures. Commission Regulations (EC) No 244/2009 and No 245/2009 of 18 March 2009 implementing Directive 2005/32/EC (Ecodesign of Energy-using Products) of the European Parliament and of the Council have set requirements for non-directional household lamps and for fluorescent lamps without integrated ballast, for high intensity discharge lamps, and for ballasts and luminaires able to operate such lamps. These regulations will effectively remove incandescent lamps, mercury lamps and certain inefficient fluorescent and HID lamps from the European market (Commission Regulation (EC) n. 244/2009, Commission Regulation (EC) n. 245/2009, Council Directive 2005/32/EC). Similar legislative actions are carried out around the world: Australia has banned the import of incandescent lamps from February 2009, and USA has enacted the Energy Independence and Security Act of 2007 that phases out incandescent lamps in 2012-2014. Also other countries and regions have banned, are on their way to ban, or are considering banning inefficient light sources.

Electroluminescent light sources

Further technological developments on electroluminescent light sources are forecasted. These developments involve improvements in the device efficiency, light output and cost of lumens per package. The referred developments will enlarge the possibilities of electroluminescent light sources being utilized in applications dominated until now by conventional lighting technologies such as high-intensity discharge lamps. Improvement on external quantum of inorganic LEDs is one of the main technological development goals of optoelectronic and lighting industry. Additionally, semiconductor material structures have to be improved in order to address the effects known as "*droop*" and "*green hole*". These limitations are related with the decrease of light output at high currents and the low efficiency of LEDs emitting in the green region. Nowadays the applications involving LEDs are innumerable and the application varieties impose a clear demand on design of controllable LED drivers. At luminaire level, controllers and drivers are becoming indispensable components. As the LED technology continues to evolve, the possibilities for new and more intelligent products or systems based on intelligent controllers and drivers is expected to grow.

OLEDs bring new and different illumination possibilities than inorganic LEDs to the lighting field due to the large emitting surface and slim profile. Due to the fact that OLEDs are relatively more recent technology than inorganic LEDs, their efficiency performance still lags behind. Similarly to inorganic LEDs, improvements on internal quantum efficiency and light extraction are required in the future. Especially efforts have to be placed on the improvement of the efficiency of blue OLED emitter. Before a significant market penetration can take place, the lifetime of OLEDs is another important aspect to be improved.

Future developments in the solid-state lighting field are difficult to predict. However, the trend is towards the increasing and gradual adoption of this technology to replace conventional light sources, like the transistor replaced the valve in the past.

Discharge lamps

A special concern of all discharge lamps working with phosphors (fluorescent lamps, barrier discharge lamps etc.) is the conversion from short-wavelength to long-wavelength radiation. One UV-photon generates at most one visible photon, until today. For example, the photon energy in the middle range of the visible spectrum accounts for less than 50% of the photon energy of the main Hg-resonant-line (254 nm) and only 30% of the Xe2-eximer radiation. It is expectable in the future that luminescent materials will be able to convert one short-wavelength photon into two long-wavelength photons inside the visible spectrum region.

Another problem of most discharge lamps, with the exception of low pressure sodium and barrier lamps, is the use of mercury. From the point of view of plasma physics, Hg is the ideal buffer gas, but on the other hand, a perfidious environmental toxin. Practicable countermeasures are the systematic disposal of discarded lamps or a substitution of Hg. There exist few potential mercury free alternatives to current HID including metal halide lamps using zinc iodide as a substitute for mercury, and mercury-free high-pressure sodium lamps (UNEP 2008). OSRAM has recently introduced mercury free HID-headlamp system with performance comparable to xenon lamps containing mercury (OSRAM 2009).

A disadvantage of high pressure discharge lamps, especially for indoor applications, is the long warming-up period. By special electronic ballasts with a boosted power starting phase and modified lamp fillings, it is possible to considerably shorten this time. Such systems have already been realized for 35 W gas-discharge car headlamps. The UN-ECE regulation No. 99 (UN-ECE 2009) demands these lamps to reach 80% of the final luminous flux in 4 s after ignition.

5.5 Luminaires

5.5.1 Introduction

The discussions on phasing out the incandescent GLS-type lamps and new findings on the effects of light on human well-being and health have increased the public awareness of lighting. Beside the lamps, luminaires are important elements in lighting installations, and their quality defines the visual and ecological quality of the whole lighting in large part. During the last two decades, the development of lighting engineering has been driven by computerization of research and design of both luminaires and lighting systems, by wide use of electronics in products and control systems, and by application of new structural and lighting materials.

Nowadays, one of the main future trends in lighting industry is to offer products which are adaptable to the changing needs of the users, and which are energy efficient and ecological at the same time. These luminaires have to be integrated in the building management systems (or other control systems). Undoubtedly, the strongest trend in luminaire industry is towards LED-luminaires. New manufacturing and material technologies like high-reflective ($\rho > 98\%$) reflectors and complex surface techniques allow completely new luminaire concepts. Additionally, LED is revolutionizing the whole lighting industry by changing it from a sheet metal forming industry to a high tech electronic industry.

5.5.2 Definition of a luminaire

A luminaire is a device forming a complete lighting unit, which comprises of a light source and electric operating devices (transformer, ballast, ignitor, etc.). It also includes the parts for positioning and protecting the lamp/s (casing, holder, wiring), and connecting the lamp/s to the power supply, and the parts for distributing the light (optics). The function of luminaire (if not a pure decorative fitment) is to direct light to desired locations, creating the required visual environment without causing glare or discomfort. Choosing luminaires that efficiently provide appropriate luminance patterns for the application is an important part of energy efficient lighting design.

Different lamp technologies require different luminaire construction principles and features. For example, a metal halide lamp HCI 150 W (extreme high power density, very small, luminance 20 Mcd/m^2, bulb temperature ca. 600°C) compared to a T8 fluorescent lamp HO35W (diameter 16mm, 1.5m length, surface temperature 35°C, luminance 20000 cd/m^2) require completely different luminaire types.

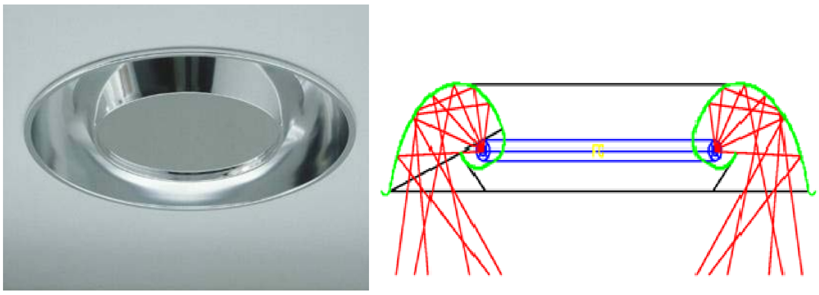


Figure 5-17. *Example of a technical luminaire (circular fluorescent, secondary radiation technique, high quality shielding).*

Luminaires can be classified by their different features such as:

- Lamp type (incandescent, tungsten halogen, FL, CFL, HID,etc.)
- Application (general lighting, downlight, wallwasher, accent light, spotlight,etc.)
- Function (technical, decorative or effect luminaires)
- Protection class (e.g. ingress protection IP-code)
- Installation (suspended, recessed or surface-mounted, free standing, wall mounted, etc.)
- Type of construction (open, closed, with reflectors and/or refractors, high-specular louvers, secondary optics, projectors, etc.).

Figure 5-18. *Technical luminaire – louver grid.*

Figure 5-19. *Decorative luminaire.*

Technical luminaires are optimized for a certain function (e.g. a special luminous intensity distribution according to the task, prevention of glare, etc.), whereas decorative luminaires are designed with the focus on aesthetical aspects.

5.5.3 Energy aspects

The luminaire is an important part of the electricity-luminance – chain (lamp including ballast, luminaire, room). It is decisive for the energy efficiency of the lighting installation. The energy efficiency of a luminaire ($\eta_{\text{Luminaire}}$) is characterized by the light output ratio (LOR), which is given by the ratio between the total luminous flux of the lamp when installed on the luminaire (ϕ_{Luminire}) and the lamps alone (ϕ_{Lamp}).

$$\eta_{\mathbf{Luminaire}} = \frac{\Phi_{\mathbf{Luminaire}}}{\Phi_{\mathbf{Lamp}}} = \mathbf{LOR}$$

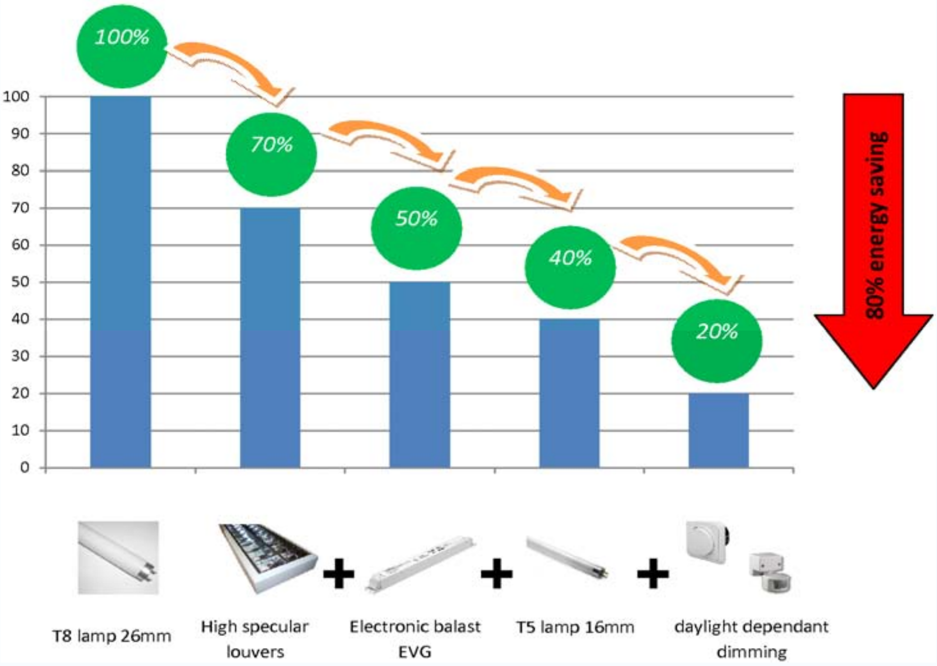


Figure 5-20. *Historical development of linear fluorescent lamp luminaires regarding energy consumption.*

The efficiency of a luminaire depends mainly on the lamp type, control gear and optical components (defining the optical efficiency). The new generation of linear fluorescent lamps, the T5 (diameter 16mm), together with high frequency ballasts, allows us to increase energy efficiency and decrease the costs at the same time, compared to the old magnetic ballasts and T12 and T8 technologies. New generations of lamp of CFL, high-pressure sodium, metal halide and IRC incandescent lamp types, have been introduced. Together with the appropriate luminaire technology and lighting controls they can reduce energy consumption of lighting significantly.

The development of high reflective surfaces (high specular or diffuse reflectance) for lighting purposes, of complex surface calculation methods and of new manufacturing technologies (e.g. injection molded plastics with Al-coating) has improved the efficiency (light output ratio) of luminaires reaching 80% or more. The developing LED-technology will also continue this trend. Thus, the technical potential for energy saving lighting solutions is already available. Adopting it is only a matter of time and application. 80% - 90% of the current lighting installations are older than 20 years. The replacement of these inefficient lighting installations with energy efficient components (lamps, control gears and luminaires) provides a huge energy saving potential. With this strategy, in parallel, the lighting quality could be improved.

5.5.4 LED Luminaires

LEDs will revolutionise the lumininaire practices and market in the near future. The long lifetime, color mixing possibility (flexible color temperature T_f), spectrum (no infrared), design flexibility and small size, easy control and dimming are the benefits of LEDs. These features allow luminire manufacturers to develop new type of luminires and designers to adopt totally new lighting practices. Further benefits include safety due to low-voltage operation, ruggedness, and a high efficacy (lm/W) compared to incandescent lamps. Due to the low prices and high lumen output, fluorescent lamps are the most economic and widely used lamps. Today, more than 60% of the artificial light is generated by this lamp type (IEA 2006) Compared to fluorescent lamps, LEDs are expensive (costs/lumen output) and offers today a much lower light output per one unit.

The gap between conventional light sources and LEDs is decreasing but still exists at the moment. In residential lighting incandescent and tungsten halogen lamps are the most widely used lamps in spite of their very low luminous efficacy and short lifetime (<4000h). LEDs are an economic alternative to incandescent and tungsten halogen lamps. Up to now, the LED general lighting market has been mainly focused on *architectural lighting*.

Figure 5-21. *LED Downlight.*

Other barriers for mainstream applications of LEDs are the missing industrial standards (holders, controls and ballasts, platines, etc.), the required special electronic equipment (drivers, controls), short innovation cycles of LEDs, and required special optics different from the conventional metal fabrication. The spectral distribution and intensity of the LED radiation depends strongly on its temperature, LEDs being much more sensitive to heat conditions than conventional lamps. It is therefore essential to care for an optimal heat transport to keep the LED's *p-n* junction temperature as low as possible.

LEDs of nominally the same type may have a wide spread in their radiation features (production tolerances). They are therefore grouped in so called binnings, i.e. they are graded in different classes regarding luminous flux, dominated wavelength and voltage. For applications with high demands on color stability, it is necessary to compensate and control these production and operating tolerances by micro controllers to reach predefined color features (spectra). All these features and requirements make the development of an LED luminaire a highly demanding task. Following the actual LED performance forecast, white LED lighting will soon outperform some traditional lamps with superior lifetime, decreasing prices, and increasing luminous efficacy, which opens the way for LEDs in a broad field of applications. Due to the continuous spectrum of white LEDs, it is the perfect lamp for replacing incandescent and halogen lamps. LEDs need to be equipped with special electronics and optics and this will create a whole new industry for LED luminaires. One of the challenges will be the maintenance of LED luminaires.

New findings regarding biological effects (e.g. melatonin suppression) of light and the influence of light on health (e.g. shift working) generate an increasing demand for innovative lighting that gives better control over the spectrum, distribution, and intensity of light. This creates demands for LED applications in general lighting and for luminaire manufacturers.

5.6 Network aspects

Description of phenomena

Contemporary electric lighting systems are sources of several electro-magnetic phenomena, which exert influence on the supplying network as well on other electric energy users and cannot thus be neglected. The most important are: harmonics and low power factor. The sources of harmonics are (Armstrong 2006, Henderson 1999):

- Lighting systems due to the discharge plasma.
- Saturation of transformers in low voltage systems.
- Electronic dimmers and voltage reduction circuits.
- Ballasts in *high-frequency* fluorescent lamps (actually single-phase ac-dc switch mode power converters).
- Low voltage halogen lighting powered by so-called electronic transformers (Armstrong 2006).

The current waveform of a compact fluorescent lamps (CFL) and its spectrum (Figure 5-22), the current waveform of an AC supplied LED lamp with its spectrum (Figure 5-23) and the current waveform of an *electronic transformer* supplying a halogen lamp (Figure 5-24) are presented below.

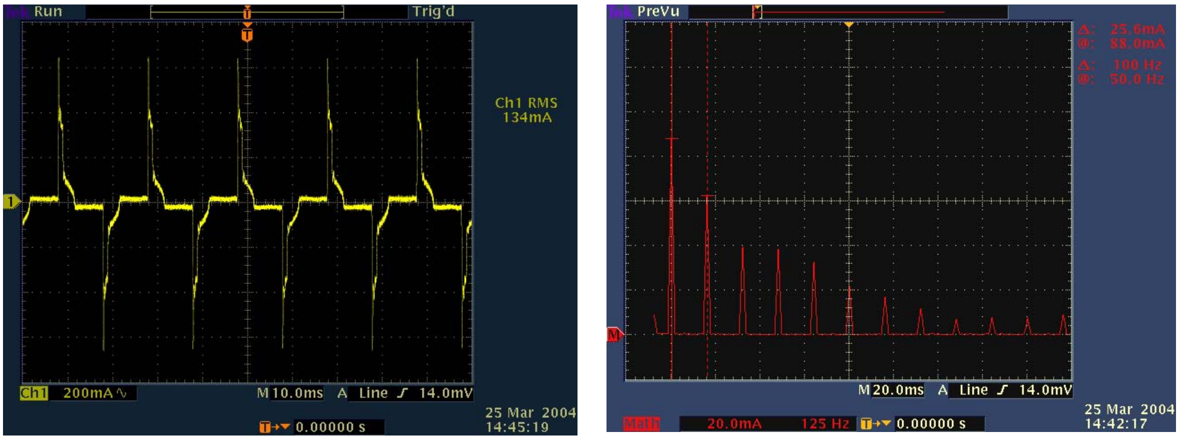


Figure 5-22. *Current of a 20W CFL FLE20TBX/827 (GE) lamp and its spectrum.*

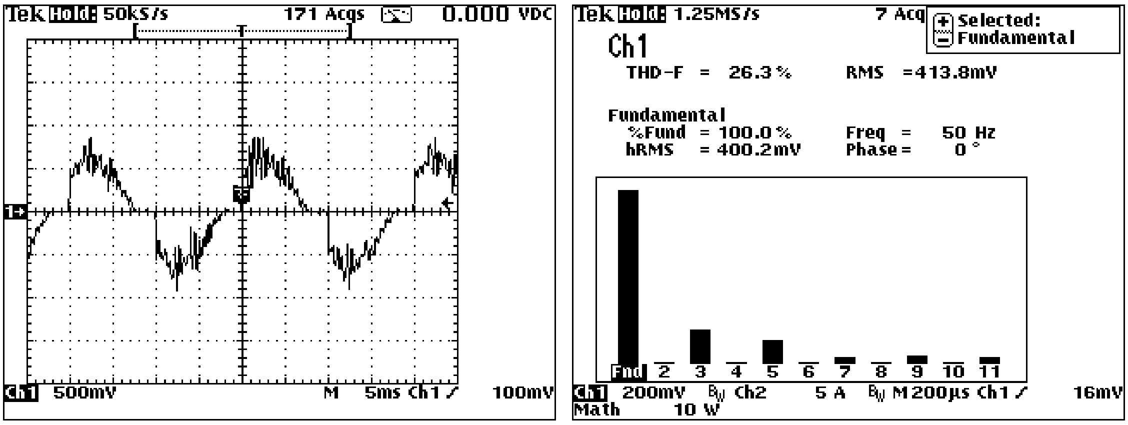


Figure 5-23. *Current waveform of a 0,9 W AC driven LED lamp (20 diodes) and its spectrum.*

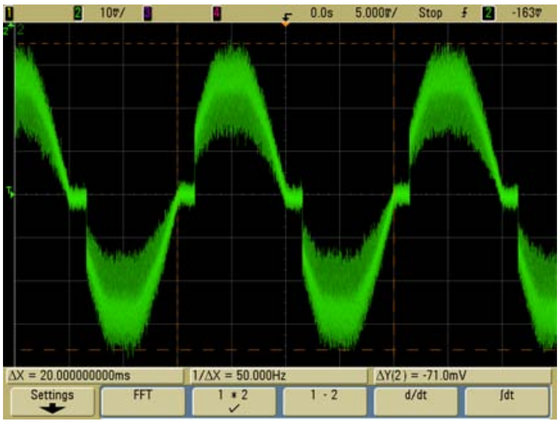


Figure 5-24. *Primary current waveform of an electronic transformer supplying a 50W halogen lamp.*

In Figure 5-25, for comparison, the current waveform of an incandescent lamp is presented.

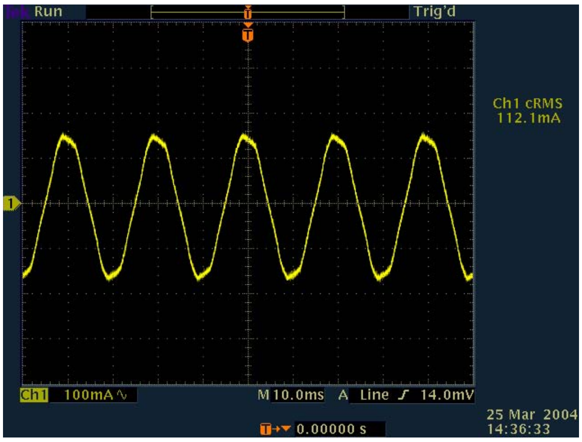


Figure 5-25. *Current waveform of the 20W incandescent (standard) lamp.*

From the figures presented above, it can be seen that the currents supplying lamps with electronic elements (ballasts, suppliers, and controllers) are not sinusoidal and that their spectrum includes all odd harmonics. The power factor (PF) of these lamps is low. For the compact fluorescent lamp (Figure 5-22) PF is equal to 0.64 and for the AC supplied LED lamp (Figure 5-23) it is 0.26.

Single phase converters emit significant levels of third harmonics, which are a particular nuisance because they are added linearly in neutral conductors and in zero-phase transformer flux causing additional heating of cables. Total neutral current (in modern offices) can be as much as 1.7 times greater then the highest phase current, while the building neutrals are not fused (Armstrong 2006).

In the domestic sector, most houses do not have large three phase lighting circuits, so the above mentioned problems do not occur. However, the utility must be designed for such circumstances, if the estimated load in a given district is predominantly discharge lamps lighting. The design of the utility in an electric domestic reticulation system should reflect this when calculating the After Diversity Maximum Demand (ADMD) value for each house.

When electric water heaters and stoves are installed, requiring high currents, the lighting loads will be relatively low and the effect of harmonics on the reticulation system will be small (Henderson 1999). Harmonic currents may contribute to failures of power system equipment. The most common failures are (Henderson 1999):

- Overheating of the power capacitor due to higher currents flowing at higher frequencies.
- Power converters failure induced by incorrect switching and causing the malfunction of the unit.
- Failure of transformers and motors caused by overheating the windings due to harmonic currents and higher eddy currents in the iron core.
- Higher voltage drops because of additional losses in the supply conductors due to the skin effect of the high harmonics.
- In communication systems, the cross-talk effect in the audible range and in the data link systems.
- Effects on metering if the harmonics are extreme and may cause relays to malfunction.
- Malfunction of the remote control system in the house (e.g. harmonics have been known to cause the television set to change channels or the garage door to open).

In the houses that run on non electric energy sources for cooking, heating water and for central heating, the lighting load will be a high proportion of the maximum power demand. With the introduction of CFLs in those situations the harmonic content of the network will be high. Therefore the effect of the harmonic currents on the transformers must be calculated using the formula for de-rating where the harmonic distortion levels are higher than 5%. For a typical installation with a large number of CFLs on a small transformer, the transformer would have to be de-rated to 88% of its full load current or its rated kVA. The current reduction using CFLs instead of incandescent lamps is a 80% reduction of load (e.g. from 100 W GLS to a 20 W CFL), which now must be adjusted back by 12%. The saving on the transformer would be 0.88 x 0.8 = 0.72 per unit, or 72% reduction in load. The transformer would be able to supply 3.5 times more CFLs lamps than incandescent lamps, which must translate into a reticulation cost saving to the utility (Henderson 1999).

Stroboscopic effect occurs when the view of a moving object is represented by a series of short samples, and the moving object is in rotational or other cyclic motion at a rate close to the sampling rate. This effect is observed when fluorescent lamps with magnetic ballasts are installed. The stroboscopic effect can be eliminated by using lamps with electronic ballasts which usually change the frequency of the power from the standard mains frequency to 20,000 Hz or higher. Electric and electronic equipment in buildings generates electromagnetic fields. The health aspects related to electro-magnetic fields are discussed in Chapter 3.7 and standards and recommendations connected with electric and electromagnetic aspects are described in chapter 4.3.7.

Risks and opportunities

The harmonics of different manufacturers of CFLs are slightly out of phase, and then the total network harmonics can be smaller if a variety of CFLs are installed in the community. The cancelling effect is small and it is difficult for a utility to control (Henderson 1999, IAEEL 1995). Henderson has given the measurements of harmonic magnitudes and phase angle of some CFLs. (Henderson 1999)

Modern appliances have good designs or filters to stop the harmonics going back into the network. Filters are usually network of inductors and capacitors that resonant at the harmonic current frequency and, accordingly, reduce the magnitude of the harmonic currents. The filters are effective, however when they are connected to the network, a harmonic generated elsewhere on the system will find the filter. The result will be that the correcting filters of another user may filter harmonics generated by a different user. The CFLs are small users of energy and the filters would naturally be small. When these are connected to a dirty system (system with harmonic currents), they will try to filter the harmonics from other users and, consequently overheat, causing the failure. And therefore, CFL failures have to be monitored by the utility to determine if the supply to an area is the cause of failure (Henderson 1999).

The total harmonics distortion (THD) of CFLs is high, but similar to that of other domestic appliances. The use of filters in the CFLs may cause excessive lamp failures because the filters would attempt to reduce the harmonics created by other equipment. The LEDs must be supplied with appropriate current. This can involve shunt resistors or regulated power supplies. Some LEDs can be operated with an AC voltage, but they will emit light only with positive voltage, causing the LED to flicker at the frequency of the AC supply. This causes different solutions of LED drivers and diodes configurations which provide to self-canceling harmonics within the single LED lamp (Freepatentsonline 2004)

The best way to reduce electromagnetic fields is grounding all lighting equipment. The profitability of the special networks for lamps, computers and other appliances should be individually considered for buildings. For example, application of DC networks might simplify suppliers (one main transformer instead of the individual transformers for every device). This would ease the power factor compensation and harmonics reduction, and increase efficiency of the whole electric installation and its appliances.

5.7 Hybrid lighting

5.7.1 Introduction

An integrated lighting system utilizing both daylight and electrical lighting is called here a hybrid lighting system.

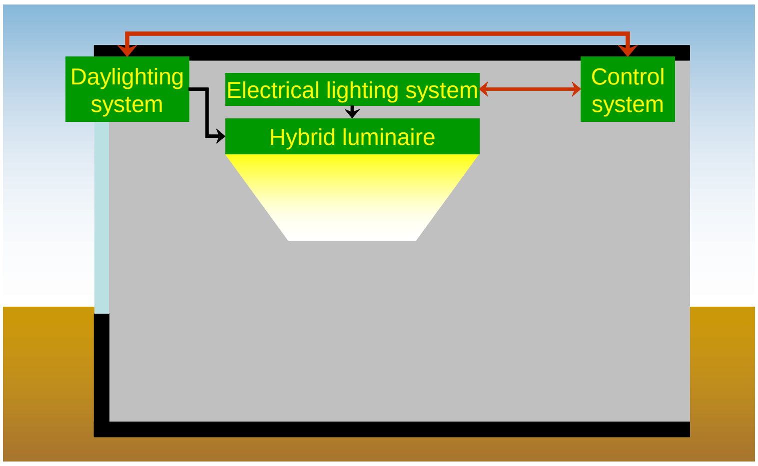


Figure 5-26. *Hybrid (integral) lighting system overview.*

A hybrid (integral) lighting system usually consists of the following major elements (Figure 5-26):

- A daylighting system (provides natural light to the hybrid lighting system)
- An electrical lighting system (provides artificial light, if it is required)
- A lighting control system (enhance the energetic performance)
- A hybrid luminaire (integrated lighting delivery system for both daylight and electrical lighting)
- Transportation modules (in special cases)

5.7.2 Energy savings, lighting quality and costs

Daylight is a free and sustainable source of light and the supply of daylight is typically at its highest during the hours with peak electrical energy loads. Usually, there is enough daylight to meet the demand for lighting of a building during most of the working hours. Daylight is, however, also associated with negative factors such as glare and increased cooling loads. The challenge is to control daylight in a way that the light is utilized without glare, and the heat is kept out. Studies have shown that benefits of daylighting are not only energy savings but also improved satisfaction, motivation of the occupants and productivity of the workers (Hartleb and Leslie 1991, Figueiro et al. 2002).

Costs can be reduced by integrating the components and utilizing the same materials for capturing, transportation and delivery of daylight and electrical lighting. Costs can also be reduced by combining the control systems for daylighting and electric lighting. In order to achieve costeffectiveness over its lifecycle, a functional hybrid system needs to be combined with an inexpensive actuation system. Its design has to be compatible with standard construction techniques.

5.7.3 Examples

Hybrid Solar Lighting (HSL)

Daylight is collected by a heliostat (sun tracking light collector). A transportation system (here: optical fibers) is used to distribute the collected sunlight throughout the building interiors.

Figure 5-27. *Hybrid Solar Lighting. Illustrations from Oak Ridge National Laboratry.*

Lightshelf systems

Daylight is collected and distributed to the ceiling by a reflector (lightshelf) positioned in the upper part of the window, completed by an integrated electric lighting.

Figure 5-28. *A prototype of the Daylight Luminaire. Upward reflected sunlight as well as electrical light can be seen on the wall to the left of the luminaire.*

Lightpipes

Sunlight is collected by fixed mirrors or by sun tracking mirrors (heliostats) and transported into the building through lightpipes which can also transport and distribute the electrical lighting from a centrally located electrical light source.

Figure 5-29. *Pictures from an Arthelio project installation in Berlin. The heliostat on the roof supplies the light pipe with concentrated sunlight (left). An electrical light source supplies the light pipes with electrical light when needed (right).*

5.7.4 Summary

Hybrid (integral) lighting systems (not to be confused with daylight systems) are niche applications, their market penetration is too small to play a role in lighting and energy, but they attract attention, thus they are important signs increasing the awareness of energy and daylighting.

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