CHAPTER 14

Energy Efficient Electrical Services

Much energy is needlessly wasted in buildings through neglect of electrical services. This chapter investigates energy-saving measures which can be applied specifically to electrical services in buildings. In particular, low energy lighting and the use of variable speed motor drives are discussed.

14.1 Introduction

Much energy is needlessly wasted in buildings through poor design and maintenance of electrical services. The energy that is wasted is of the worst kind, namely expensive electrical energy, which can be up to five times as expensive as the unit cost of heat. Unfortunately, excessive electrical energy consumption is all too often overlooked by misguided building designers, who focus on thermal energy consumption, which is relatively inexpensive. It has been shown that in a typical 'standard' air-conditioned office building in the UK, an average of £3.30 per m^2 (of floor area) per annum is spent running pumps and fans, and a further £2.97 per m^2 is spent on the lighting [1]. This compares with an average of only £1.78 per m^2 spent on heating, and £1.71 per m^2 spent on cooling [1]. These figures demonstrate that in the average office building much more money is spent on running fans, pumps and electric lighting than is spent on operating boilers or refrigeration plant. Yet there are a number of relatively simple technologies that can be applied to motor drives and luminaire installations to dramatically reduce energy costs. That energy costs in these areas can be greatly reduced is clear from the evidence of the UK office building study, which found that in *good practice* standard air-conditioned office buildings, only £1.65 per m^2 per year is spent running the pumps and fans, and only £1.48 per m^2 is spent on the lighting [1]. This equates in each case to energy cost reductions of about 50% when compared with typical air-conditioned office buildings.

14.2 Power Factor

Electric induction motors and fluorescent lamp fittings are classic examples of reactive (i.e. inductive) electrical loads. Reactive electrical loads are important because, unlike resistive loads such as incandescent light, they cause the current to become out of phase with the voltage (see Figure 14.1). This, in simple terms, means that items of equipment which are inductive in nature draw a larger current than would be anticipated by their useful power rating. Ultimately, it is the consumer who has to pay for this additional current.

The electrical power consumed by a resistive load can be determined by:

$$W = V \times 1 \tag{14.1}$$

where W is the power (W), V is the voltage (V), and I is the current (A).

Equation (14.1) defines the useful power consumed and applies to all types of resistive load where the current is in phase with the voltage. However, eqn (14.1) does not hold true for reactive loads, where the current lags behind the voltage, since reactive loads consume more power than can be usefully used. A reactive load, such as an induction motor, will therefore draw a larger current than would be anticipated by its useful

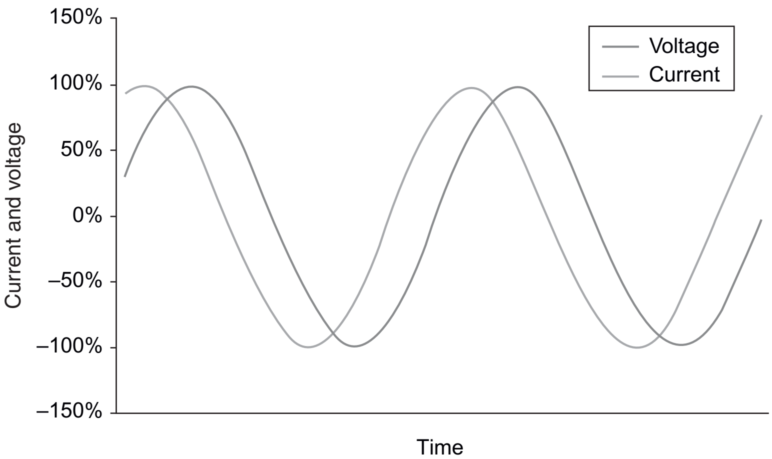

FIG 14.1 The effect of an inductive load on an electrical current and voltage.

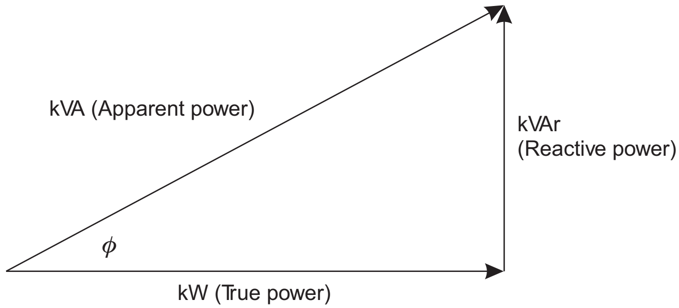

FIG 14.2 The relationship between kW, kVA and kVAr.

power rating. The reactive components of the load consume what is termed *reactive power*. In order to determine the apparent power consumed by a reactive load, the true power must be added vectorially to the reactive power, as shown in Figure 14.2.

It should be noted from Figure 14.2 that the reactive power is drawn at right angles to the true power. The apparent power is therefore a function of the true power consumed and the reactive power, and can be expressed as:

$$\text{Apparent power} = \frac{\text{True power}}{\cos\phi} \tag{14.2}$$

where $\cos\phi$ is the power factor.

From Figure 14.2 and eqn (14.2) it is evident that when the current and voltage are in phase with each other (i.e. a resistive load), the apparent power is the same as the true power. When the two are out of phase (i.e. a reactive load) the apparent power consumed is always going to be greater than the true power. In order to differentiate between true and apparent power, true power is measured in watts (W) or kilowatts (kW), and apparent power is measured in volt amps (VA) or kilovolt amps (kVA). Similarly, reactive power is measured in volt amps reactive (VAr) or kilovolt amps reactive (kVAr). The ratio of true power to apparent power is known as the *power factor*. For a pure resistive load the power factor would be 1, and for a pure inductor the power factor would be 0:

$$\text{Power factor} = \frac{\text{True power}}{\text{Apparent power}} \tag{14.3}$$

14.2.1 Effects of a Poor Power Factor

In many buildings and other installations the overall electrical load is heavily influenced by the presence of reactive loads such as induction motors and fluorescent tubes which create a lagging power factor. As a result, power factors of 0.7 or less are often experienced. Example 14.1 illustrates the impact of such a poor power factor.

Example 14.1

A 240 V single-phase electric motor has a true power of 1.8 kW and exhibits a power factor of 0.7. Determine:

(i) The current required to drive the motor.
(ii) The current required if the power factor was 1.

Solution

$$\text{True power (W)} = \text{Apparent power (VA)} \times \text{Power factor}$$

Therefore

$$\text{Current} = \frac{\text{Watts}}{\text{Volts} \times \text{Power factor}}$$

$$\text{(i)} \quad \text{Current} = \frac{1800}{240 \times 0.7} = 10.71 \text{ A}$$

$$\text{(ii)} \quad \text{Current} = \frac{1800}{240 \times 1} = 7.5 \text{ A}$$

Example 14.1 demonstrates that the lower the power factor, the greater the current required to provide the same useful power. The increased current required as a result of a poor power factor has the knock-on effect of increasing power losses. Because cables and other items of equipment have an electrical resistance, power is lost as heat when a current flows. The power (or I^2R) loss can be expressed as:

$$\text{Power loss} = I^2 \times R \tag{14.4}$$

where I is the current (A), and R is the resistance (Ω).

It can be seen that for a circuit with a constant resistance, the greater the current, the greater the I^2R losses. In addition to increased currents and increased I^2R losses, a poor power factor has the knock-on effect that switchgear, cables and transformers all have to be increased in size. Example 14.2 illustrates this fact.

Example 14.2

A building is served by a 415 V (line-to-line) three phase supply and has a true power load of 210 kW and a power factor of 0.7. Compare the installation with a similar one having a power factor of 1.

Solution

$$\text{Total current} = \frac{210{,}000}{415 \times 0.7 \times \sqrt{3}} \times 417.4 \text{ A}$$

If however, if the power factor was 1, then

$$\text{Total current} = \frac{210{,}000}{415 \times 1 \times \sqrt{3}} = 292.2 \text{ A}$$

TABLE 14.1 Impact of poor power factor

	Power factor = 0.7	Power factor = 1
Total current	417.4 A	292.2 A
Apparent power (kVA)	300 kVA	210 kVA
Switchgear rating	450 A	350 A
Transformer rating	400 kVA	300 kVA
Cable size	240 mm^2	150 mm^2

The impact of this reduction in current is shown in Table 14.1.

Examples 14.1 and 14.2 show that the lower the power factor the greater the current drawn and the greater the size of the infrastructure required. Therefore, if a consumer has a poor power factor the electricity utility company has to supply more 'electricity' than will be recorded as 'true power' in kW at the electricity meter. This means that the utility company will not be paid in full for all the electricity which it is supplying to the consumer. Utility companies overcome this problem by adopting one of two strategies:

Strategy 1: Installing meters and offering tariffs which record electricity consumption in kVA and not in kW.

Strategy 2: Using meters and tariffs which record electricity consumption in kW and levy an additional charge for the number of reactive power units (kVAr) consumed.

By using either approach a utility company can ensure that it receives the correct revenue for the electrical energy it supplies.

14.2.2 Power Factor Correction

The simplest way to correct a poor power factor is to minimize the problem in the first place. In many applications a poor power factor occurs as a result of the use of induction motors. Induction motors are commonplace in buildings and are used to drive fans and pumps. As such they are a necessity and cannot be avoided. The power factor of induction motors varies with the motor loading. Motors which may have a power factor of 0.8 at full load may have a power factor approaching 0.1 at low load, with the result that almost 90% of the total current drawn is reactive in nature [2]. Motors should therefore be selected with care, since an under-loaded large motor will exhibit a low power factor. The power factors exhibited by smaller motors are not as good as those of larger motors. Despite this, it is usually better to select a smaller motor than use an under-loaded large motor to perform the same job.

It is possible to correct a poor power factor by installing capacitors. The effect of capacitors on an alternating current is the opposite to that of a reactive load. They cause the current to lead the voltage. By installing capacitors into an electrical circuit it is possible to counteract the effect of any reactive load and correct a poor power factor. Power factor correcting capacitors can either be installed in a central bank before the main distribution panel, or mounted on individual items of equipment. It is generally considered better to correct the power factor for reactive loads at the item of equipment itself. This reduces the current drawn by the item of equipment and thus reduces the

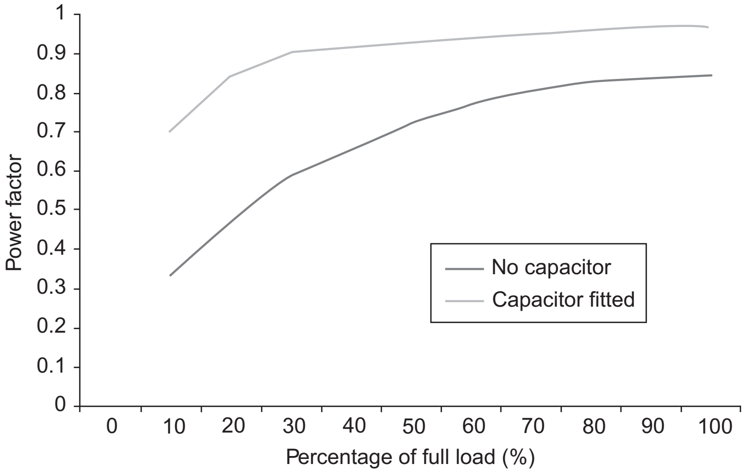

FIG 14.3 Impact of power factor correction on induction motors [2].

I^2R losses in all the wiring leading to the item of equipment. By fitting capacitors to an induction motor it is possible to greatly improve its power factor. An example of this is shown in Figure 14.3, where the introduction of capacitors results in the power factor being virtually constant with all loads over 50% of full load [2].

In large installations it may be more cost-effective to install a central bank of capacitors to correct power factor. It is possible to use banks of capacitors which automatically switch on and off in order to maintain an optimum power factor.

14.3 Electric Motors

Induction motors are widely used in many applications. Pumps, fans, compressors, escalators and lifts are all powered by motors of one type or another. Induction motors are therefore essential to the operation of most modern buildings. Furthermore, electric motors are often the most costly items of plant to run in many office buildings. It is therefore well worth understanding how induction motors use electrical energy and investigating possible energy-conservation measures.

All induction motors have inherent inefficiencies. These energy losses include [3]:

- Iron losses which are associated with the magnetic field created by the motor. They are voltage related and therefore constant for any given motor and independent of load.
- Copper losses (or I^2R losses) which are created by the resistance of the copper wires in the motor. The greater the resistance of the coil, the more heat is generated and the greater the power loss. These losses are proportional to the square of the load current.
- Friction losses which are constant for a given speed and independent of load.

These losses can be divided into those which vary with motor load and those which are constant whatever the load. When a motor is running at full load, the split between the two is about 70% and 30% respectively [3]. Under part load this split changes; at low load the current drawn is small and the I^2R losses are low. Consequently, the iron losses predominate and since they result from the consumption of reactive current, the

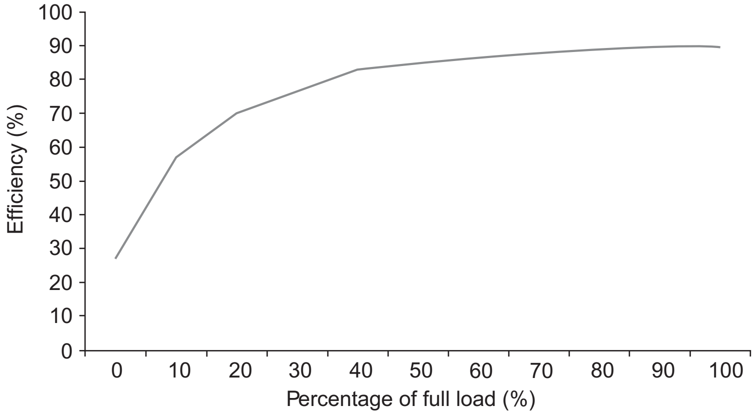

FIG 14.4 Relationship between motor loading and efficiency [2].

power factor is correspondingly low. Even at full load, induction motors exhibit a relatively poor power factor, typically around 0.8 [3].

14.3.1 Motor Sizing

Correct sizing of electric motors is critical to their efficient operation, since oversized motors tend to exhibit poor power factors and lower efficiencies. Depending on size and speed, a typical standard motor may have a full load efficiency between 55% and 95% [2]. Generally, the lower the speed, the lower the efficiency and the lower the power factor. Typically motors exhibit efficiencies which are reasonably constant down to approximately 75% full load. Thereafter they may lose approximately 5% down to 50% of full load, after which the efficiency falls rapidly (as shown in Figure 14.4) [2].

It can be seen from the performance curve in Figure 14.4 that it is possible to oversize a motor by up to 25% without seriously affecting its efficiency, provided that a motor is run at a relatively constant load. If the load fluctuates and rarely achieves 75% full load, then both the efficiency and the power factor of the motor will be adversely affected. In fact the power factor tends to fall off more rapidly than the efficiency under part-load conditions. Therefore, if motors are oversized, the need for power factor correction becomes greater. Oversizing of motors also increases the capital cost of the switchgear and wiring which serves the motor.

14.4 Variable Speed Drives (VSD)

Most induction motors used in buildings are fitted to fans or pumps. The traditional approach to pipework and ductwork systems has been to oversize pumps and fans at the design stage, and then to use commissioning valves and dampers to control the flow rate by increasing the system resistance. While mechanical constrictions are able to control the flow rate delivered by fans and pumps (see Figure 14.5), the constriction itself increases the system resistance and results in increased energy loss. This situation is highly undesirable and is one of the main reasons why the energy consumption associated with fans and pumps is so high in so many buildings [1]. An alternative approach to the use of valves and dampers is to control the flow rate by reducing the

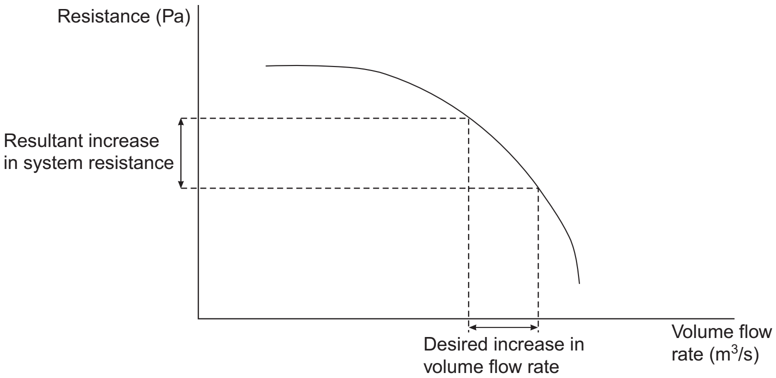

FIG 14.5 Impact of a volume control damper on system resistance.

speed of the fan or pump motor. This strategy results in considerable energy savings, as illustrated in Example 14.3.

Example 14.3

It is proposed to use a forward-curved centrifugal fan in a mechanical ventilation system. The fan is required to deliver a volume flow rate of 1.8 m^3/s and the estimated system resistance is 500 Pa. However, the proposed fan delivers 2.06 m^3/s against a resistance of 500 Pa while running at a speed of 1440 rpm. Determine the fan power input, if:

(a) A volume control damper is used to achieve a volume flow rate of 1.8 m^3/s by increasing the total system resistance to 750 Pa.
(b) The fan speed is reduced in order to deliver 1.8 m^3/s.

Solution

(a) Fan air power input:

$$W = \dot{v} \times P_t$$

where $\dot{v}$ is the air volume flow rate (m^3/s), and P_t is the total system resistance (Pa).

Let W_1 be the fan power when delivering 2.06 m^3/s against a resistance of 500 Pa, and W_2 be the fan power when delivering 1.8 m^3/s against a resistance of 750 Pa.

Therefore

$$W_1 = 2.06 \times 500 = 1030 \text{ W}$$

and

$$W_2 = 1.8 \times 750 = 1350 \text{ W}$$

Therefore

$$\text{Increase in power consumption} = \frac{1350 - 1030}{1030} \times 100 = 31.1\%$$

(b) The fan laws state that:

$$\dot{v} \propto N$$

and

$$W \propto N^3$$

where $\dot{v}$ is the air volume flow rate (m^3/s), N is the fan speed (rpm), and W is the fan air power input (W).

Let N_1 be the fan speed when delivering 2.06 m^3/s against a resistance of 500 Pa, N_3 be the fan speed when delivering 1.8 m^3/s, and W_3 be the fan power when delivering 1.8 m^3/s.

Therefore

$$N_3 = 1440 \times \frac{1.8}{2.06} = 1258.3 \text{ rpm}$$

$$W_3 = 1030 \times \frac{1.8^3}{2.06^3} = 687.2 \text{ W}$$

Therefore

$$\begin{matrix}\text{Reduction in power consumption} \\ (W_3 \text{ compared with } W_1)\end{matrix} = \frac{1030 - 687.2}{1030} \times 100 = 33.3\%$$

However

$$\begin{matrix}\text{Reduction in power consumption} \\ (W_3 \text{ compared with } W_2)\end{matrix} = \frac{1350 - 687.2}{1350} \times 100 = 49.1\%$$

It can be seen from Example 14.3 that:

- The use of volume control dampers to regulate air flow significantly increases fan energy consumption. The precise magnitude of this increase will depend on the characteristics of the particular fan selected.
- Reducing the fan speed to regulate the air flow rate always results in fan energy savings.

The fan power savings which can be achieved through reducing fan speeds are considerable, especially when compared with the fan power increase which results from using volume control dampers. As a result there are great advantages to be gained, if fan and pump speeds can be controlled.

The energy savings achieved in Example 14.3 are indicative of the type of savings which can be achieved through the use of VSDs on fans and pumps. In most applications the potential for saving energy through the use of VSDs on pumps, fans and compressors is considerable. Most designers overestimate system resistances with the result that most pumps and fans are theoretically oversized before the actual fan or pump selection is undertaken. During the selection process, the cautious designer is unlikely to find a fan, or pump, which matches the theoretical 'calculated' specification and thus a larger one is selected which is sure to perform the required task. This strategy protects the system designer and ensures that he/she does not negligently undersize the fans or pumps. Unfortunately, it also ensures that the system is greatly oversized and that during the commissioning process, volume control dampers and dampers will have to be used to reduce the volume flow rate. Consequently, both the capital and future operating costs of the system are greatly increased. By using VSDs it is possible to ensure that even if fans and pumps are oversized, energy consumption will not be greatly increased. This makes the installation of VSDs one of the most cost-effective energy efficiency measures that can be taken. It has been estimated that for VSDs payback periods of less than 2 years are the norm [2].

In addition to the energy savings gained through using VSDs on constant flow systems, even greater savings can be made by employing VSDs on variable volume flow systems. When the load profiles and duty cycles of heating, air-conditioning and ventilation systems are examined in detail, it is found that most regularly operate well below their intended design specification. The main reason for this is that system designers are overcautious at the design stage. As a result, over-large constant volume flow rate, variable temperature systems are designed. While this approach works in practice, it means that pump and fan running costs are constant and high, no matter what the operating load. An alternative approach is to keep the temperature constant and vary the flow rate, so that pump and fan running costs reduce as the operating load reduces. The classic system which adopts this approach is the variable air volume (VAV) air-conditioning system, for which VSDs are ideally suited.

14.4.1 Principles of VSD Operation

Modern electronic VSD systems adjust the mains alternating current to regulate motor speed. Various electronic VSD systems are available. One of the most popular types is the *variable frequency drive*, which achieves speed control by varying the voltage and frequency output. Such drives regulate the voltage to the motor in proportion to the output frequency in order to ensure that the ratio of voltage to frequency remains relatively constant. Changes in motor speed are achieved by modulating the voltage and frequency to the motor. Figure 14.6 shows the basic components in a *variable frequency drive* VSD system.

Variable frequency drive systems comprise two main components, a rectifier and an inverter. The rectifier converts standard alternating current (ac) (e.g. 240 V and 50 Hz)

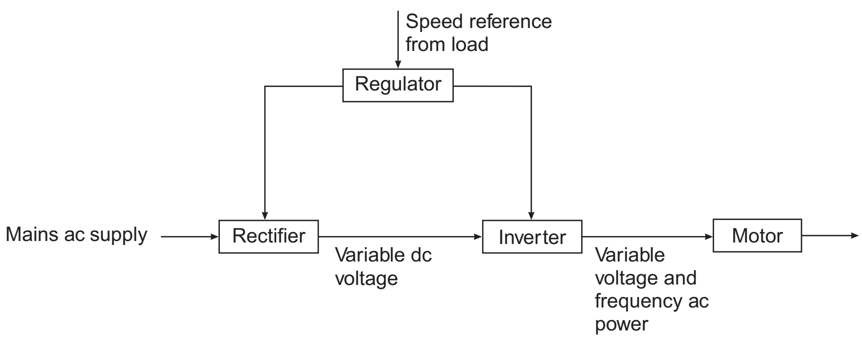

FIG 14.6 Components of a variable speed drive. Crown copyright: reproduced with the permission of the Controller of Her Majesty's Stationery Office and the Queen's Printer for Scotland [4].

to an adjustable direct current (dc), which is then fed to the inverter. The inverter comprises electronic switches which turn the dc power on and off to produce a pulsed ac power output. This can then be controlled to produce the required frequency and voltage. The switching characteristics of the inverter are modified by a regulator, so that the output frequency can be controlled.

The inverter is the critical part of a VSD system. One type of inverter currently in use is the pulse width modulated (PWM) inverter, which receives a fixed dc voltage from the rectifier and adjusts the output voltage and frequency. The PWM inverter produces a current waveform which approximates to the pure sine wave of mains ac supply.

14.5 Lighting Energy Consumption

The energy consumed by electric lighting in most building types is considerable. Table 14.2 shows the proportion of overall energy consumed by lighting for a variety of building types in the UK.

Although in many buildings the energy consumed by the heating system is often greater than that consumed by lighting, the energy costs associated with lighting are often considerably greater than those associated with the heating [1]. It is possible to achieve considerable energy cost savings through the careful design and maintenance of lighting schemes. On average, *good practice* 'standard' air-conditioned office buildings in the UK experience an annual lighting cost of £1.48 per m^2, which compares very favourably with the typical value of £2.97 per m^2 of floor space [1].

14.5.1 Daylighting

Although the focus of this chapter is on electrical services, daylighting is relevant to the subject of artificial lighting and so a short discussion is included here. The ability of daylighting to reduce lighting energy costs should not be underestimated. Daylight can make a substantial contribution to the lighting of buildings by reducing reliance on artificial lighting.

The major factors affecting the daylighting of an interior are the depth of the room, the size and location of windows, the glazing system and any external obstructions. These

TABLE 14.2 Typical energy consumption on lighting for various applications in the UK [5]

Building type	Typical percentage of energy consumed by lighting (%)
Banks	19
Factories	15
Hotels	9
Offices	16–20
Schools	9–12
Supermarkets	11

factors usually depend on decisions made at the initial design stage. Through appropriate planning at an early stage it is possible to produce a building which is energy efficient as well as having a pleasing internal appearance. Glazing can, however, impose severe constraints on the form and operation of a building. If poor design decisions are made concerning fenestration it is possible to create a building in which the occupants are uncomfortable, and in which energy consumption is high. Glazing should therefore be treated with care.

14.5.2 Lighting Definitions

Before discussing the factors which influence the energy consumption of artificial lighting schemes, it is important first to understand the terminology involved, and to appreciate how lighting schemes are designed. A full discussion of the subject of lighting design is, however, beyond the scope of this book.

When an incandescent lamp is switched on, it emits a luminous flux in all directions. The fundamental SI unit of luminous flux is the lumen (lm). It should be noted that the lumen is simply a measure of the quantity of *luminous flux*. It tells us nothing about the direction of the light. When a lamp is placed in a luminaire fitting with an integral reflector, the luminous flux from the lamp will be directed in one particular direction (e.g. downward in the case of a ceiling-mounted fitting). A certain number of lumens are therefore focused in a particular direction with a certain *luminous intensity*. Luminous intensity, as the term suggests, is the intensity of luminous flux in any given 3-dimensional angular direction and its SI unit is the candela (cd). 'Three-dimensional angular direction' is a difficult concept to define; but it is usually referred to as *solid angle*. It is the 3-dimensional equivalent of a 2-dimensional angle. The steradian is the SI unit of *solid angle* and is the 3-dimensional equivalent of the radian. The candela can therefore be defined as being a lumen per steradian. More precisely, one candela can be defined as the luminous intensity from a source producing light at 540,000,000 MHz and at a specific intensity of 1/683 W per steradian [6].

Lighting manufacturers use a system of polar diagrams to describe luminous intensity distribution from luminaire fittings. Figure 14.7 shows a typical polar diagram for a transverse section across a ceiling-mounted luminaire fitting. It should be noted that luminous intensity produced by the lamp is not the same in all directions. For example, while the intensity in a vertical direction is 112 cd per klm of lamp flux, the intensity at 40° to the vertical is only 88 cd per klm. Lighting manufacturers usually specify intensity in terms of cd per klm of installed lamp flux because it is often possible to use a variety of lamps in any particular luminaire fitting.

From a purely functional point of view, it is not so much the intensity of light coming from a light source (i.e. a luminaire fitting) that is important, but rather the amount of light that is falling on a particular surface. For example, a room may be illuminated only by spotlights which shine brightly on certain specific objects while leaving the rest of the room in relative darkness. If a person tries to read a book in a region of the room which is not well lit, they will experience difficulties. Although there may be a large luminous flux in the room, the problem is that very little of it is falling on the pages of the book. The person then experiences difficulties in reading. The amount of luminous

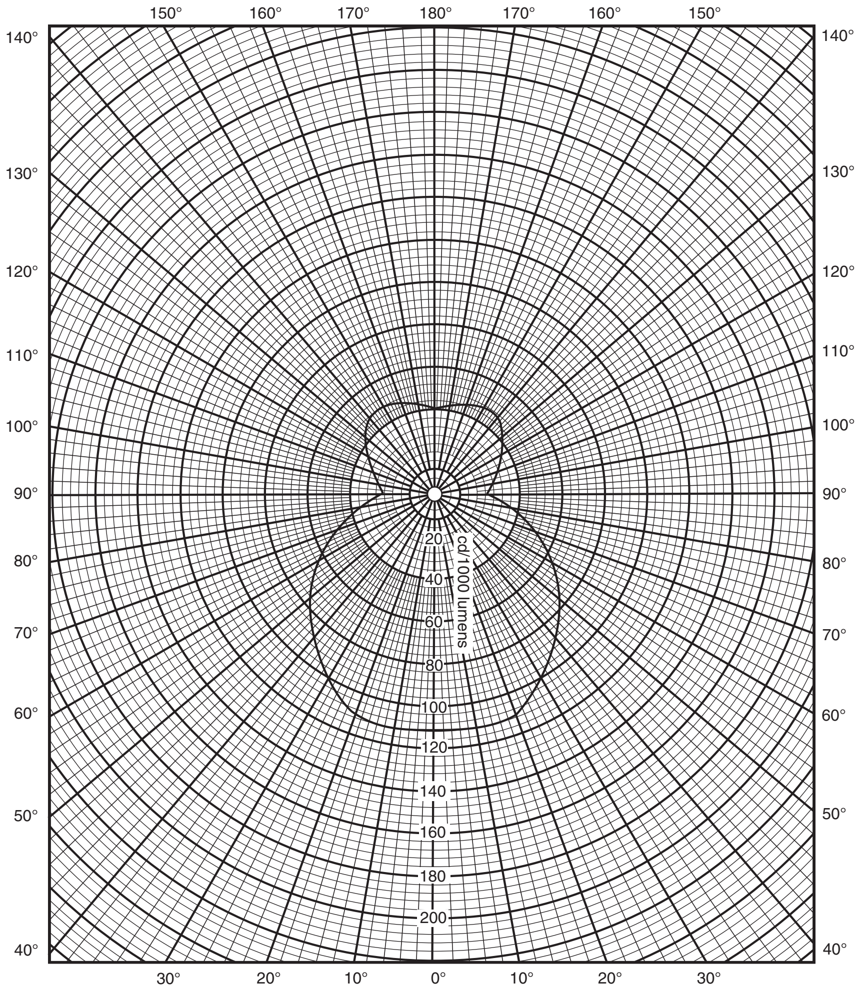

FIG 14.7 Polar intensity diagram. From Smith, Phillips and Sweeney (1987) *Environmental Science* © Longman Group Ltd, reprinted by permission of Pearson Education Ltd [6].

flux falling on a surface is therefore of great importance. It is referred to as *illuminance* and has the SI unit, the lux (lx). One lux is defined as a luminous flux of 1 lm falling on a surface having an area of 1 m^2. Artificial lighting schemes are usually specified as being capable of supplying a specified number of lux on a horizontal working plane. Generally, the more demanding the work, the higher the level of illuminance required.

Because light is a form of radiant energy, its ability to illuminate a surface (i.e. its illuminance) varies inversely with the square of the distance between the source and the surface. In simple terms, if the distance increases, the illuminance decreases by the square of the distance. This relationship is known as the inverse square law. Also, if a horizontal surface is illuminated from the side, so that the light hits the surface at an angle other than 90°, the available luminous flux is shared out over a larger surface area so that illuminance decreases. The angle at which light strikes a surface is therefore of importance. This fact can be combined with the inverse square law to produce the cosine law of illuminance, which can be expressed as

$$\text{Illuminance on a horizontal surface } E_h = \frac{I_\theta}{d^2} \times \cos\theta \tag{14.5}$$

where θ is the angle at which light strikes the horizontal surface (i.e. angle from the vertical) (°), I_θ is the luminous intensity in direction θ (cd), and d is the distance of plane from light source (m).

Example 14.4 shows how the cosine law can be applied to the data contained in the polar diagram shown in Figure 14.7.

Example 14.4

Using the luminaire polar diagram shown in Figure 14.7, determine the illuminance on a horizontal surface. (Assume that the luminaire fitting contains two fluorescent tubes each with a luminous flux of 3200 lm.)

(i) At a point (a) 3 m directly below the luminaire.
(ii) At a point (b) 2 m to the right of point (a).

Solution

(i) From Figure 14.7 it can be seen that the luminous intensity in the vertical direction is 112 cd per klm of lamp flux. Therefore

$$\begin{aligned}\text{Luminous intensity in the vertical direction} &= 112 \times (2 \times 3.2)\\ &= 716.8 \text{ cd}\end{aligned}$$

Therefore:

$$\text{Illuminance on a horizontal surface at point (a)} = \frac{716.8}{3^2} \times \cos\theta = 79.6 \text{ lx}$$

(ii) Considering point (b)

$$\tan\theta = \frac{2}{3} = 0.667$$

Therefore

$$\theta = 33.69°$$

and

$$d = \sqrt{(2^2 + 3^2)} = 3.606 \text{ m}$$

From Figure 14.7 it can be seen that the luminous intensity at 33.7° in the vertical is 96 cd per klm of lamp flux. Therefore

$$\text{Luminous intensity in the vertical direction} = 96 \times (2 \times 3.2) = 614.4 \text{ cd}$$

Therefore

$$\text{Illuminance on a horizontal surface at point (b)} = \frac{614.4}{3.606^2} \times \cos 33.69 = 39.3 \text{ lx}$$

14.6 Artificial Lighting Design

The performance of an artificial lighting scheme is influenced by:

- The efficacy of the lamps (i.e. the light output per watt of electrical power consumed).
- The luminaire performance.
- The layout of the luminaire fittings.
- The surface reflectance of the decor and furnishing.
- The maintenance standards.

All these factors have to be allowed for when designing any lighting scheme. One method which is frequently used and which considers all these factors is the *lumen design method*. The lumen method enables regular lighting schemes to be designed quickly and easily, and so is particularly popular as a design method. The method enables the number of luminaires to be determined for any rectangular room space using eqn (14.6):

$$\text{Number of luminaire fitting required } n = \frac{E_{av} \times A}{\phi \times \text{UF} \times \text{MF}} \tag{14.6}$$

where n is the number of luminaire fittings required, A is the area of working plane in room (i.e. room area) (m^2), E_{av} is the average illuminance required on the working plane (lx), θ is the lighting design lumens per fitting (lm), UF is the utilization factor of luminaire fitting, and MF is the maintenance factor.

Each of the terms in eqn (14.6) corresponds with the list of factors outlined at the beginning of this section. However, in order to understand the relevance of each term, some explanation is required.

14.6.1 Average Illuminance (E_{av})

The required illuminance in a room depends on the nature of the tasks being undertaken in the space. Visual acuity improves at higher levels of illuminance. The more visually demanding the task, the higher the level of illuminance required on the working plane. The working plane is normally taken to be desk height. Table 14.3 shows appropriate levels of illuminance for a variety of activities and spaces.

TABLE 14.3 Required standard illuminances for various activities [7]

Standard maintained illuminance (lx)	Representative activities
50	Cable tunnels, indoor storage tanks, walkways
100	Corridors, changing rooms, bulk stores, auditoria
150	Loading bays, medical stores, switch rooms, plant rooms
200	Entrance foyers, monitoring automatic processes, casting concrete, turbine halls, dining rooms
300	Libraries, sports and assembly halls, teaching spaces, lecture theatres
500	General office spaces, engine assembly, kitchens, laboratories, retail shops
750	Drawing offices, meat inspection, chain stores
1000	General inspection, electronic assembly, gauge and tool rooms, supermarkets
1500	Fine work and inspection, hand tailoring, precision assembly
2000	Assembly of minute mechanisms, finished fabric inspection

14.6.2 Lighting Design Lumens (ρ)

The term *lighting design lumens* simply refers to the total lumen output of the lamps in a particular luminaire fitting. It should be noted that this is the lumen output when the lamps are new. It is also important to appreciate that lighting manufacturers produce luminaire fittings which might accommodate a variety of lamps, each of which will emit a different luminous flux. The type of lamp to be used in the luminaire should therefore be specified.

14.6.3 Utilization Factor (UF)

The UF can be expressed as:

$$\text{UF} = \frac{\text{Total flux reaching the working plane}}{\text{Total lamp flux}} \tag{14.7}$$

The UF takes into account both the direct luminous flux which reaches the working plane straight from the luminaire and the flux which reaches the working plane having been reflected from the walls and the ceiling. The UF is influenced by the nature of the luminaire used, the room surface reflectance and the room dimensions. Table 14.4 shows a typical set of UF data produced by a manufacturer for a particular luminaire fitting.

TABLE 14.4 Luminaire utilization factor

Room reflectance's ceiling (%) [wall %]	Room index					
	1.00	**1.25**	**1.50**	**2.00**	**2.50**	**3.00**
0.50 [50]	0.50	0.54	0.57	0.61	0.63	0.65
50 [30]	0.47	0.51	0.54	0.58	0.61	0.63
50 [10]	0.44	0.48	0.51	0.56	0.59	0.61

It should be noted that both the room surface reflectance and the room geometry are allowed for in Table 14.4. The room geometry is allowed for by the 'room index' which is expressed as:

$$\text{Room index} = \frac{L \times W}{H_m \times (L + W)} \tag{14.8}$$

where L is the length of room (m), W is the width of room (m), and H_m is the mounting height (i.e. height above working plane) (m).

14.6.4 Maintenance Factor (MF)

The effective light output from any luminaire decreases with time. This is because of a number of factors:

- Lamp output decreases with time.
- Luminaire reflectors and diffusers become dirty with time.
- Room surfaces become dirty with time.

To compensate for this drop in luminaire output, an MF is introduced into the lumen design method. The MF also allows for the fact that periodically individual lamps fail and remain unattended for some period of time until they are replaced.

Both lamp survival and lamp output fall with time. Figure 14.8 shows output and survival characteristic curves for fluorescent and tungsten filament lamps. It can be seen that two types of lamps behave very differently. The lumen output of a fluorescent lamp falls by nearly 10% during the first 500 hours of operation [7]. Thereafter, the output decreases less rapidly. With a tungsten filament lamp the decrease in light output is much more gradual, although the lamp life is much shorter than that of a fluorescent tube.

The extent to which luminaire fittings become dirty depends very much on the type of fitting. For example, a ventilated luminaire, used in conjunction with an extract plenum, will cause dust and dirt from the room space to collect on the luminaire reflector with the result that it may quickly become dirty. Figure 14.9 shows how light output decreases with dirt deposition for a variety of luminaire types.

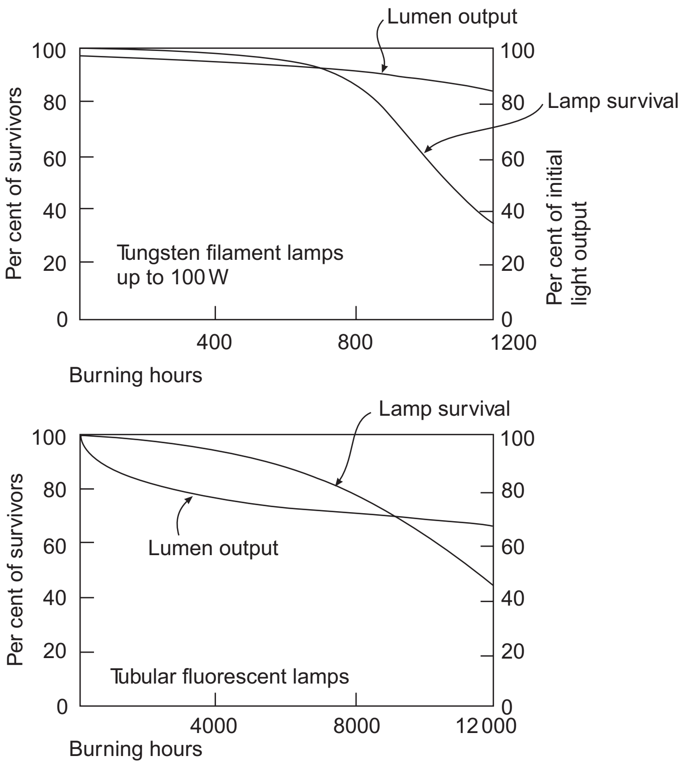

FIG 14.8 Lamp output and survival curves [7].

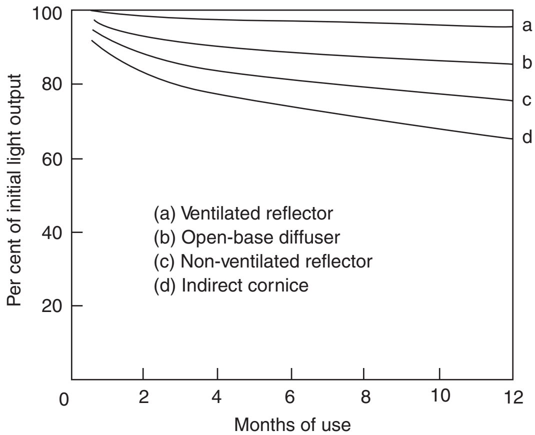

FIG 14.9 Fall in light output due to dirt deposition [7].

Tables 14.5, 14.6 and 14.7 are attempts to quantify the various factors associated with decreased luminaire output. Table 14.5 quantifies lamp performance over time in two ways, the *lumen maintenance factor* (LLMF) is the proportion of initial lamp lumens 'remaining' after a given time period, while the *lamp survival factor* (LSF) is the proportion of lamps surviving (i.e. lamps that have not failed) after a given time [8].

TABLE 14.5 Lamp lumen maintenance and survival factors

Lamp type	Factor	Operating hours		
		6000	10,000	12,000
Fluorescent (tri-phosphor)	LLMF	0.87	0.85	0.84
	LSF	0.99	0.85	0.75
Metal halide	LLMF	0.72	0.66	0.63
	LSF	0.91	0.83	0.77
Sodium (high pressure)	LLMF	0.91	0.88	0.87
	LSF	0.96	0.92	0.89

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TABLE 14.6 Luminaire maintenance factor (LMF)

	6 months cleaning interval			12 months cleaning interval			18 months cleaning interval		
Luminaire type	Clean	Normal	Dirty	Clean	Normal	Dirty	Clean	Normal	Dirty
Batten	0.95	0.92	0.88	0.93	0.98	0.83	0.91	0.87	0.80
Enclosed IP2X	0.92	0.87	0.83	0.88	0.82	0.77	0.85	0.79	*
Up-lighter	0.92	0.89	0.85	0.86	0.81	*	0.81	*	*

*Not recommended.

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TABLE 14.7 Room surface maintenance factor (RSMF)

Room index	Luminaire flux distribution	12 months cleaning interval			24 months cleaning interval		
		Clean	Normal	Dirty	Clean	Normal	Dirty
2.5–5.0	Direct	0.98	0.96	0.95	0.96	0.95	0.94
2.5–5.0	General	0.92	0.88	0.85	0.89	0.85	0.81
2.5–5.0	Indirect	0.88	0.82	0.77	0.84	0.77	0.70

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The *luminaire maintenance factor* (LMF) referred to in Table 14.6 quantifies the impact of various maintenance regimes on different luminaire types in a variety of environments.

The impact of various cleaning regimes on room surface reflectance is quantified in Table 14.7 by using a *room surface maintenance factor* (RSMF).

Example 14.5 shows how a realistic MF might be developed in practice.

Example 14.5

The lighting scheme in an office space comprises 60 batten-type luminaire fittings with fluorescent (tri-phosphor type) tubes. The lamps are changed in bulk every 6000 hours and the luminaire fittings and room surfaces are cleaned every 12 months. The cleanliness of the environment within the office space is normal and the luminous flux distribution from the luminaries is 'general' in nature. Determine a suitable maintenance factor for the installation.

Solution

From Table 14.5

$$\text{LLMF} = 0.87$$
$$\text{LSF} = 0.99$$

From Table 14.6

$$\text{LMF} = 0.98$$

From Table 14.7

$$\text{RSMF} = 0.88$$

Therefore

$$\text{MF} = 0.87 \times 0.99 \times 0.98 \times 0.88 = 0.74$$

When designing a lighting scheme it is important to ensure that the illuminance on the working plane is evenly distributed. If the luminaires are too far apart, gloomy patches will appear on the working plane. This makes it important not to exceed the *spacing to mounting height ratio* stated for the particular luminaire being used. The nominal spacing for luminaire fittings can be determined using eqn (14.9):

$$\text{Nominal spacing between fittings, } S = \sqrt{\frac{A}{n}} \tag{14.9}$$

The process involved in the lumen design method is illustrated in Example 14.6.

Example 14.6

A $15 \times 9 \times 3\,\text{m}^3$ high office space is required to be illuminated to 500 lx. Given the following data, design a suitable artificial lighting layout for the space.

Data:

Height of working plane = 800 mm
Height of luminaire fittings above floor level = 3000 mm
Design lumens per fitting = 8000 lm
Maintenance factor = 75%

Ceiling reflectance factor = 50%
Wall reflectance factor = 50%

Maximum spacing to mounting height ratio = 1.2:1.0

Room reflectance's ceiling (%) [wall %]	Room index					
	1.00	**1.25**	**1.50**	**2.00**	**2.50**	**3.00**
50 [50]	0.50	0.54	0.57	0.61	0.63	0.65
50 [30]	0.47	0.51	0.54	0.58	0.61	0.63
50 [10]	0.44	0.48	0.51	0.56	0.59	0.61

Solution

Mounting height = 3.0 − 0.8 = 2.2 m

Using eqn (14.6)

$$\text{Room index} = \frac{15 \times 9}{2.2 \times (15 + 9)} = 2.56$$

Since the ceiling reflectance is 50%, the wall reflectance is 50% and the room index is 2.56. Therefore

$$\text{UF} = 0.632$$

Using eqn (14.6)

$$\text{Number of luminaire fitting required } n = \frac{500 \times (15 \times 9)}{8000 \times 0.632 \times 0.75} = 17.8$$

Since it is impossible to have 0.8 of a luminaire fitting, the number of luminaires required (*n*) must be 18.

Using eqn (14.9)

$$\text{Nominal spacing between fittings, } S = \sqrt{((15 \times 9)/18)} = 2.739 \text{ m}$$

Therefore

$$\text{Spacing:Mounting height} = 2.739{:}2.2 = 1.245{:}1.0$$

However, this spacing to mounting height ratio exceeds the maximum permissible ratio of 1.2:1.0. Therefore, it is necessary to increase the number of fittings to, say, 20.

Therefore

$$\text{Nominal spacing between fittings } S = \sqrt{((15 \times 9)/20)} = 2.598 \text{ m}$$

Therefore

$$\text{Spacing:Mounting height } 2.598 : 2.2 = 1.181 : 1.0$$

This spacing to mounting height ratio is acceptable. Therefore

$$\text{Number of luminaire fittings required } = 20$$

and

Suggested design layout: 4 rows of 5 fittings

14.7 Energy Efficient Lighting

The main factors which influence the energy consumption of lighting schemes are:

(i) The light output per watt of electrical power consumed (i.e. lamp efficacy).
(ii) Luminaire performance.
(iii) The number of luminaires and their location.
(iv) The reflectance of internal room surfaces.
(v) Maintenance and procedure standards.
(vi) Duration of operation.
(vii) The switching and control techniques used.

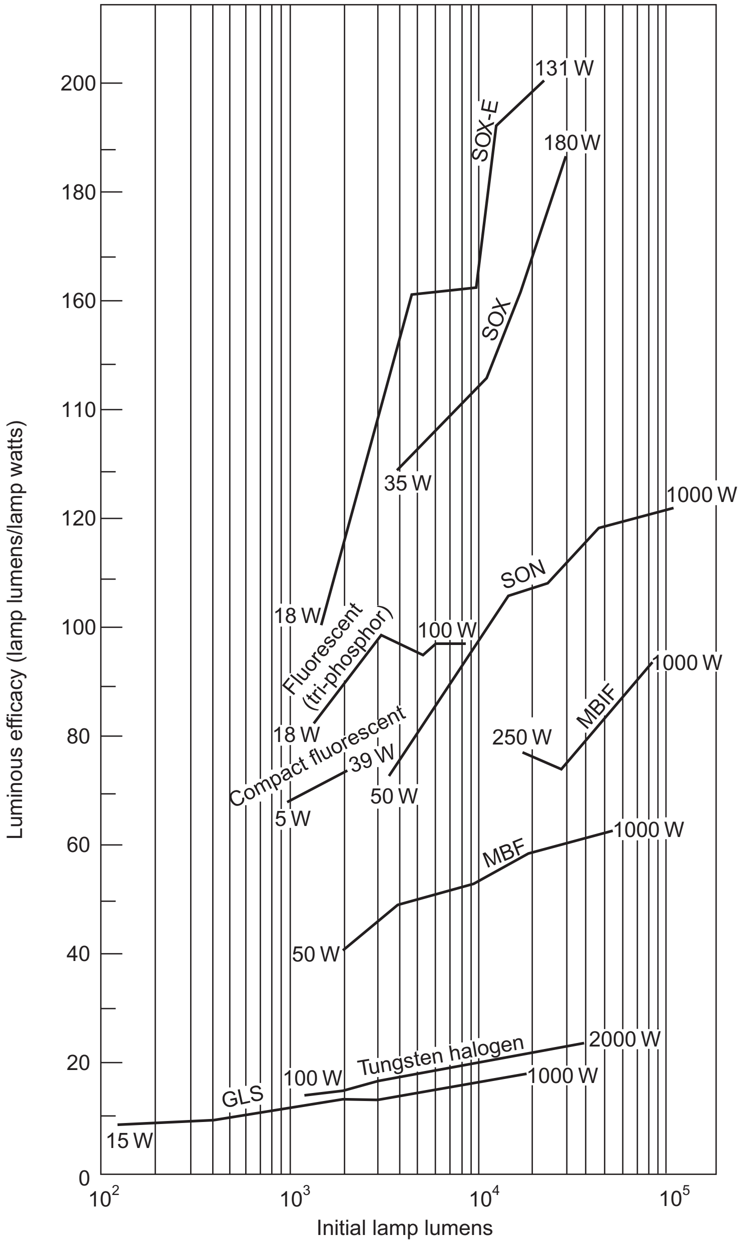
While points (i) to (iv) above are concerned with the fundamental efficiency of any installation, points (v) to (vii) relate to the management and operation of the installation.

When considering the overall energy efficiency of luminaires it is helpful to look in isolation at the individual components which together make up the luminaire; namely the lamp, the control gear and the fitting.

14.7.1 Lamps

There are a wide variety of lamps which can be used in artificial lighting schemes. Fluorescent, tungsten filament, tungsten halogen, metal halide (MBI) and high-pressure sodium vapour (SON) are amongst the many lamp types in common use. Energy consumption varies greatly with the type of lamp used. Figure 14.10 shows comparative lamp efficacies for a variety of lamp types. Luminous efficacy is defined in lumens produced per watt of electricity consumed.

It can clearly be seen from Figure 14.10 that there is a wide variation in the luminous efficacy between the various lamp types. For example, compact fluorescent lamps have an efficacy of approximately 70 lm/W, while tungsten filament lamps exhibit an efficacy of approximately 10 lm/W. Clearly, the compact fluorescent lamp is a much more energy efficient option. It should also be noted that the luminous efficacy of any lamp type increases as power input is increased. While this increase may only be slight in some types of lamp (e.g. tungsten filament and tungsten halogen lamps), in others, such as high- and low-pressure sodium lamps (SON and SOX), the increase can be substantial.



Key: GLS Tungsten filament
MBF High-pressure mercury discharge (fluorescent)
MBIF High-pressure mercury discharge (metal halide)
SON High-pressure sodium discharge
SOX Low-pressure sodium discharge

FIG 14.10 Efficacies of various lamps [9].

When designing new artificial lighting installations, it is important to install lamps which exhibit high efficacy. In older installations, it may be worth considering refurbishing existing luminaire fittings, so that they can incorporate newer more efficient lamp types. Refurbishment of older installations using modern equipment can often result in substantial energy savings as well as improved visual conditions. It is possible to improve older, less efficient, luminaires by replacing existing diffusers with modern reflector systems at relatively low cost. However, some changes can be considerably more expensive, such as replacement of the existing control gear to facilitate the use of low energy lamps.

Tungsten Filament Lamps

Although the use of tungsten filament lamps is widespread, they are particularly inefficient consumers of energy and should be avoided where possible. They have efficacies in the region of 8–15 lm/W [9], with most of the electrical energy being converted to heat, which can lead to space overheating problems. Lamp life is short, with most tungsten filaments burning out after approximately 1000 hours of use [7].

Compact Fluorescent Lamps

Because standard tungsten filament lamps exhibit such poor efficacies, compact fluorescent lamps were developed as a replacement. Where possible, tungsten lamps should be replaced by compact fluorescent lamps. These give comparable light output to tungsten lamps, but only consume approximately 20% of the power required by tungsten lamps [8]. As the rated life of the compact fluorescent lamps is in the region of 8000–12,000 hours, eight times longer than tungsten lamps, maintenance costs are greatly reduced, albeit at a higher initial cost.

Compact fluorescent lamps can be divided into two distinct categories: those with integral control gear and those which require separate gear. Since the life of control gear is generally longer than that of a fluorescent lamp, it is often better to install lamps with separate control gear, as this is more cost-effective. Lamps with integral control gear are more expensive, being specifically designed as a direct replacement for existing tungsten filament lamps. As with all discharge lamps, compact fluorescent lamps exhibit a poor factor, often as low as 0.5. However, this can be corrected by using capacitors.

Fluorescent Tubes

Fluorescent tubes are commonplace in most buildings and exhibit efficacies in the region of 80–100 lm/W [9]. Depending on the type of lamp and ballast used, they can last up to 18 times as long as tungsten filament lamps. In recent years the 26 mm diameter fluorescent tube has replaced the 38 mm diameter tubes as the standard for new installations. These slimmer lamps produce approximately the same light output as the larger diameter lamps, but consume around 8% less electricity [10].

Metal Halide Lamps

MBI lamps have become popular for a wide variety of applications and are available in a wide range of power ratings, 70–2000 W. They exhibit efficacies in the region of 70–100 lm/W, depending on their power rating [9]. MBI lamps are particularly popular in industrial applications.

High-Pressure Sodium Lamps

SON lamps have proved particularly useful for lighting large high bay areas, such as factories and warehouses, where their high efficacy (e.g. 70–120 lm/W) can produce a very energy efficient lighting scheme. They are also useful for exterior lighting, car parks and floodlighting. They are manufactured in a wide range of power ratings from 50 to 1000 W.

14.7.2 Control Gear

Because of their nature, all discharge lamps, such as fluorescent lamps, require control gear to operate, which comprises a starting device and ballast. A starting device is required to create the high potential difference between the lamp electrodes, so that an electrical discharge is promoted. Starters can be of a plug-in glow type, which should be replaced every second or third lamp change, or else should be of an electronic type. Ballast is necessary to control the current drawn by the lamp. If ballast were not installed, then the current would increase dramatically as the ionization process takes place with the result that damage would be caused to wiring and the fitting itself.

In addition to the lamp load, ballast consumes electricity. The type of ballast used therefore has an impact on overall energy consumption. Traditionally, ballast has come in the form of a wire-wound choke, comprising a copper wire wrapped around a metal core. Current flowing through the wire produces a magnetic field which dampens the growth of any further current, thus 'choking' the current to the desired level. While conventional wire-wound chokes work very well, they result in excess energy losses, typically in the region of 15–20% of total energy consumption. Recently new high-frequency electronic ballasts have been developed. These ballasts run at frequencies between 20 and 40 kHz [10], and can be fitted either with a rapid-start mechanism to facilitate instantaneous starting, or a 'soft-start' which prolongs the lamp life. High-frequency ballasts consume up to 30% less power than wire-wound chokes and have the additional benefit of increasing lamp life [10].

14.7.3 Lighting Controls

The appropriate use of lighting controls can result in substantial energy savings. These savings arise principally from better utilization of available daylight and from switching off electric lighting when a space is unoccupied. Therefore, when designing a lighting control strategy for any given application, it is important to understand the occupancy pattern in the space, since this will heavily influence the potential for energy savings.

There are four basic methods by which lighting installations can be controlled:

- Time-based control.
- Daylight-linked control.
- Occupancy-linked control.
- Localized switching.

Time signals may come from local solid-state switches or be derived from building management systems. These signals switch the lights on and off at set times. It is important to include local override so that lighting can be restored if the occupants need it.

Photoelectric cells can be used either simply to switch lighting on and off, or for dimming. They may be mounted either externally or internally. However, it is important to incorporate time delays into the control system to avoid repeated rapid switching caused, for example, by fast moving clouds. By using an internally mounted photoelectric dimming control system, it is possible to ensure that the sum of daylight and electric lighting always reaches the design level by sensing the total light in the controlled area and adjusting the output of the electric lighting accordingly. If daylight alone is able to meet the design requirements, then the electric lighting can be turned off. The energy-saving potential of dimming control is greater than a simple photoelectric switching system. Dimming control is also more likely to be acceptable to room occupants.

Occupancy-linked control can be achieved using infrared, acoustic, ultrasonic or microwave sensors, which detect either movement or noise in room spaces. These sensors switch lighting on when occupancy is detected, and off again after a set time period, when no occupancy movement is detected. They are designed to override manual switches and to prevent a situation where lighting is left on in unoccupied spaces. With this type of system it is important to incorporate a built-in time delay, since occupants often remain still or quiet for short periods and do not appreciate being plunged into darkness if not constantly moving around.

Localized switching should be used in applications which contain large spaces. Local switches give individual occupants control over their visual environment and also facilitate energy savings. By using localized switching it is possible to turn off artificial lighting in specific areas, while still operating it in other areas where it is required, a situation which is impossible if the lighting for an entire space is controlled from a single switch.

14.7.4 Maintenance

With the passage of time, luminaires and room surfaces get dirty, and lamp output decreases. Lamps also fail and need replacing. Consequently, the performance of all lighting installations decreases with time. It is therefore necessary to carry out regular maintenance in order to ensure that an installation is running efficiently. Simple cleaning of lamps and luminaires can substantially improve lighting performance. Therefore, at the design stage maintenance requirements should always be considered. Luminaires should be easily accessible for cleaning and lamp replacement. Bulk replacement of lamps should be planned, so that they are replaced at the end of their useful life, before light output deteriorates to an unacceptable level. The cleaning of lamps and luminaires should be planned on a similar basis. In order to minimize disruption to staff, planned cleaning and lamp replacement can take place during holiday periods.

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