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Lamps for improving the energy efficiency of domestic lighting

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Change is coming to the domestic lighting market. The light source that has dominated domestic lighting since the birth of electric lighting is going to be squeezed out and others with different characteristics will replace it. Some of these are already on the market, some are entering the market now and some have yet to make an entrance. The householder is certainly going to have plenty of lamp types to choose from, all of them claiming to be 'low energy'. Alternative domestic light sources include compact fluorescents which produce enormous energy savings over the incandescent lamp, but do not have its visual appearance, colour quality or instantaneous full light output. Tungsten halogen lamps do possess the light qualities of the incandescent lamp and are available in the traditional light bulb shape, but do not provide the same energy savings as compact fluorescents. LED's are potentially the ideal replacement for incandescent lamps having a long life with a discrete appearance, but improvements to efficacy for the warm white version are required to meet Building Regulations. Research on OLEDs continues, but current usage is limited to display applications, a situation which may not change for some years.

1. Introduction

Electric lighting is unusual amongst developed technologies in that the first light source developed, the incandescent lamp, is still the most widely used. This situation arises from its widespread use in homes. There are estimated to be some 375 million incandescent lamps used in homes in the UK, about 60% of the total.[1] But this situation is about to change. In its 2008 Climate Change Bill, the British government committed itself to a reduction in UK carbon emissions of 80% from 1990 levels by 2050, with intermediate targets between 26% and 32% reduction by 2020. For these targets to be met without major economic and social disruption, the efficiency of the most common energy using products has to increase. Domestic lighting products have a role to play in this, for a number of reasons. First, as explained above, there are a lot of them. Second, there are a number of light sources available or about to become available that could be used in the home with luminous efficacies from twice to five times that of the incandescent lamp. Third, these lamps can often be retrofitted into existing luminaires. Fourth, the short life of incandescent lamps, about 1000 h, means that the homeowner has to replace them frequently so the changeover can be fairly rapid. Fifth, the cost of such a changeover can be passed to the householder.

Figure 1 shows the change in total annual domestic lighting energy consumption that the British government is seeking up to 2020.[1] The solid line indicates the expected growth in UK annual domestic lighting energy consumption based on persuasion and market

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trends in the supply, sales and use of domestic lighting. The dashed line indicates what the government is hoping to achieve. If met, this target would lead to the annual energy consumption of domestic lighting falling to 8.9 TWh. The means used to bring about this reduction are two-fold. First, the 2006 Building Regulations Part L requires that all new homes or existing homes being extended or rewired in England and Wales should have at least one dedicated energy efficient luminaire per 25 m^2 of floor area of the dwelling or one in four luminaires, if greater. Similar regulations apply to Scotland and Northern Ireland. Second, the government has 'persuaded' major UK lamp retailers and suppliers to voluntarily withdraw incandescent lamps from the market in a rolling programme. This programme requires that in 2009 retailers will cease selling incandescent GLS A-shaped lamps of more than 60 W; in 2010 they will cease selling incandescent GLS A-shaped lamps of more than 40 W and in 2011 they will cease selling incandescent GLS A-shaped lamps of all wattages as well as 60 W candle and golf ball shaped incandescent lamps.

All the above has been happening in the UK, but there are other moves afoot in the European Union (EU) which will eventually replace this initiative by making the withdrawal of products compulsory rather than voluntary. Specifically, European leaders are committed to reducing primary energy consumption by 20% relative to the projected consumption in 2020. One element designed to meet this commitment is the draft regulation, endorsed by the Member States Committee in 2008, which calls for incandescent lamps to be phased out from the EU market in a process starting in 2009.[2] The criterion to be used to determine if a light source will be allowed on the EU market is the energy label class as applied to household lamps. This label has classes ranging from A to G. with A being the most energy efficient class and G the least. Table 1 shows the energy label class for various lamp types currently available. Table 2 shows the energy label classes that will be allowed to put on the

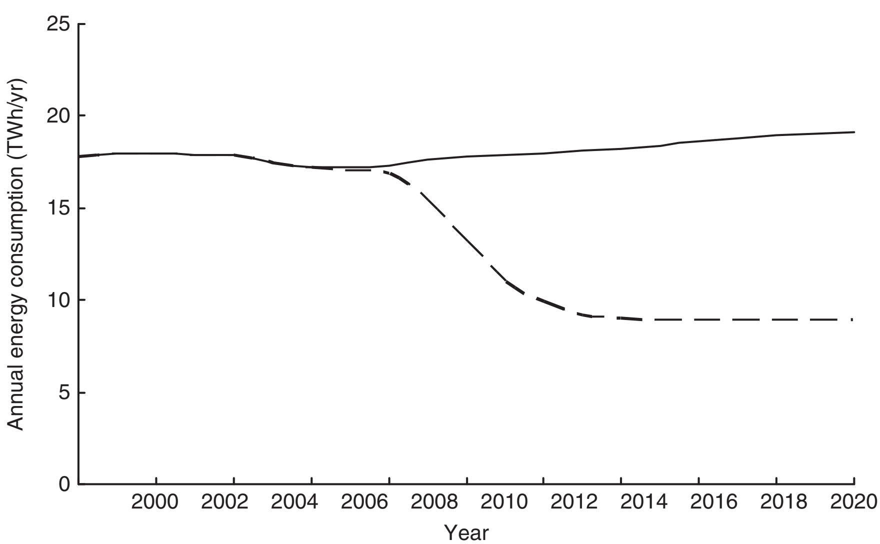

Figure 1 Predicted (solid line) and hoped-for (dashed line) annual energy consumption for domestic lighting in the UK

EU market for different wattages and light outputs of household lamps after different dates under the proposed regulations. One obvious division in Table 2 is between frosted lamps and clear lamps. Frosted lamps are those that distribute light approximately equally in all directions, e.g., pearl incandescent lamps. From Table 2, it is apparent that after September 2009 all frosted lamps placed on the EU market will have to be of energy label class A, effectively eliminating incandescent lamps and replacing them with compact fluorescent lamps (CFLs). It should be noted, that this regulation does not make it illegal to use incandescent lamps after September 2009, but it will make it increasingly difficult to obtain them. As for clear lamps, Table 2 shows that the allowed energy classes are more and more restricted until by September 2012, all clear household lamps on the EU market will have to be at least energy label class C which will effectively eliminate incandescent lamps from the market, but will allow some forms of tungsten halogen as well as CFLs to be sold. And this is not the end. There is provision for a review of the regulations in 2014 and the intention to enhance the requirement for clear lamps to a minimum of class B in 2016.

The energy label given to a lamp depends on the lumen output and the wattage of the lamp. To determine if a CFL without an integrated ballast is energy label class A the wattage (W) of the lamp has to be less than or equal to the number calculated from the lamp lumen output (L) using the Equation (1).

$$W \leq 0.15\sqrt{L} + 0.0097L \quad (1)$$

For other lamp types, Equation (2) is used

$$W \leq 0.24\sqrt{L} + 0.0103L \quad (2)$$

If the lamp cannot meet the requirements for energy label class A, an energy efficiency index is calculated, the energy efficiency index (E_I) being the ratio of the actual wattage (W) and the reference wattage (W_R) of the lamp.

Table 1 EU energy label classes for different lamp types

Lamp type	EU energy label class
Incandescent	E, F, G
Mains voltage halogen	D, E, F
Low-voltage halogen	E
Halogen IRC 50% energy saver	B
Retro LED	B
Compact fluorescent with cover	B
Bare compact fluorescent	A

Table 2 Allowed energy label classes for domestic lighting lamp types proposed for different dates by the draft EU regulation

Wattage and light output limits	Envelope type	Stage 1 09/2009	Stage 2 09/2010	Stage 3 09/2011	Stage 4 09/2012	Stage 5 09/2013	Stage 6 09/2016
≥80 W; >950 lm	Clear	ABC	ABC	ABC	ABC	Increased	AB
	Frosted	A	A	A	A	quality	A
≥65 W; >725 lm	Clear	ABCDE	ABC	ABC	ABC	requirements	AB
	Frosted	A	A	A	A		A
≥45 W; >450 lm	Clear	ABCDE	ABCDE	ABC	ABC		AB
	Frosted	A	A	A	A		A
≥7 W; >60 lm	Clear	ABCDE	ABCDE	ABCDE	ABC		AB
	Frosted	A	A	A	A		A

Table 3 Energy label classes corresponding to different ranges of the energy efficiency index

Energy label class	Energy efficiency index (E_I)
B	<0.60
C	= or >0.60 and <0.80
D	= or >0.80 and <0.95
E	= or >0.95 and <1.10
F	= or >1.10 and <1.30
G	= or >1.30

The reference wattage of the lamp is given by Equation (3).

$$W_R = 0.88\sqrt{L} + 0.049L \qquad (3)$$

Table 3 shows the energy label class assigned to different ranges of the energy efficiency index.

Clearly, change is coming to the domestic lighting market. The light source that has dominated domestic lighting since the birth of electric lighting is going to be squeezed out and others with different characteristics will replace it. Some of these are already on the market, some are entering the market now and some have yet to make an entrance. The householder is certainly going to have plenty of lamp types to choose from, all of them claiming to be ‘low energy’. What follows is a summary of the main lamp types and their characteristics.

Figure 2 Examples of CFLi lamps, stick and spiral

Figure 3 An example of a CFLni lamp

2. Alternative light sources

2.1 Compact fluorescent lamps

At the moment, CFLs are being promoted as the obvious replacement for incandescent lamps. CFLs are divided into two types, namely integrated (control gear being built into the lamp base CFLi) (Figure 2) and non-integrated (separate control gear CFLni) (Figure 3).

Both types are used domestically, but the CFLni lamps are predominantly used for commercial applications as the size of the lamp and luminaire is generally considered inconsistent with the domestic environment. However, Part L of the Building Regulations used in England and Wales now require a percentage of non-integrated lamps to be installed in new homes, the non-integrated CFLni being chosen because luminaires

Table 4 Light outputs for different wattages of incandescent and CFLi lamps

Description	Lamp type	Wattage	light output (lm)
Incandescent	25 W, Pearl	25	225
GLS	40 W, Pearl	40	420
	60 W, Pearl	60	710
	75 W, Pearl	75	940
	100 W, Pearl	100	1360
	150 W, Pearl	150	2180
Incandescent	25 W, Coated	25	200
Soft output	40 W, Coated	40	370
	60 W, Coated	60	630
	75 W, Coated	75	840
	100 W, Coated	100	1200
CFLi	5 W, Stick	5	230
Stick shape	8 W, Stick	8	420
	11 W, Stick	11	600
	14 W, Stick	14	810
	18 W, Stick	18	1100
CFLi	5 W, A Shape	5	200
GLS look-a-likes	8 W, A Shape	8	380
	12 W, A Shape	12	610
	16 W, A Shape	16	815
	20 W, A Shape	20	1160
CFLi	5 W, Spiral	5	300
Spiral shape	8 W, Spiral	8	500
	12 W, Spiral	12	725
	15 W, Spiral	15	1000
	20 W, Spiral	20	1350
	23 W, Spiral	23	1550

designed to take them cannot easily be fitted with incandescent lamps.

The popular and already widely used replacements for incandescent GLS lamps are the integrated CFLi which are available for most wattages, and will generally save around 80% in energy usage and increase life by a factor of between 6 to 12 times over incandescent lamps.

Some confusion has arisen within the domestic market regarding the proper equivalent replacement wattages, with users sometimes complaining that the lamps are not as bright as the incandescent lamps they have replaced. This is invariably due to two reasons. Domestic CFLi lamps are not directly compared by The Lighting Association or manufacturers to standard GLS incandescent lamps for comparative light output, but are in fact compared to ‘soft output’ lamps which have a lower light output. For comparison and guidance, Table 4 will help to identify suitable replacements for both standard incandescent and soft output incandescent lamps based on matching light output. As can be seen, the introduction of the spiral form of CFLi lamps has improved the lumen output and has a greater wattage equivalent range, which may prove more acceptable within the domestic environment.

The other factor that makes the CFL less attractive is that a GLS lamp is generally considered to be a point source of light, the filament being mounted in a localised position within the glass outer envelope, making the lamp seem brighter when compared directly against a CFLi lamp. A CFL is primarily a long fluorescent tube bent into a compact shape to suit the size and dimensions of a light bulb. The light output is spread evenly over the whole of the glass tube giving it a much softer appearance than that of an incandescent lamp, hence the accepted comparison with soft output incandescent lamps by both manufacturers and The Lighting Association.

Other issues that arise in the domestic environment include the time that CFLs take to achieve full output (~1 min). If used in a room which is only occupied for short periods, then the CFL is not the ideal replacement choice, but where the lamp is left on for much longer timescales and can be placed in such fixtures as table lamps, floor standing uplighters, wall lights or ceiling fittings, then the CFLi is an acceptable option.

The colour quality of CFL is also a factor, which requires a brief explanation, as occasionally, some domestic users have asked why the lamps have a slightly less warm appearance than incandescent lamps. Although the Colour Rendering Index of compact fluorescents is good (generally in excess of 80 compared to the GLS lamp at 100) and the correlated colour temperature matches that of incandescent lamps (2700 K), the CFL does not operate directly on the black body locus as tungsten lamps do, thereby causing a slight colour shift which is perceived as a less than perfect colour appearance comparison.

Control of the lamps is also an issue, but given that the technology is fluorescent, dimming is impractical with domestic resistive dimmers, which are basically designed to limit current flowing through a piece of metal (the filament), whereas CFLs require high-frequency controllers which control the current flowing through the gas discharge. This can create non-acceptance of the compact fluorescent technology within the household and is not likely to be solved in the near future. This particular solution may well lie with the use of replacement tungsten halogen lamps, which are covered in detail in the next section.

Figure 4 A low-voltage tungsten halogen dichroic lamp

2.2 Tungsten halogen lamps

Tungsten halogen lamps have been used within the domestic environment for many years, mainly as dichroic or aluminium, low voltage or mains operated spotlights (Figure 4), typically as recessed MR16 downlights.

However, recent developments have produced an alternative tungsten halogen lamp designed to replace the GLS lamp. These lamps are not as efficient as compact fluorescents, but have a better all round performance than incandescent lamps and will save either 30 or 50% of energy depending on type. Instead of a tungsten filament mounted inside a glass outer bulb, there is a halogen capsule controlled by electronic control gear inbuilt within the lamp base (Figure 5). The lamp may then be inserted into either a mains-connected conventional bayonet cap or Edison screw lampholder exactly as a GLS filament lamp. The halogen capsule employs an infrared coating (IRC), which ensures that the filament reaches the required operating temperature from a combination of electrical current directly heating the filament, plus

Figure 5 A tungsten halogen retrofit lamp

radiated heat reflected back from the IRC surrounding the filament. It is lightweight, easy to make, provides a perfect colour quality instant light, can be dimmed easily (increasing life), has no significant disposal problems but is more expensive than GLS lamps. However, lamp life is increased from 1000 to 4000 h which when allied to the energy savings, will ultimately save on total cost of ownership for the household.

The main advantage of these tungsten halogen lamps is that they can be used wherever GLS lamps are currently utilised in exactly the same way, including dimming, providing the user with an alternative choice to CFLs, although with smaller energy savings.

2.3 Light emitting diodes

A light emitting diode (LED) is a compound semiconductor device that converts electrical energy directly into light. Recent developments have enabled luminous efficacies of 130 lumens per watt to be achieved for the basic white LED alone in the laboratory. Turning this into a practical and efficient lamp or luminaire currently requires a highly technical manufacturing process to ensure that the LED junction temperature is maintained at a suitable level in order to produce a useful light output and suitable correlated colour temperature without compromising the very long service life. LEDs are currently integrated into practical formats for both internal and external applications. However, for domestic internal usage, these formats are, at present, only marginally better than tungsten halogen lamps, with practical luminous efficacies around 20–30 lumens per watt. It is predicted that by 2010, luminous efficacies will be at or above 40 lumens per watt which will enable LEDs to be used within domestic dwellings in line with the lighting requirements of Part L of the Building Regulations.

Currently, the best light outputs are achieved with LEDs of cooler colour appearance (4000 K) whereas warmer lamps similar to tungsten halogen (3000 K) suffer from slightly lower efficacies, due mainly to the conversion of the blue light generated by the LED into white light through a yellow phosphor coating. The latest technology has produced a newer type of LED which utilises ‘flip chip’ technology to enhance thermal management, which results in a higher light output. This technology has already been incorporated into newly available LEDs which may be used in the home and for commercial applications (e.g. hotel foyers, corridors, toilets, etc.). With a lifetime of around 40,000 h, this effectively means that these LEDs used in the home are likely to witness the change of at least a couple of homeowners if we take 1000 h as normal domestic annual usage. Perhaps 25,000 h may be a more appropriate life for the domestic LED, which would allow higher current through the LED and thus create a higher light output. Such a development would enable earlier compliance with Part L and

Figure 6 Examples of LED commercial downlights and LED light engines

subsequently a much higher uptake for both existing and new dwellings.

Further developments include newer phosphor technology in combination with very efficient nonintegrated drivers. The LED is mounted beneath a cover, which in turn is treated with a very even phosphor coating, rather than individually coating the LED (Figure 6). In combination with much improved temperature control, this technique produces a very smooth and efficient light output of over 60 lumens per watt. This particular system is intended primarily for the professional market in combination with commercial downlighters. The normal dimensions of a commercial downlight may be considered too big and, therefore inappropriate for the domestic market, as the popular choice in the home appears to be a fixture with a more discreet appearance which matches the size of current tungsten halogen spotlamps (MR16 s).

Currently, there are many types available that are a physical match to an MR16 lamp and will operate either from a low-voltage transformer suitable for halogen lamps or directly from the mains supply. In the case of low-voltage conversions, the LED load can be very small at 1 or 2 watts, and will only produce a light package of about 30–40 lumens (in total) but may have problems staying on as the low-voltage transformer is usually designed for much higher loads.

A more practical LED solution for domestic lighting at this time appears to be a mains operated version with an integral driver, which can be manufactured in various formats providing equivalent types to GU10 spotlights, incandescent GLS lamps and R63 spotlamps (Figure 7). These LED versions can replace existing equivalent incandescent lamps on a point for point basis without the need for additional wiring, but in the case of the GU10, may require an alternative downlight fixture as the lamp is taller than a conventional dichroic or aluminium lamp.

2.4 Organic light emitting diodes

Organic light emitting diodes (OLEDs) are considered as light sources for the future and are, in all realistic terms, exactly that. Research has been going on since 1993 and so far, the most practical usage appears to be with mobile phones and TV sets (Figure 8). It is likely that in the near future, another use may be localised display lighting, but as a light source for general lighting, it will probably not be available for several years to come.

The basic principle of OLEDs is to pass electricity through one or more extremely thin organic semi-conductive layers. These layers are sandwiched between a negatively charged layer of aluminium and a positively charged transparent layer of indium tin oxide. The whole sandwich is then attached to a sheet of glass or other transparent material known as a substrate. The current applied to the aluminium layer is conducted to the positive layer through the organic film which then

GU10 spot lamp E27 A55 bulb lamp E27 NR63 spot lamp

Figure 7 Examples of 7 W LED integrated driver retrofit lamps

Figure 8 A warm white coloured OLED research sample measuring 35 $mm^2 \times 35\ mm^2$ (Photo: Philips)

emits light. Different materials emit different colours of light.

As the OLED is a solid device, this potentially could have some bearing on the amount and type of commercial application, but developments based around flexible substrates would open a whole new concept of lighting. Imagine closing your curtains in the evening and they also become the primary or secondary light source to the room. Or maybe the OLED takes the shape and place of the decorative glass or plastic shades that would normally cover the lamps – a light fitting without any traditional lamps, or indeed becoming the lamp itself. The potential for OLEDs appear to be limited only by the designer's imagination, and as such are considered to be the next stage of evolution for LED technology.

3. A problem or an opportunity

The luminous efficacies in Table 5 suggest that there should be no difficulty in meeting the annual energy consumption target shown in Figure 1 provided compact fluorescents are the main lamp type used to replace incandescents. However, it is instructive to consider why the CFL, which has been available for more than 20 years, has made so little headway into the domestic lighting market, so little that persuasion is now being abandoned and compulsion introduced. The answer is that the incandescent lamp has a number of advantages to offset its poor luminous efficacy and short life. It is cheap, has good colour

Table 5 A retrofit lamp comparison table

Light source	Light output (lm)	Luminous efficacy (lm/W)	Colour rendering index	Dimming availability
Incandescent	225–2180	9–15	100	All
Low-voltage halogen dichroic spotlight 36°	230–925	12–19	100	All
Low-voltage halogen dichroic IRC spotlight 36°	230–925	17–24	100	All
CFLi Stick	230–1100	46–61	82	Some
CFLi GLS look-a-like	200–1160	40–58	82	Some
CFLi Spiral	300–1550	60–67	82	Some
LED Retro	150 (Warm)	21 (Warm)	83 (Warm)	Some
LED Retro	230 (Cool)	33 (Cool)	70 (Cool)	Some

properties, provides full light output almost immediately and is easily dimmed. Relative to this, the compact fluorescent is more expensive, has inferior colour properties, takes a noticeable time to produce full light output and is not easily dimmed. What the failure to achieve the widespread adoption of CFLs for domestic lighting implies is that there is more to the choice of a light source for domestic lighting than its luminous efficacy and life. And the factors that influence the householders' choice extend further than the light source characteristics. Interviews with householders have revealed that fashions in interior design have a marked influence on the lighting used in homes with a consequent impact on energy consumption.[3] This poses a problem for those concerned with reducing the energy consumption of domestic lighting. Removal from the market of light sources with low-energy luminous efficacies will certainly bring about a reduction in energy consumption, but how fast that will happen and how much resistance is experienced will depend on how adequate the lighting produced is seen to be. The reduction in energy consumption will be achieved more rapidly and with less resistance if the resulting lighting could be shown to be as good as if not better than that achievable with incandescent lamps. For this to occur, lighting practitioners need to be encouraged to develop designs for domestic lighting that meet householder's desires. In this sense, the fading away of the incandescent lamp represents an opportunity for lighting manufacturers and designers to show what they can do.

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