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Aiming to achieve net zero energy lighting in buildings*

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Abstract: *Energy consumption for interior lighting is rapidly increasing and takes up 17.5% of the total global electricity consumption on average. With European office buildings using 50% of their total electricity consumption for lighting alone, and other shares of electricity of 20-30% in hospitals, 15% in factories, 10-15% in schools and 10% in residential buildings, there is significant potential to reduce energy consumption for lighting. By implementing a combination of key measures, such as minimisation of lighting power density; use of highly-efficient lighting technologies based on renewable energy sources; use of appropriate lighting control systems; and maximisation of daylight use, energy saving targets can be pushed forward to aim at achieving net zero energy lighting in buildings. This paper presents findings from Building Research Establishment projects for public and private buildings to reduce lighting energy consumption whilst improving the quality of the internal luminous environment.*

Keywords: energy performance, interior lighting, daylight, efficient lighting, lighting controls.

1. Current background

Lighting is a large and rapidly increasing source of energy demand in buildings. In 2005 grid-based electricity consumption for lighting was 2650 TWh worldwide, or around 19% of the total global electricity consumption, whilst the electricity consumption for interior lighting alone was estimated at 2438 TWh worldwide, or about 17.5% of the total global electricity consumption (Halonen, Tetri and Bhusal, 2010). Interior lighting accounts for a significant part of the electricity consumption in buildings. According to International Energy Agency (IEA) research, heating is the leading energy consumer in EU commercial buildings, followed by lighting (Fig. 1).

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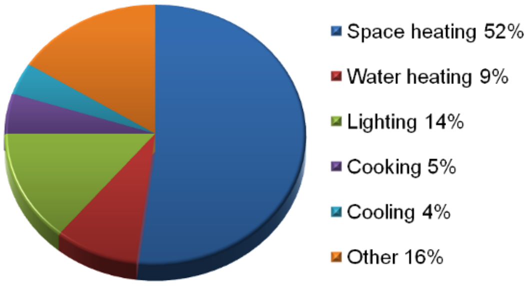


Fig. 1. Energy consumption by end use in EU commercial buildings (source: IEA).

The electricity consumption for interior lighting varies with the type of building. In some buildings, lighting is the largest single category of electricity consumption; office buildings, on average, use the largest share of their total electricity consumption in lighting. 50% of total electricity consumption in European office buildings is used for lighting, 20-30% in hospitals, 15% in factories, 10-15% in schools and 10% in residential buildings (EC, 2011). The heat generated by lighting represents a significant fraction of the cooling load in many internal spaces, and contributes to further consumption of electricity.

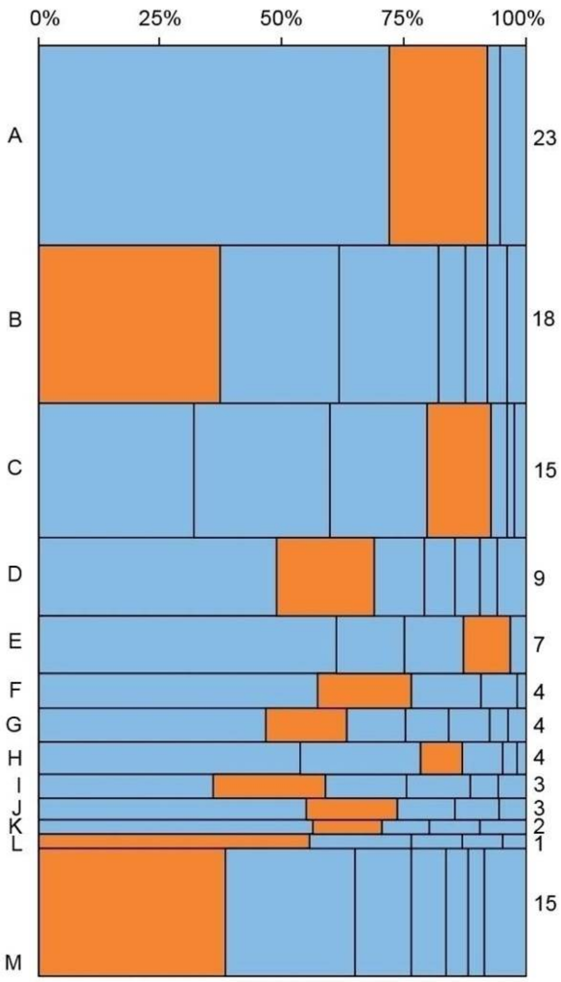


Fig. 2. Emissions by building type and end use (source: Carbon Trust). Figures on the right indicate carbon emissions in $MtCO_2$; letters on the left indicate building types: A – industrial; B – retail; C – hotels & restaurants; D – commercial offices; E – schools; F – healthcare; G – government estate; H – further & higher education; I – sports; J – heritage & entertainment; K – public offices; L – transport/communications; M – miscellaneous.

Fig. 2 illustrates findings of BRE and Carbon Trust analysis on carbon emissions from different building types and end uses (Carbon Trust, 2011). Carbon emissions from lighting are shown in orange.

Whilst more than 50% of all lamps installed in Europe are still not classed as energy efficient, the potential for improvements and energy savings is significant. Increases in energy price can also act as a driver towards efficiency, and encourage energy-efficient lighting solutions.

The EU is aiming for a 20% cut in Europe's annual primary energy consumption by 2020. In order to increase energy efficiency, the Commission has implemented EU Ecodesign regulations (EC, 2009a; EC, 2009b; EU, 2012a) to gradually remove from the market inefficient products like tungsten lamps, less efficient tungsten halogen, compact fluorescent, and metal halide reflector lamps, all high pressure mercury lamps, less efficient sodium and metal halide lamps, the least efficient LED lamps and magnetic ballasts. The Commission has also implemented Green Public Procurement (GPP) criteria to increase resource and energy efficiency within the public sector (EC, 2012). The GPP criteria also include lighting in buildings covering lamp efficacy and overall power consumption of the whole system. Other Commission measures refer to the use of smart meters that encourage consumers to manage their energy use better, and to the labelling of energy-using products (EU, 2012b).

The Energy Performance of Buildings Directive (EU, 2010) strengthens the requirements for building energy performance by requiring each Member State to establish minimum energy performance requirements for new and existing buildings, and to implement energy certification schemes. The Directive also requires that all new buildings are nearly zero-energy by 2021, with new buildings occupied and owned by public authorities nearly zero-energy by 2019. An approved methodology is employed to determine energy performance which also includes impacts from daylighting and built-in lighting systems.

In the UK, the updated Part L of the Building Regulations (DCLG, 2014) requires that new lighting in office, industrial and storage spaces should have an average luminaire efficacy (the amount of light emitted from the luminaire divided by its circuit wattage) of at least 60 lm/W. Lower efficacy values apply if some types of automatic lighting control are used in some types of space. An alternative, more complex approach uses the Lighting Energy Numeric Indicator (LENI), which is a measure of the energy used for lighting per square metre over the whole year. For lighting in other non-domestic spaces, an average lamp efficacy (the amount of light from the lamps divided by the circuit wattage) of 60 lm/W is required. For display lighting the average lamp efficacy should be at least 22 lm/W. In new dwellings three out of every four light fittings should be low energy, with a lamp efficacy of at least 45 lm/W.

Other energy efficiency initiatives include schemes like BREEAM and the UK Enhanced Capital Allowance (ECA). BREEAM assesses the environmental performance of new and existing buildings, with BREEAM International addressing buildings outside the UK (BREEAM, 2014). Although it is a voluntary scheme, it is often required by client specifiers. Lighting related credits refer to minimum floor areas being adequately daylit, suitable shading, the right quality of light according to relevant codes and standards, appropriate lighting system zoning and control, separate sub-metering of energy use including lighting, and energy efficient external lighting. The ECA scheme (DECC, 2014) gives tax incentives for companies to install energy-efficient equipment including lighting, by writing off capital costs against Corporation Tax in the first year after installation.

Despite the various measures to increase the efficiency of electric lighting, there is still substantial potential to reduce further the energy consumption for lighting and the associated carbon emissions. Whilst there is a trend in the international community to reduce the electricity consumption for lighting with new technology to below 10 kWh/m^2 (EC, 2011), the arrival of advanced, optimised daylighting technologies and of state-of-the-art electric lighting technologies using renewable energy sources can help push forward the target by aiming to achieve net zero energy lighting in buildings.

2. Methods to achieve net zero energy lighting

Modern lighting techniques and equipment, and more efficient light sources, provide opportunities for significant reductions in the use of energy, while achieving a greatly enhanced level of illumination and improved visual appeal. Cutting wasted energy for lighting can also reduce overheating, and therefore cut the high cost of air conditioning.

Although lighting products are becoming more efficient, longer occupancy hours and higher light levels have increased the energy used for lighting in buildings. Also, inappropriate control strategies and improper choice of light sources result in energy being wasted.

Key areas for minimising lighting energy consumption in buildings include: minimisation of lighting power density through optimisation of lighting strategies and levels of illuminance; use of highly-efficient lighting technologies; use of appropriate lighting control systems; and maximisation of daylight use. Quality should not be neglected when implementing measures to increase lighting efficiency, and therefore attention should always be given both to the effectiveness and the quantity and quality of lighting.

2.1 Minimising lighting loads

The general illuminance level in a space has a substantial influence on the energy consumption for lighting. Reducing the general illuminance has a direct impact on energy consumption, as the power consumed is roughly proportional to illuminance.

Recent research and consultancy projects carried out by BRE for public and private clients have revealed that illuminance levels in various types of internal space are higher than those recommended by current relevant standards and guidelines. For example, opportunities to decrease illuminance levels and therefore the lighting energy use have been noted in case of retail buildings. A survey carried out by BRE revealed that the average lighting power density in retail spaces was 36 W/m^2, compared to 10–12 W/m^2 in a modern office space with efficient lighting (Ticleanu, Littlefair and Howlett, 2013). Significant energy savings can be achieved by changing the lighting design philosophy so that instead of aiming for an overall level of illuminance the focus falls on the lit effect of the scheme, and hence on delivering lighting to where it is required. Two main techniques are proposed for retail buildings: using the right proportions of task and ambient lighting, so that low illuminance levels are achieved in the bulk of the store, whilst using accent lighting on displays to guide shoppers to key focal areas; and lighting the perimeter of the space to make the whole space look better lit by making the walls brighter. Another possibility is to use daylight to provide some or most of the ambient light levels.

A good practice example is shown in Fig. 3, which illustrates a store that reduced its energy use by 30% and its carbon emissions by 23% by implementing measures that included lower ambient light levels of 300 lux and higher illuminances only on vertical surfaces of the merchandise. In combination with highly-efficient LED lighting, this led to a reduced lighting load of 7 W/m^2 (Ticleanu, Littlefair and Howlett, 2013).

Fig. 3. Lower ambient light levels leading to lower energy consumption (source: Philips Lighting).

These techniques can be employed in a similar manner in other types of space or building, in accordance with standard recommendations. Reducing illuminance levels to the values recommended by relevant standards and codes, and optimising lighting strategies typically lead to significant reduction of lighting power densities (in W/m^2) and normalised lighting power densities (in W/m^2.100lux), with direct consequences for the energy use for lighting.

2.2 Using highly-efficient lighting technologies

Fluorescent lamps are by far the most popular lamps for lighting non-domestic buildings, although metal halide lamps and even tungsten halogen lamps are widely used in various applications that include accent or display lighting. Metal halide lamps are also a typical choice for high bay internal spaces. LED technologies are increasingly used following their significant advances in the last years. Various types of luminaires are used for indoor lighting, depending on the type of building.

Given the phase out of inefficient technologies brought about by EU legislation, new alternatives have been developed, with higher luminous efficacy and reduced environmental impacts. New types of lamp include LEDs, highly efficient fluorescent lamps and improved tungsten halogen lamps. Highly efficient compact fluorescent lamps use up to 80% less energy than conventional tungsten lamps, while improved tungsten lamps incorporating halogen technology use 20% to 45% less energy for the same light output than conventional tungsten lamps. The latest developments in compact fluorescent technology include lamps with higher luminous efficacy and lower mercury contents. Recent developments of the metal halide lamp type include ceramic metal halide lamps driven by electronic ballasts that are highly energy efficient. Having the array of wattages expanded to lower values of 20-22W, ceramic metal halide lamps driven by electronic ballasts last up to 20,000 hours and can reach lamp efficacies of up to 104 lm/W.

The most significant technical developments have been made by LED technology, which is increasingly being used for various lighting applications and lasts longer than other light sources. Not only has the variety of LED fittings increased, but the luminous efficacy of LEDs is improving year on year and is now comparable with that of fluorescent lamps. Whilst state-of-the-art white LED lamps have already reached efficacies of 100-150 lm/W, LED lamp efficacy is growing fast and, as shown in Fig. 4, further improvement is expected over the next 5-10 years (IET, 2013). Osram is already claiming a lamp efficacy of 215 lm/W for a T8 replacement LED tube that will be launched in 2015 in both warm white and cool white appearance (Osram, 2014). With a 95% efficiency driver, the claimed system efficacy is 205 lm/W.

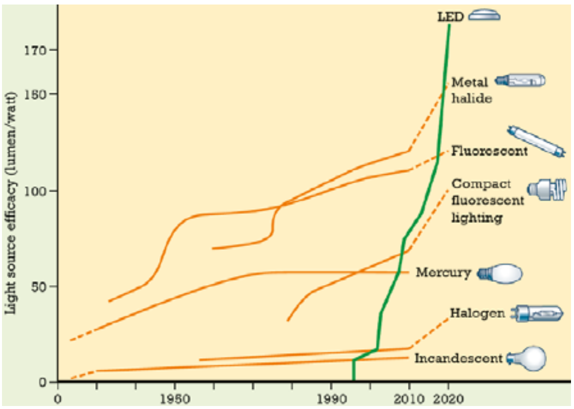


Fig. 4. Accelerated increase in LED lamp efficacy (source: IET).

Other technical developments in lighting include high-efficiency optics for luminaires with increased light output ratio, and optimized lamp-ballast systems consuming less energy and providing longer lamp life.

Fig. 5. LED luminaire rated at 100 lm/W luminaire efficacy (source: Philips Lighting).

In order to reduce the energy consumption for lighting, the overall efficiency of the lighting system should be addressed. There is no sense in placing an efficient lamp in an inefficient luminaire, so the most efficient luminaires should also be used.

2.3 Employing adequate lighting controls

The control strategy for lighting in building is usually set according to the type and complexity of the building and application. It can include various controls ranging from localised manual switching to daylight-based photoelectric dimming and complex management systems.

The choice of lighting controls from simple manual switches and dimming switches to presence detectors and light-level sensors has a large impact on total lighting energy use. However, currently most lighting control systems are under-specified, and electric light is often delivered to spaces where no one is present, or for which there is already adequate daylight. Most spaces are typically lit fully on during occupancy hours and this leads to substantial energy consumption even when sufficient illuminance levels can be provided by incoming daylight. Using photoelectric control linked to daylight sensors in daylit areas leads to significant energy savings depending on the characteristics of the interior space and the existing lighting systems.

For example, the illuminance measured at various points inside a car showroom display area was in the range 860-5100 lux, which was generated mostly by daylight. However, all electric lighting was maintained fully on continuously during the day and there were neither daylight-linked, nor dimming controls. A multi-gang switch was used to manually control the lighting both in the showroom and other open-space areas. Implementing daylight-based controls of the electric lighting in the car showroom can save 25 MWh of electricity each year, or around 8% of the total electricity used (including all consumers e.g. cooling, small and large power), and 13 tonnes of carbon each year, or around 6% of the total carbon emissions of the showroom.

Research shows that simply providing users with the capacity to control lighting levels in the space they occupy can significantly lower lighting energy use. Effective lighting controls can save 40-60% of the building’s lighting energy use (Littlefair, 2014). Energy can be saved after working hours and when work stations are unoccupied, and when daylight is sufficient. Even a short switch off (5 minutes or more) can save energy and money. If dimming is provided, additional savings can be made by dimming lamps early in the maintenance cycle when their output is high. This can typically save around 10% of lighting energy use even in a non-daylit space. With LED lighting the savings can be higher (15% or more) and the lifetime of the LEDs can be increased due to dimming (Littlefair, 2014).

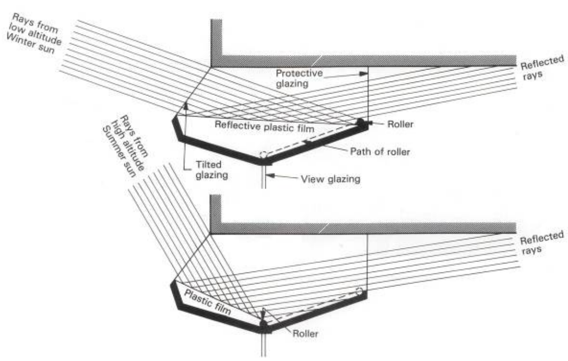
Fig. 6. Examples of user interfaces for lighting controls (source: Helvar).

A wide variety of control types are now available (Fig. 6), with new forms of manual control including wireless and smart phone controls. Occupancy sensing is especially valuable for infrequently used spaces. Photoelectric controls switch or dim the lamps in response to daylight. Time switching is appropriate for buildings with set hours of occupancy. Sophisticated lighting management systems are available which can control the lighting in an entire building, combining all these different control types if required. It is important to take into account the type of space, how it is used and the amount of daylight available.

2.4 Maximising the use of daylight

Daylight has physiological and psychological benefits for building occupants and can improve performance and wellbeing. At the same time it is a freely available light source that can provide high quality lighting to internal spaces at zero costs and with no carbon emissions. However, using daylight successfully requires careful planning and design to avoid associated problems such as glare from direct sunlight or solar heat gains.

Sidelighting can provide a view out that may be appreciated by building occupants and can be integrated in multi-storey buildings. However, the amount of daylight that penetrates into the space depends on the building orientation and the absence of obstructions, and there is a higher risk of glare from direct and reflected sunlight.



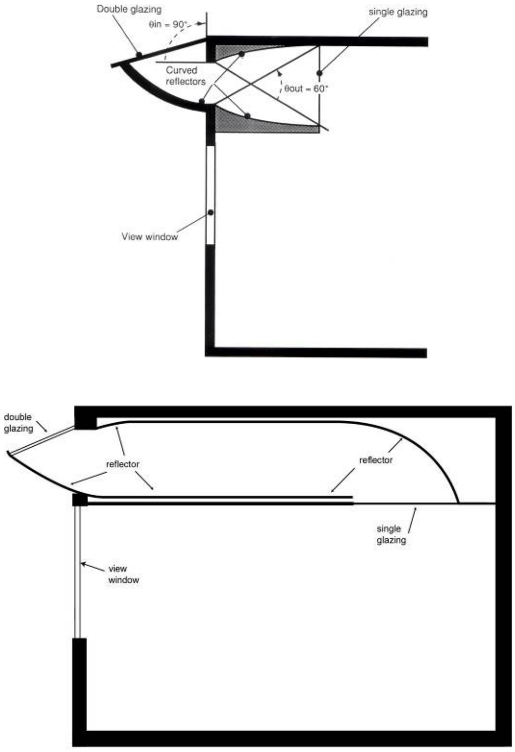


Fig. 7. Sidelighting techniques. From top to bottom: variable-area, light-reflecting assembly; anidolic reflector system; anidolic ceiling arrangement.

The distribution of daylight in the space from sidelighting is uneven, with higher daylight levels in areas nearer to windows and decreasing amounts further away into the space. For this reason, sidelighting is not effective for internal spaces with a deep layout. Advanced sidelighting strategies (Fig. 7) can improve daylight penetration into the depth of the building by redirecting it onto a reflective ceiling. Light shelves, sun-directing glass or anidolic collectors can be installed in the upper part of windows to redirect daylight deeper into the buildings (Littlefair, 1996).

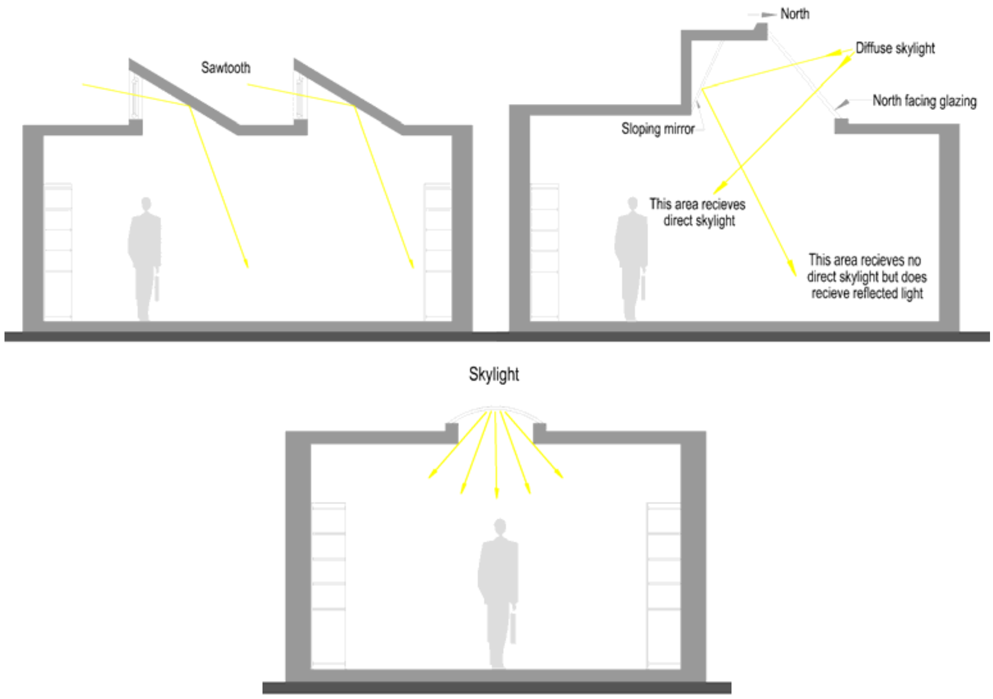


Fig. 8. Toplighting techniques. From top to bottom: northlight; sawtooth; rooflight.

Toplighting strategies (Fig. 8) use openings in the roof to allow daylight penetration into a space: hence their application is limited to single-storey buildings, or to the top floor of multi-storey buildings. However, daylight uniformity is significantly improved throughout the whole space, and there is less impact from obstructions, with maximum available daylight at all times. There is a limited view out, but toplighting strategies in atria and courtyards allow occupants to experience connection to the outside at all times of the day. Because of higher and longer exposure to sunlight, irrespective of orientation, toplighting strategies – other than northlights – typically incur a higher risk of overheating than sidelighting. Soft-coat, low-emissivity glazing with low solar transmittance (g-value) but higher daylight transmittance should be considered for such strategies.

Typically roof apertures over 8–10% of the whole roof area can be sufficient to keep electric lighting turned off during a significant part of the daytime. Substantial savings can be made by capitalising on the availability of natural light, while creating a pleasant, airy atmosphere that is favoured by occupants.

Optical systems are able to redirect or harvest daylight by means of tubular light-guiding systems, fibre optics, or arrays of mirrors and lenses. Daylight-guiding systems (Fig. 9) can lead daylight collected at roof level into internal spaces via highly reflective, mirrored tubes, and are more effective under clear sky conditions, although some of them can deal quite effectively with diffuse skylight. This helps reduce the need for electric lighting during the day. Fibre optic systems rely mainly on direct sunlight, as they are typically integrated within complex arrangements using sun-tracking collectors.

Sophisticated arrangements of mirrors and lenses can be used to direct daylight (mainly direct sunlight) into specific internal areas of interest.

Fig. 9. Daylight guidance systems using light-pipes (source: Monodraught).

Using daylight as a primary light source can potentially save energy by reducing the need for electric lighting. However, over-glazing can lead to high solar heat gains. The aim should be to provide generous levels of daylight with reasonably low associated solar heat gains to avoid using extra energy for cooling. Daylight into internal spaces needs to be controlled, and lighting controls are required to adjust the electric lighting to match daylight variability. Significant energy savings can be achieved by correct zoning of the electric lighting that establishes the groups of luminaires that should be controlled simultaneously, based on different factors that include daylight availability. The electric lighting system needs to be controlled separately in the daylit and non-daylit areas to maximise energy savings while providing the required light levels. Typically, luminaires should be grouped together in each zone that receives a similar amount of daylight.

2.5 Using renewable energy sources

Recent developments in renewable energy technologies, such as photovoltaic panels and wind turbines, have made it realistic to conceive nearly-zero or even zero energy lighting systems, particularly if highly-efficient lighting technologies and adequate controls are used. However, solar or wind powered lighting systems are still not commonly used in buildings due to a number of technical and financial challenges. Although government schemes support the uptake of such technologies by practising attractive feed-in tariffs, payback is typically long (particularly for smaller systems) and electricity generation is strongly affected by climatic conditions. Additional equipment is also required, such as inverters or batteries, and this requires supplementary storage and power optimisation.

Nevertheless, by nature, LED lighting systems are most commonly DC devices, operating from a low voltage of direct current. This makes it easier to integrate them with renewable energy based technologies, whilst achieving a higher system efficiency that allows for net zero energy.

3. Case studies

A number of projects have already been completed or are being assessed in order to reduce the energy consumption for lighting whilst improving the quality of the internal luminous environment.

3.1 Clothes store

Illustrated in Fig. 10, the LED-only scheme delivers an average light level of around 500 lux on the walkways and a light level on specific focal areas of the merchandise of around 900-1000 lux. By using LEDs rated 16W and 50 lm/W, which deliver warm white light of 3000K colour temperature and colour rendering index CRI of 90, the installed lighting load is 17 W/m^2 (Ticleanu, Littlefair and Howlett, 2013).

Fig. 10. Fully LED-lit clothes store (source: Reggiani).

3.2 Superstore

The use of pre-wired, daylight-based, dimmable 2 × 73W T5 Eco fluorescent fittings, with adjustable reflector and louvre for precise direction to the point of sale, as shown in Fig. 11, provided a 28% energy saving, 30% reduction in the number of lamps required, and 25% reduction in installation time compared with the previous lighting scheme (Ticleanu, Littlefair and Howlett, 2013).

Fig. 11. Daylight-based, dimmable T5 fluorescent fittings with adjustable reflectors and louvres producing the right light output at the level of the merchandise (source: Whitecroft Lighting).

3.3 Supermarket

The sales area is lit by a combination of ceiling-recessed square modules and round spotlights using LEDs with a colour temperature of 4000K, while chiller cabinets are lit by 4200K CRI 80 LED tubes concealed from the shoppers' view and aimed at the merchandise (Fig. 12). This delivered a well-lit solution at less than 9 W/m^2 and achieved an energy reduction of approximately 40% (Ticleanu, Littlefair and Howlett, 2013).

Fig. 12. LEDs used for general and display lighting.

3.4 Fashion store

It is proposed to upgrade the lighting in the 2-storey store shown in Fig. 13 from conventional fluorescent and metal halide technologies to warm white LED lighting. The design philosophy is tackled to provide the right amount of light to each type of area (e.g. 300 lux ambient illuminance and a minimum of 500 lux accent illuminance in sales areas) and to minimise the number of luminaires by choosing optimum positions and tilt angles. In so doing, 51% electricity savings and carbon reduction would be achieved, and lighting power density would decrease by 46% to 18 W/m^2 in sales areas and by 70% to 6 W/m^2 in fitting rooms. Around 83% of the energy used by the new LED lighting system could be supplied by 100 monocrystalline PV panels rated at 320W$_p$ and 19.6% efficiency covering 163m^2 of the total roof area available (Topriska, 2012).

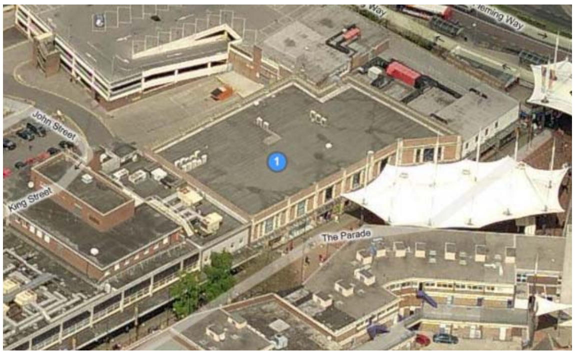


Fig. 13. Fashion store to incorporate LED lighting supplied with electricity from roof-mounted PV panels.

3.5 Office building

The office building illustrated in Fig. 14 has been assessed in order to increase its energy efficiency and substantially reduce its carbon footprint. The current lighting system consists of fluorescent fittings using electromagnetic ballasts and is controlled via wall-mounted switches in offices and presence detection in circulation and other communal areas. No daylight-linked controls are used. The total lighting load currently installed is 14.3kW, with an estimated energy consumption of 36,190 kWh/year, whilst the average lighting power density is around 14.7 W/m^2 throughout the building.

Fig. 14. Glazed façade office building proposed to be lit by a net zero energy lighting system.

The aim is to develop a net zero energy lighting system using highly-efficient LED lighting, adequate lighting controls and roof-mounted PV panels. A change in layout is also considered, as the current cellular offices will be converted into larger open-plan office areas. By using the latest LED lighting systems, the total lighting energy consumption can be reduced by 54% to 16,560 kWh/year, at an estimated normalised lighting power density of 1.5 W/m^2.100lux on average in office areas and 2.5 W/m^2.100lux on average in other areas.

Large glazed areas are present on west, south and east façades. By adding daylight-based dimming controls to reduce the light output of electric lighting when sufficient daylight is available to achieve the maintained illuminances during work hours (9.00 to 17.30), the energy consumption for lighting can be further reduced by an additional 29% to 5,740 kWh/year.

Net zero energy lighting can be further achieved by adding an array of grid-connected monocrystalline PV panels rated at 235W$_p$ and 14% efficiency, with a total estimated electricity production of 5,800 kWh/year (Park, 2013). The PV panes would require 50m^2 of roof area for the installation, and a simple payback period would be 10.5 years.

4. Conclusions

Lighting is a rapidly increasing source of energy demand and takes a significant part of the electricity consumption in buildings. More than half of all lamp technologies installed in Europe are still not classed as energy efficient, and continuous increases in energy prices are expected for the coming years. The EU is aiming for a 20% cut in Europe's annual primary energy consumption by 2020, and the Commission has implemented a number of measures to increase energy efficiency. These are supplemented by various schemes, standards and codes to reduce carbon footprint and energy use.

In this context, where various drivers towards energy efficiency exist, the potential for improvements and energy savings in lighting of buildings is substantial.

Although there is a trend in the international community to reduce the electricity consumption for lighting with new technology to below 10 kWh/m^2, recently developed daylighting technologies and state-of-the-art electric lighting technologies using renewable energy sources can give the potential for net zero energy lighting in buildings. This can be possible if such technologies are integrated into optimised design strategies such as minimising lighting power density through optimising lighting strategies and levels of illuminance; use of highly-efficient lighting technologies; use of appropriate lighting control systems; and maximising daylight use.

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