



Light emitting diodes: Eco-design Innovation Roadmap

Executive Summary

Lighting is a very significant user of electricity in the UK, representing about 20% of the total UK energy usage. Commercial lighting is dominated by fluorescent technologies except in the leisure and retail markets where more incandescent lamps are used. The domestic market is still dominated by incandescent lamps although compact fluorescent lamps (CFLs) are making a significant impact on energy efficiency.

Two new technologies Light Emitting Diodes (LEDs) and Organic LEDs (OLEDs) have a potential to significantly reduce lighting energy use in the medium to long term although a significant amount of development work is needed before their efficacy outstrips fluorescent technologies.

Drivers that may encourage the development and use of LEDs other than energy efficiency are discussed. They include waste minimisation as LEDs are small, long-lived and contain no mercury (unlike fluorescent lamps). As one of the barriers to the uptake of CFLs in the home has been the lack of 'sparkle' from these lamps, the small bright point sources of LEDs could provide a suitable replacement for tungsten filament and halogen lamps. The lighting market is global in scope with much of the production being in the Far East. Both the Chinese and Japanese are progressing the development and use of LEDs. At present LEDs are relatively expensive and have technological problems that need to be solved before their full potential can be realised. They are being extensively used in decorative lighting, emergency lighting and way marking and traffic signals, as well as in the automotive industry. However, bulk markets for general lighting products need to be developed.

Ten goals are set out for LED performance and development. These include product standards, technology improvements, market building etc.

The effect of LED developments on the MTP scenarios for energy usage in commercial and domestic lighting is modelled. In both cases significant improvements are shown over the current best practice assumptions. Enablers and key actions include applied and fundamental research, market building, and standards and performance specification.

Five recommendations are given around these key actions:

Recommendation 1

To support fundamental research through EPSRC (and/or EU Framework) and the DTI Technology Programme funding in the areas of:

- OLED development.
- Semiconductor materials (substrates, buffer layers, epitaxial layers).
- Semiconductor physics.
- Integrated LED optics.
- Phosphors and encapsulants.

Recommendation 2

The UK Government through the DTI or Carbon Trust could provide support for small businesses in the applied research necessary to develop LED luminaires of high efficiency for use in the home and commercial decorative fittings.

Recommendation 3

UK manufacturers should provide support and encouragement for the development of Standards by ISO and/or CEN in order that all LED products can be marketed from a level playing field of quality and safety.

Recommendation 4

The UK Government through the Department of Transport and the Road Lighting Board should encourage the market for LED traffic signals to stimulate market growth in LEDs and to reduce energy usage.

Recommendation 5

That when some 'standard' LED products of sufficient efficacy are on the general lighting market, the Carbon Trust should develop criteria for inclusion in the Enhanced Capital Allowance scheme.

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1 Sector profile

Lighting in the UK is using 66 TWh of electricity - 48TWh in the commercial sector and 18 TWh in homes, representing about 20% of total electricity usage in the UK [1, 2]. Energy saving policies introduced to date (December 2005) are expected to level off electricity demand in the commercial sector over the period 2005 to 2020, despite a projected growth in floor area and operating hours. However, electricity consumption in homes is still expected to grow during the same period to 21 TWh by 2020, due to the expected increase in the number of homes built.

Currently, the commercial lighting market is dominated by fluorescent technologies; sales data place the existing fluorescent technologies in the order T8 (26mm) linear, Compact Fluorescent Lamps (CFL), T5 (13mm) linear, and T12 (38mm) linear. There are also significant sales of tungsten filament (GLS – General Lighting Service) and tungsten halogen lamps, particularly in the leisure (hotels, restaurants, bars) and retail markets and in small businesses based in essentially converted houses. High intensity discharge lamps are used in industrial and outdoor applications and small metal halide lamps are starting to penetrate the retail market.

In the domestic sector tungsten filament (GLS and candle bulbs) and tungsten halogen lamps are still the most widely used. Since 2002 Building Regulations [3] have required the installation of some CFLs in new houses (and large refurbishments) and there have been major initiatives, notably EESOP (Energy Efficiency Standards of Performance) and EEC (Energy Efficiency Commitment), which have helped to install CFLs in existing housing, in particular in social housing.

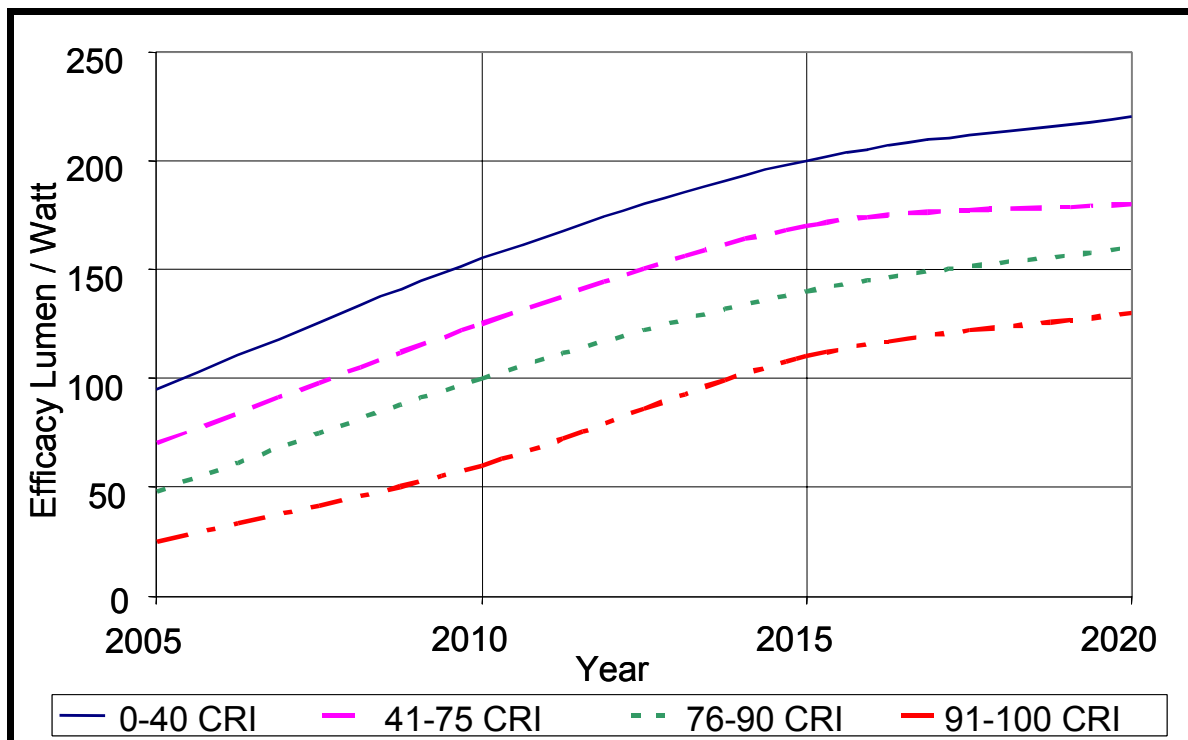
2 Technology drivers

2.1 Energy reduction

Most lighting technologies are well developed and are reaching the peak efficiency expectation with the best technologies reaching lamp efficacies of 105 Lumen per Watt (LPW) for white light and 200 LPW for monochromatic (low pressure sodium) light. Two related technologies are still in their infancy and are showing significant improvements in efficiency year on year, they are light emitting diodes (LEDs) and light-emitting polymers or organic light emitting diodes (OLEDs).

The newest white light LEDs in production at present are giving about 70 LPW. Projections made in 2003 predicted 100 LPW in production by 2010 rising to 160 LPW by 2020 for high colour rendering index white light LEDs (Ra = 76 - 90) [4]. It is possible that current development is moving development of LEDs at an even faster rate than that (thought to be) moderately optimistic scenario. Some sources suggest that the current rate of development is up to 2 years ahead of these projections.

Figure 1: Estimate of Navigant Inc. data [4] on the growth of LED efficacy with time



The colour rendering index (CRI or Ra) is a measure of how well a light source shows the accurate colour of an object. Most triphosphor T8 and T12 fluorescent lamps and CFLs fall in the high CRI category, whereas incandescent lamps (Tungsten filament and halogen) are in the very high CRI category.

Very high CRI LEDs ($R_a > 90$), which could be the direct replacements for the lamps preferred in the domestic sector, are expected to reach 70 LPW by 2010 rising to 130 LPW by 2020. These lower figures are still a very significant improvement over the tungsten filament (6 -15 LPW) and tungsten halogen (10-30 LPW) lamps commonly used in the home today. OLEDs are lagging behind LEDs in efficacy (currently giving about 30 LPW in development) but could offer more potential in the long term, with efficacies rising to 200 LPW.

However, if LED sources are to be useful for general lighting it is important that efficacy is not pursued by making brighter and brighter light sources. If too much light is emitted from a single point source, the light will be uncomfortable bright. It would be preferable to aim for lower lumen output at lower wattages and to use good luminaire design to combine multiple LEDs.

2.2 Waste minimisation

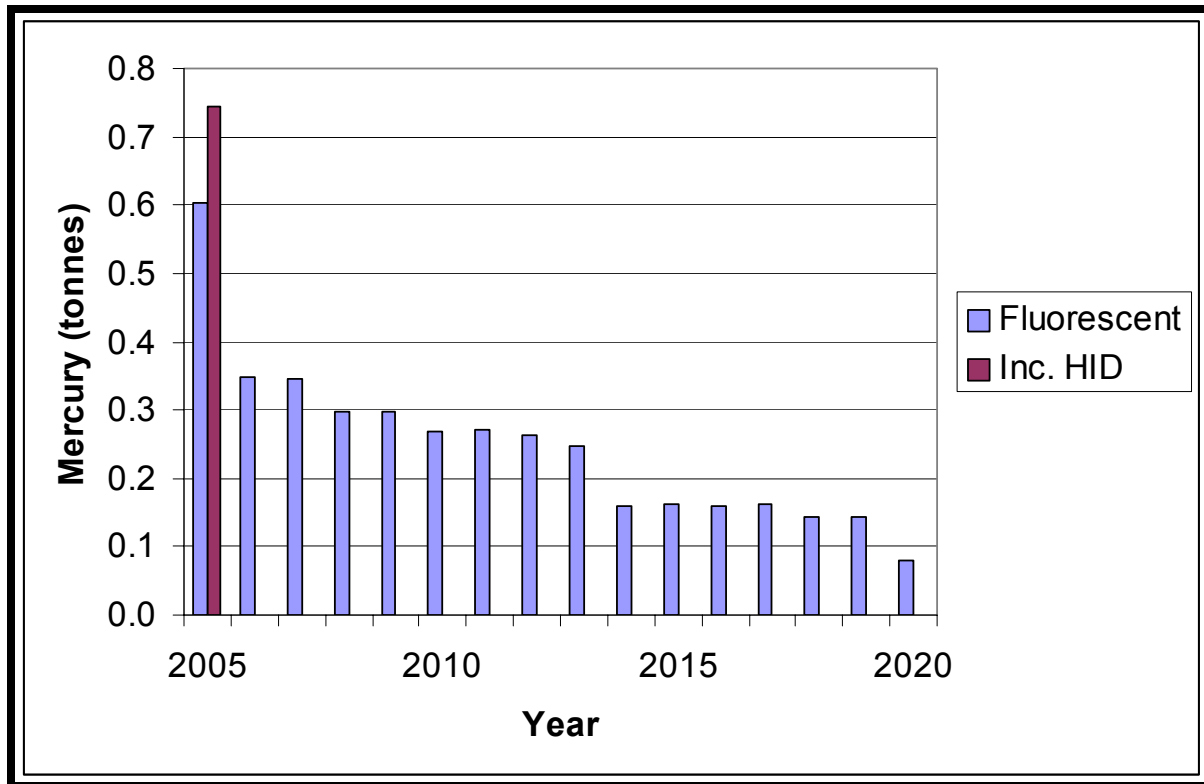
One of the most serious waste issues in lighting at this time is that the vast majority of fluorescent and high-intensity discharge lamps utilise mercury to initiate the discharge. Mercury is a very toxic chemical and although most lamps use less than 10 mg of mercury in each lamp, mercury's toxicity is such that the mercury from one fluorescent tube can contaminate 30,000 litres of water beyond a safe standard for drinking. Fluorescent lamps are also quite large and use significant quantities of glass, metal, fluorescent chemicals and polymeric carrier material, leading to about 7,000 tonnes of waste material from fluorescent lamps per year.

The amount of mercury used in fluorescent lamps has been reducing with a number of step changes over the last thirty years. Current mercury levels are about 5% of those used in 1976 and the trend of reducing mercury levels is ongoing. In figure 2 the large step change between 2005 and 2006 is an indication that most of the old T8 lamps with mercury levels of 10mg per lamp (current average is 5mg) will have been eliminated by 2006. The latest 'green' production lamps have about half the mercury of the current average figure with no loss of lumen output. There are even mercury-free fluorescent lamps, although these do currently have reduced luminous efficacy. Extrapolating the current mercury reduction trend into the future, MTP estimates that the total mercury entering the waste stream from fluorescent lamps will reduce from about 0.6 tonnes per annum in 2005 to about 0.08 tonnes in 2020 (see figure 2). There is also a chance that all discharge lamps may be mercury-free by 2020 (although they would need to be mercury free by about 2014 for mercury to be removed from the waste stream by 2020). The 2005 column includes a datum point showing the added mercury from high-intensity discharge lamps. Not enough data is available to project the mercury waste from these lamps into the future but they are also expected to use less mercury with time and there are already some mercury-free lamps on the market.

LEDs are small point sources comprising semiconductor wafers encapsulated in a small polymeric lens set on a metallic heat sink; the same electronic driver runs several LEDs. One major advantage of LEDs is that they do not contain any mercury. They do contain compounds such as gallium, arsenic, nitrogen, indium and phosphorus in compound form and in very small quantities, and hence present a very much lower hazardous waste risk than fluorescent lamps. They have the potential to use relatively less material overall (on a

lumen by lumen basis) although currently quite massive metallic heat sinks are needed to give a good lifetime for high lumen package lamps. Also in the long term, the projected lifetime of LEDs 50,000 to 100,000 hours means that there will be relatively less waste on a year by year basis as they will last at least 5 times longer than fluorescent lamps and up to 100 times longer than GLS lamps. In many instances, particularly in the domestic setting, they may last for the whole useful life of the luminaire itself.

Figure 2: Mercury entering the waste stream from lamps



OLEDs, being polymeric sheets, are not as good from a waste minimisation point of view as they are likely to use more material per lumen than LEDs. It is also likely that different manufacturers will use different polymeric materials making recycling difficult as the products would need to be graded into product types. They will still benefit from extended lifetimes and the lack of hazardous chemicals.

2.3 Society and how it is changing

Traditionally the domestic market preference for tungsten filament lighting has been hard to break. CFLs are not very popular because even the 'warm white' lamps have a colder appearance than GLS bulbs. They also have a more diffuse light and lack the ability to give sparkle to glass and metallic objects in the home.

In recent years tungsten halogen lamps have made an impact in the home, especially in kitchens and modern interiors as they give a lot of sparkle to the clean and metallic finishes that are in vogue.

LEDs offer the option of high efficiency point sources take can give the kind of sparkle prized by lighting designers for domestic and leisure and retail commercial applications. As such they have the possibility to make more of an impact in the domestic sector than CFLs have done, as long as suitable sources can be developed. They also offer instantaneous full lumen output and dimming potential, thereby avoiding two other technical challenges of CFLs.

In the home LEDs are likely to make their first impact in task lighting (table and desk lamps, and under cupboard kitchen lighting) and possibly accent lighting. For LEDs to make a major impact into the home a complete change is required in how we view home lighting. LEDs could be moulded into architectural mouldings or window frames and sills. OLEDs offer a quite different design option for lighting designers, as they are sheet materials that could be used for 'wallpaper' or self-luminous lamp 'shades'. LEDs are making a significant impact in domestic outside lighting, particularly solar-powered garden lighting and decking lights.

For the domestic market it is more important to have a low-cost product with a lifetime of about 30,000 hours (i.e. the lifetime of the whole luminaire) and with good lumen maintenance. An efficacy of 50 LPW would be an adequate starting position in order to improve the overall lighting efficiency of domestic lighting as the LEDs are mainly competing with incandescent light sources.

LEDs have already taken over the commercial decorative lighting market where coloured lights and colour-change effects are well used. LEDs are relatively efficient for coloured lighting applications as most coloured LEDs are of higher efficacy than white-light LEDs and previously coloured lighting was provided by adding coloured filters to white light sources. Colour change lighting for visual effect is also starting to prove popular in the domestic setting.

The one area where there is a strong need for more efficient lamps at this time is the retail spot-lighting niche market, currently dominated by tungsten halogen spot lights. However, as LEDs get more efficient, and as lighting designers start to learn how to design with LEDs or later with Organic LEDs (OLEDs), all the commercial lighting sectors are potential markets for LEDs in the long term.

2.4 Globalisation of production and markets

Lighting is a very global market; more and more of the global production of fluorescent lamps is occurring in cheap labour markets such as China and Brazil. LEDs are a different prospect at the moment as they are a more high-technology product being based on semi-conductors. The majority of the development of LEDs themselves is centred in semiconductor companies (or joint ventures between lighting and semiconductor companies) in Japan and the United States. It is likely that Europe and China will also be major players in the development area in the future.

China is a hotbed of development of lighting products based on LEDs supplied by other companies. Some of the products starting to be introduced to the market place are spot lamps; addressable 'picture walls'; light 'bricks'; 'look-alike' products imitating fluorescent tubes and small round bulbs; and Christmas lights. In many of these applications, the heat sinking needs of the LEDs are not well addressed, leading to significantly lower product lifetimes.

Some more established uses of LEDs are way marking and emergency signage, traffic signals (particularly green lights) and automotive lights. Solar powered garden lights using LEDs are making an impact in the market in the UK – this is a useful development from a domestic lighting energy efficiency point of view as garden lighting is becoming more prevalent. These solar-powered LED systems are important from a global perspective as they can be used to improve the living standards of third-world areas with no access to mains power and provide a much more efficient alternative to kerosene lanterns.

It is very likely that the development of useful lighting products based on LEDs and the development of the LEDs themselves will take place within different companies and possibly within different countries as well. From a UK point of view there is much more scope for designing lighting fittings (luminaires) that make use of LEDs produced elsewhere.

2.5 Economic factors

LEDs are relatively expensive, although the unit price is reducing rapidly. However, there is still a correlation between quality and price at present. More bulk markets need to be developed and several technological challenges need to be addressed before the cost will come down to tungsten filament lamp or halogen lamp levels. The automotive industry is helping to start the development of bulk markets and advances in LED technology has meant that LED light clusters in car rear lights have reduced from about 2,800 disks to 12 disks per cluster. Way marking products are being more widely used because of the long lifetime and relatively low intensity requirements make them useful products in areas where maintenance is difficult.

One large market in which LEDs are fast becoming the technology of choice is as backlights for LCD displays. Data from Lumileds Lighting for 2004 [5] gives the market share for LEDs as: LCD Displays 40%; Signs 23%; Automotive 18%, illumination 5%; Signals 2% and other 12%.

One area for which LEDs offer an energy efficient solution now is that of traffic signals. All colours of traffic signals are more energy efficient than tungsten filament bulbs with filters and maintenance intervals can theoretically be increased due to the longer lifetimes of the lamps. There are some technical problems still being worked on by manufacturers – most notably the need to produce a warning that a red light is not operating, as this has major safety implications. LEDs can still have a major affect on savings from green light installations only and these could provide the focus for a major joint procurement project.

There are some technological problems that add to the cost of LED products (especially white-light ones) including:

- The need for massive heat sinks and/or fans to cool higher intensity fittings.

- The need to sort white-light LEDs into separate colour appearance bins, as there is a considerable variation in colour temperature (and hence appearance) within individual batches.

The OIDA roadmap [6] suggests that the whole life ownership costs of LED lights in the USA will be lower than those of incandescent lamps by 2007 and lower than fluorescent lamps by 2012. The roadmap also suggests that the ability to focus light where it is needed could have a beneficial effect on the human visual experience and enhance productivity with related economic benefits.

3 Goals

- To improve heat sinking techniques to allow the development of high lumen output fixtures suitable for general lighting applications.
- To produce fittings / luminaires which maximise the benefits of LEDs and are liked by the decorative lighting market.
- To develop light directing systems (lenses, reflectors etc.) to make full use of small point sources.
- To produce white-light (Ra 80) LED systems with efficacy of 100 LPW by 2010 and 160 LPW by 2020.
- To produce white-light (Ra >90) LED systems with efficacy of 70 LPW by 2010 and 130 LPW by 2020.
- To produce efficient and stable phosphors and phosphor application methods to achieve constant colour temperature within batches and good warm white lights.
- To improve encapsulant materials to improve lumen maintenance properties and avoid yellowing with age.
- To develop Standards for testing LEDs and systems using them to give more market confidence in product performance.
- To build markets for LEDs in the UK, for example by encouraging Local Authorities to use LED traffic signals.
- To increase minimum standards for commercial lighting to a level that will preclude inefficient incandescent lighting products by 2011.

4 Effect on MTP scenarios

The Market Transformation Programme develops scenarios for energy use by different sectors now and into the future. The Reference Line gives an estimate of the usage if no new energy saving measures are taken in the future [1, 2]. The EBP or earliest best practice scenario assumes that all measures that are technically feasible and economically affordable on a reasonably short payback time are adopted (using a ten year roll-out process) as soon as they become economic. The policy or P1 line indicates the effect of a number of potential policy instruments (as set out in the MTP policy briefs - see Mtprog.com) - although these policies may not yet be adopted by bodies capable of carrying out the policies.

The effect of LEDs on the EBP line is illustrated by the division of the line beyond 2010 – the difference indicates the added savings by using LEDs rather than other efficient technologies. Individual graphs are shown below for commercial and domestic lighting as they are almost independent markets and are modelled as such within MTP. The effect of LEDs has been simply modelled for each market.

In the commercial model it was assumed that 25% of the energy usage in 2010 could be saved by 2020 (and that the saving would be rolled out in a linear progression starting in 2010). This simple assumption actually requires LEDs to be used for the majority of lighting and may be overstating the likely savings. The policy line reaches the EBP line because it is assumed that minimum standards (Building Regulations) will be raised to a level whereby inefficient incandescent lamps cannot be widely used in commercial premises.

In the domestic model a more cautious approach has been taken and it has been assumed that only 10% of the potential savings (i.e. from 100% transformation to LEDs) has been achieved by 2020 (and that again it has been rolled out in a linear progression from 2010). This assumption leaves very significant scope for reductions in domestic lighting energy reduction beyond 2020 (assuming that suitable light fittings have been developed) as the potential savings from using LEDs could reduce the domestic lighting energy use to less than 3 TWh per annum in the longer term, compared with the 2005 figure of 19 TWh per annum.

Figure 3: Unit Energy Consumption of Commercial Lighting

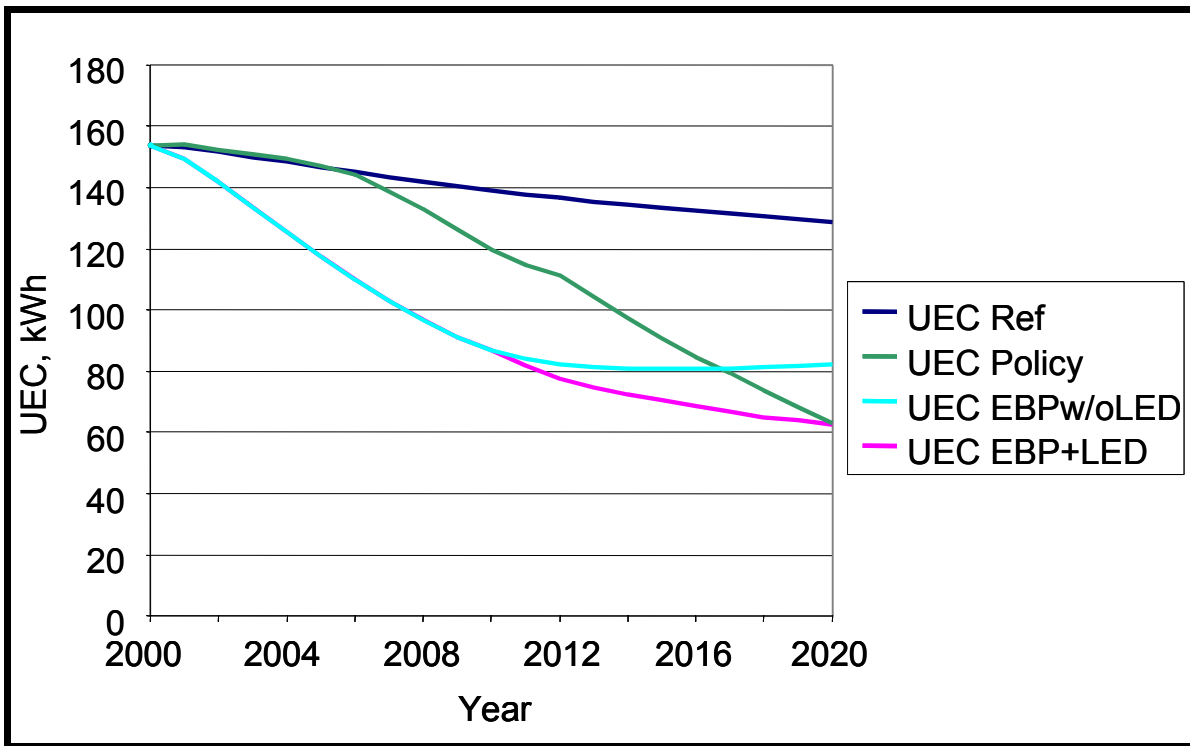
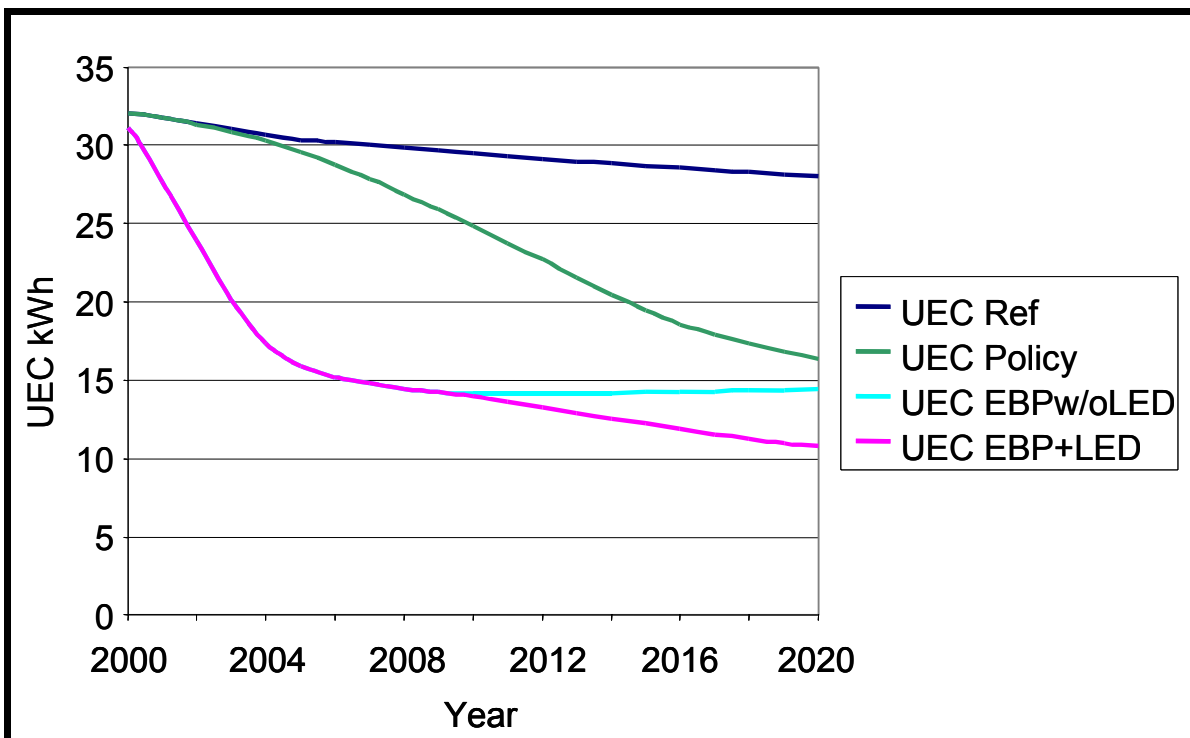


Figure 4: Unit Energy Consumption of Domestic Lighting



5 Enablers and key actions

5.1 Applied research

Several areas need to be tackled either by manufacturers (with the support of Government - DTI Technology Programme - if they are small or medium enterprises, or the Carbon Trust), or with the aid of research programmes funded by EPSRC and/or the EU Framework programme. In all cases, this work will help to make energy efficient luminaires that can be made and marketed in the UK and EU.

The main issues are:

- Heat sinking must be improved to allow sufficient lumen output for general lighting whilst retaining long LED lifetimes. Currently large lumps of metal plus, in some cases, a fan are used to conduct heat away from the LED chip. It is possible that the luminaire or fitting itself could be used as the heat sink incorporating the practical needs for cooling with a decorative design feature.
- The luminaire design is also vital in making the best use of the light emitted. Careful design of the optics associated with the LED chips could maximise 'fitness for purpose' of luminaires. Holistic solutions and lateral thinking is required to make the most use of these new light sources.

5.2 Fundamental research

Although UK researchers are unlikely to provide the whole solution to problems associated with LED and OLED efficiency and reliability, they do have a good track record of provide some parts of the overall solution in many technical areas. This type of research can produce patentable advances that can be marketed elsewhere as well as raising the UK profile as a high-technology leader. There have been a number of very high profile patent court cases around LED technology, so it might be preferable to concentrate on OLED technology development. The UK is already a leader in OLED technology (through Cambridge Display Technology) and this work and other work in a similar vein should be supported.

There is one large research project on OLED development being funded through the 6th EU-Framework programme called OLLA. This project is being led by Philips and includes 22 partners from universities, research institutes and industry across Europe – there are no UK partners.

It is not appropriate to give details of the challenges to fundamental research in increasing LED efficiency in this overview paper. These challenges have been well set out in reference 6, but they encompass improvements to semiconductor materials in the areas of substrates, buffer layers and epitaxial layers. Advances are also needed in the fundamental understanding of the light producing physics within the semiconductor and how the light is released from the chip.

Research into improved phosphors and encapsulants should address the colour temperature and colour rendition of the LED and the stability of the process to produce the same colour output from every chip. The encapsulant also needs to have excellent aging properties to avoid yellowing with age. Yellowing affects both the colour appearance of the LED and the lumen output.

In August 2005, the US Department of Energy announced a \$4 million call for research projects on both fundamental and applied research into LED and OLED technology. The US Energy Policy Act passed this year authorized the formation of the 'Next Generation Lighting Initiative', a public-private finance initiative which could provide up to \$50 million annually commencing October 2006. For the year commencing October 2005, the funding is thought to be around \$12.7 million.

5.3 Market building

The market for LEDs in decorative commercial applications has grown quickly because the product has many perceived benefits over previous practice, namely, tuneable colours without filters, long life, cooler running, flexibility of placement, and greater energy efficiency.

Some of these properties are also relevant for making LEDs a good choice for traffic signals. One major drawback is the price of LED signals compared with conventional tungsten filament signals. A good method for building markets and challenging costs is to adopt a bulk procurement strategy. Traffic signals in the UK are the responsibility of either the Highways Agency (for major roads) or Local Authorities. Whilst the Highways Agency may have a large enough stock to make use of bulk procurement on its own, this is not likely to be the case for Local Authorities.

There are, however, several fora where local authority representatives do get together, for example the Traffic Signals User Group and the Road Lighting Board. It might be possible with the help of one of these fora for local authorities to get together to develop a common procurement specification and to place a bulk procurement contract. Another possible route for gathering enough local authorities for a bulk procurement contract might be via a joint maintenance contractor – there are a number of contractors who work for more than one local authority.

The market for LEDs is already being significantly built by their use as backlights for LCD displays (see consumer electronics section of the MTP website) and the automotive industry. Both these sectors are likely to grow during the next few years.

5.4 Standards and performance specification

In order to give designers and specifiers confidence that the LED installation is going to give the performance they need, it is vital to have good test Standards for LEDs and LED fittings. Some Standards are under development within IEC/CEN and the US IES at the moment but Standards development needs to match the rate of development of the product to reduce the uncertainty in adopting the new technology. There seems to be quite a lot of pressure to fast-track these Standards. Standards for measuring LED properties

must be developed so that they allow a realistic comparison with existing lighting systems whilst not constraining the development of innovative lighting solutions.

As LED and OLED systems become more commonplace in the general lighting market, performance standards need to set for good practice installations. In the USA this would be in terms of Energy Star criteria, in the UK this would be criteria for the Enhanced Capital Allowance scheme.

6 Recommendations

Although lighting is a very global market and the main areas of excellence may be centred elsewhere in the world, there are a number of areas in which UK policy could help to advance LEDs and OLEDs, which are likely to be one of the cornerstones of a low carbon lifestyle in the 21st Century. The UK should adopt and implement the following recommendations:

Recommendation 1

To support fundamental research through EPSRC (and/or EU Framework) and the DTI Technology Programme funding in the areas of:

- OLED development.
- Semiconductor materials (substrates, buffer layers, epitaxial layers).
- Semiconductor physics.
- Integrated LED optics.
- Phosphors.
- Encapsulants.

Although UK researchers are unlikely to provide the whole solution to problems associated with LED and OLED efficiency and reliability, they do have a good track record of provide some parts of the overall solution in many technical areas.

Recommendation 2

The UK Government through the DTI Technology Programme or Carbon Trust could provide support for small businesses developing LED luminaires of high efficiency for use in the home and commercial decorative fittings. Design preferences are heavily affected by cultural backgrounds and luminaires developed in other countries may not appeal to the UK market. Many of the luminaires sold in the UK today are designed and made by relatively small UK companies and it is these companies who would have to be engaged in order to effect a strong market transformation towards LEDs.

Recommendation 3

Where appropriate, UK manufacturers should provide support and encouragement for the development of Standards by ISO and/or CEN in order that all LED products can be marketed from a level playing field of quality and safety.

Recommendation 4

The UK Government through the Department of Transport and the Road Lighting Board should encourage the market for LED traffic signals, particularly green signals, to stimulate market growth in LEDs and to reduce energy usage.

Recommendation 5

That when some 'standard' LED products of sufficient efficacy are on the general lighting market, the Carbon Trust should develop criteria for inclusion in the Enhanced Capital

Allowance scheme. (In the USA, Energy Star criteria should also be developed.)

References

[1] See Commercial Lighting Policy Brief and briefing note BNCL01 on www.mtprog.com

[2] See Domestic Lighting Policy Brief and briefing note BNDL01 on www.mtprog.com

[3] Building Regulations 2002, Approved Documents L1 and L2 (Conservation of fuel and power)

[4] Navigant Consulting Inc. 'Energy Savings Potential of Solid State Lighting in General Illumination Applications', U.S. Department of Energy, 2003.

[5] Quoted in R Forster, BG 3/2005. 'Light-emitting diodes – a guide to the technology and its applications', BSRIA, Bracknell, 2005.

[6] J Y Tsao Ed., 'Light Emitting Diodes (LEDs) for General Illumination', Optoelectronics Industry Development Association, 2002

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