Quantifying lighting energy efficiency: a discussion document

DL Loe  MPhil CEng FCIBSE FSLL FIESNA
BRE and Society of Light and Lighting, Energy in Lighting Panel

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Energy efficiency is now an important part of lighting design and operation, but so far there is no agreed way of determining its energy efficiency performance rating when considering all the elements that influence it. This discussion paper is based on the work of the Society of Light and Lighting, Energy in Lighting Panel which sets out a possible way forward by describing a formula which combines all the major elements. It also indicates areas that still need investigation.

1. Introduction

Lighting energy efficiency is now well established as an important element of all lighting design but so far no quantification system has been established that incorporates all the elements that will affect the overall efficiency of the installation with respect to time. The following approach has been developed by the Energy in Lighting Panel of the Society of Light and Lighting and it is presented as a discussion document with the aim of establishing a system that will be a useful aid to all participants. Although this has been developed for the UK it is possible it could receive wider acceptance. This would be particularly useful as it would enable lighting energy efficiency to be judged on the same basis in many different centres worldwide.

In the UK electric lighting consumes about 58000 GWh per annum which amounts to around 20% of the total electricity generated. It is important that this value be reduced to minimize carbon dioxide emissions, which arise through burning fossil fuels for electricity generation. These in turn can cause climate change, and the possibility of future drastic consequences for the quality of life on our planet.

Although energy efficiency is important it must be achieved in combination with the overall quality of the lighting for the particular application, its users and the architecture into which it is installed. If not then the productivity and the safety of the users could be compromised.

The lighting industry has made considerable advances in improving the efficiency of lighting equipment but currently the means of quantifying the energy efficiency of a lighting installation is over simplistic and is dealt with in different ways by different players. The Society of Light and Lighting offers targets for average installed power density for a range of particular applications and task illuminances. The Building Regulations for England and Wales and Scotland concentrate on the efficiency of lighting equipment and the use of lighting controls, as does a UK tax incentive scheme ‘Enhanced Capital Allowance’. But in the end the efficiency of a lighting installation is dependent on the amount of electrical energy it uses with respect to time e.g., kilo Watt hours per annum for a particular activity and scaled to a ‘standard’ year.

The components that affect the total lighting energy use per year are dependent on a number of elements and include the following:

- The lighting equipment used e.g., lamps and luminaires

Address for correspondence: DL Loe, 48 New Park Drive, Hemel Hempstead, Hertfordshire HP2 4QE. E-mail: loed@bre.co.uk

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The lighting installation design e.g., task illuminance, illuminance uniformity or distribution and installation maintenance.

The electric lighting use with respect to daylight availability (including the use of any window blinds), user occupancy (presence and absence) and the lighting controls.

A further benefit of approaching energy efficiency in this holistic way is that it could give designers or clients a degree of flexibility in how the lighting is provided. It is also felt that if lighting is provided in a way that the users prefer, perhaps through the distribution of light and shade and the individual’s ability to adjust the lighting as required, there is the possibility that there could be further economic benefits through enhanced productivity, but this still needs to be proved.

The following sets out the issues and suggests solutions; it also shows how the elements can be combined. But it is essential to develop a system that suits all the participants e.g., designers, users and regulatory bodies to improve energy efficiency in lighting both nationally and internationally.

2. Considering the lighting equipment

The lighting equipment efficacy will be a combination of the initial lamp efficacy and the luminaire efficiency. The initial lamp efficacy is already well defined and is measured in lumens/Watt when the lamp is new and where the electricity consumed incorporates the power in watts consumed by the lamp and its ballast. This is sometimes described as a lamp’s circuit watts. The measurements are made using a standard procedure already established by the CIE.5

The luminaire efficiency is more complicated because the light output distribution as well as the total amount of light emitted need to be considered. The total light emitted is usually quoted as a proportion of total lamp light output and is described by the total light output ratio (LOR). But it is also necessary to define the light output distribution so that luminaires with similar light output distributions, or applications, can be compared. For example, it would be meaningless to compare just the LOR as a measure of efficiency for an uplight luminaire compared to a downlight luminaire if the basis for comparison was horizontal plane illuminance. But the LOR for two uplight luminaires could be compared. An alternative approach may be possible which is to use LOR as an efficiency metric but with respect to a particular application. In this case not only the task illuminance is considered but also the appearance of the lit scene which includes any building lighting that is required. In other words embracing the whole quality of the lighting installation including its lit appearance. However for this approach, where perhaps more than one luminaire type is used, it may be necessary to consider a combined, or averaged, luminaire efficiency.

The American lighting industry is using a system based on the luminaire efficiency (equivalent to the total light output ratio) together with a simple system of describing the light output distribution. This allows the comparison of the performance of similar types of luminaire. It also states minimum efficiency values. For details see the NEMA website.6

The luminaire efficiency factor will be quoted either as a fraction or a percentage. Therefore the lighting equipment efficacy for equipment at the start of its life equates to:

\[
\text{Initial equipment efficacy (lm/W)} = \frac{\text{Initial lamp circuit efficacy (lm/W)}}{3} \times \text{Initial luminaire efficiency factor}
\] (1)

The term initial has been used to indicate that the equipment efficiency is when the lamp is new, or at the point of stabilization which is usually after 100 hours of life, and when the luminaire is clean.

3. Considering installation design

One of the first requirements of a lighting installation is usually the task illuminance (lux). This can be provided in a number of ways but often it is by a regular array of identical luminaires
fitted to the ceiling. In this case the horizontal plane minimum illuminance uniformity is usually specified as 0.7 (minimum illuminance/average illuminance), which allows for the task to be carried out anywhere on the horizontal task plane. The weakness of this approach is that the task illuminance is provided in the none task areas, for example, the circulation spaces.

Alternatively the approach may be to use a combination of task and building lighting. This is where the task lighting only illuminates the task areas and with the building lighting illuminating the areas in between to a lower level as well as ensuring an appropriate lit appearance for the space as a whole. This approach will usually use less energy because the task area will only occupy a fraction of the total area and even when the building lighting is added the average horizontal plane illuminance will usually be lower and therefore have a reduced electrical energy consumption. It may also have a further benefit in that it could reduce the effect of light obstruction caused by furniture etc.

To allow for this a factor would need to be developed to moderate the average task illuminance on the basis of the lighting design approach. The moderating factor could be calculated with great accuracy but the important point is for the designer or user to understand that some lighting design approaches could use less energy than others and to take this into account by modifying the average illuminance for the whole space. This factor will also need to take account of any additional building or appearance lighting. Hence:

Illuminance moderating factor =
[Average illuminance for the design approach(e.g., task and building lighting)]
/[Average task illuminance from a regular array type installation (e.g., uniformity 0.7)]

The maintenance factor of the installation will also have an effect in that it will determine the number of lamps and luminaires required for the planned maintained illuminance.

Combining the above items gives the average installed maintained illuminance (lm/m²).

Average installed maintained illuminance (lm/m²) =
Design maintained task illuminance ×
Illuminance moderating factor

(2)

4. Lighting installation power density

The lighting installation power density is commonly used to define a lighting energy efficiency benchmark. This can be found by combining the equipment efficiency and the average installed maintained illuminance.

Lighting installation power density W/m² =
Equation (2)/Equation (1) =
[Average installed maintained illuminance(lm/m²)]
/[equipment efficacy (lm/W)]

(3)

This defines the designed installation power density for a particular application, task illuminance and design approach. It can also be used to assess an existing installation.

5. Considering lighting use

Although designers are encouraged to provide electric lighting controls to ensure that lights are switched off when there is adequate daylighting and for rooms that are not occupied the allowance for this is currently quite small and does not take full account of the amount of daylight available. 2

This could be improved, however, by introducing a proportion of the year that the lighting is required i.e., when daylight alone is insufficient. It could also take account of lamp dimming used to supplement the daylight. The use of window blinds will also need to be taken into account. All these options could be accounted for through the proportion of the year that the lights are on full as an equivalent full load. A similar approach could take account of the use of occupancy controls where lights are automatically switched off when people are away from their work place. These two elements could be combined, however, it would need to take
account of any overlap between the two e.g., when there is adequate daylight and the workplace is also unoccupied. In other words, the two elements are not necessarily additive.

From this, the effect on energy use could be defined as a percentage of the normal working year. This value could then be applied to the power density of the installation to give the average power density per annum. For example, if through reducing the period of the normal working year, for the particular application, the electric lighting is only needed for 45% of the time. Then the average power density per annum would be only 45% of that required for a similar situation that did not have the lighting off at all — and hence a saving of 55%.

6. Average annual lighting energy use

By multiplying the Lighting installation power density (Equation 3) with the proportion of the year that the lighting is operating on full (or the equivalent full load) recommended target values could be determined or estimated (av. kW h/m² pa), probably with respect to an application, and with respect to a ‘standard’ year. It will be necessary to use a ‘standard year’ for comparison purposes.

Average energy density per annum
(\text{av. kW h/m}^2 \text{ pa}) = 
\frac{[\text{Installation power density (Equation 3)}] \times \text{[Equivalent annual hours of lights on full]}}{1000}

7. Discussion

Defining a lighting installation energy efficiency rating in terms of av. kW.h/m² pa, as described in the previous section, uses a term that incorporates all the controlling elements in one unit and is one that should be understood by most people involved with building energy use and efficiency. It also gets over the problems experienced when power density per 100 lux is used. This was a term used by the UK lighting profession to combine power density and illuminance without the need to specify power density targets for a range of different task illuminances, but many outside the profession found it difficult to understand. In this case since illuminance is incorporated through the ‘average installed maintained illuminance’, rather than an absolute task illuminance, it has less relevance.

By having a lighting energy efficiency metric that combines all the elements should enable designers and users to decide how to engineer an installation to the best advantage and therefore to give them a degree of design flexibility. However, to monitor energy use would mean measuring the annual electricity units consumed by lighting per annum as a way of checking the performance, modern control technology is making this possible.

Elements of the system could also be used individually if it was felt worthwhile. For example, the initial equipment efficacy (Equation 1) could be used for incentive schemes to encourage the use of efficient equipment. It could also be used as an element for building regulations along with the lighting installation power density (Equation 3). But any limits that are set would need to provide opportunities for flexibility because without it there could be a serious constraint on design.

However, before an all embracing system can be established there are still a number of issues that would need to be decided, they include:

- How best to classify the light output distribution of the luminaire, or its application, for use with the luminaire efficiency e.g., light output ratio?
- How to allow for the use of a task and building lighting approach rather than a uniform task illuminance approach?
- How to determine the proportion of the working year that the lighting is on full allowing for daylighting and occupancy as well as any overlap between them?
• Also whether there is switch or dimmer control?

These are now considered:

7.1 Considering luminaire classification

The basic element of a luminaire’s efficiency is the amount of light that is emitted relative to the lamp light output for the intensity distribution required. This is defined by the light output ratio (LOR) but it will require a method of defining the light output distribution so that comparisons can be made on a like for like basis. Utilization factor had been suggested as an alternative but this does not just apply to the luminaire but to an array of luminaires in a particular situation and therefore does not have the same fundamental nature.

In the USA, NEMA (National Electrical Manufacturers Association) has devised a classification system based on the following luminaire classifications which accounts for the majority of luminaires used:

1) Downlights using incandescent lamps, HID lamps and CFLs
2) Industrial luminaires using HID lamps
3) Ceiling recessed luminaires using fluorescent lamps with a lensed controller (prismatic or diffuser controller)*
4) Ceiling recessed luminaires using fluorescent lamps with a louvre controller (specular or otherwise)*
5) Plastic wraparound using fluorescent lamps (prismatic or diffuser controller)*
6) Strip lights using fluorescent lamps (bare batten)*
7) Industrial using fluorescent lamps (reflector controller)*.

* My interpretation of points 3–7

This seems relatively crude but is it good enough or could a better system be devised?

For fluorescent lamp luminaires, if the NEMA classification is not good enough could they be described by their transverse luminous intensity distribution perhaps using a graphical description? Another possibility might be to use the luminaire flux fraction ratio. This is the ratio of upward luminous flux to downward luminous flux.

In terms of defining downward intensity distribution could downlights and high bay luminaires be classified by their beam angle (twice the angle between downward intensity and the angle of half the peak intensity)? The classification would need to exclude luminaires which use lamps which incorporate their own optics e.g., reflector lamps.

None of this takes account of uplights or are they all so similar that one LOR minimum value would be sufficient? There are also other luminaires with particular uses e.g., wall-washing luminaires.

There is much to consider here but we need to begin to investigate a comprehensive approach because without an agreed luminaire classification system it will be difficult to specify luminaire efficiency. Perhaps as a start the most popular luminaire types should be considered. Once this has been agreed minimum efficiency values can be determined. The main purpose of this is to eliminate poor efficiency equipment.

7.2 Considering the lighting design approach

So far lighting energy efficiency is based on a uniform task illuminance over the whole space with no credit being given to other approaches; these include localized, local and task and building lighting. These approaches tend to illuminate the task areas to an appropriate level, but the surround area in between, to a lower value. But this approach is also likely to require some additional building lighting to ensure that the lit appearance of the room is appropriate. Nonetheless the average working plane illuminance is likely to be less and therefore a lower average installed power density. Little work has been done on estimating the likely savings but work carried out by Veitch et al., indicates that savings of around 50% are possible. However at this stage, until more experience can be gained, it is probably wise not to assume a saving greater than 25%.
7.3 Considering daylight availability and electric lighting use

Benefits can be accrued through using daylight wherever possible as long as the electric lighting is switched off, or reduced, when not needed. There are two control options: (a) switch control by rows parallel to the window wall or (b) continuous dimming control by rows parallel to the window wall.

If there are windows on more than one side then either use the main window wall i.e., the window wall with the greatest window area or some other approximation.

Further the saving will depend on the amount of daylight available and although this can be determined reasonably accurately a simple system, based on the calculated average Daylight Factor, is probably good enough. One of the benefits of this approach is that it can take account of windows and rooflights.

In this case consider three options of average Daylight Factor (DF):

i) Average DF = 2%. With windows in one wall and evenly spaced, the 2% DF contour occurs at about $0.8 \times$ window head-height from the window wall. This will allow the first row of luminaires to be turned off for some period of the working year depending on the required task illuminance.

ii) Average DF = 3.5%. With windows in one wall and evenly spaced the 2% DF contour occurs at about $1.3 \times$ window head-height from the window wall. This will allow the first row of luminaires to be turned off for a period of the working year depending on the required task illuminance. There will also be a reduced period when the second row of luminaires is not required.

iii) Average DF = 5%. With windows in one wall and evenly spaced the 2% DF contour occurs at about $1.6 \times$ window head-height from the window wall. This will allow the first row of luminaires to be turned off for a period of the working year depending on the required task illuminance. There will also be a reduced period when the second row of luminaires is not required.

Table 1 shows the estimation of savings of annual electrical energy used for lighting with respect to daylighting. These are based on a room $10 \times 10 \times 2.8$ m. with average room reflectance 50%, glass transmittance 70% and with windows in one wall with no external obstruction. The electric lighting is from three rows of luminaires parallel to the window wall but it is expected that saving will only be made from the first two rows as the third row will need to be on all the time.

The potential savings indicated are based on UK daylight availability data and apply to switch control, and only represent an indication of possible savings for the area that is daylit. If, however, the luminaires are dimmer controlled with a sensor on each row the savings will be higher.

7.4 Considering occupancy (presence and absence) and electric lighting use

Further reductions in energy used for lighting can be achieved if task lights are switched off automatically when individuals are away from their work-station. To some extent the saving will depend on the lighting design but if a task and building lighting approach is used with individual occupancy controls then an estimate of the saving can be made.

For example, if 30% of the total lighting load is building lighting, and it is on all the time the room is occupied, and the remaining 70% is task lighting and is controlled via occupancy sensors. If the occupancy is say 80% of the total year then the lighting load will be reduced to 86% \([30 + (70 \times 80)]\). And for an occupancy of 50% the lighting load will be reduced to 65% \([30 + (70 \times 50)]\). But these figures take no account of benefits from daylight.

For this scenario task lights can be ceiling mounted or located on or by the workstation.

7.5 Combining the lighting energy saving options

In the preceding sections an indication of the possible energy savings with respect to the parti-
Table 1  Estimation of savings of annual electrical energy used for lighting with respect to daylighting conditions

<table>
<thead>
<tr>
<th>Av. DF Calculated</th>
<th>Likely min. DF for area covered by 1st row of luminaires</th>
<th>Likely % of year when 1st row of luminaires are off-task illum. 300 lux</th>
<th>Likely % of year when 1st row of luminaires are off-task illum. 500 lux</th>
<th>Likely % of year when 2nd row of luminaires are off-task illum. 300 lux</th>
<th>Likely % of year when 2nd row of luminaires are off-task illum. 500 lux</th>
<th>Likely min. DF for area covered by 2nd row of luminaires</th>
<th>Likely min. DF for area covered by 2nd row of luminaires</th>
<th>Likely % of annual energy saved by first two rows of luminaires</th>
<th>Likely % of annual energy saved by first two rows of luminaires</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>1.5%</td>
<td>43%</td>
<td>20%</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3.5%</td>
<td>2%</td>
<td>53%</td>
<td>32%</td>
<td>1%</td>
<td>23%</td>
<td>5%</td>
<td>38%</td>
<td>21%</td>
<td>18%</td>
</tr>
<tr>
<td>5%</td>
<td>3%</td>
<td>68%</td>
<td>50%</td>
<td>1.5%</td>
<td>43%</td>
<td>20%</td>
<td>55%</td>
<td>38%</td>
<td>35%</td>
</tr>
</tbody>
</table>

cicular approach has been shown, but to estimate the possible savings when more than one approach is incorporated is more difficult. For example if it is decided to combine daylight linked controls with occupancy controls, whilst it may be possible to estimate the individual savings, the combined effect will need to take account of any overlap, which is more difficult to estimate. For example if the lighting is off because there is sufficient daylight any saving for non-occupancy, at the same time, should not receive the full credit.

If, for a particular client, the workforce is usually away from their work-stations in the middle of the day the occupancy reduction factor will not be very high because this is the period of maximum daylight illuminance. In some cases a reasonable assessment can be made. If not then an approximation is all that is possible.

Table 2 shows estimated reduction factors for annual lighting energy for different daylight and occupancy scenarios.

Using the information in Table 2 let us consider a particular situation with different lighting approaches.

For example, an open plan office with a floor area of 60 m² (10 m wide × 6 m deep) requiring 300 lux task illuminance can be achieved with a power density of 7W/m² see SLL target values.¹ If the office operates for 2000 hours pa the installation will consume 840 kW h pa [7 × 60 × 2000/1000 = 840].

If the office has windows in one long wall which provide an average DF of 5% with daylight linked switched lighting, then the reduction factor is 0.5 (see Table 2) and an annual electrical energy consumption of 420 kW h pa [840 × 0.5 = 420] i.e., a saving of approximately 50%.

Now if the lighting is provided on the basis of a task and building lighting approach then the annual electrical energy consumption could be reduced to 630 kW h pa [840 × 0.75 = 630]. This presumes that this design approach has an illuminance moderating factor of 0.75 and hence will save at least 25% electrical energy.

If the installation is also controlled through daylight sensors and occupancy sensors (on the basis of 80% occupancy) then the consumption could be further reduced by a factor of 0.4 (see Table 2). This means that the installation would consume 252 kW h pa [630 × 0.4 = 252], which

Table 2  Estimated reduction factors for annual electrical energy used for lighting for different daylight, task illuminance and occupancy scenarios

<table>
<thead>
<tr>
<th>Average daylight factor and illuminance</th>
<th>Occupancy 100%⁰</th>
<th>Occupancy 80%</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2% and 300 lux⁴</td>
<td>0.79 (0.8)</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>2% and 500 lux⁴</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>3.5% and 300 lux⁵</td>
<td>0.62 (0.6)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>3.5% and 500 lux⁵</td>
<td>0.82 (0.8)</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>5% and 300 lux⁶</td>
<td>0.45 (0.5)</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>5% and 500 lux⁶</td>
<td>0.65 (0.7)</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

⁰In this case the reduction applies to the first row of luminaires only.

ⁱIn this case the reduction applies to the first two rows of luminaires only.

⁰The values in brackets are rounded to one decimal place.

¹The values in brackets are rounded to one decimal place.

²The values in brackets are rounded to one decimal place.
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compares to the original installation of 840 kW h pa, a saving of 70%.

8. Conclusion

The preceding exploration of different approaches to lighting design and the possible reduction of electricity consumption are based on a number of assumptions and approximations and therefore they need to be treated with a degree of caution. However they do serve to indicate the order of possible savings but the various factors presented will need to be checked and agreed.

The purpose of this exercise is not just to propose a way forward for an holistic approach to save energy, but also to allow the designer and client a degree of freedom over the design approach by being able to trade one element of the equation against another.

If this approach is to be developed then the question of overall targets will have to be determined with a view to establishing an approach to lighting energy efficiency that can be used and understood by all. However, it must be stressed that the human effectiveness and therefore the quality of the lighting should not be compromised because if it is, then performance and productivity may be affected. This means that any new energy efficiency targets will need to be set to encourage maximum energy efficiency without restricting the lighting quality in all its aspects.

It is possible that to have a visually effective and energy efficient installation may result in a higher capital costs but with lower life cycle costs and hence an overall benefit. Therefore it will be essential to consider both costs when assessing the value of the installation and for the life of the installation which is often well over 10 years.

Further if this overall approach to lighting energy efficiency, based on annual installation electricity consumption is to be used, then this could have an effect on the way we currently present recommendations. This in turn provides opportunities for governments to create regulations e.g., Building Regulations\(^2,3\) or incentives to encourage energy efficiency e.g., UK Enhanced Capital Allowance\(^4\) but also that fit into an overall system rather than having an ad hoc approach.

The next stage is for further discussion to develop a system to the point when it can be used for the good of lighting and energy efficiency.

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