8

Lighting

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Nowadays, lighting significantly contributes to energy consumption and greenhouse gas emissions. The electricity used to operate lighting systems corresponds to an important fraction of total electricity consumed worldwide: 5–15% of the national electricity consumption in the industrialized countries, and even higher than 80% in some developing countries. In 2003, the use of artificial light was estimated to result in the consumption of approximately 650 Mtoe of primary energy, representing 8.9% of total global primary energy consumption [1]; accordingly, lighting-related CO_2 emissions were estimated at 1900 Mt, equivalent to approximately 8% of world emissions. Even so, these data are not accurate for the present day but they do serve to indicate the size of the problem.

On the other hand, there is a widespread use of obsolete lighting technologies, especially in the residential sector. According to [2], two thirds of all lamps currently installed in the European Union are energy inefficient (in EU homes, about 85% of lamps are energy inefficient); in the UK, there are estimated to be some 375 million incandescent lamps used in homes, about 60% of the total [3].

At the same time, the energy saving potential in the lighting sector is high even with the existing technologies. Indeed, according to literature, the average luminous efficacy has scarcely increased from about 18 lm/W in the 1960s to roughly 50 lm/W in 2005; however, this is not uniform across all lighting applications, ranging from only a little above 20 lm/W in the residential sector to slightly above 50 lm/W in the commercial sector and to about 80 lm/W in the industrial sector. As other lighting technologies are emerging on the market, lighting applications represent a good objective for demand-side energy efficiency initiatives targeting large-scale implementation of efficient lighting technologies. These initiatives can offer very appropriate solutions, with significant benefits for all those involved, as shown below [4]:

- *Customers*: energy savings, reduced bills, mitigation of impact of higher tariffs;
- *Utilities*: peak load reduction, reduced capital needs, reduced costs of supplying electricity;
- *Governments*: reduced fiscal deficits, reduced public expenditures, improved energy security;
- *Environment*: reduced local pollution and reduction in greenhouse gas emissions.

Electrical Energy Efficiency: Technologies and Applications, First Edition. Andreas Sumper and Angelo Baggini.

In lighting, the energy efficiency is defined as optimization of energy consumption, with no sacrifice in lighting quality. Although the amount of electricity consumed by lighting is an important issue, to reduce the human effectiveness of the illumination on the basis of energy efficiency would be a serious retrograde step for human performance and, in the long term, counter-productive. Therefore, the problem that the lighting specialists must address is how to provide illumination at best practice standards while, at the same time, using the minimum amount of electricity necessary [5]. The right solution will be a combination of several items from the following: accurate choice of illumination level, appropriate selection of lamps and luminaries, and thoughtful design and choice of a fitting control system. Furthermore, the integration of the lighting system in the environment or space that is being lit must be also considered.

8.1 Energy and Lighting Systems

8.1.1 Energy Consumption in Lighting Systems

A very comprehensive analysis of energy consumption in lighting systems is presented in [6]. According to this report, more than 33 billion lamps operated worldwide in 2005, consuming annually around 2650 TWh of energy (19% of global electricity consumption, or slightly more than the total electricity consumption of OECD Europe for all purposes); over half of this electricity consumption is in IEA member countries, but their share is declining: by 2030, non-OECD countries are expected to account for more than 60% of global lighting electricity demand. The annual cost of this service including energy, lighting equipment and labour is US$ 360 billion, which is roughly 1% of the global GDP (electricity accounts for some two thirds of this).

The total lighting-related CO2 emissions were estimated to be 1900 million tons (equivalent to 70% of the emissions from the world's light passenger vehicles), namely about 7% of the total global CO_2 emissions from the consumption and flaring of fossil fuels.

The largest proportion of electricity used in lighting is consumed by the indoor illumination of tertiary-sector buildings; on average, lighting accounts for 45% of tertiary-sector electricity consumption and 14% of residential consumption in OECD countries (in non-OECD countries these shares are usually higher; globally, they are 31% for residential and 43% for commercial). Outdoor stationary lighting (mainly including street, roadway, parking and architectural lighting) uses less than one-tenth of total lighting electricity consumption (about 8%), while an estimate of 490 TWh/an of final electricity was consumed by industrial lighting (amounting to about 18% of total lighting electricity consumption and just over 8.7% of total electricity consumption in the industrial sector).

On the other hand, according to [7], the global electricity consumption for lighting is distributed as follows: approximately 28% to the residential sector, 48% to the service sector, 16% to the industrial sector, and 8% to street and other lighting. Other information regarding the energy consumption in EU-27 is presented in [8] and [9]. In 2007, lighting represented 10% of the final electricity consumption with the most important weight in the residential sector (at 10.5% it represents the third main consumer after electricity for heating and cold appliances), tertiary-offices (21.6%) and street lighting (4.7%); in industry it is generally not more than 5% [10].

With reference to the USA, lighting systems consume approximately 20% of the electricity generated [11] or about 30% of the total energy consumption in the US [12]; in Japan, about 14% of generated electric energy is consumed for lighting [13]. Demand for artificial light is strongly linked to per-capita GDP, but there are important variations between economies; [6] presents an estimation for per-capita consumption of electric light in 2005, expressed in megalumen-hours: North America: 101 Mlmh; Europe: 42 Mlmh; Japan/Korea: 72 Mlmh; Australia/New Zealand: 62 Mlmh; China: 32 Mlmh; Former Soviet Union: 32 Mlmh; Rest of the world: 8 Mlmh (India, for instance, uses only 3 Mlmh).

Over the last decade, global demand for artificial light grew at an average rate of 2.4% per annum, slower in IEA countries (1.8%) than in the rest of the world (3.6%). With the current economic and energy efficiency trends, it is projected that global demand for artificial light will be 80% higher by 2030 and will still be unevenly distributed. If this comes to pass and the rate of improvement of lighting technologies does not increase sufficiently, global lighting electricity demand will reach 4250 TWh. Furthermore, without additional energy efficiency policy measures, lighting-related annual CO_2 emissions will rise to almost 3 Gt by 2030.

8.1.2 Energy Efficiency in Lighting Systems

According to [14], energy efficiency in lighting systems is defined as the optimization of energy consumption, with no sacrifice in lighting quality; its implementation supposes the thoughtful design and selection of appropriate lamp(s), luminaire(s) and control system, and the informed choices of the illumination level required (the integration and awareness of the environment or space that is being lit must be also considered). The aim is to achieve a lighting system enabling tasks to be performed efficiently and effectively whilst providing a good balance of cost and energy consumption. Every visual task has different lighting requirements and the following elements must be taken into account to assure an appropriate visual perception: (i) level of lighting; (ii) luminance in the field of vision; (iii) absence of irritating reflection (glare); and (iv) colour rendering. As a result, the most suitable lighting technology for each circumstance varies and the best practice in lighting depends highly upon the application.

On the other hand, for economic evaluation of different lighting solutions, a life cycle cost analysis has to be made as, usually, only the initial (investment) costs are taken into account [15]. People are not aware of the variable costs, which include energy, lamp replacement, cleaning and reparation costs. The energy costs of a lighting installation during its entire life cycle are very often the largest part of the whole life cycle costs. It is essential that in future lighting design practice, maintenance schedules and life cycle costs will become as natural as, for example, illuminance calculations already are.

Fortunately, there is a significant potential to improve energy efficiency of old and new lighting installations already with the existing technologies. The following three basic steps to improving the efficiency of lighting systems are indicated in [11]:

1. Identify necessary light quantity and quality to perform visual task.
2. Increase light source efficiency if occupancy is frequent.
3. Optimize lighting controls if occupancy is infrequent.

Step 1, identifying the proper lighting quantity and quality is essential to any illuminated space, whilst steps 2 and 3 are options that can be explored individually or together; they can both be implemented, but often the two options are economically mutually exclusive.

The first step is very important especially in lighting retrofits: in these cases, it is often overlooked because most energy managers try to keep the same illumination level as in the old system, even if this is over-illuminated and/or contains many sources of glare. Unfortunately, although levels recommended by international standards have continuously declined, nowadays there are still many excessively illuminated spaces in use. Energy managers can obtain remarkable savings by simply redesigning a lighting system in order to achieve proper illumination levels.

The second step addresses the efficiency of lighting system components, including in this term the lamp, the ballast and the luminaire. From this point of view, increasing the efficiency simply means a better global luminous efficacy (getting more lumens per watt out of the lighting system). This goal may be reached by increasing the source efficacy, replacing the magnetic ballasts (by more efficient versions or by electronic ballasts) or improving the fixture efficiency. Increasing the efficacy of the light source is the most popular choice because energy savings can more or less be guaranteed if the new system consumes fewer watts than the old one. Nevertheless, this energy criterion should be compatible with other lighting design criteria: in many applications, the optical features (colour temperature, colour rendering index, light distribution curve, etc.) are frequently the leading criteria instead of the lamp efficacy in choosing lamp types (lamp efficacy may become a secondary consideration).

Finally, the third step aims to implement a variety of control techniques in order to reduce the energy consumed while the system is operating (by daylight, for instance) or to turn artificial lighting systems off when they are not needed. Nevertheless, it is important to underline that influencing user's behaviour can also bring important savings if the use of control systems is too costly.

On the other hand, when dealing with energy efficiency in lighting installations, the concern in other topics such as directing light to where it is needed or using reflective room surfaces is also important.

In conclusion, efficient and effective lighting systems will [14]:

- provide a high level of visual comfort;
- make use of natural light;
- provide the best light for the task;
- provide controls for flexibility;
- have low-energy requirements.

The biggest energy saving and lighting quality opportunities are found in older, over lit buildings that use inefficient technologies or in locations where utility costs are very high and where lighting is uncontrolled and left on all night. Apart from the owners' economic motivation, the implementation of efficient lighting systems must be supported by policy measures addressing the following objectives [6]:

- phasing out or substantially reducing the use of low-efficiency lamps and control gear;
- encouraging the adoption of high-efficiency luminaires and discouraging the use of their low-efficiency counterparts;

- encouraging or requiring the use of appropriate lighting controls;
- ensuring lighting systems are designed to provide appropriate lighting levels according to national or international norms;
- stimulating better lighting design practice to encourage task lighting, individual user control of lighting needs and dynamic integration with daylight rather than uniform artificial illumination;
- encouraging greater and more intelligent use of daylight in the built environment, resulting in energy, health and productivity benefits;
- reducing light pollution, especially for outdoor applications;
- stimulating the development and early adoption of new, more efficient lighting technologies;
- overcoming market barriers to efficient lighting and negating the overemphasis on first costs in favour of life cycle costs;
- protecting consumers from poor-quality lighting components, such as low-quality compact fluorescent lamps (CFLs) and linear fluorescent lamps (LFLs) with a lifespan, light output or efficacy that does not meet declared and/or minimum values.

According to the European Lamp Companies Federation, more than 50% of all lamp technologies installed in Europe are still not the most energy efficient [2]; therefore, the potential for improvements and savings (of energy, costs and CO_2 emissions) for Europe is significant. The majority of these savings (between 75% and 80%) can be achieved in the area of professional lighting (in streets and offices for example); for that reason, the public sector has an important role to play in setting an example and influencing the market place through green procurement. 'Green' procurement is a key element in controlling consumption of energy in Europe. Europe's local authorities spend 14–16% of EU GDP on public procurement each year; this money can be used wisely to help save energy consumption through purchasing energy efficient technologies, such as modern lamps or ballasts. Although in general this equipment is initially more expensive, based on their 'total cost of ownership', savings can be made through operational costs in electricity, maintenance and disposal.

8.2 Regulations

Different lighting guidelines, with a significant influence on the amount of light provided and, hence, on the amount of lighting energy required, have been issued at the national or international levels. The recommendations in the guidelines have evolved considerably and frequently over the last 80 years and yet remain divergent from one jurisdiction to another, with large associated implications for lighting energy demand [6]. The main European standards and directives are as follows.

1. EN 12665: Light and lighting. Basic terms and criteria for specifying lighting requirements
2. EN 12464-1: Light and lighting. Lighting of indoor work places
3. EN 13201 series: Road lighting
4. EN 13032 series: Light and lighting. Measurement and presentation of photometric data of lamps and luminaries
5. EN 60598 series: Luminaires

6. EN 61000-3-2: Electromagnetic compatibility. Limits. Limits for harmonic current emissions (equipment input current $\leq$ 16A per phase)
7. prEN 15193: Energy performance of buildings. Energy requirements for lighting
8. Directive 2006/32/EC on energy end-use efficiency and energy services (repealing Council Directive 93/76/EEC)
9. Directive 98/11/EC on Energy labelling of household lamps
10. EuP Directive 2000/55/EC on energy efficiency requirements for ballasts for fluorescent lighting
11. Directive 2002/91/EC on the energy performance of buildings
12. Directive 2004/108/EEC on Electromagnetic Compatibility (EMC).

8.3 Technological Advances in Lighting Systems

A lighting system is made up of lamps, luminaires and the control gear (which controls switching, ignition and regulation system). Designing an appropriate lighting system for each specific task takes into consideration a range of performance characteristics and, beyond the quantity and quality of light, the choice of technology is influenced by considerations of economy, durability and aesthetics. Over the last decades the lighting equipment industry has made considerable advances in the energy efficiency of equipment, including new lamp technologies, improved optical performance of luminaries and high frequency, low-energy electronic control gear for discharge lamps.

8.3.1 Efficient Light Sources

The lamp is the first component to consider in the lighting design process; the choice of lamp determines the light quantity, colour rendering index, colour temperature, as well as other different technical and economic characteristics of the whole lighting system. According to [6], the average luminous efficacy of lighting systems has improved from about 18 lm/W in 1960 to roughly 48 lm/W in 2005; the rate of improvement appears to have been relatively constant from 1960 to 1985, at about 2.8% per year, but since 1985 onwards it slowed to 1.3% per year.

Most artificial light is nowadays generated by three processes: (i) incandescence (the glow from hot solids); (ii) direct emission in gas discharges; (iii) luminescence (conversion of ultraviolet into visible radiation). The last decades have witnessed a new technology emerging, based on light emission from semiconductor devices (SSL or LED).

Figure 8.1 presents the existing types of electric lamps while their main characteristics are listed in Table 8.1. In practice, various lamp technologies are used for different applications depending, in part, on the quality of the light they generate; this covers the amount and colour characteristics of the light produced, the speed of ignition and the time taken to reach full output, and the ease of control.

Incandescent lamps represents the oldest electric lighting technology; they are also the least efficacious (only 5% of the electricity is converted into light, 95% of the power taken up is lost as heat) and have the shortest life. Alternatively, incandescent lamps have a relatively high quality light (especially excellent colour rendering), being preferred by many consumers because of their familiarity, and low purchase price (however, if life cycle cost analyses

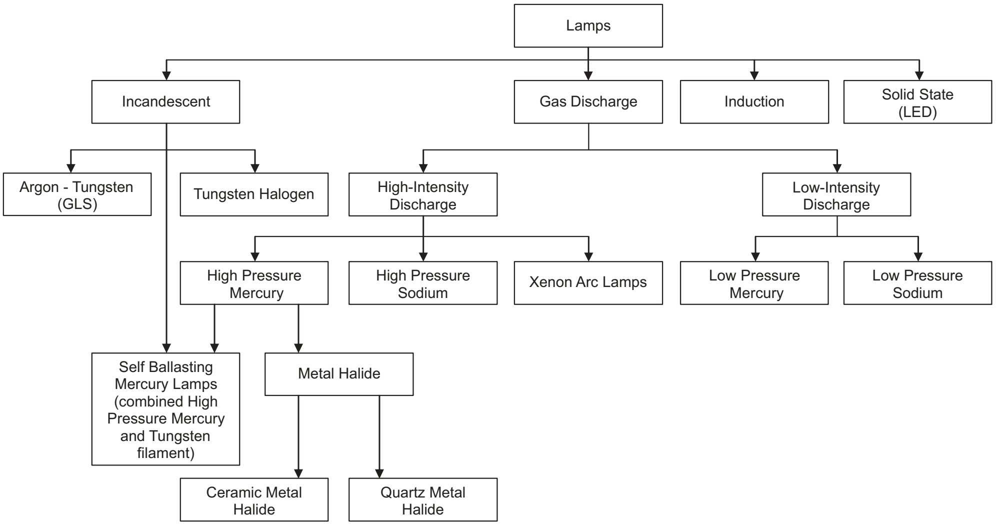

Figure 8.1 Categories of light sources

are used, incandescent lamps are usually more expensive than other lighting sources with higher efficacies); these bulbs are quiet, dimmable, and turn on instantly. Because of their low efficiency, many governments have adopted regulations in order to replace inefficient incandescent lamps with more efficient alternatives.

Linear fluorescent lamps are the most common gas discharge lamps and have been used in commercial and industrial settings since their commercialization in 1937 due to lower operating costs; nowadays they provide the bulk of global lighting.

Fluorescent tubes have much higher efficacy levels and much longer operating life than incandescent lamps. With a high colour rendering index (CRI), these lamps can also be designed to provide a large diversity of colour temperatures, ranging from 2700 K (as found with an incandescent lamp) to 7500 K (daylight). Fluorescent lamp technology has made significant advance in performance in the last two decades, and the old T12 lamps, operated by inefficient magnetic ballasts, have been replaced by new versions (T8 and T5).

The T8 lamps were developed in the early 1980s and rapidly became the best solution (along with the efficient magnetic or high frequency electronic ballasts that drive them) for fluorescent upgrades for several years. Recent advances in T8 lamps are improvements in colour rendering (due to its tri-phosphor coating), a longer life (20% longer than standard T8 lamps), and a rated lumen maintenance of 0.94.

The T8 lamp with an electronic ballast combination provides a light level comparable to the T12 with an electromagnetic ballast system, and has the benefit of consuming up to 40% less electrical energy; also, the T8 lamp life is about 50% greater than the T12 lamp. Most T8 lamps can operate on conventional electromagnetic ballast, and can be used to directly replace T12 lamps; however, it is worth noticing that not all electromagnetic ballasts and T8 could harmoniously work together, and a trial of a few selected luminaire should be conducted before large-scale replacement [16].

Table 8.1 The main characteristics of existing light sources

	Incandescent		Low intensity discharge		High intensity discharge			Solid state
Characteristics	Light globes	Quartz halogen	Fluorescent tube	Compact fluorescent	Mercury vapour	Metal halide	Sodium vapour	LED
Efficacy* [lm/W]	Low (8–17)	Low (20–30)	Moderate to high (60–100)	Moderate to high (50–65)	Low to high (15–70)	High (60–100)	High (75–160)	High (200)
Lamp life [h]	Shortest (less than 2000)	Short to moderate (750–12 000)	Moderate to long (7500–24 000)	Moderate to long (10 000–20 000)	Moderate to long (6000–24 000)	Moderate (1500–15 000)	Long (14 000–24 000)	
Colour rendering	Excellent (100)	Excellent (100)	Medium to good (50–98)	Medium to good (50–80)	Poor (15–50)	Medium to good (60–90)	Poor (17–25)	Good (>80)
Normal wattage range** [W]	Up to 1500	Up to 1500	8–220	4–40	40–1000	70–2000	70–1000	
Installation cost	Low	Low	Low	Low	Moderate	Moderate to high	Moderate to high	
Running costs	Highest	Highest	Moderate to low	Moderate to low	High to moderate	Moderate to low	Low	
Replacement costs	Low	Medium	Low	Medium	Low	High	High	
Relight time	Immediate	Immediate	Immediate	Immediate –3 sec	3–10 min	10–20 min	Less than 1 min	Immediate

* Includes power consumption of control gear or ballast
** Lamp only

The *high-performance T8 lamps* are part of a dedicated lamp/ballast system that can save about 19% energy over standard T8 systems with the same light output and double the lamp life (on program-start ballasts); supplementary, they exhibit high lumen maintenance (95%) and high CRI (86).

The T5 lamps come in two distinct and different families: *standard* (high-efficiency) and *high output* (HO); all these lamps are powered only by electronic ballasts. They are designed to peak in their lumen rating at 35°C as opposed to 25°C for T12 and T8 lamps; this characteristic provides higher light output in confined applications where there is little or no air circulation. Standard T5 lamps are 12–18% more efficient than T8 lamps and 10–15% more efficient than the T5HO. T5s employ rare-earth phosphors with CRI greater than 80 and lamp lumen maintenance rated at 95%.

High output T5 linear lamps are physically the same size as standard T5 lamps, but provide higher lumen output. T5HO lamps generate from 1.5 to 2 times the light output of the standard T5 and nearly twice the light output (188%) of T8 and T12 systems with the same number of lamps; unfortunately, they can be up to 8% less efficient than standard T8 systems.

Normally, T5 cannot replace T8, as this lamp requires its own high frequency ballast that is different from that of a conventional T8. Also, the T5 tube is slightly shorter in length than the T8, and the holding end-caps on the luminaire have to be spaced differently. In conclusion, a retrofit of existing lighting of T8 or T12 to use the new T5 will require the replacement of the ballast and probably the entire luminaire as well; the result is a higher cost of retrofit. To avoid retrofitting the luminaire when switching from T8 or T12 on electromagnetic ballast to T5 on electronic ballast, the Plug&Enhance (PnE) technology, introducing a quasi-electronic ballast (QEB) in the tube replacement, is nowadays available [16]. The QEB is an electronic device that is attached as an end cap or inside a fitting, and works with the original electromagnetic ballast to light up the fluorescent tube. With the QEB, a T5 can be fitted directly in place of the T8 or T12, and the overall efficiency after replacement is similar to a simple T5 on electronic ballast arrangement. A short circuit component is required to replace the original starter for some systems.

Compact Fluorescent Lamps (CFLs) usually consist of 2, 4 or 6 small fluorescent tubes that are mounted in a base attached to a ballast (for ballast-integrated models), or are plug-in tubes (for the non-integrated alternative). Integrated lamps use either a screw-in base or bayonet cap in the same way as standard incandescent lamps; more recent models are available in a variety of screw-in diameters and represent one of the most efficient solutions available today for improving energy efficiency in residential lighting. In fact, CFLs consume 20 to 25% of the energy used by incandescent light bulbs to provide the same level of light (about 25% of electricity consumed is converted to visible light compared with just 5% for a conventional incandescent lamp). However, the perceived ratio is nearer 30%; the reason for this is probably because the spectral distributions of the two lamp types are very different in that the incandescent lamp has smooth distribution, similar to a black body, while a CFL has a distribution with many peaks and troughs [5].

They were first commercialized in the 1980s and improvements to CFL technologies have been occurring every year since they became commercially offered. Products available today have a reduced environmental impact (use mercury as an amalgam), provide higher efficacies, instant starting, reduced lamp flicker, quiet operation, smaller size and lighter weight. They also come in a broader series of colour temperatures ranging from the same temperature as incandescent lamps up to much higher values nearer to daylight. Life expectancy is from

6000 hours (mainly marketed for the residential sector) to beyond 15 000 hours and it is no longer affected by switching (the current standards for accreditation require over 3000 switching cycles per 8000 hours of tested life; moreover, some manufacturers produce heavy duty CFLs with up to 500 000 switching cycles capability and 15 000 hours life). CRI typical values (80 to 85) are high enough for most applications and prices have also fallen substantially over the preceding decade.

Dimmable CFLs are now available (screw-base dimmable CFLs were introduced in 1996) and the next generation (also known as Super CFL) will increase their performances: fully dimmable (smooth dimming down to 10% light output, with no colour shift), the capacity for the lamp to restart at any light level setting, high power factor, higher efficacy (a minimum of 70 lm/W), etc.

As a drawback, the current THD from electronically ballasted compact fluorescent lamps can exceed 30%, though nowadays low-harmonic units are also available. Compact fluorescent lamps with magnetic ballast typically produce THD of 15–25%, which is acceptable in most applications. Technological improvements and cost reductions in compact fluorescent lamp electronic ballasts make them economically viable, providing instant starting, three-lamp capabilities, reduced flickers, hum, size and weight, and efficacy increase of 20%. Even if the electronic compact fluorescent lamp system costs several times more than the comparable incandescent lamp, the life-cycle cost is usually worthy of consideration.

High Intensity Discharge (HID) lamps produce light by discharging an electric arc through a tube filled with gases at a greater pressure than fluorescent lamps. Originally developed for outdoor and industrial applications, they are also used in office, retail and other indoor applications. Most of these lamps have relatively high efficacies and long life expectancy (from 5000 to more than 24 000 hours); unfortunately, they require time to warm up and should not be turned on and off for short intervals. There are three popular types of HID sources (listed in order of increasing efficacy): mercury vapour, metal halide and high-pressure sodium.

High-pressure mercury gas discharge lamps are based on the oldest HID technology and can be considered obsolete as they are relatively inefficient (30–60 lm/W), provide poor CRI and have the highest lumen depreciation rate of all HIDs.

Metal halide lamps produce light by passing an electric arc through a high-pressure mixture of gases (argon, mercury, and a variety of metal halides) and are among the most energy-efficient sources of white light available today (up to 100 lm/W). With nearly twice the efficacy of mercury vapour lamps, metal halide lamps are commonly used in industrial facilities, sports arenas and other spaces where good colour rendition is required (colour rendering is very good, up to 96). The high-wattage pulse-start versions (175 to 1000 W), operated by electronic ballasts, are rapidly replacing standard metal halide lamps, providing a quicker re-strike time (3–5 minutes) versus previous models (8–15 minutes). The implemented technological improvements result in higher lamp efficacy (up to 110 lm/W), enhanced lumen maintenance (up to 80 %), and consistent lamp-to-lamp colour (within 100 K).

In the last years, ceramic metal halide lamps (CMH or CDM), operated by electronic ballasts, also became commercially available; in this case, a polycrystalline alumina (PCA) arc tube is used. These systems have the following advantages: 10–20% higher lumen output (i.e. a better efficacy), the best colour stability, high CRI (83–95), limited colour shift (from ± 75 K to ± 200 K), excellent lamp-to-lamp colour consistency, and good lumen maintenance (0.70–0.80).

High Pressure Sodium (HPS) lamps produce golden (yellow-white) light and represent an economical choice for most outdoor and some industrial applications where good colour rendition is not required (the luminous efficacy is about 100–150 lm/W, but colour rendering is low, at about 25). Nowadays, they are losing position to white-light sources, such as metal halide or fluorescent; to face this situation, several improvements have been introduced in new-generation HPS lamps such as the elimination of end-of-life cycling (characteristic of standard high-pressure sodium lamps), reduced or zero mercury content, etc.

Induction lamps were introduced in the early 1990s and work on the basis of electromagnetic induction, i.e. they use an electromagnetic field (produced by a high-frequency electronic generator) to induce a plasma gas discharge into a tube or bulb that has a phosphor coating. Therefore, these lamps have no electrodes and will operate 5–8 times longer than fluorescent and metal halide systems and about four times longer than HPS systems; they have good luminous efficacy (80 lm/W) and colour rendering (80–90). Additionally, induction lamps come on relatively quickly and have short re-strike time compared with HID lamps. As the long life (60 000–100 000 hours) is the primary advantage of these systems, a good payback can be provided where maintenance labour cost is high.

Solid state lighting (SSL) represents a lighting technology involving light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs), semiconductor devices that emit light when a current passes through them. Solid state lighting is making substantial progress and initially has experienced rapid gains in niches of the illumination market (for instance task lighting, signal purposes, portable lighting, or the use of LEDs with photovoltaic); however, they have recently become available for general illumination, both indoor and outdoor. Manufacturers are developing new types of LED bulbs for general lighting and anticipate rapid cost reductions.

With significant advantages (long lifetime, colour-mixing possibilities, spectrum, design flexibility and small size, easy control and dimming, no mercury content, etc.) it is expected that LEDs will radically transform lighting practices and the market in the near future. The energy performance of LEDs is continuing to improve considerably; according to [2], the maximum luminous efficacy of phosphor converted cool-white LEDs is expected to be around 200 lm/W by 2015 (from 120 lm/W today), while the luminous efficacy of warm white LEDs is expected to be above 140 lm/W (from 80 to 100 lm/W at present).

OLEDs are another promising technology that ultimately could produce devices that are significantly less expensive than LEDs; although OLEDs are some way behind LEDs in performance improvements, they have already reached efficacies of 32–64 lm/W at 1000 cd/m^2 [3, 17].

As efficacy increases, the thermal management, one of the major problems with LEDs, is simplified, and the system costs can be reduced. Indeed, to a large extent, the general performances depend on the luminaire, which should keep the LED chip cool by dissipating the heat efficiently. In other words, the design of a luminaire, especially the provision of heat sinks, plays an important role in determining the life expectancy of the LEDs.

8.3.2 Efficient Ballasts

All discharge lamps have a negative impedance characteristic, and a supplementary device (called ballast) should be used for proper operation; it supplies a high voltage to initiate the discharge arc and then limits the current to levels that allow the discharge arc to be stabilized during normal operation (it may also include capacitors to correct the power factor). There are two broad categories of ballasts: electromagnetic (also known as ferromagnetic or core and coil ballasts) and electronic (also called high-frequency or solid-state ballasts). Electromagnetic ballasts comprise a magnetic core of several laminated steel plates wrapped with copper windings and are the most popular. Although they enable step or continuous lamp-dimming capability (however, not below 20% for the last versions), electromagnetic ballasts have large size and weight, low efficiency, and sensibility to voltage changes [18]. Electronic ballasts can overcome all these drawbacks offering simultaneously more possibilities for lighting control; they use electronic reactors to allow lamps to be operated at much higher frequencies (over 20 kHz, where the lamp efficacy can rise by 10–15%). Other benefits of lamps operated by electronic ballasts are [6]: an increased mean lumen output (may be up to 20%, depending on lamp type), longer lamp life (up to 30%), smaller size and lower weight; much less lamp flicker, less lamp noise, improved lumen maintenance, better starting and operational control of the lamp, a power factor of one without the need for a power factor correction capacitor, more accurate lamp and circuit control that enables full dimming capability or a seamless integration into building energy management systems (BEMS), etc.

The latest products offer additional functions: they may incorporate photocells, automatically dimming the output of a fluorescent lamp according to the daylight availability (saving significant amounts of energy); some ballasts include circuits that automatically detect and adapt to the input voltage, allowing a single ballast to be used on multiple voltages; the use of intelligent circuitry to optimize lamp starting and restarting, which allows fluorescent lamp life to be increased (this function is important if the lamp is being activated frequently through, say, the use of energy-saving occupancy sensors).

In conclusion, electronic ballasts are energy efficient, produce less heat load for the air conditioning system, and eliminate flicker and hum. Products are available for compact fluorescent and full-size lamps, connecting up to four lamps at a time (3–lamp and 4-lamp ballasts reduce material and energy costs, as compared with 2-lamp ballasts, because less units will be required). Fewer types of ballast can also increase the overall system efficiency as the gear loss of 4-lamp electronic ballast is typically less than the sum of the gear loss of four 1-lamp electronic ballasts. However, as the cable between the ballast and the lamps will be well screened for electrical safety as well as to restrict the electromagnetic interference to an acceptable limit, the multiple lamps on single ballast arrangement are usually applied to lamps in the same luminaire [16].

As an integral component of the lighting system, ballasts need power in order to function; ballast power losses range from a few percent to as much as 40% of the total lighting system consumption, depending on the efficiency of the ballast adopted (the latest generation of high-efficiency magnetic ballasts reduce losses to about 12% while electronic ballasts are typically 30% more energy efficient). In order to steadily phase out inefficient ballasts, the European Union adopted the Directive 2000/55/EC on energy efficiency requirements for ballasts for fluorescent lighting that came into effect on 21 May 2002 (the purpose of this directive is to improve the efficiency of the lighting systems by limiting the ballast losses); it requires manufacturers to mark ballasts, indicating their efficiency, and it bans the sale of inefficient ballasts throughout the EU. Similar norms have been introduced in the USA [19].

For this purpose, CELMA (Federation of National Manufacturers Associations for Luminaires and Electrotechnical Components for Luminaires in the EU) developed a classification system that takes both the lamp and the ballast into account; ballasts are classified according to their Energy Efficiency Index (EEI) in the following classes [15]:

- Class D: magnetic ballasts with very high losses
- Class C: magnetic ballasts with moderate losses
- 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 considered 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 setting, the total input power is equal to or less than 50% of the power at the 100% light output setting.
- The ballast must be able to reduce the light output to 10% or less of the maximum light output.

The sale of Class D ballasts has been banned since 21 May 2002 and Class C ballasts since 21 November 2005. A date for the phasing out the less efficient Class B ballasts (Class B2) may be set if EU sales of Class A ballasts do not increase sufficiently [20].

8.3.3 Efficient Luminaries

A luminaire (fixture) is a unit consisting of the lamps, ballasts, reflectors, lenses or louvers and housing. The main function is to focus or spread light emanating from the lamp(s) without creating glare. The efficiency of a fixture is the percentage of lamp lumens produced that actually exit the luminaire in the intended direction; it varies greatly among different fixture and lamp configurations.

Improperly designed or maintained luminaires can cause lamp or ballast overheating and reduce product lifetime, while those with a low luminaire maintenance factor (LMF) will require an over-dimensioning because the LMF depreciation factor must be taken into account when installations are calculated according to the existing standards. On the other hand, in order to obtain a high utilization factor (UF) it is important to direct the light to the intended surface or area (the higher the UF is, the lower is the energy needed to operate the lamp). Several technical solutions for an increase in LMF, but also in luminaire utilization factor are:

- a higher degree of ingress protection (IP rating);
- use of new materials (for instance glass with self-cleaning activated by UV rays);
- use of internal top reflectors or reflective top shielding covers;
- appropriate use of transparent protector material with reduced diffuse optic properties and high optic transmittance;
- multi-facet reflector technology for highly asymmetric light distribution;
- the change from a painted reflector to an aluminized reflector.

8.4 Energy Efficiency in Indoor Lighting Systems

Although the use of modern, energy efficient lighting technologies has been increasing over the last several years, particularly in the commercial sector, a large proportion of total lighting energy is used by inefficient and outdated technologies, e.g. incandescent lamps, low-efficacy fluorescent lamps with low-efficiency ballasts, etc. As an example, in 2007, in the EU-27 the incandescent lamps (GLS) still held the dominant position with 767 million units sold and some 54% (2.6 billion units or 13.1 lamps/household) of the existing stock; one third (33%) of the sold non-directional GLS lamps are 60 W and 31.6% are 40 W [21].

8.4.1 Policy Actions to Support Energy Efficiency

Recognizing that the incandescent technology is very inefficient and that higher-quality and lower-priced new lamps are becoming increasingly available and popular, a number of countries have enacted since early 2007 legislation or regulations to phase out incandescent lamps and other low-efficient lighting sources within their jurisdictions [17]. The intention of the regulations already adopted or under preparation is to encourage the usage of higher efficiency lamps (most notably CFLs) in place of standard GLS lamps and thereby eliminate a key source of energy waste. The timing of the phase-out varies between different countries; in most cases, and for all the larger markets, a phased approach is being adopted where certain parts of the GLS market are prohibited from sale earlier than others. The start dates for when the phase-out regulations begin to enter into force vary from as early as the end of 2008 in the case of Australia to the beginning of 2012 for the United States, Canada and Korea; end dates for first tier requirements are between 2009 and 2014 for those that are already known. In the EU, the adopted regulations operate phased stages beginning in September 2009 and concluding in 2012. In addition to the regulatory approaches being adopted, many softer options are being implemented or are under development, including large-scale market transformation programmes, utility energy efficiency schemes, retailer initiatives and fiscal/financial incentives. Many of these schemes are of sufficient scale to have a major impact on local GLS and CFL markets.

Alternatively, the EU Regulation also imposes minimum requirements on discharge lamps, ballasts and luminaires, resulting in minimum efficiency and quality requirements on remaining products and in phasing-out as follows [21]:

- Linear T12 and T10 halo-phosphate lamps will be banned starting 2012 with the exception of lamps for special purposes.
- Minimum performance requirements for T8 and T5 linear lamps will be imposed and the T8 halo-phosphate lamps will be banned starting 2010.
- From 2012 new luminaires must be sold with electronic ballasts and from 2017 magnetic ballasts will not be permitted even for replacement in existing luminaires.
- Requirements on minimum lumen maintenance levels have been introduced.
- From 2017 (8 years after the Regulation takes effect) all fluorescent lamps must be designed to work with an electronic ballast.

The criterion to be used to determine if a light source will be allowed on the EU market is its energy label class (ranging from A to G, with A being the most energy efficient class

Table 8.2 Energy label classes corresponding to different ranges of the energy efficiency index

Energy label class	Energy efficiency index (E_I)
B	< 0.60
C	$=$ or > 0.60 and < 0.80
D	$=$ or > 0.80 and < 0.95
E	$=$ or > 0.95 and < 1.10
F	$=$ or > 1.10 and < 1.30
G	$=$ or > 1.30

and G the least). A lamp belongs to the energy label class A if its wattage (W) fulfils the condition [3]:

$$W \leq 0.15\sqrt{L} + 0.0097L \tag{8.1}$$

for a CFL without an integrated ballast, or

$$W \leq 0.24\sqrt{L} + 0.0103L \tag{8.2}$$

for other lamp types; in (8.1) and (8.2), L is the lamp lumen output. If the lamp cannot meet the requirements for energy label class A, an energy efficiency index is calculated. The energy efficiency index (E_I) is the ratio of the actual wattage (W) and the reference wattage (W_R) of the lamp, given by (8.3):

$$W_R = 0.88\sqrt{L} + 0.049L. \tag{8.3}$$

Table 8.2 shows the energy label class assigned to different ranges of the energy efficiency index.

The available alternatives to replace incandescent lamps are:

- *Conventional low-voltage halogen lamps*: available until 2016 (can reach C-class efficiency and can live up to 4000 hours);
- *Halogen lamps with xenon gas filling (C-class)*: use about 25% less energy for the same light output compared with the best conventional incandescent lamps;
- *Halogen lamps with infrared coating (B-class)*: use about 45% less energy for the same light output compared with the best conventional incandescent lamps and can live up to 3000 hours;
- *Compact fluorescent lamps (CFLs)*: use 65–80% less energy for the same light output compared with the best conventional incandescent lamps;
- *Light-emitting diodes (LEDs)*: a fast emerging technology having the luminous efficacy in the same range as CFLs (moreover, they do not contain mercury and live longer).

A comparative analysis of these technologies is presented in Table 8.3. Owing to the above regulations, EU citizens are expected to save close to 40 TWh and reduce CO_2 emission by about 15 million tons per year; about 5–10 billion Euros are expected to be reinvested in the EU economy [21].

Table 8.3 Efficiency of lamp technologies compared with conventional incandescent lamps (E-class)

Lamp technology	Energy savings	Energy class
Incandescent lamps	–	E, F, G
Conventional halogens (mains voltage 230 V)	0–5%	D, E, F
Conventional halogens (low voltage 12 V)	25%	C
Halogens with xenon gas fillings (mains voltage 230 V)	25%	C
Halogens with infrared coating	45–50%	B (lower end)
CFLs with bulb-shaped cover and low light output, LEDs	65%	B (higher end)
CFLs with bare tubs and high light output, LEDs	80%	A

Despite these advantages, the adoption of energy efficient lighting has to overcome several barriers [22]:

- *Economic Barriers*: The initial cost of new energy-efficient appliances is high; therefore, many household owners may be unable or unwilling to spend money for this purpose because of the slow rate of return on the investment despite rising energy costs. On the other hand, in businesses and industries, the main driver for the adoption of energy-efficiency measures are higher energy costs; unfortunately, sometimes the investment in retrofitting projects may have a long payback time (two or more years), especially for small and medium-sized businesses. This represents a barrier to adoption of the best solutions because the beneficiaries are not sure if they will be in business long enough to recover their costs. In addition, the overall economic slump also creates a disincentive to invest in these appliances.
- *Institutional Barriers*: Usually, any new construction code-changing process takes to much time to be passed into law, implemented and then enforced. This aspect also represents an important barrier to the adoption of energy-efficient lighting. For older buildings, only the high cost of retrofitting may represent an economic barrier.
- *Consumer Barriers*: From the consumer point of view, a lack of knowledge or awareness about the availability and potential of energy efficient lighting may represent a significant barrier to the adoption of new solutions (this is especially true for residential costumers). In the commercial and industrial sectors, despite a greater incentive from the point of view of the cost to benefit ratio, a large number of retailers and businesses still use inefficient solutions. Other consumer barriers include poor aesthetics because the user may not like or may not be used to certain colour characteristics of the new lighting product. Unacceptable performance is also a barrier, for example, people have sometimes reported flickering or buzzing sounds in their CFLs.
- *Manufacturing Barriers*: Different failures in the manufacturing process, negatively affecting the final product performances (life time, CRI, lumen output, etc.), also represent a barrier to the availability and adoption of efficient lighting products. Furthermore, emerging technologies, such as white LEDs are still at the developmental stage and have not yet attained a high level of overall performance.
- Conversely, numerous commercial buildings are leased and so tenants may be unmotivated to invest in a building they do not own, while the landlords are unmotivated because they usually make their tenants responsible for the utility bills.

8.4.2 Retrofit or Redesign?

When assessing the opportunities for improvement to an existing lighting system, the first step is to measure how effectively the existing light levels and characteristics serve their function. Next, the basic option facing the facility manager is whether to retrofit or redesign. In a retrofit, new lamps and ballasts are installed in existing luminaires, while the existing controls can be replaced (improved); in a redesign, the fixtures themselves may be replaced or moved.

8.4.2.1 (a) Redesign

If the building's primary spaces have been designated to new purposes for which the existing lighting system provides insufficient lighting conditions, the space may benefit from a redesign. Generally, in order to achieve an energy-efficient solution, the following design criteria have to be implemented and fulfilled [16]:

- light sources of high luminous efficacies;
- lamp control-gears of low energy losses;
- luminaires of high light output ratios;
- room surfaces of high reflectance;
- optimum mounting height.

However, the energy-efficiency criteria interact with other lighting effect criteria, and appropriate trade-offs may be necessary. For instance, from the energy efficiency point of view, it is recommended light sources are chosen with high luminous efficacies; nevertheless, such energy criterion must be compatible with other lighting design criteria, i.e. colour rendering. Moreover, in many applications, the optical features are frequently the lead criteria in choosing lamp types and lamp efficacy may become a secondary consideration.

A careful selection of luminaires results in a reasonable illuminance, minimum direct glare, reflected glare and veiling reflections; as a result, both the tasks of visibility and productivity can be improved. Some important factors in this procedure are the Utilization Factor (UF), luminaire dirt depreciation (LDD), room surface dirt depreciation (RDD), lamp lumen depreciation (LLD), and lamp failure factor (LFF).

8.4.2.2 (b) Retrofit

There are many opportunities for cost-effective retrofits to an existing lighting system and it is possible to simultaneously increase lighting levels and use less energy if the most efficient technologies and practices are implemented. The business benefits of an appropriate lighting system should also be considered. From an economical point of view, retrofitting the existing lighting system of less energy efficient equipment into new energy efficient equipment reduces its operating costs, but can also improve the light quality, reduce operating costs, increase the working productivity, improve the visual environment, etc. [16].

On the other hand, a basic choice will be whether to replace the existing lighting system all at once in a planned upgrade or replace individual components as they fail. Apparently, replacing individual components appears to be the easiest path forward as it avoids the upfront cost of equipment and installation labour and the potential disruption of a renovation. Based on these arguments, most companies replace lamps when someone notices a lamp is burned out [11]; however, a planned upgrade presents several major advantages [11, 19]:

- good lighting performance, uniformity and space appearance by switching from a type of light source to another all at once, avoiding confusion resulting from maintaining luminaries with different light output;
- higher energy savings and greater lighting quality resulting from re-evaluating the existing lighting system and upgrading it to current best practices;
- bulk purchasing may yield savings;
- reduced time and labour costs.

The rule of thumb suggests that group re-lamping must be done at 50–70% of the lamp's rated life as the lamp's operating interval depends on site-specific factors i.e. quality of power supply, environmental conditions, number of On–Off commutations, user behaviour, etc. As a result, the same light source may have different operating characteristics and lives from one location to another and must be replaced at different times. Therefore, it is important for the energy manager to maintain records on lamp and ballast replacements and determine the most appropriate re-lamping interval; this also helps keep track of maintenance costs, labour needs and budgets.

Evaluation of various retrofit options can be made in terms of their payback periods. Although there are numerous potential combinations of lamps, ballasts and lighting systems, a few retrofits are very common; they are presented below.

1. Lamp Changes

In this case, the most used solutions are:

- Incandescent lamps to CFLs: it represents one of the most efficient solutions available today for improving energy efficiency in residential lighting. More details helping to identify suitable replacements for both standard and soft output incandescent lamps can be found in [3];
- Incandescent lamps to halogen incandescent lamps (C and B energy class);
- Incandescent lamps to LED lamps (the efficacy of LEDs has been improving rapidly and has doubled roughly every two years since the 1960s);
- Standard halogen lamps to white-LED lamps;
- Fluorescent lamps to fluorescent lamps (T12 to T8 or T8 to high-output T5 lamps; the T5/T8 lamp with electronic ballast combination is practically the most popular choice);
- Fluorescent lamp to LEDs.

2. Ballast Type Changes

The existing solutions are:

- Magnetic ballast to magnetic ballast with low or very low losses;
- Magnetic ballast to electronic ballast.

3. Luminaire Changes

When it is decided to go for retrofitting, reflectors replacement can be a very simple and cost effective option; in this case, the luminaire efficiency is increased because less light is trapped and wasted within the luminaire fitting. The effectiveness of the reflector depends on its geometrical shape, coating material and the efficiency of the luminaire. Reflector replacement can usually reduce the number of fluorescent lamps in three- and four-lamp luminaires for the same light output levels (usually, the remaining lamps may need to be relocated in order to maximize light output and uniformity). In combination with higher output fluorescent lamps and electronic ballasts, light output may be increased significantly with suitable reflectors. Old and degraded luminaires that cannot be rectified by cleaning alone are generally excellent reflector retrofit candidates.

Conversely, shielding devices are usually installed in luminaires to control uncomfortable glares but inefficient shielding devices will degrade even the most efficient lamps and ballasts. Therefore, balancing visual comfort (glare control) and luminaire efficiency should be the key to achieving success in reflector retrofit.

Sometimes replacing rather than retrofitting the luminaires can be more economical and cost effective, especially where there is a major change in the lighting system requirements: new luminaires can optimize efficiency, visual performance, technology compatibility and aesthetics, etc. [16].

4. Lighting Control Upgrades

Taking into account the complexity of this problem, the lighting control is presented in detail in the next section.

8.4.3 Lighting Controls

Nowadays, the inappropriate operation of lighting systems is causing a large proportion of electric light to be delivered to spaces where no one is present, or for which there is already adequate daylight. Energy consumption can be reduced by suitably controlling the number of operating hours and/or the level of lumen output; lighting controls offer the ability for systems to adjust their characteristics to the existing specific conditions.

Lighting controls may be manual or automatic, or a combination between the two; they must also be ‘user friendly’. There are several control technology upgrades for lighting systems, ranging from simple (for instance, installing manual switches in proper locations) to more sophisticated (installing occupancy sensors). The choice of lighting controls has a large impact on total lighting energy use; according to [6], using advanced automatic controls will save an important fraction of energy (20–35% is typical) and can be highly cost-effective. Energy used for electric lighting depends upon the degree to which the lighting controls reduce or turn off the lights in response to [16]:

- the availability of daylight;
- changes in visual tasks;
- occupancy schedules;
- cleaning practices.

Improvements in the technology and continuously decreasing prices of lighting controls, combined with economic and environmental considerations, are leading to the increased use of advanced lighting controls, particularly in the commercial and public sectors, where lighting represents an important share of total energy costs. At the same time, automatic controls should be designed to avoid annoying the occupants; for instance, abrupt changes in the illuminance could be irritating in critical task areas and may create labour or security problems. As a result, often the automatic controls do not provide the saving expected because of user dissatisfaction or sabotage (they are not sufficiently user friendly) [5].

Nowadays, automatic lighting controls are used in only a small fraction of the cases where it would be currently economic to install them; consequently, lighting control offers important energy-saving opportunities. Currently, various control strategies are implemented, their suitability depending on the specific applications and patterns of energy usage. All of them can be framed into one of the following two major types:

- On/Off control;
- level control.

For the first type, controls offer only the ability to turn on and off the existing lighting system; by using the level control, the luminous flux emitted by lamps may be adjusted continuously or in steps (usually, two or three). All control strategies can be implemented either manually or automatically.

8.4.3.1 (a) Manual Control

Manual control is the simplest form of control, providing mainly on/off functions; in this case, the energy conservation device is represented by the standard manual, single-pole switch. The efficiency of manual control mainly depends on switch location because if switches are far from room exits or are difficult to find, occupants are more likely to leave lights on when walking out a room (occupants do not want to walk in darkness to find exits) [11]. An interesting opportunity for retrofitting consists in conveniently dividing the existing supply circuits and installing supplementary switches everywhere needed in order to obtain local lighting systems.

Solid-state dimmers for incandescent lamps level control are also available but in the future their importance will diminish (incandescent lamps will be banned). Fortunately, some ballast producers nowadays offer the opportunity to use these dimmers in combination with energy-efficient CFL lamps, thus facilitating the upgrading of incandescent systems.

8.4.3.2 (b) Automatic Control

Automatic lighting controls are also known as *responsive illumination*; despite representing a mature technology, they are being adopted only slowly in buildings and thus still offer a huge unrealized potential for cost-effective energy savings [6].

(b1) Automatic on/off Control

Energy consumption can be reduced by controlling the number of operating hours namely by turning off the light when it is not needed; all spaces that are not used continuously should

Table 8.4 Estimated savings from occupancy sensors [11]

Application	Energy savings [%]
Offices (Private)	25–50
Offices (Open spaces)	20–25
Rest rooms	30–75
Corridors	30–40
Storage areas	45–65
Meeting rooms	45–65
Conference rooms	45–65
Warehouses	50–75

have automatic switching, allowing lights to be turned off when the space is not in use. The automatic on/off control can use occupancy detection or timers.

Nowadays, *occupancy (or motion) sensors* are accepted as an effective energy-saving device (Table 8.4); there are three types of occupancy sensor, all of which are based on the detection of motion: passive infrared *PIR* (detects the motion of the heat sources), ultrasonic *US* (detects objects moving in the space) and hybrids (called also Dual-Technology (*DT*) sensors, they have both ultrasonic and passive infrared detectors; this technology avoids false turning on produced by wind-blown curtains or papers, for instance. Another dual technology control incorporates a microphone sensor, which detects small sounds, such as the turning of pages, even though an occupant would not show any appreciable movement in the room).

When the sensor detects motion, it activates a control device that turns on the lighting system; if no motion is detected within a specified period, the lights are turned off until motion is sensed again. With most sensors, sensitivity (the ability to detect motion) and the time delay (difference in time between when sensor detects no motion and lights go off) are adjustable. Occupancy sensors can be combined with dimming controls or stepped switching so that illuminance levels might be lowered to low ambient levels when the occupants leave a space [6, 11].

Occupancy sensors are available as wall-mounted or ceiling-mounted units; the first version may be used for small spaces that do not have obstacles to signal detection; the latter is recommended for larger spaces, irregularly shaped rooms and those with partitions. It is important to underline that energy savings may not be realized if the sensors are improperly installed or are disabled by frustrated occupants. For instance, *PIR* detectors must have a direct line of sight to the occupants to detect motion; on the other hand, *US* sensors do not require a direct line of sight to occupants, but wind-blown curtains or papers can trigger the sensor incorrectly.

Timers or *Time Clocks*, available in electronic or mechanical technologies, switch lights on and off at pre-set times; therefore, they can be used to control light systems when their operation is based on a fixed (imposed) schedule. However, regular check-ups are needed to ensure that the time clock is controlling the system properly, or to change setting according to different seasons (normally, the timer should be re-set at least twice annually to suit the sun summer/winter set/rise times). After a power loss, electronic timers without battery backups can get off schedule-cycling on and off at the wrong times.

Occupancy sensors and timer switches are occasionally configured to a manual on/automatic-off arrangement, by which the occupants turn lights on in their work space at the beginning of the day, or when needed [16]; timers are frequently used in combination with very low level emergency-egress lighting to ensure that users can always find their way safely around a space.

(b2) Automatic Level Control

In this case, electric-lighting levels are automatically adjusted in response to the detected illuminance level to maintain a pre-set value. Automatic level controls are a combination of photosensors and electronic ballasts with dimming functions: sensors continuously measure the illuminance level, while ballasts automatically adjust the lumen output of artificial light sources. Such an automatic dimming system has the following advantages:

- It compensates for the wasted power due to lamp lumen depreciation and luminaire dirt depreciation.
- It adjusts the lighting levels in accordance to the activity levels.
- It responds to variations in daylight availability (see the next subsection).

Generally, electronic ballasts with dimming functions operate linear fluorescent lamps; many of these products start the lamps at any dimmer setting, and do not have to be ramped up to full-light output before they dim. Most dimmable ballasts now have separate low-voltage control leads that can be grouped together to create control zones, which are independent of the power zones. The dimmer modules used in the high-power lighting systems are suitable for interfacing with time clocks, photocells or computers and may assure dimming ranges from 100 to 1%. Several manufacturers offer dimming ballasts for higher-wattage rapid-start compact fluorescent lamps; the lowest dimming limit is 5% and the dimming range varies with the manufacturer. They are designed to accept the AC phase-control signals from incandescent wall-box dimmer controls in order to facilitate upgrading an older incandescent system to an energy-efficient CFL system (no new wiring required).

The control generally uses DC 0–10 V signals, even if dimming ballasts designed to accept AC control signals are also available on the market [11]. Different control standards provide the interface platform, in particular for equipment and devices of the same manufacturer; in order to guarantee the exchangeability of dimmable electronic ballast from different manufacturers, the international standard DALI (Digital Addressable Lighting Interface) is now available. It was developed to overcome the problems associated with the analogue 1–10 V control interface and provides a simple (digital) way of communication between intelligent components in a local system; by using DALI, each luminaire of a lighting system could be individually addressed and programmed (as a result, different groups of luminaries may be programmed to fulfil various tasks) [23].

The impact of electronic ballasts on power quality sometimes can be harmful; fortunately, most of the models available on the market respect the restrictions imposed by [24], having a current total harmonic distortion (THD) of less than 15% throughout the dimming range. Normally, dimmable lighting systems are expensive and may not be applicable for every installation. It is recommended that dimmers should be used only where it is anticipated that lighting level control is needed.

Compared with on–off controls, level controls generally increase energy savings, better align lighting with human needs, and extend lamp life; they are also useful for spaces that have more artificial (electric) lighting than is currently needed, and have the added benefit of dimming lights further when natural light from outside is available. Such systems can also be used to dim lights for other reasons, such as for presentations. Dimming armatures by as much as 50% may be barely noticeable to building occupants, unless they are involved in tasks requiring visual acuity [11].

Micro-processor control can also be applied to a lighting system, from a stand-alone system in a single space to the entire system in a building. It is usually connected with controlling devices such as timers, photosensors, etc. to provide the desired lighting group/system performance. It offers great flexibility to lighting control as typical control functions usually include the following:

- automatic compensation for lamp lumen depreciation and luminaire dirt depreciation;
- fine tuning of lighting level to suit actual requirements;
- scheduling of lighting operations to minimize the operating hours;
- automatic daylight compensation control.

8.4.4 Daylighting

The sustainable development concept has revived the interest for daylighting, i.e. for the use of daylight as a primary source of illumination in a space; in fact, daylight is a flicker-free source, generally with the widest spectral power distribution and highest comfort levels. By daylighting a space, both psychological and energy efficiency benefits can be obtained [25]:

- Psychologically, the presence of controlled daylight improves the overall attitude and well-being of the occupants (increases in worker productivity and mood, and decreases in absenteeism and errors are commonly stated advantages).
- From an energy efficiency point of view, daylighting can offer great energy savings due to reduced electric lighting loads. Reported savings in lighting energy consumption from daylight design and harvesting vary between 15% and 80% [6]. Because preponderant edifice occupancy patterns are high for non-domestic buildings during the day, there is a greater potential to save energy by using daylighting in this zone (it is often the most energy-efficient lighting option, particularly for warehouses that have large roof areas with large open spaces).

On the other hand, poorly introduced daylight can negate some of these benefits by direct sunlight introducing disabling glare or distracting veiling reflections, or solar gains causing uncomfortable thermal conditions.

Over the last decades there has been a steady increase in interest in the use of daylight in architecture, especially in European countries. Depending on cloud conditions and building location, daylight luminance levels may be highly variable. However, they are almost always more than high enough to provide necessary minimum internal illuminance levels, on condition that the design allows enough daylight to enter the building and be distributed appropriately. Various studies have proved that the area close to the window receives enough daylight for all illumination needs to be provided on some occasions, only by daylight; deeper into the room, a mixture of artificial light and daylight is needed, and deeper still almost all light is needed from artificial light. Energy savings are between 60% and 70% in the day-lit area, 30% and 40% in the mixed-light area and 5% and 20% in the artificial-light area [6].

The previous data indicating the energy saving potential give an idea about the value of having the daylight-responsive control systems and the extra savings that can be achieved by increasing the availability of daylight deeper into the floor plan. Unfortunately, daylight is a dynamic source of lighting, i.e. the illuminance from the sky is not constant, and the variations in daylight can be quite large depending on season, location or latitude, and cloudiness. These variations must be compensated by the control system, in order to maintain a constant and uniform illuminance in the task area, avoiding the occupants' discomfort.

There are at least two dimensions to daylight-responsive controls [11,26]: the control of the daylight input to the space, and the control of the electric lighting output. The first is critical for providing adequate quantity and quality of daylight in interior spaces (simultaneously, with proper fenestration solar control, solar gains during cooling load periods can be mitigated and solar gains during heating load periods can be beneficial, reducing both the overall cooling and heating requirements of a space); the second saves energy and improves the overall distribution of light when and where daylight is insufficient.

The daylighting control employs strategically located photosensors and uses continuous dimming techniques that allow users to adjust lighting levels over a wide range of lighting output and offer far more flexibility than step-dimming controls. The fluorescent lighting is dimmed to maintain a required band of light level when there is sufficient daylight present in the space. As continuous dimming follows the daylight pattern very closely, it is often more acceptable to occupants, and can produce higher energy savings, particularly in areas with highly variable cloud cover. Continuous dimming also responds to changes in light output due to dirt depreciation on luminaires and lamps, and lamp lumen depreciation due to lamp aging. It is achievable using either analogue or digital ballasts. As classic control systems present some difficulties to adjust their performances to the rapid changes in daylight and to occupants' preferences, new analysis methods and controllers based on Artificial Intelligence techniques (for instance, Artificial Neural Networks and Fuzzy Control) have been proposed [26–28].

Usually, the room is divided into several zones, according to the existing fenestration and working tasks; the correct placement of sensors is critical to balancing lighting quality and energy saving (various type of automatic sensors should be located in a manner such that the portion of the lighting zone being controlled experiences fairly uniform daylight illuminance levels). Electric lighting systems should be designed to be compatible with the daylighting system in respect of luminance ratios, controls and colour rendition. This co-ordination helps to enhance the daylight quality and improve user acceptance of the energy saving features.

8.5 Energy Efficiency in Outdoor Lighting Systems

Globally, an estimated 218 TWh of final electricity was consumed by outdoor stationary lighting in 2005, amounting to about 8% of total lighting electricity consumption; the average luminous efficacy of the used light sources was 74 lm/W, higher than in any other sector except industry [6]. Road and street lighting represents a large amount of energy consumption each year as light intensity is often excessive when traffic density is low; therefore, energy conservation for large-scale illumination tasks such as street lighting is gaining considerable importance. By correct investments and utilizing the existing technology it is possible to reduce today's energy consumption in this sector by as much as approximately 60% (for Europe as a whole, this stands for about 36 TWh a year); in addition, a significant saving on maintenance costs can be achieved [29].

8.5.1 Efficient Lamps and Luminaires

At present, high intensity discharge (HID) lamps are the popular choice as light sources in road lighting; the HID lamp family includes high-pressure sodium (HPS), low-pressure sodium (LPS), metal halide (MH), and mercury vapour lamps [30]. According to [6], almost 62% of total outdoor light is provided by high- and low-pressure sodium lamps, 30% by mercury vapour lamps and 6% by metal halide lamps; the remaining 2% is mostly provided by halogen and incandescent lamps. HPS lamps are the most widespread type of light source used for outdoor applications, due to two important economic considerations: low initial and operating costs. Despite these economic advantages, MH lighting systems are gaining continuously wider acceptance for outdoor applications in large part because they have become more competitive on reducing system costs, both initial and operating. In addition, MHLs are more efficacious for night-time applications because, for the same wattage, MH spectra are better tuned to the spectral sensitivity of the human retina at mesopic light levels [31].

Mercury vapour street lamps are outdated and use far more energy than HPS or MH devices. These light sources are extremely inefficient and use obsolete technology, which results in a very high cost of ownership through high energy use; if all the inefficient mercury vapour street lighting in Europe was upgraded to the latest technology, Europe would achieve 1 billion Euros in running cost savings (based on 2006 energy prices) [32]. This is equivalent to:

- 4 million tons of CO_2 savings;
- 14 million barrels of oil per year;
- the equivalent consumption of 200 million trees.

In recent years, LED array illumination has received attention as an energy-reducing light source. LED road illumination requires only about 30–50 % of the electric power needed for HID lighting, while its lifecycle can be more than three times longer [33]; the amount of time needed to exchange defective fixtures could be reduced, and it is expected that an LED system would be comparatively maintenance free. Other LED advantages address the free content of mercury, lead or other known disposal risks and instant operation, without run-up time or re-strike delay. Further, while MH and HPS technologies continue to improve incrementally, LED technology is constantly improving very fast in terms of luminous efficacy, colour quality, optical design, thermal management, and cost [33]. In such a background, and as a result of the significant improvements to luminescent efficiency in recent years, LED lighting can be expected to fully replace previously used light sources within our lifetimes.

However, current LED product quality can vary significantly between manufacturers, so due diligence is required in their proper selection and use. LED performance is highly sensitive to thermal and electrical design, weaknesses that can lead to rapid lumen depreciation or premature failure. Further, long-term performance data do not exist given the early stage of the technology's development.

Energy efficiency of outdoor lighting systems cannot be obtained by simple selection of more efficient lamps alone; indeed, it also encompasses the optical efficiency of the luminaire, and how well the luminaire delivers light to the target area without casting light in unintended directions. The goal is to provide the necessary illuminance in the target area, with appropriate lighting quality, and only efficient luminaires along with the lamp of high efficacy may achieve the optimum efficiency. Luminaires differ in their optical precision. Photometric reports for outdoor area luminaires typically state downward fixture efficiency, and further differentiate downward lumens as 'streetside' and 'houseside' [34]. Mirror-optic luminaires with a high output ratio and bat-wing light distribution can save more energy; simultaneously, the luminaire should ensure that discomfort glare and veiling reflections are minimized. System layout and fixing of the luminaires also play a major role in achieving energy efficiency. In conclusion, fixing the luminaires at optimum height and usage of mirror optic luminaries leads to energy efficiency.

LED luminaires use different optics than MH or HPS lamps because each LED is, in effect, an individual point source. Effective luminaire design exploiting the directional nature of LED light emission can translate to lower optical losses, higher luminaire efficacy, more precise cut-off of backlight and up-light, and more uniform distribution of light across the target area. Better surface illuminance uniformity and higher levels of vertical illuminance are possible with LEDs and close-coupled optics, compared with HID luminaires. Their special design offers the following advantages:

- a reduction in luminous intensity in the 70° to 90° vertical angles to avoid glare and light trespass;
- zero to little intensity emitted between 90° and 100°, the angles that contribute the most to sky glow;
- a higher reduction in light between 100° and 180° (zenith), which also contribute to sky glow.

Several comparative data between luminaires containing HID lamps and LED luminaires presented in [34] highlight the following potential benefits offered by well-designed LED luminaires for outdoor area lighting:

- the uniformity was improved by more than a factor of two;
- a better control of the illuminance;
- improved uniformity ratio.

Moreover, since HID lamps are high-intensity near-point sources, the optical design for these luminaires causes the area directly below the luminaire to have a much higher illuminance than areas farther away from the luminaire; this over-lighting represents wasted energy, and may decrease visibility since it forces adaptation of the eye when looking from brighter to darker areas. In contrast, the smaller, multiple point-source and directional characteristics of LEDs can allow better control of the illuminance distribution.

The EU Regulation concerning the eco-design requirements includes the following issues referring to the outdoor lighting [21]:

- Minimum performance requirements are introduced for high intensity discharge (HID) lamps, consisting in phasing out of high-pressure mercury (HPM) lamps following an agreed schedule, the largest wattages being phased out first.
- Requirements on minimum lumen maintenance levels are introduced.
- 90% of the high-pressure sodium (HPS) lamps should have a lifetime of more than 16 000 hours.
- Metal halogen lamps should have a minimum life time of 12 000 h for 80% (frosted) and 90% (clear) reduction on lumen output.
- Requirements of directional light sources for street lighting luminaires (not only HID) are established in order to reduce light pollution.
- New minimum performance requirements are introduced for all HID lamps to minimize mercury content.

The following recommendations are of interest in the case of output lighting systems retrofit:

- Replacement of mercury vapour lamps with higher-efficiency alternatives
- Replacement of probe-start metal halide lamps with higher-efficiency options (e.g. pulse-start metal halide lamps)
- Installation of metal halide lamps for colour critical applications when higher illumination levels are required
- Installation of high pressure sodium vapour lamps for applications where colour rendering is not critical
- Ensure high-pressure sodium and metal halide lamps permitted on the market have adequate efficacy levels and are matched to good ballasts and lighting controls
- Higher luminaire efficiency
- The photometric performance of all luminaires should be measured and available according to standard test procedures. If the latter are not yet developed for specific luminaire or lamp combinations they need to be established
- Outdoor luminaires should generally be of a cut-off variety to avoid light trespass and minimize light pollution unless there is a strong aesthetic argument to the contrary
- Better control systems

Finally, some aspects regarding power quality are of interest in outdoor lighting systems. On the one hand, all high-pressure discharge lamps are non-linear loads generating a significant amount of current harmonics (important levels of current total harmonic distortion (THD) were observed) [35]; on the other hand, all lamps are single-phase loads producing the unbalance of the three-phase supply system. These electromagnetic disturbances produce supplementary power losses in all line and neutral conductors [36, 37]; for large outdoor lighting systems, the amount of these additional losses may become unacceptable, and measures to mitigate the generated disturbances must be implemented. Intolerable voltage drops can also appear for too long supply lines.

8.5.2 Outdoor Lighting Controls

Currently, the outdoor lighting control systems range from very simple to the most modern applications. The amount of light necessary on the road depends on legal requirements, tarmac, traffic volume, type of road, speed limit and surroundings. In the case of one of these parameters changes during the night (e.g. traffic volume, speed limit), the luminous flux can be decreased by reducing power (voltage) of the lamps or switching lamps off at all. The reduction in voltage is however limited, since the usual physical voltage drop, which is a function of the length of cable, is the limiting factor for lamps to come on at the end of an installation's cable. In order to estimate savings, the structural condition of the affected installation has to be analysed individually.

8.5.2.1 High-intensity Discharge Lamp Dimming

Generally, HID lamp dimming can result in energy savings, peak demand reduction and greater flexibility in multi-use spaces. For the first purpose, dimming can be achieved either manually (via input from a switch) or automatically (via input from a control device such as timers, occupancy sensors, photocells, etc.); for the second one, dimming can be scheduled using a time-programmable controller during times of peak demand. It is important to point out that shutting off and restarting the HID lamps does not represent a practical solution taking into account their characteristics (long warm up time and significant shorter lamp life if the burn time per start decreases below 10 hours); on the contrary, if the lamps are dimmed in response to a signal from an occupancy sensor or time-programmable controller, significant energy savings can occur during these periods, but the lamps will be able to achieve full light output quickly when the space becomes occupied again. HID lamps can be dimmed using step-level or continuous-dimming systems [38].

(a) *Step-level dimming* enables wattage reduction, usually from 100% to a step between 100% and 50% of rated power; accordingly, this solution is also known as a two-level dimming system. Depending on the lamp type and wattage, in a bi-level dimming system, the Low level may be 15–40% of light output and 30–60% of wattage (with possible energy savings as high as 40–70%). Tri-level dimming systems operating at three fixed light levels are also possible, offering a greater degree of flexibility to address multiple uses of the space. This dimming method usually employs constant-voltage autotransformer magnetic ballast with one or two additional capacitors, depending on whether the ballast provides bi- or tri-level dimming. Relay switching of the capacitors results in additional impedance, which reduces the lamp current and the wattage. The capacitor circuit configuration may be a parallel or series connection.

The solution is less expensive than continuous dimming systems and allows individual luminaire control (it is suitable for retrofit). In addition, fixtures are available with a dedicated occupancy sensor and dimming ballast, appropriate for direct fixture replacement. Ideal applications for step-dimming include spaces that may be unoccupied for long periods of time but still need to be lighted, such as parking lots, warehouses, supermarkets and malls. High pressure sodium lamps are typically used for parking lots and warehouses, while metal halide lamps are generally used for supermarkets and malls. It is worth mentioning that when HID lamps are dimmed below 50% of rated power, they may experience degradation in service life (by 90%), efficacy, colour and lumen maintenance, or they may even extinguish. As a result, NEMA recommends that the maximum dimming level is 50% rated lamp wattage for both metal halide and high pressure sodium lamps.

(b) Continuous (line-voltage) dimming enables a smooth, continuous reduction of lamp wattage; this technique is used anywhere it is advantageous to adapt the lighting system to a wide range of light levels. The control system may be one of the following three types:

1. Variable voltage transformer: reduces the primary voltage supplied to the ballasts, reducing light output and electrical input (enabling a reduction in rated power down to 50%).
2. Variable reactor: changes lamp current without affecting the voltage (enabling a reduction in rated power down to 50%).
3. Electronic control circuits: change the waveform of current and voltage input to the ballasts enabling a reduction in rated power down to 50%.

All these control solutions use electromagnetic ballasts with large size and weight, low efficiency, and sensibility to voltage changes. Electronic ballasts can overcome these drawbacks, supplementary offering more possibilities for lighting control. There are three main dimming methods for HPS lamps with electronic ballasts [18]: (i) variation of operating voltage of inverter; (ii) variation of operating frequency of inverter; and (iii) variation of pulse-width of inverter output signal (PWM). Variation of the voltage or frequency is easy to implement, but the colour of light will be affected; PWM is more complicated, but the colour of light output will be affected only minimally. No matter which ballasts are applied, the dimming range is limited for HPS lamps, and colour rending starts to shift even at 60% of rated power.

Several manufacturers offer solid state electronic ballasts for MH lamps, claiming that these ballasts provide better performance in a smaller package, have a high power factor, save more energy, generate less heat, and have lower maintenance costs compared with electromagnetic ballasts. These ballasts are more commonly available for lamps below 150 watts.

For all cases, the light output will be reduced further than the wattage reduction. In general, light output reductions are about 1.2–1.5 times the power reduction for metal halide lighting systems, and about 1.1–1.4 times the power reduction in high-pressure sodium lighting systems.

8.5.2.2 LED Dimming

LEDs offer many advantages for control and operation. This feature, combined with the ready ability to control each LED in an array individually via a microcontroller, may offer potential benefits in terms of controlling light levels (dimming) and colour appearance. Dimming drivers can dim LEDs over the full range from 100% to 0% by reducing the forward current, pulse width modulation (PWM) via digital control, or more sophisticated methods. Dimming does not result in a loss of efficiency as the LEDs are still operated at the same voltage and current as during full light output. In addition, lamp life is not affected by dimming, as is sometimes the case with frequently dimmed HID lighting. Therefore, dimming LEDs may lengthen the useful life of LEDs, because dimming can reduce operating temperatures inside the light source [39]. As LED driver and control technology continues to evolve, this is expected to be an area of great innovation in lighting. Dimming, colour control, and integration with occupancy and photoelectric controls offer potential for increased energy efficiency and user satisfaction.

8.5.2.3 Digital Lighting Control Systems

Modern digital lighting control aims to integrate the lamp dimming capabilities into more complex management systems consisting of three main elements [40]:

1. control unit in the luminaire;
2. CPU and GSM module in each of the switchboards of the installation;
3. remote data processor for management and controlling the individual installations.

In this case, modern technologies for supervision of the traffic will optimize the lighting: it will still need to supply for the worst case scenario but should also be able to automatically adapt fully to the current needs. If the light levels of a lighting system are adjusted according to predefined parameters such as time, traffic density, weather conditions, etc, the lighting system can be called *adaptive* or *dynamic*; such a system can be *intelligent* when light levels are adjusted in real time according to real needs. An intelligent road lighting control system is defined as a modern lighting control system based on the technology of computer science, communication, automation, and power electronics, which can automatically collect system information, analyse, deduce and estimate the collected information, and realize the optimum lighting control effect by changing the lamp light output in real time according to real needs [18]. Its main purpose is to save electricity and maintenance costs without negative effects on traffic safety. From the lighting point of view, this means providing the optimum luminance level based on the prevailing traffic and weather conditions.

These systems are capable of operating each luminaire individually from an installation. Moreover, they inform online about the state of each luminaire and its individual components including detailed fault detection. The savings are claimed to be up to 30% for electricity and 40% for maintenance. Investment costs for such systems, especially when retrofitting, are high and life cycle costs have to be calculated individually to estimate the payback time [40].

Communication is the key issue in an intelligent road lighting control system. As the control centre is far from the remote control unit and lamps, different communication solutions must be used. Wireless communications, such as radio and GSM/GPRS, are possible answers with high transmission rate and high capability for large-scale long-distance; however, they have relatively high operation costs. Wired communication, such as optic fibre, telephone lines or even power line carriers, are also potential solutions, depending on the budget. The use of optic fibre is very expensive but it has high capability and transmission rate; the telephone line is an economical solution, but has a low capacity and low transmission rate, while power line communication is economical due to the existing wires, but it is easily affected by interference. The choice of communication systems depends on the specific applications, requirements, and budget. There is only a right solution for the right application, whereas there is no single solution that is better than others in all cases [18].

In conclusion, the obvious advantage of using adaptive lighting, with built in intelligence, is reduced energy consumption and reporting from the lamp of the current status. This gives better control of the installation and ensures that the equipment actually delivers what is required to the customer, leading to an improvement in the quality of the delivered product, ‘road lighting’ [29]. Better control also gives increased predictability and secondarily it lowers maintenance and running costs, by being able to achieve better planning and better implementation of error corrections in the installations. Adaptive lighting introduces demands for better energy measurements in the installations allowing the automatic regulation of both electrical parameters, burning hours and light levels. If the same system implements the measurement function and the control function then the communication expenses will be reduced, it will minimize the number of components needed in the system so reducing costs and simplifying the operation and maintenance.

8.6 Maintenance of Lighting Systems

For all lighting systems, the general performances decease over time. This degradation can be the result of lamp lumen depreciation, lamp and ballast failure, dirt accumulation on lamps and luminaires, luminaire surface deterioration, room surface dirt depreciation, and many other causes; in combination, these factors commonly reduce the light output by 20–60% [18]. It is evident that all lighting installations need to be maintained to perform at maximum efficiency.

Designing lighting systems to compensate for lack of system maintenance can waste lighting energy since more light is provided initially than is necessary; assessing the future maintenance condition of the installation in the design step always results in a significant add-on margin. In some extreme cases, the margin can be as high as 40–50%, which means that the installation is over designed by 40–50% at its initial operating period [16]; however, the energy consumption may be reduced by using appropriate control systems. Taking into account this aspect, but also the labour cost, the maintenance schedule should be reviewed frequently during the initial operating period of an installation so that an optimum frequency for maintenance can be established.

The optimum interval for bulk re-lamping and the cleaning depends on the following factors [16]:

- *Type of premises*: governs the operational needs of the lighting installation (whether the requirement of maintaining the illumination level is stringent or loose, whether there are specific personnel to be responsible for the utilities management or not, etc.).
- *Location of premises*: affects the rate of dirt accumulation in luminaires.
- *Usage rate of a particular space and the existing control*: affects how long will it take for the illumination of a lamp to depreciate to an unacceptable level.
- *Type of luminaire*: affects the ease of accumulation of dirt, the loss in Utilization Factor resulted, and the labour efforts for cleaning.
- *Type of lamp*: governs the characteristic of the lumen depreciation as well as the nominal average lamp life of the installation.
- *Electricity and labour costs*: key factors in the economic analysis of the maintenance schedule (according to [40], total costs of a typical street lighting installation over a period of 25 years consist of 85% maintenance and electricity and only 15% investment costs).

From a maintenance point of view, it may not be cost effective to replace the lamp at a time when the lamp burns out, because it is labour consuming and the burn out of lamps occurs more or less in a random manner; it is therefore more cost effective to carry out group replacement at the economic lamp life. In this issue, intelligent road lighting control systems have great potential in the optimization of lighting maintenance in the following respects:

- Based on the information of burning hours and lamp types, it is possible to predict the end of lamp life, which can be used in planning the group replacement schedule.
- The control centre can detect lamp fault instantly (consequently, work time, response time, and inspection frequency can be reduced).
- With luminance meters or light output sensors, light levels can be adjusted to provide the proper amount of light.

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