Lighting Res. Technol. 2009; **41**: 209–218

Energy efficiency in lighting – considerations and possibilities

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Received 6 November 2008; Revised 20 March 2009; Accepted 3 April 2009

Energy efficiency is a prime consideration for all lighting professionals with reasons ranging from the threat of climate change through burning fossil fuels to the sustainability and availability of energy supplies as well as rapidly increasing costs. But it must be balanced against the need for well-lit environments to ensure the productivity, well-being, safety and health of the people it serves. A well-lit environment must provide both visual function and visual amenity for the particular application and for the architecture, together with an efficient use of energy. This means considering all the elements that contribute to the design and operation in an all-embracing manner. The challenge now is to address more critically the design, operation and specification of electric lighting in combination with available daylight. This will require new thinking and research to achieve satisfactory, efficient environments that will need investment for optimum results. But the outcome could be a long-term benefit to society with the benefit being greater than the sum of the parts.

1. Introduction

There is no doubt that energy efficiency is now an essential consideration for all lighting professionals. This has been prompted, initially, by the widely held view that burning fossil fuels causes carbon dioxide emissions, which in turn can contribute to climate changes that could have dramatic environmental implications affecting the planet. More recently, however, there is the substantial increase in energy costs particularly through the dramatic increase in the cost of oil and gas. There is also the subject of sustainability – it is estimated that around 80% of the UK electricity is generated by burning fossil fuels, much of which comes from abroad. In the long term these are a finite resource, which will one day run out, but even in the short term it means that the UK depends on resources beyond its direct control, which is a situation that applies to other countries too. Because of all these elements, the lighting profession must take a responsible view of energy efficiency and do all it can to minimise electricity consumption whilst, at the same time, ensuring high-quality lit environments for the people it aims to serve.

It is estimated that UK electric lighting currently consumes around 58,000 GWh per annum, this amounts to ~20% of the total amount of electricity generated. It has also been estimated that of that 20%, the electricity consumed by lighting divides by application as follows: Service Lighting (retail, commercial, exterior etc.) 11.5%, Industrial 2.6% and Domestic 5.9%. It must be stressed, however, that some of this information stems from studies made in the mid-1990s, contained within an internal Building Research Establishment report, so it may not be

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 10.1177/1477153509338884

accurate for the present day, but it does serve to indicate the size of the problem.

However, although the amount of electricity consumed by lighting is an important issue, it must be balanced against the functional and amenity requirements of the users. For 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 profession must address is how to provide illumination to at least modern day best practice standards while, at the same time, using the minimum amount of electricity necessary. This will require considerable attention from the lighting industry and the design professions. It will also require them to be imaginative and innovative and to look beyond the solutions often provided today.

New energy efficient solutions will also require clients to be prepared for higher installation costs and users to be prepared to be open minded to new lighting solutions including their operation. To achieve this will require the attention of the research and development community, particularly those dealing with lighting equipment, light and lighting measurements and lighting design.

It will also require investigations by behavioural scientists who specialise in human factors relating to light and lighting. Lighting as we know it today, in many ways is still in its infancy, particularly relating to our knowledge on the effect of light and lighting on human response, and hence on performance in the widest sense. But with a greater understanding of these issues, together with the need to be as energy efficient as possible in how lighting is provided, there arises an opportunity for the profession to move lighting from being purely a building service to a service that enhances human performance, well-being and health.

2. Areas for consideration

To begin to see how improved energy efficiency in lighting might be achieved it will be useful to explore the chain between the electricity supply and the illumination required for the particular situation. But in the end it is the number of units of electricity that are consumed, with respect to time, for a given lighting performance that will determine its energy efficiency.

The amount of energy used is determined by the lighting equipment e.g. the lamps and luminaires. It will also be determined by the lighting requirement for the application, which includes both the task illumination and the lighting, which illuminates the surroundings, sometimes referred to as ambient or building lighting to complement the task illumination. This will determine the type and number of luminaires used. It will also be determined by the degree of installation maintenance to ensure the lighting equipment is at optimum operation.

The total number of units of electricity consumed by the lighting installation will also be affected by the length of time the lighting is switched on. This will be affected by the amount of daylight that is present and whether the room is occupied, but also whether there are suitable lighting controls. These may be manual or automatic, or a combination between the two to ensure optimum lighting conditions without lighting being left on unnecessarily, which is often the case. They must also be 'user friendly'.

To most lighting professionals this chain of elements affecting lighting electricity consumption will be obvious, as will the fact that all elements need to be considered for optimum energy efficiency. However, it is not always obvious to clients who may look at the initial capital cost of an installation rather than considering the capital costs in conjunction with the occupant's performance and the operating costs, all of which will be important.

Nor is it apparently obvious to governments anxious to reduce energy demand – see the hasty and ill-considered proposal to withdraw some incandescent lamps from the market to encourage a greater use of compact fluorescent lamps (CFLs) – which has caused much disquiet by the public and the profession.

3. Considerations for improved energy efficiency

The lighting industry has made considerable advances over recent years in improving lighting equipment both in terms of quality and efficiency, but areas remain which still deserve consideration. Figure 1 indicates the elements between the electricity consumed and the lighting installation where energy efficiency may need further consideration.

3.1 Lamps and light measurement

Over the last few decades lamps have developed considerably through improved efficacy (lumens/watt), colour performance and operation, but one problem that has emerged, particularly through the pressure on consumers to switch to using more CFLs, particularly those with integrated control gear, is that the same light output, or lumen output, from a GLS incandescent lamp to that emitted by a CFL does not appear to be equal. The manufacturers' claim an energy efficiency ratio between incandescent lamps and CFLs is typically 5 : 1 (or sometimes even 6 : 1). In other words an incandescent lamp provides 12 lumens per watt while a CFL provides 60 lumens per watt. This suggests a considerable saving of electricity as well as an increased lamp life. However the perceived ratio is nearer to 3 : 1. In non-critical situations this may not matter but in many cases it does. Also when a CFL has a similar colour appearance and colour rendering numerical rating to an incandescent lamp they often do not appear to be sufficiently the same, particularly for critical tasks. There are other problems too regarding run-up times, UV emission, poor power factor correction and mercury content. This has led to dissatisfaction by consumers and has damaged the move to improved energy efficiency.

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. An interesting addition to this problem is that modern linear fluorescent lamps do not appear to suffer the same difficulties. What this suggests is that our measurement systems, either of luminous flux in lumens, or colour performance including colour rendering and colour appearance, are not sufficiently critical to meet the needs of the user and a more critical approach is necessary. This is a disturbing issue because luminous flux and light colour measurements are central to illumination provision and development. It is essential therefore that work needs to be done to investigate these differences and where necessary to make changes. A further related problem is in measuring the lighting and colour performance of light emitting diodes (LEDs). If changes to our measurement systems are required they will have major implications, but it is important that the subject is given some priority rather than being ignored with the hope it will go away. Figure 2 indicates where light and lighting measurements need to be considered for modern times with the aim of improved energy efficiency and human performance.

3.2 Lighting design

From the very beginning of electric lighting provision the people involved recognised that lighting was a combination of art and science, or more correctly function and appearance. They also recognised that fundamental to it was the human reaction to light and lighting in terms of visual ability including comfort and

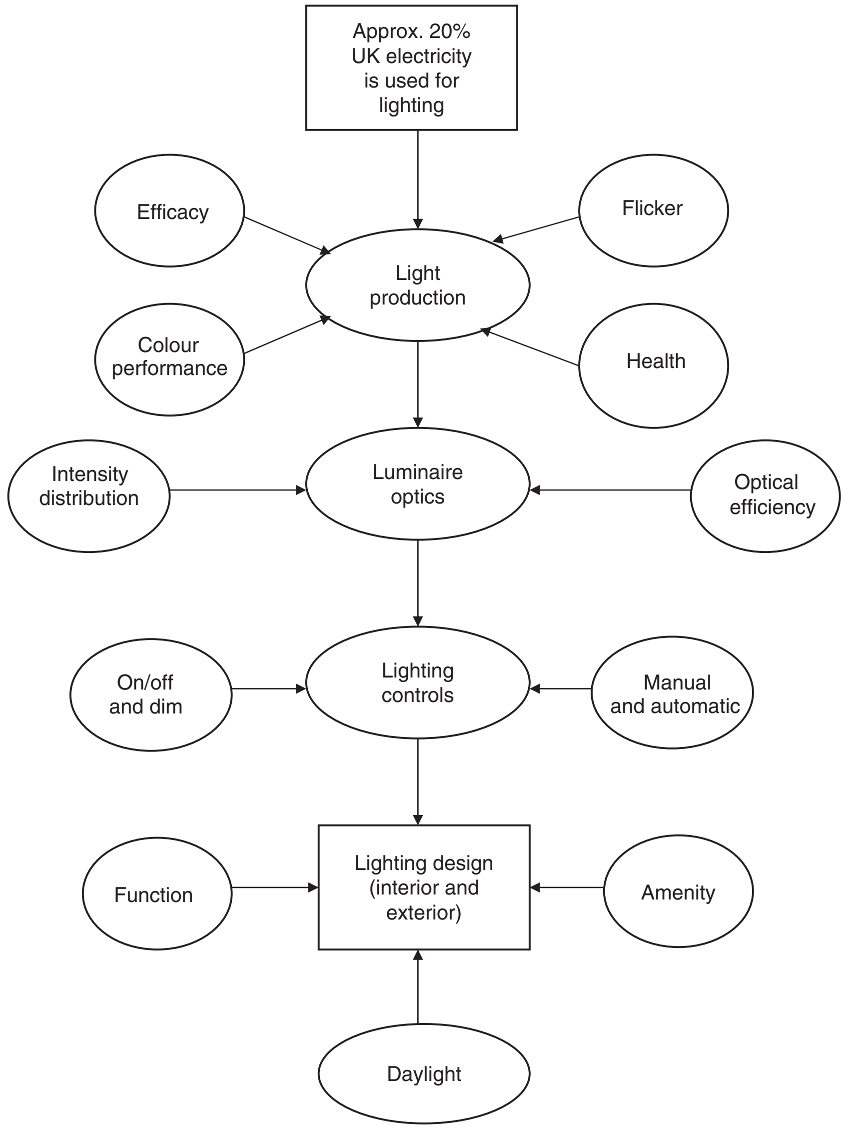

Figure 1 Elements in the provision of light and lighting that need to be considered for enhanced human performance and energy efficiency

efficiency, but they also believed that it influenced the psychological profile of human beings, which in turn would affect performance. Health is another issue that needs to be addressed and over the years it has been claimed that light exposure is essential to good health, and yet people working most of their lives indoors now have a much less exposure than their forefathers. Also there have been claims of light having detrimental effects including the possibility of causing cancer. The subject of human reaction to light and lighting desperately needs further investigation to improve human and energy efficiency.

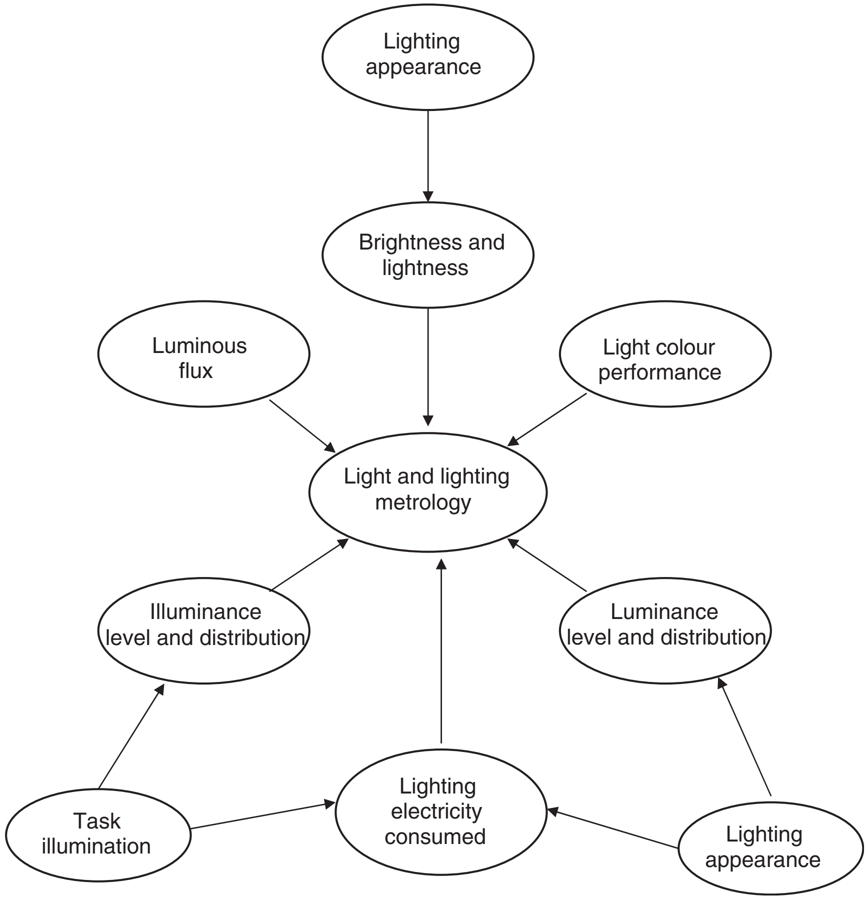

Figure 2 Elements of light and lighting metrology that need to be considered for enhanced visual effectiveness and energy efficiency

Many good quality modern lighting installations, particularly in offices and other places of work, comprise a regular array of ceiling mounted luminaires, the luminaires having a luminous intensity distribution that avoids direct discomfort glare and glare reflected from display screens, as well as noticeable flicker. These installations are designed to provide a near uniform horizontal working plane illuminance of a value appropriate for the application. This means that the occupants should have optimum working conditions and if high-quality lighting equipment is selected, installed and maintained, should have good energy efficiency as well.

However, because this approach provides a uniform lighting condition with little flexibility, energy can be wasted through illumination being provided to a level, or at a location, not required. Modern lighting controls can provide different conditions either on–off or dimmed, relative to occupancy or to the amount of daylight present, but often they do not meet user's requirements, and hence do not provide the saving expected because of user dissatisfaction or sabotage. Another possible problem is that modern lighting equipment contains electronic components, that sometimes, do not have the life and reliability of old fashioned wire and metal components, but this is a manufacturing problem and by using quality equipment it can be overcome.

For many years now some lighting designers and researchers have claimed that the lit appearance of a space affects the performance of the occupants. There have been examples when the correct horizontal task illuminance has been provided, but the occupants were dissatisfied because the room appeared gloomy. Often the problem was caused by low reflectance wall finishes in combination with luminaires which provided little light on vertical surfaces, and hence the room did not appear 'light' and was deemed to be under-lit and therefore unsatisfactory.

In the 1960's a number of studies were made to test subjectively the acceptability of a lit room in terms of 'is there sufficient light for the task?' One study by Saunders[1] showed that when a room was lit by ceiling mounted diffuser type fluorescent lamp luminaires the observers preferred the condition where at least 1000 lx was provided on the working plane. Whereas visual performance tests would have indicated that only 500 lx was necessary. This suggests that it is not just the task illuminance that needs to be considered, but the illumination of the whole space.

Other studies on lighting appearance by Loe *et al.*[2] have claimed that not only do observers prefer a space to appear 'visually light' they also like an element of 'visual interest' – or a degree of light and shade. This provides the occupants with a more interesting and stimulating space, which in turn could enhance performance, but proof of this has been illusive. However recently, Veitch *et al.*[3] has suggested, that through a 'linked mechanisms approach' this may indeed be the case.

A further consideration is that there are advantages to the occupants working conditions if the task is lit to a slightly higher level than the surroundings and a ratio of 3 : 1 is often suggested in lighting design codes. It is claimed that this approach focuses attention on the task and could improve performance, but it is not sufficient to provide a traditional desk light to create a high illuminance patch of light just on the task. Nonetheless this approach would reduce the average horizontal plane illuminance perhaps by as much as half, and hence the electricity consumption.[4]

A further element of a lighting installation that needs development is the way it is controlled. All too often lighting is left on unnecessarily, either because the electric light is superfluous to the daylight or because people are away and hence energy is wasted.

There are many control systems both manual and automatic, but few operate as well as intended because they are not sufficiently user-friendly. The problems include individuals not being responsible for their own lighting. Perhaps, because the lighting design is such, that particular luminaires do not relate to an individual's work area. If this is the case then switching lights off could cause annoyance to other occupants. Also it would not allow for a 'task and surround' lighting approach.

For many years now the level of illuminance provided for a particular task has been determined by visual performance studies and specified in codes of practice. In general these have provided, in most cases, satisfactory guidance. However, recent investigations by Moore *et al.*[5] and Boyce *et al.*[6], where occupants of a space were given the opportunity to set their own preferred level of illuminance they have set values different to the recommendation – some higher and some lower. This may be because people are just different or because of differences in age – this being particularly important now with a greater number of older people in the work place. But it may also mean that the current recommendations are not always appropriate, and again energy will be wasted with an over provision. However, to remove the current task illuminance recommendations, without strong evidence to counter them could have serious detrimental effects. But since occupants like having control over their task illumination, savings could be achieved by individuals setting to levels of illuminance, which are less than the recommended values. This will mean recommending a band of adjustable task illuminance for particular situations rather than a minimum level.

Another problem is where the electric lighting is linked to the amount of daylight automatically, and electric lighting is switched off when there is sufficient illuminance from the daylight. This approach has often been met with disapproval from the occupants, except where the electric lighting is switched off when the occupants are unaware of the change. Nonetheless a great deal of energy is wasted when it is on and not required.

4. Possibilities for improved energy efficiency

The above discussion has indicated where there are areas of illumination and measurement that deserve consideration with a view to improving lighting for people that could also improve energy efficiency. It has also indicated areas of electric lighting design and operation where energy could be saved perhaps by as much as 50% or more.[4] But to achieve these benefits will require further exploration as well as a change in attitude to be prepared to accept changes. For this to occur will not just require input from the lighting research and manufacturing sectors of the industry, but from designers and by clients too to ensure that the best possible outcome is achieved.

But how to proceed? The possible problems in measuring luminous flux, if indeed there are problems, can only be overcome by comparing what we see to what we measure. This approach will also apply to changes in how we define the lit environment, and hence how it can be quantified and measured. This will make lighting design specification more difficult, but we should not shirk from the challenge. There are opportunities now through digital cameras, which can provide luminance values, in terms of individual elements and areas of the field of view. These can be measured more easily than once would have been possible. These values can also be calculated through modern computer software. A further question that this raises is that the camera will measure luminance, but the eye will see 'brightness'. Now while these are not the same, it is possible that for practical purposes, the measure of luminance will be sufficiently accurate for most cases. However, if it is not how should it be modified?

Similarly spectral distributions of light sources can be measured relatively easily, but what will be more difficult will be how to characterise these distributions for practical purposes. Again it will be necessary to compare light source colour with human requirements for appearance and colour rendering. A few years ago when discharge lamps' colour performance was less good than today an issue was raised about whether visual clarity could be enhanced by better colour performance lamps. The work did not go very far but it is often observed that illumination provided by sodium lamps, even high-pressure lamps, seem less clear than 'white' lamps.

All of these issues of measurement will require the work of physicists and human factor scientists including ophthalmologists and psychologists. It will be an expensive project and it would be best divided between experts from around the world all working to a common goal and a sharing of costs funded by governments. These projects would be exploring the fundamentals of light measurement and specification. The obvious route would be through the CIE technical committees, but the rate by which many of them deliver guidance does not bode well for a speedy result.

Regarding how illumination design is explored and improved for human and energy efficiency on the basis of the issues raised above will require input from researchers. But it will also require an input from designers who often have a natural instinct for what is required. Some work has been done in this area by the Bartlett team,[7] but more may still be required.

An alternative approach to lighting design would be to separate the elements of task lighting and building or amenity lighting and to control them both independently, but in an integrated way. This is not a new approach as it was used in the early part of the 20th century when lighting was extremely expensive, both in terms of the electricity it consumed and the cost of equipment, particularly lamps. It has also been used in shops by preferentially lighting supermarket shelves and in libraries by preferentially lighting book stacks. Then by complementing the task lighting with building lighting, particularly with lighting which provides a 'light' appearance space with luminance variation.

This approach has been used in offices and factories by providing adjustable desk lamps to boost the task illuminance. However, in offices these have often not provided a successful solution, because the patch of light they provide is relatively small, often causing annoying shadow patterns and the luminaire can also be a physical nuisance. The alternative would be to use floor-mounted units illuminating most of the work area. Alternatively to incorporate the task lighting into the work-station furniture. The operation of the task lighting would be by the user switching on, and setting the illuminance they require. To switch off, would be either by the user, in series with an occupancy sensor to switch off the luminaire automatically, after a suitable time delay, when the individual has left the work area. These units could also provide 'background or amenity' illumination through upward indirect light, but they would also require separate control relative to the daylight conditions. This approach of separating the task lighting from the building fabric can also allow for a greater flexibility in the layout or use of the space since the work areas do not have to relate to a ceiling array of luminaires. A further consideration will be the relative colour and efficacy if different lamps are used.

The 'building lighting' element would need to provide an appropriate lit appearance of the space, which would also need to provide sufficient illumination between the work areas for safe movement by the occupants. It would also need to be an integral part of the architecture and to complement it in terms of how the building lighting is provided.

Having designed a system it would need to be built and tested in a live situation with a number of work-stations, and over a reasonably long period of time e.g. 12 months. It would also need to be compared to a similar situation, but with a traditional lighting design, and measuring energy use and human performance under both conditions. It is only then that real evidence could begin to be available and changes to lighting practice implemented.

For this project a team of designers, lighting equipment manufacturers and performance researchers would be necessary as well as a facility willing to participate.

In much of this section so far, interior lighting has been considered, but exterior street lighting should also be reconsidered to search for opportunities to save energy. For example has visibility at night on our roads been considered recently, and has it been considered in conjunction with modern, or even further improved, vehicle lighting? Again this may be a case for separating task and surround illumination. The task lighting would relate to photopic illuminance provided mainly by the vehicle lighting equipment perhaps automatically controlled. While the surround lighting could be provided by traditional street lighting equipment that concentrated its illumination mainly on the sides of the road and be related to the newly defined mesopic illuminance. See the work of Akashi *et al.*[8] as well as the work carried out by the Mesopic Optimisation of Visual Efficiency programme[9] and that of Rea and Bullough.[10] An investigation of this proposal would require a similar approach to that for the interior lighting study.

There still remains the opportunity for saving energy by using daylight as much as possible. Daylight is nearly always the preferred light source and with proper consideration it can save energy, particularly in domestic interiors but in many others too, particularly in single story buildings where roof lights can be used in addition to windows. However, direct sunlight penetration can be a problem and this must be addressed if problems of glare and overheating are to be avoided. Another problem occurs when work-stations are placed adjacent to windows. This means that the people near the windows suffer the most discomfort and control any blinds that may be necessary, which can be an annoyance to other users. A solution to this perhaps, is to make the areas adjacent to the window into multi-occupancy spaces such as circulation and rest areas.

A further issue with daylighting is the conflict between providing light and maintaining a comfortable and efficient thermal environment. The problem is that windows usually have a poor thermal performance compared to other building materials and to overcome this will require windows with improved thermal insulation, which will be costly, but necessary in the long term. In the past when this problem has occurred the solution was to reduce the window size but this means poorer illumination and a reduction in amenity with less visual contact with the outside so was no solution at all. It is essential that both the lit and thermal environments are considered together to achieve a satisfactory design solution. This will require some numerical guidance to ensure a satisfactory solution. In the UK the 'Average Daylight Factor' has been a useful guide, but this only really applies to a temperate climate with many cloudy situations. The other difficulty is that daylight levels of illumination will usually vary considerably over a room, due to distances from the windows, meaning that electric light will be needed to supplement it. This will also require more detailed planning for a satisfactory solution.

5. Conclusions

This paper has endeavoured to identify some areas of lighting where greater energy efficiency could be achieved, but they will require some effort to investigate and perhaps refine. This will require investment particularly from governments. It will also benefit from having a co-ordinated research effort preferably through collaboration across national boundaries to share the knowledge quickly and to share the cost.

Over the last decade or so the lighting equipment industry has made considerable advances in the energy efficiency of equipment – lamps and luminaires. These include improved optical performance of luminaires and through the use of high frequency, low-energy electronic control gear for discharge lamps. It is possible that the industry could go further through improved light sources including the development of LEDs, but it is expected that more traditional light sources will have a major role to play for some time yet.

This means that it will be developments in the design and control of the lighting installations that are likely to provide substantial energy saving opportunities in the immediate future. The lighting profession as we know it in Great Britain is 100 years old in that the Illuminating Engineering Society was formed in 1909. Throughout those 100 years there have been considerable improvements, but it is now time to move lighting provision on to new heights of quality and energy efficiency appropriate for the 21st century with the expectation that the benefits will be greater than the sum of the parts.

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