Life Cycle Assessment of Ultra-Efficient Lamps

Navigant Consulting Europe, Ltd.

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5th May 2009

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Glossary

AP	Acidification Potential
ARD	Abiotic Resource Depletion
CCT	Correlated Colour Temperature
CERT	Carbon Emissions Reduction Target
CFC	Chloro-Fluoro-Carbon
CFL	Compact Fluorescent Lamp
CH4	Methane
CIE	Commission Internationale de l'Eclairage
CMH	Ceramic Metal Halide
CML2001	Centre of Environmental Science, University of Leiden, 2001 LCIA Dataset
CO2	Carbon Dioxide
CRI	Colour Rendering Index
DCB	Dichlorobenzene
DEELS	Domestic Energy Efficient Luminaires
Defra	Department for Environment, Food and Rural Affairs
DOE	US Department of Energy
EA	Environment Agency
EC	European Community
EDIP2003	Environmental Design of Industrial Products 2003 LCIA Dataset
EDP	Ecosystem Damage Potential
EEC	European Economic Community
EIPRO	Environmental Impact of Products
ELC	European Lamp Companies Federation
EP	Eutrophication Potential
EPBD	Energy Performance of Buildings Directive
ESR	Energy Savings Recommended
EST	Energy Savings Trust
EU	European Union
EuP	European Energy-using Products Directive
FAETP	Freshwater Aquatic Ecotoxicity Potential
FAETP100	FAETP over the next 100 years
FL	Fluorescent Lamp
GE	Generic Electric
GLS	General Lighting Service (lamp)
GWP	Global Warming Potential
GWP100	GWP over the next 100 years

HID	High Intensity Discharge (lamp)
HMSO	Her Majesty's Stationery Office
HTP	Human Toxicity Potential
HTP100	Human Toxicity Potential over the next 100 years
HWL	Hazardous Waste to Landfill
ISO	International Standards Organisation
ITFSP	International Task Force for Sustainable Products
LA	Local Authority
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LLDPE	Linear Low Density PolyEthylene
LPW	Lumens Per Watt (i.e., efficacy)
LU	Land Use
MAETP	Marine Aquatic Ecotoxicity Potential
MAETP100	MAETP over the next 100 years
MH	Metal Halide
MLm-hr	Megalumen-hour
MR	Multifaceted Reflector
NHWL	Non-Hazardous Waste to Landfill
O2	Oxygen
O3	Ozone
ODP	Ozone Depleting Potential
ODP10	ODP over the next 10 years
OLED	Organic Light Emitting Device
PAN	Peroxyacetyl Nitrates
PBB	PolyBrominated Biphenyl
PBDE	PolyBrominated DiphenylEther
PCB	PolyChlorinated Biphenyl
pc-LED	phosphor converting Light Emitting Diode
PET	Polyethylene Terephthalate
PO4	Phosphate
POCP	Photochemical Ozone Creation Potential
RWL	Radioactive Waste to Landfill
SCP	Sustainable Consumption and Production
SO2	Sulphur Dioxide
SSL	Solid State Lighting
TAETP	Terrestrial Ecotoxicity Potential
TAETP100	TAETP over the next 100 years
TV	Television

TWh	Terawatt-hours (of electricity, 10^12 watt-hours)
UEL	Ultra Efficient Lamp
UK	United Kingdom
US	United States
USL	Ultra Sustainable Lamp
UV	Ultra Violet
VOC	Volatile Organic Compound
WC	Water Closet
WEEE	Waste Electrical and Electronic Equipment

Executive Summary

There are approximately 25.1 million homes in the UK, with slightly more than 750 million lamps actively in service. Electricity consumption for domestic lighting is slowly increasing, with the Market Transformation Programme projecting that the domestic lighting sector could reach 19.2 TWh by 2020 (Defra, 2008). Government and industry are working together to try and transform the lighting market and encourage energy-efficient lighting.

This study evaluates and sets a common, normalised basis for the evaluation of environmental impacts associated with all stages of the life cycle of ultra-efficient lamps (UELs) for the domestic sector. UELs are products that emit 100 or more lumens of white-light for each circuit watt of normal household power consumed. The products studied in this report would all be covered under Lot 19, Parts 1 and 2 from the Preparatory Studies for Eco-design Requirements of EuPs.

Table ES.1 Performance Criteria for an Ultra Efficient Lamp

UEL Metric	Numeric Value
Lamp and Ballast Operating Efficiency (i.e., Lamp and Ballast System Efficacy)	100 lumens / Watt or higher
Quality White Light	CCT 2500 – 4000K; Falling within region defined by 0.01 change in u’v’ of the black body locus

This study evaluates four products with the potential to be UELs:

- Light Emitting Diodes – integrally ballasted
- Light Emitting Diodes – dedicated luminaire
- Ceramic Metal Halide
- T5 Linear Fluorescent

Integrally Ballasted LED Lamp

Dedicated LED Luminaire

Ceramic Metal Halide

T5 Linear Fluorescent

Of these four light sources, none have achieved 100 lumens per system Watt by mid-2009, however they all have the potential of reaching that level by 2014. Although all of these lighting technologies are found in the commercial sector, particularly in office and retail applications, they are rarely used in the domestic sector. Reasons for the lack of domestic market penetration include cost, lumen package and controllability, light quality, lamp availability and fixture requirements and designs.

Although the domestic market penetration is very low at this time, all four of these technologies are expanding their respective market shares in the commercial sector, and are expected to continue to grow into that sector. Historically, more efficient and expensive light sources have entered the commercial market first, later transitioning to the domestic market (e.g., T8 linear fluorescent lamps, halogen lamps). For this reason, these four lamp types have been included in the scope of this study, as they are expected to penetrate the domestic sector in the future, albeit in specific niche applications at first.

The four market leading lamp manufacturers are: Philips (based in the Netherlands), OSRAM (based in Germany), General Electric (based in the U.S.) and Havells-Sylvania (based in Europe). While these companies are based in either Europe or the United States, the majority of their lamp manufacturing operations are located in China. Dependence on the Chinese lamp manufacturing industry is projected to intensify, as the transition is made away from incandescent lamps, and the uptake of CFLs and LED lamps increases. Traditionally European lamp manufacturers have supplied EU countries with incandescent lamps produced within the EU, however as incandescent lamps are to be phased out under the Eco Design Framework Directive, concerns have been expressed over the projected job losses associated with demand being met entirely by energy efficient lamps manufactured in China.

Within the UK, there are several small businesses manufacturing dedicated LED luminaires, sourcing raw materials locally and overseas. The nature of LEDs enables small manufacturers to develop niche products and compete with larger luminaire manufacturers for the rapidly growing market. In conducting the stakeholder interviews for this study, it transpired that there are many small UK based companies that manufacture and assemble LED luminaires for the UK and European markets. The LED lighting market is recognised as a high growth area, and consequently the opportunity exists for further future small business start-ups within the UK in order to meet the growing demand.

Of the more than twenty lighting industry experts interviewed for this study, no supply-chain constraints or material shortages were identified for any of the UELs analysed in this report.

This study uses the ecoinvent life cycle impact assessment database to assess (1) raw material production, (2) manufacture, (3) distribution, (4) use / consumption and (5) end-of-life impacts through fifteen environmental indicators.

The use/consumption stage dominated environmental impacts for all four lighting systems, representing 54% or more of the impacts across all fifteen categories and four lamp types. Setting aside human toxicity, freshwater aquatic ecotoxicity, radioactive waste landfill and hazardous waste landfill (discussed separately below), the energy in use stage represents 85% or more of the impacts in the eleven remaining categories.

The integrally ballasted LED lamp did not score well on hazardous waste landfill and radioactive waste landfill because of its abbreviated operating life assumption (i.e., 20,000 hours). That is, compared to the dedicated LED luminaire, which contains similar parts and components, the dedicated LED luminaire has a smaller impact due to its ability to amortise the impacts over a longer assumed operating life (i.e., 50,000 hours). Also, while the energy in use phase had the dominant impact relative to all other life-cycle assessment stages, the aluminium heat sinks in the two LED products contributed to their relatively poor scores in human toxicity and freshwater aquatic ecotoxicity impacts.

The ceramic metal halide and T5 fluorescent lamp systems both did not score well in hazardous waste landfill due primarily to its in use energy consumption and secondarily because of the printed circuit board (which is assumed to be sent to the landfill 80% of the time).

Some of the other life cycle phases were found to make very little contribution to the environmental impacts of the luminaire systems. For all four UELs analysed, the production of the packaging and the distribution by road and by sea all contribute less than 1% to the total impact.

For comparative purposes, a 100 watt incandescent lamp and 23 watt integrally-ballasted compact fluorescent lamp were also evaluated for their relative impacts. Normalising for light output, it was found that the impacts of the incandescent lamp far out-weighed the impacts of each of the four UELs evaluated, and indeed, that of the integrally-ballasted CFL as well. The impacts for the incandescent lamp were driven almost exclusively by the energy in-use phase, which represented between 95% and 99.9% of the impacts across the fifteen life-cycle assessment categories. Looking at a few specific indicators of interest, it was found that:

- comparing the performance of an incandescent lamp to a T5 fluorescent lamp, the incandescent produces 5.7 times more carbon dioxide per unit of delivered light;
- the integrally ballasted CFL had a similar general profile to that of the integrally-ballasted LED, although the LED had slightly higher impacts in all categories due to the aluminium content in the heat sink; and
- the incandescent lamp is the worst performing light source evaluated in this analysis due to its high energy consumption per unit of light produced.

In order to evaluate the fifteen impact measures of interest across the four UELs and two comparative light sources considered, spider graphs were prepared. Each of the fifteen impacts is represented (and labelled) by a spoke in the web. Those products having the greatest impact of the set analysed are the greatest distance from the centre of the web. The other products are then normalised to that impact, so the distance from the centre denotes the severity of the impact relative to that worst performing source considered. Those sources with the least impact will have their circle close to the centre and those with the greatest impact would be on the outer perimeter of the web. All of the data plotted in this graph is also normalised for light output (i.e., a fixed quantity of light output for a defined period of time, 1 million lumen-hours).

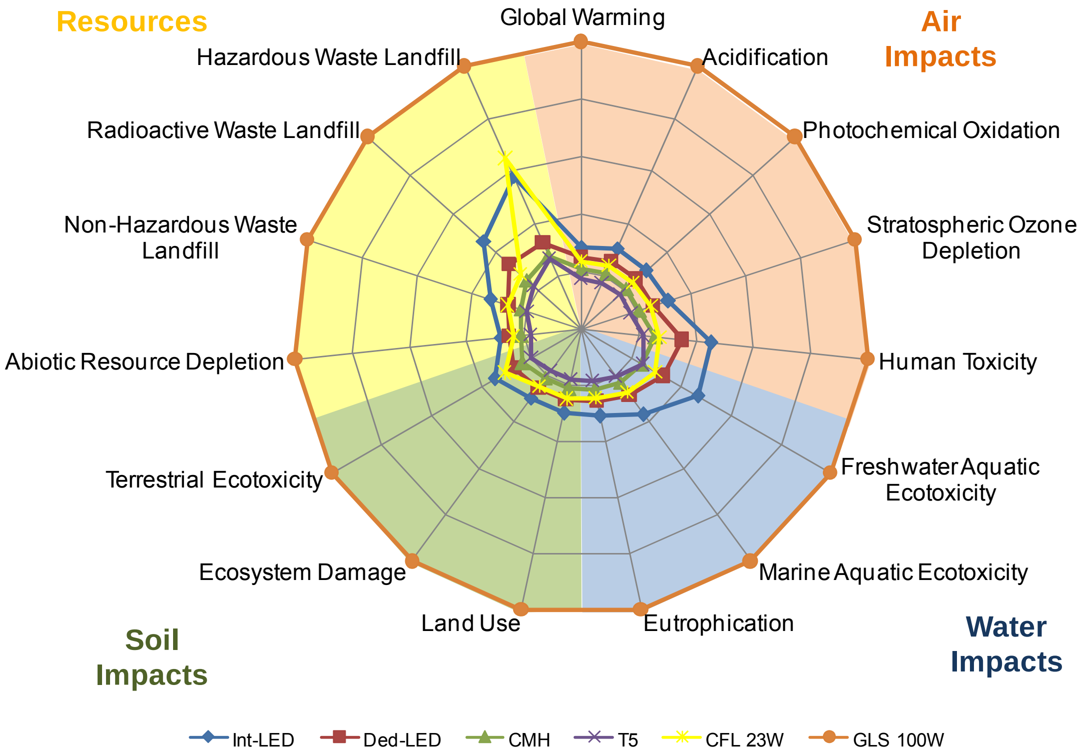

Figure ES.1 Relative Life-Cycle Assessment Impacts of the Lamps Analysed

It is clear from this figure that the incandescent lamp has the highest impact per unit lighting service of all the sources considered (it occupies all of the outermost points on the chart). This result is intuitive because this lamp has the lowest efficacy of the four UELs and two reference lamps considered.

The next worst performer is the integrally ballasted LED, followed by the integrally ballasted compact fluorescent lamp. Apart from the incandescent lamp, these two sources had the shortest analytical period, and therefore had a smaller amount of lighting service over which to amortise the environmental impacts. The best performer was the linear fluorescent T5 system, which had an impact, in total, of just 20% that of the incandescent lamp. From this analysis, we would therefore conclude that, on the basis of the data considered, the T5 UEL is the best of the lighting technologies investigated in 2009.

A hypothetical analysis was also prepared, to find out how the graphs would change if the system efficiencies of the UELs improved between 2009 and 2014, as assumed below:

- Integrally ballasted LEDs improve by 70%, going from 60 lm/W to 102 lm/W
- Dedicated LED Luminaire improve by 120%, going from 65 lm/W to 143 lm/W
- CMH improve by 35%, going from 77 lm/W to 104 lm/W
- T5 improve by 10%, going from 93 lm/W to 102 lm/W
- CFL improve by 10%, going from 69 lm/W to 76 lm/W
- Incandescent GLS assumed to have no improvement in efficacy

The results of this hypothetical ("future") analysis are presented in Figure ES.2 below. The use phase has already been demonstrated to be the most significant for the majority of the environmental impacts, so it was expected that improving the efficacies of the UELs would change their relative environmental performance, and so it proved. The UELs all improved their performance, and as such, moved closer to the centre of the web, reducing their associated environmental impacts. The dedicated LED source was found to be the best performing in this future scenario, with the smallest surface area covered in the spider plot. If the anticipated efficacy improvement in LED is realised, it would enable this UEL to outperform or match the other luminaire systems for every one of the environmental indicators, with the exception of hazardous waste landfill. With the efficacies very close in this scenario, the T5 and CMH impacts are similar.

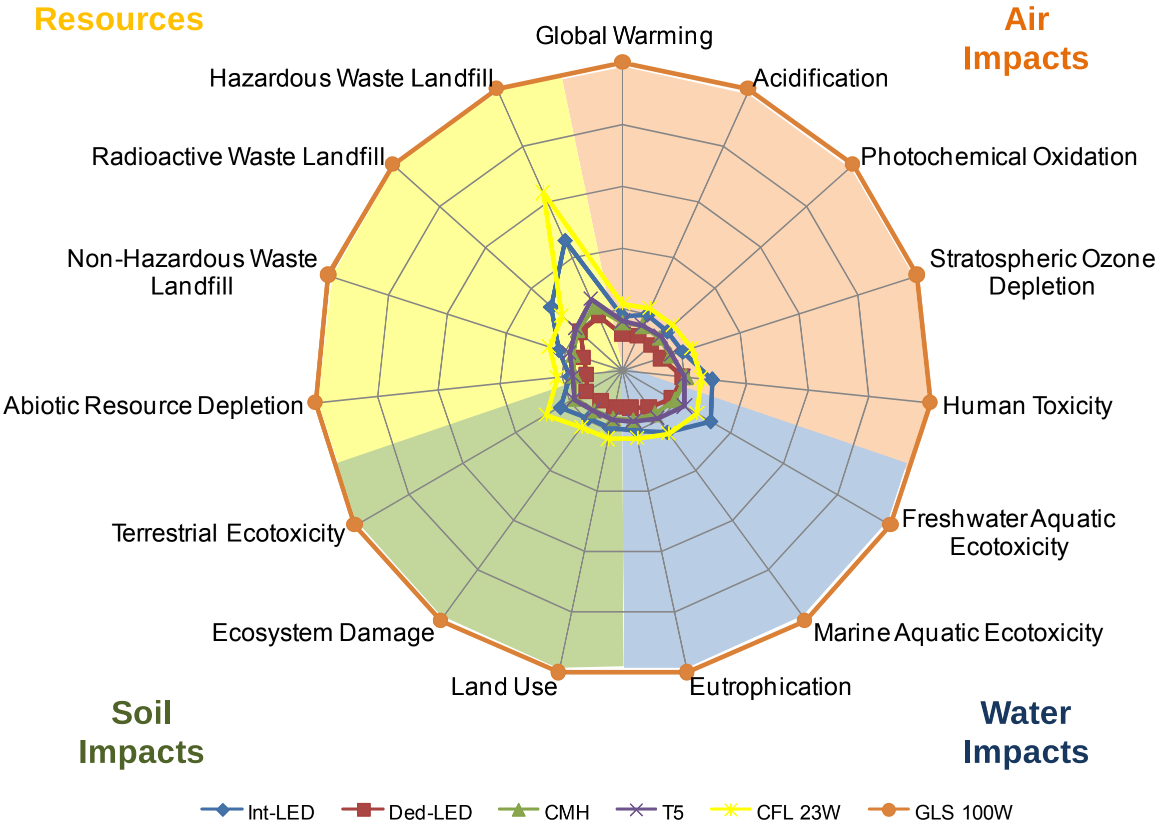

Figure ES.2 Future Relative Life-Cycle Assessment Impacts of the Lamps Analysed

The important finding from these graphs is not necessarily the minor relative differences between the four different UELs analysed, but instead the great reduction in environmental impacts that will result from any of the four UELs (or indeed, the CFL) replacing an incandescent lamp. Environmental impact reductions on the order of 4 to 5 times are possible through transitioning the market to these new, more efficacious sources. Because of the dominant role of energy consumption in driving the impacts, continued focus on efficacy targets and incentives is worthwhile. Furthermore, the greatest environmental impact after energy in-use for the LED sources is the aluminium heat sink, which would be reduced as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat).

Finally, this study outlines a few possible actions which the Government and others may wish to consider in order to maximise the potential overall environmental benefits associated with UELs. These activities should be taken in the context of EU regulatory action on domestic lamps, already established for LOT 19 Part 1 (non-directional lamps) and under development for LOT 19 Part 2, directional lamps and luminaires. Some of the practical actions for intervention discussed include:

- Research Support – co-sponsor research to advance the UK-knowledge base of UEL technologies, developing domestic IP (i.e., “the science of today is the surplus of tomorrow”);
- Business Incubator – actively work to encourage and nurture small and medium size enterprises entering the UEL supply chain, either as a manufacturer or component supplier;
- Market Enforcement / Monitoring – protect consumers from unscrupulous manufacturers making exaggerated claims, while complimenting existing programmes like the Energy Savings Recommended label;
- Informational Labels – as part of a consumer awareness campaign to shift thinking about light from watts (i.e., of an incandescent lamp) to lumens of service;
- Bulk Procurement – potentially aggregating procurement offices of a few government departments. Offer contract awards / competitions to promote efficacy; prize money and/or large supply contract;
- Affordability – direct financial support for consumers and/or the supply chain, perhaps supported by revenue from the Carbon Emissions Reduction Target scheme;
- Fiscal Instruments – remove trade barriers applied to energy-efficient products; and
- Better Regulation – support development of harmonised, international test methods and quality / performance standards.

1 Introduction and Objectives

1.1 Defra's Life Cycle Assessment Programme

The Department for Environment, Food and Rural Affairs (Defra) has initiated a series of product roadmaps that are working to help better understand the environmental and other sustainability impacts of certain products and thereby identify ways in which these impacts can be mitigated. The overall aims of these life cycle assessment roadmaps are:

- To identify the impacts areas across each product's full life cycle;
- To define a vision for each product in order to address its impact and ultimately make it more sustainable; and
- To outline a course of action – covering the whole time spectrum for measures with a focus on the high impact life cycle stages.

All the roadmaps are developed gradually and collaboratively with a wide range of stakeholders. The ten roadmaps that are examined in this phase of the Defra programme are: clothing; domestic lighting; electric motors; fish and shellfish; milk; passenger cars; plasterboard; televisions; windows; and WCs.

These ten priority areas were selected because they are thought to be the most harmful product groupings from an environmental perspective at both a domestic and international level. A study called 'The Environmental Impact of Products' (EIPRO), published in May 2006 was used as the principal source of evidence, showing that four product groupings account for 70-80% of all environmental impacts, these are:

- Food and drink – 20-30% of impacts.
- Passenger transport – 15-35% of impacts.
- Housing (including buildings, construction and appliances[1]) – 20-35% of impacts.
- Clothing – 5-10% of impacts.

The observed impacts at the various life cycle stages can take on an environmental form, such as greenhouse emissions, air and water pollution, resource depletion and biodiversity loss or they can be of a social form, such as child labour, health and safety risks, poor working conditions and low wages.

The roadmap process is designed to work in close proximity with the stakeholders in order to agree both an accurate characterisation of the impacts and a range of practical actions to intervene and improve sustainability performance. Possible interventions could include:

- Voluntary agreements;
- Introduction/improved product standards;
- Improved labelling;
- Support for new businesses;
- Greater information provision to consumers;
- Sustainable procurement;
- Fiscal instruments – environmental levy; and
- Better regulation.

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[1] Including TV's, Domestic Lighting and Electric Motors.

Domestic Lighting Roadmap – Lighting is one of the priority products for Defra's Sustainable Consumption and Production (SCP) group. The European Energy-using Products (EuP) Directive identified lighting as product that uses significant quantities of energy and constitutes large sales volume in the EU. As such, it is a priority product that should be evaluated and considered for regulation and market interventions to reduce the environmental impacts and burdens.

In accordance with the EU Eco-design of the EuP Directive, environmental performance improvements will be required for EuPs. This includes lighting products over a phased period. Other Directives such as, the Waste and Electrical and Electronic Equipment (WEEE) Directive, and the Restriction of Hazardous Substances Directive are already in place, and since they also cover lighting products, are working to reduce some of the environmental impacts associated with lighting.

1.2 Life Cycle Assessment

This report presents a Life Cycle Assessment (LCA) study that was conducted on a limited number of lamps and lighting systems. A LCA is an analytical technique that quantifies the environmental and sustainability impacts across a range of categories for a product over its entire life cycle. The overarching aim of an LCA is to study and compare different products to determine where they have their greatest environmental impact. This report is consistent with the life cycle stages outlined by ISO 14062-2002, "Environmental management -- Integrating environmental aspects into product design and development." Figure 1.1 illustrates the key phases of the LCA process. A brief description on each of these phases follows the diagram.

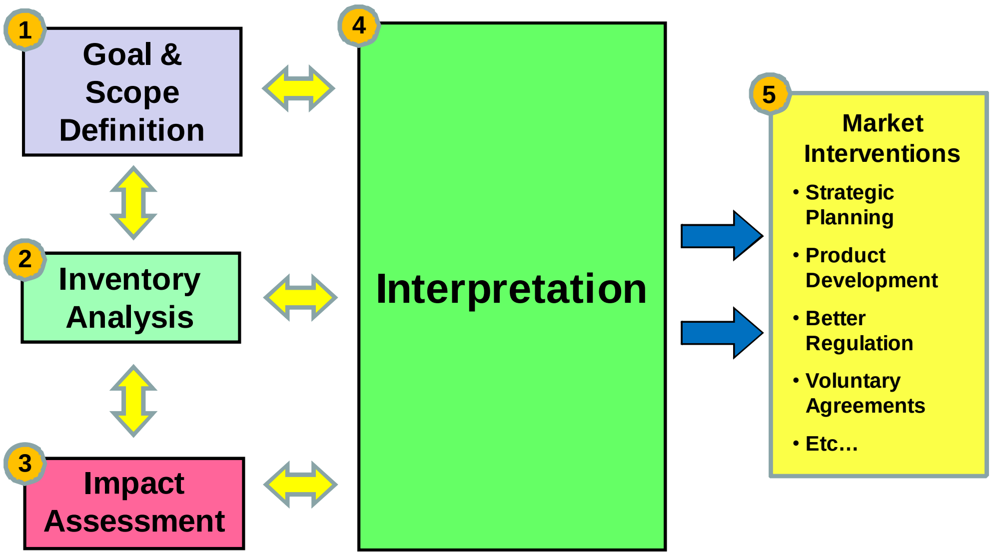

Figure 1.1 Key Phases of the LCA Process

1. ***Goal & Scope Definition:*** The first phase of an LCA is to specify the goal and scope of the study. At this stage the functional unit[2] is defined, the system boundaries are established, and a method used to assess potential environmental impacts is described.

---

[2] The functional unit is quantified performance of the product/service system for use as a reference unit in the LCA study.

2. ***Inventory Analysis:*** The second phase is characterised by the assimilation of data and the modelling of flows for the product under study. The data collected and used in this phase includes all environmental and technical quantities for all relevant unit processes within the system boundaries.

3. ***Impact Assessment:*** The third phase centres on evaluating the contribution to the impact categories. Examples of the impact categories include: resource depletion (energy, water, fossil fuels, chemicals etc), land use, greenhouse gas emissions, and water pollution. The principal task is to calculate the impact potential based on the inventory analysis. In some studies, the results of this calculation are then normalised to a constant parameter, to enable comparisons between products. Finally, the process of assigning weights to impacts allows an assessment to be made on the relative importance of the respective impact.

4. ***Interpretation:*** All three previous phases are shown with links to interpretation, reflecting the fact that this phase forms a constant part of the process. Often, a practitioner will take a high-level perspective on the first three stages, making rough assumptions along the way, in order to arrive at a 'first-cut' answer. This will identify the impact 'hot-spots', and then a second iteration of data collection follows, with a focus on key processes. In conjunction with this data analysis, the practitioner will also conduct a sensitivity and gap analysis to evaluate whether the goal and scope are met. In this phase, the conclusions from the LCA study are developed.

5. ***Market Interventions:*** Once the conclusions from the LCA are known, Defra and other participating government agencies will review the findings and develop programmes and initiatives that work to mitigate the impacts found through the LCA study.

There are several variations of the LCA which tend to vary on which range of the life cycle spectrum they examine, however, in this report the 'cradle-to-grave' approach has been used. This examines the entire life cycle from raw material extraction ('cradle') to the end of life ('grave'). The time period of analysis is based on the longest lived component, to ensure the maximum service life is captured and the impacts associated with manufacturing are amortised over that service life.

This study uses the Life Cycle Assessment methodology to evaluate four lamp types: an integrally-ballasted light emitting diode (LED) lamp, a dedicated LED luminaire, a T5 linear fluorescent lamp luminaire and a ceramic metal halide lamp luminaire. This study also calculated the impacts associated with a 23 watt compact fluorescent lamp (CFL) and a 100 watt incandescent general lighting service (GLS) lamp to facilitate comparisons between the various light sources, and to provide a basis for comparison between the UEL lamps and two lamp types commonly found in the domestic sector.

Figure 1.2 presents the flow diagram of an LCA evaluation of a generic lamp, including the component parts involved in the raw material phase, the manufacturing, transport, the in-use service and the end of life disposal. Under those five key steps of the LCA study, the individual processes examined are identified.

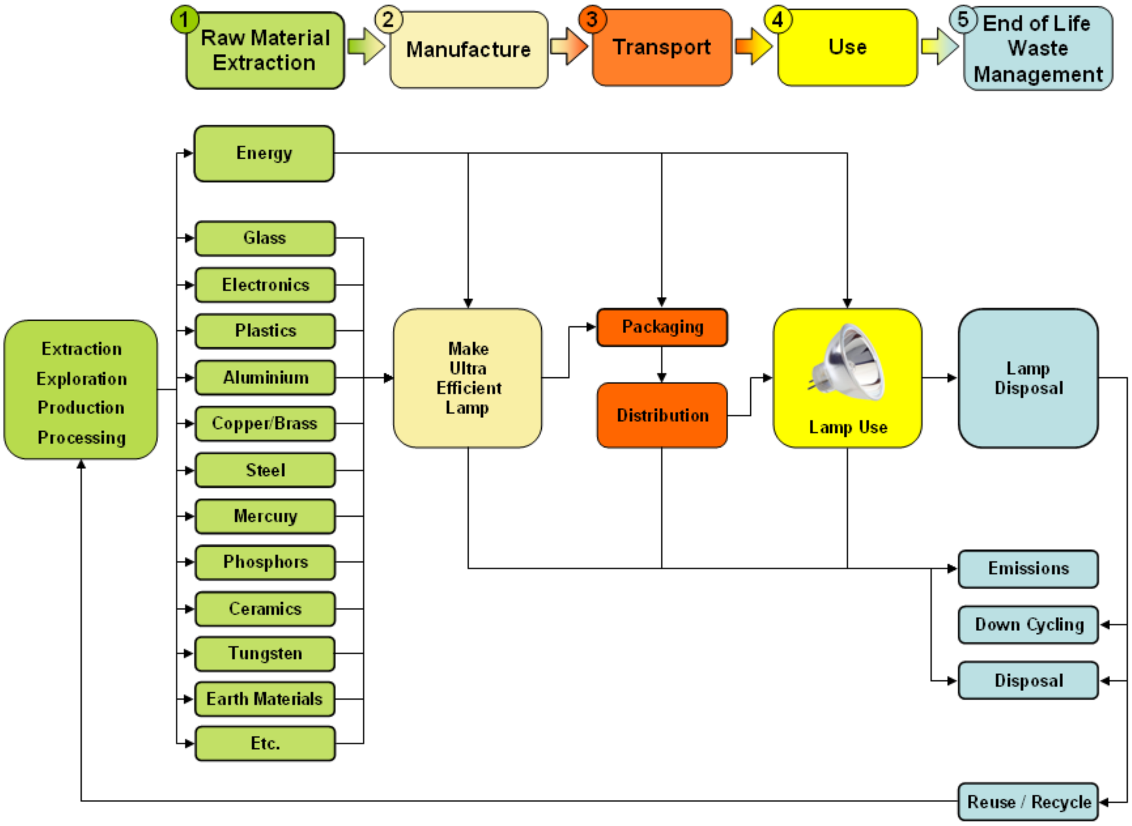

Figure 1.2 Life Cycle Assessment Flow Diagram for a Generic Lamp

1.3 Project Overview

This study evaluates and establishes a common, normalised basis for the evaluation of environmental impacts associated with all stages of the life cycle of ultra-efficient lamps (UELs). The results of this study will enable Defra to consider the relative magnitude of these environmental impacts and to create programmes and initiatives to reduce the most significant impacts.

The combination of improved and innovative technologies, and increasing awareness of energy and sustainability concerns, is establishing two new concepts in lighting – ultra-efficient lamps (UEL) and ultra-sustainable lighting (USL). These two concepts are briefly described below, with UEL being the focus of this study.

1.3.1 Ultra-Efficient Lamp

UELs are products that emit 100 or more lumens of white-light for each circuit watt of normal household power consumed. The UEL itself, which can be either a retrofit lamp or a dedicated fitting, incorporates three major components: 1) the lamp or light source itself (e.g., an LED), 2) some kind of ballast to operate that lamp or light source, and 3) if appropriate, some kind of diffuser, reflector or lens to direct and manage the light output. For some products, called 'integrally ballasted,' these major components are bundled together into a single package, such as a direct replacement LED lamp that incorporates its own device driver electronics (see Figure 1.3). In other cases, these major components are sold individually as parts of the lighting system, such as a T5 fluorescent lamp luminaire, where the lamp, ballast and fixture can all be specified and purchased separately.

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Figure 1.3 Integrally Ballasted (Directional) LED Lamp

Whether sold as an integrally ballasted retrofit lamp or a dedicated fixture with component parts, the fundamentals of the system are the same. Line-voltage electricity enters the system, this voltage is modified by the driver electronics, which in turn, causes the light source to emit light. That light is then usually managed in some capacity, such as being emitted through a lens or a diffuser to either focus or disburse the light emission. The UEL therefore functions as an ultra-efficient light source, providing an ultra-efficient light output to the end-user. More detail on the UEL specification, including a light quality requirement, is provided below in section 1.4.

1.3.2 Ultra-Sustainable Lighting

While UELs focus on the system efficiency and light quality, a USL installation takes a more holistic view, encompassing environmental impacts, light pollution, human factors, design features, and end-user economics. These more holistic considerations constitute the basis of sustainability, including economic, environmental, and social factors. More specifically, in addition to the ultra-efficient performance of an UEL, a USL installation would also include:

- Consideration of the environment - the lamp and its component parts would be designed to minimise other environmental impacts such as mercury or lead content, and would be constructed in such a way that they are easier to recycle and recover or reuse component parts of the lamp.

- Reduction of light pollution – the lighting installation and fitting are designed in such a way that the light is directed onto the intended surface(s), and is not haphazardly flooded with considerable unintended light emission and encroachment into other areas and/or the night sky.

- Human Factors – the lighting system is designed to take into account any potential benefits to human health, including for example, modifications to circadian rhythms.

- User Features – the lighting system is designed and incorporates sophisticated drive electronics to enable the installation to offer the ability to dim the light, to adjust the correlated colour temperature to match ambient conditions (e.g., ideal sunlight or firelight) and to offer occupancy / presence detection to reduce unnecessary lamp operation.

- Economic Factors – the installation will take into consideration the purchase price of the system, as well as the installation and operation & maintenance costs.

While it is possible for a UEL to also be a USL, it is important to draw a distinction between the USL concept and the UEL product. The UEL product does not have control over how it is used in an actual installation, whereas a USL must be designed and installed properly in order to be considered a USL. For example, a UEL could be installed in a fixture that has considerable light trespass and is considered a source of light pollution. This UEL would still be classified as a UEL, since it would be producing good quality light efficiently, but this installation could not be considered part of a USL system.

This study is focused on UELs, and quantifies the environmental impacts along the entire life cycle of the UEL, including such issues as mercury content and end-of life recyclability. While this study will be quantifying environmental and social impacts of a UEL, it will not be quantifying or considering issues like human health factors, economic viability, unique application requirements, light pollution and / or user features such as dimmability, correlated colour temperature (CCT) shift and occupancy sensing. Those aspects of a USL system are beyond the scope of this analysis.

1.4 Scope of Ultra Efficient Lamps

There are two critical performance metrics that describe a white-light UEL – the efficiency (or, more correctly, “efficacy” as it is a measure of light output divided by watts of electricity input) of the light source and the quality of the light emitted. For this study, the efficacy calculation takes into consideration all components involved in producing light, i.e., the light source, the electronics and the optics. For light quality, white-light UELs are defined between a certain CCT range and only a short distance from the black body locus on the 1931 chromaticity plot published by the Commission Internationale de l’Eclairage (CIE). More detail on these performance metrics is provided in the subsections that follow.

1.4.1 Light Source Efficacy

The efficacy of the UEL system must be greater than or equal to 100 lumens per system watt, including ballast/driver losses and any losses associated with the optics, such as a reflector, lens or diffuser. The overall system efficacy is the product of the efficiencies of these component parts. For many technologies, and particularly for light emitting diodes (LEDs), the system efficiency values are increasing over time. That is, the devices are becoming more efficient at converting watts of electricity into visible photons of light.

1.4.2 Quality White Light

The light emitted by the UELs should have a CCT that is considered pleasing and acceptable in a domestic setting. The most common CCT found in the average home today is 2800K, the CCT rating of an incandescent lamp. Other domestic light sources include halogen lamps which have a CCT of around 3000K, and compact fluorescent lamps (CFLs) with CCTs ranging from 2800K to 5000K. The lower CCT value resembles a warmer, yellowish-white light while the higher CCT value resembles a bluish-white light. Thus, it is believed a range of CCT values are acceptable in the domestic sector, however for the purposes of this study, UELs will be defined as having a CCT between 2500K and 4000K. The CCT values are shown in Figure 1.5, which contains the CIE’s chromaticity plot. Following along the black line through the middle of the colour surface, called the black-body locus, different light colours can be produced, including quality white light. The values along the blackbody locus represent the CCT values of light sources. As evidenced by the proximity of the white area to the coloured areas in this plot, lower CCT values such as 2850K contain more yellow light while higher CCT values such as 10,000K contain more bluish light.

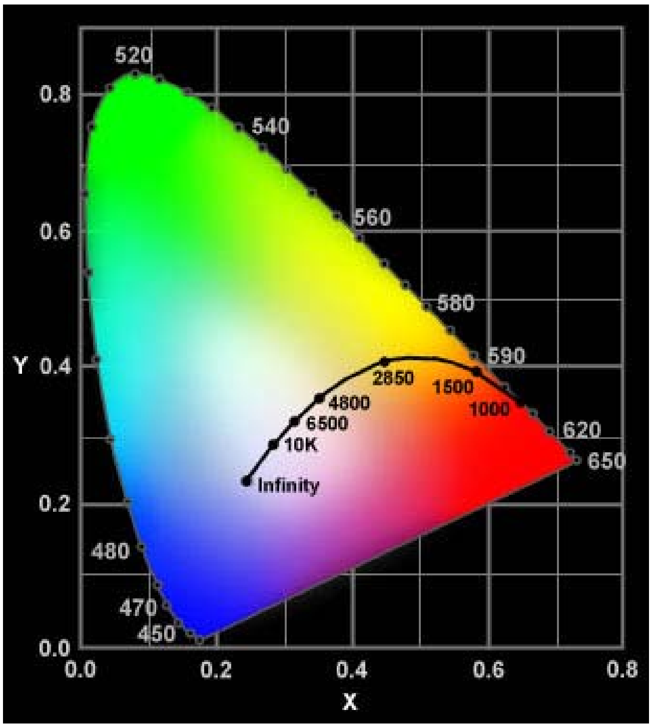

Figure 1.4 CIE Chromaticity Plot, 1931

Good quality white light sources are able to render illuminated objects and their respective colours accurately. To ensure that UELs produce good quality white light, the sources are defined as having to fall into an area within 0.01 of u' and v' of the black body locus on the CIE chromaticity graph between 2500K and 4000K. This approach to defining white-light is consistent with the approach followed by CIE and Cree, Inc.[3] Having this close proximity to the black body locus will ensure the UEL produces good quality white-light.

Given these UEL performance criteria in efficiency and quality light, Table 1.1 summarises the aforementioned requirements.

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[3] White light is defined in CIE S004/E:2001, Colours of Light Signals, as being within a certain distance from the blackbody locus. CREE, Inc. describes the term white light for illumination as the 'region defined by area of 0.01 Δ u'v' of black body locus in the CCT range of 2500K to 10,000K.'

Table 1.1 Summary of the Performance Criteria for an Ultra Efficient Lamp

UEL Performance Metric	Numeric Value	Notes
System Efficacy	100 lumens / Watt or higher	Efficacy value combining the performance of the lamp, ballast/driver and optics. Can be integrally ballasted or separate components. Lamp selected must have the potential to achieve this level of efficiency sometime between 2009 and 2014 (the analysis period under consideration in this study).
Quality White Light	CCT 2500 – 4000K Falls within region defined by 0.01 change in u'v' of the black body locus	Good to very good white-light sources. Acceptable in households, typical of incandescent, halogen and CFL performance. High CRI values, typically exceeding 80.

1.4.3 Lamps Covered

This section applies the UEL technology-neutral qualification criteria to the most efficient white light sources available in the market today, and identifies four lighting systems which are the subject of this LCA study. Although none of these light sources have a system efficacy value of 100 lumens per watt today, there is clear potential for this performance level to be reached by 2014.

This study is focused on UELs in the domestic sector, however the four products being taken into consideration in this study are not commonly sold in the domestic sector today. Instead, it is presumed that these UEL technologies sold in other sectors (e.g., commercial retail and office) will expand their market share in the future to include the domestic sector.

This study also considers the LCA impacts associated with two additional lamp types which are not UELs, but which are commonly found in the domestic sector today – a 23 watt CFL and a 100 watt GLS incandescent lamp. These two lamp types are included to enable comparisons to be drawn between the various UEL technologies under consideration and the common lamps used today in the domestic sector.

Light Emitting Diodes

There are three common methods by which LEDs produce white-light. First is the phosphor-conversion approach, in which blue or UV-light LED pumps light into a phosphor which down-converts the light to be a more distributed spectrum resembling white-light. Second, there can be discrete colour-mixing LEDs, which blend together the light of discrete-colour LEDs to create white-light. Third, there exists a hybrid approach in which phosphor-converting LEDs and discrete colour LEDs are combined to create the desired light emission.

In the UK's domestic sector, the greatest volume of lamp sales exists in the replacement market (as opposed to new fixtures in new construction and refurbishment). Thus, as the domestic market starts to shift to UELs, high volume market shares are likely to occur first in the lamp replacement market, whereby consumers will purchase and install UELs into their existing fittings and fixtures. This study considers scenarios for both a retrofittable LED direct-replacement lamp (i.e., LED integral) and a new LED luminaire where the LED is permanently installed in the fitting (i.e., LED luminaire).. More detail on the representative direct-replacement LED integral lamp and the LED luminaire are provided in the LED section of this report.

Ceramic Metal Halide

Ceramic Metal Halide (CMH) lamps were introduced into the lighting market to resolve some of the technical problems with the older-style quartz metal halide lamps.[4] Their performance attributes and unique selling propositions have contributed to these lamps being adopted widely in many retail lighting and colour-critical applications. CMH lamps offer a high quality, energy-efficient alternative to halogen lamps, with CRI values in the 80-90 range and CCT values of 3000 – 4100K that are guaranteed not to shift by more than 200K over the rated lamp life. The new CMH technology also provides improved lumen maintenance, and is presently offered in wattage ranges starting at 20 watts up through 400 watts. A 10 watt lamp is under development, which coupled with the 20 watt system, would provide reasonably equivalent lumen packages to directional lamps used in the domestic sector today. That said, there are some technical barriers that are being studied, which if not addressed, may inhibit widescale domestic market adoption. These include the ability to operate in a frequently switched environment and the delay incurred before reaching full brightness.

Currently, the retail lighting market is perhaps the single largest market for CMH lamps, given that retail lighting often requires point-source accent lighting. Many businesses are switching from comparatively inefficient, short-lived halogen reflector lamps to CMH lamps, and realising considerable energy and maintenance savings. The efficacies of the 20 watt systems are approximately 90 lumens per watt, and given the significant R&D effort being invested by many companies in this technology, they are expected to increase to 100 lumens per watt by 2014.

Linear Fluorescent

Linear fluorescent lamp technology has been improving in efficacy since it was first developed in the 1930's. The T5 lamp entered the global lighting market in the 1990's, and has continued to capture market share from other fluorescent lamps due to its high-efficiency and robust performance characteristics. Coupled with innovative, efficient and compact luminaires, T5 has been slowly establishing itself as the default linear fluorescent lamp. However, similar to LED and CMH lamps, the domestic sector has been slower to adopt T5 systems, although end-users would benefit from the efficacy and other performance improvements.

The "T" in lamp nomenclature represents the tubular shape of the lamp. The “5” in the title connotes the diameter of the lamp as 5/8ths of an inch (1.6 cm). These lamps are approximately 40% smaller than T8 lamps, which are one inch in diameter, and almost 60% smaller than T12 lamps, which are 1½ inches in diameter. Using smaller diameter lamps means that less material is used in manufacturing (i.e., less glass and phosphor and smaller metal end-caps), which reduces environmental impacts. T5 lamps all use RE80, a rare earth phosphor with a colour rendering index (CRI) value of approximately 85.

Compact Fluorescent Lamps

Compact Fluorescent Lamps (CFLs) were first developed in response to the oil supply shortages in the 1970's. The technology is based on a minature-sized version of the linear fluorescent system - a ballast and a lamp. The CFL can have the lamp and ballast either

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[4] The older metal halide quartz-capsule technology had suffered from lamp lumen depreciation, low colour rendition, and poor colour consistency.

packaged together (integrally ballasted) or sold separately (dedicated CFL luminaire). Also like linear fluorescent lamps, CFLs contain a small amount of mercury in the arc tube which is recoverable, but only if the CFL is disposed of correctly (i.e., gathered and reprocessed at a recycling plant). Correct disposal of CFLs is unlikely in the UK domestic sector, and there is, therefore, concern over mercury contamination of land fill sites as CFLs are used more widely.

CFL sales have been increasing, thanks to greater public awareness of energy costs and acceptance of the technology. And although CFL are approximately four times more efficient than incandescent lamps at producing light, CFLs are not considered a UEL in the context of this study because they do not have, not exhibit the potential to achieve, an efficacy of 100 lumens per watt. Regardless of this fact, this lamp type is included in the study for the purpose of making comparisons between the four UELs under consideration and this common lamp type found in the domestic sector.

Incandescent Lamps

Originally invented in the 1880's, this lamp type continues to hold a dominant position in the domestic lighting sector. Improvements in efficacy were made over the years, however more than 95% of the power submitted to the lamp is radiated in the infrared (i.e., non-visible) spectrum. Incandescent lamps work by heating a metal filament to the point that it is so hot, it burns "white" and emits light. The system is extremely simple, and does not require a ballast to operate or control the lamp.

Incandescent lamps are not UELs, nor do they have the potential to achieve the UEL target efficacy, however they are included in this study because they provide a comparative benchmark against which to assess the relative LCA impacts of the UELs under consideration. Due to their high degree of market penetration / presence in the domestic sector, stakeholders are broadly familiar with the technology, enabling reasonable and relevant comparisons to be drawn.

Lamp Type Not Evaluated - OLED

In this study of domestic UELs, organic light emitting diode lamps were not evaluated. OLEDs have a promising future and potentially will become a highly-efficient light source in general illumination applications, however there are no commercially available general illumination OLED products to profile at this time, furthermore, it is uncertain whether OLEDs will be commercially available in viable general illumination application products at or above the 100 lumen per watt threshold by 2014. OLED research is focusing on reliability, quantity and quality of light output, and operating life time.

1.5 Methodology

The methodology followed for this study encompasses six phases, which are shown in Figure 1.8. These phases were designed to ensure development of a study that would provide a high quality study, with a strong foundation of research literature and expert interviews, supporting the LCA and drafting of this report. The sequencing of the phases followed that underpin this report's methodology are illustrated in the diagram below.

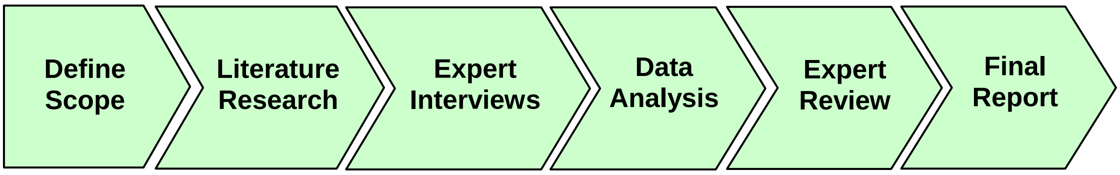

Figure 1.5 Report Methodology Outline

- ***Phase 1 (Defining Scope) –*** this stage focused on developing a technology-neutral definition of a UEL for the domestic sector, considering the time period of 2009-2014.

- ***Phase 2 (Literature Research) –*** In this phase an in-depth study and review of the relevant literature was performed. The material was collected from periodicals and technical reports, and resulted in an evidence database matrix which contains the relevant materials, sources, key data, LCA stages, etc and sorts the material according to relevance after having assessed each paper for credibility, reliability, and objectivity. In total, more than 60 documents were profiled and entered into the evidence database.

- ***Phase 3 (Expert Interviews) –*** A stakeholder group was formed through stakeholders responding to broadcast email messages sent by the Energy Savings Trust, the Lighting Association, the Lighting Industry Federation and Defra. In total, more than twenty interviews were conducted with representatives throughout the lighting market and across the supply chain, from manufacturer associations and component suppliers to lamp assemblers and fixture manufacturers. The stakeholders interviewed provided expert input and guidance on current trends in markets and technology, as well as critical data used for assessing the life cycle impacts.

- ***Phase 4 (Data Analysis) –*** This stage involved careful collation of data and preparation of a life cycle analysis on the selected UELs that are expected to meet the scope by 2014. This phase identified focus areas, data gaps, and structure for the final report.

- ***Phase 5 (Expert Review)*** – This stage involved circulating critical parts of the analysis and preliminary findings to ensure accuracy in the characterisation. In this way, stakeholders have the opportunity to review and comment on the research, results and analyses conducted.

- ***Phase 6 (Final Report)*** – This stage involved updating the analysis to reflect comment and input refinements from the expert review panel and the final preparation of the report for submission.

2 Market Assessment of Domestic Lighting

This chapter of the report provides an assessment of the UK domestic lighting market, including a brief description of the types of lamps, the applications and the technologies. This chapter also provides a summary of energy consumption by application, to set the context for this study. More detailed technical description of each of the technologies being analysed in this study can be found in the next chapter, the technology assessment.

2.1 Introduction

There are approximately 25.1 million homes in the UK, with slightly more than 900 million light bulbs[5], of which approximately 150 million are stored as spare bulbs for replacement, and 750 million (i.e., 80%) are actively in service (Lighting Association, 2008).

Electricity consumption for domestic lighting is slowly increasing, with the Market Transformation Programme projecting that the domestic lighting sector would reach 19.2 TWh by 2020 (Defra, 2008). The increase in electricity demand is primarily due to the growing number of lamps used in each home and the projected trends in new home construction.[6] Mitigating that growth however are assumptions around higher market penetration rates of more efficacious lamps.

The UK domestic lighting market is constantly evolving. Traditionally the sector has been dominated by incandescent lamps, but several factors have contributed to the wider uptake of a range of lighting technologies. Environmental awareness of issues such as climate change, rising energy prices, incentive schemes such as the CERTs[7] programme, and legislation including the 2002 Building Regulations have stimulated the uptake of energy efficient alternatives to incandescent lamps, principally CFLs, as home owners seek to reduce both their energy bills and their carbon footprint. Additionally, changes in style and home design have also contributed to the use of different lighting technologies, such as the replacement of central pendant incandescent lamps with multiple MR-16 ceiling spot lights offering general illumination and sparkle.

2.2 Light Sources

Lamps can be categorised based on the applications in which they are used, to provide either general or directional illumination. Lamps for the purpose of general illumination provide ambient, non-task, non-specific illumination of a room, and there are a range of fittings available to achieve this. Traditionally the most commonly used fittings for general illumination are pendant lights which account for nearly 40% of light fittings within an

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[5] Technically, the correct term for a 'light bulb' is a 'lamp', however in this section of the report this plain language term 'light bulb' is used to avoid confusion with terms like table lamp and desk lamp, which refer to decorative fittings, usually with a shade or lamp cover, that hold and operate light bulbs.

[6] However since that projection, there has been a significant downturn in economic conditions, which has adversely affected the house building industry. For example, The National Housing Federation estimates that the 3 million new homes that the government commissioned to be ready by 2020 may now not be achieved until 2029.

[7] The Carbon Emissions Reduction Target (CERT) places an obligation on energy suppliers to achieve overall lifetime carbon dioxide savings of 154 $MtCO_2$ through a range of investment measures including the free provision of energy efficient lamps for consumers, with a particular focus on priority groups such as households suffering from fuel poverty.

average UK household (Lighting Association, 2008). Directional lamps are typically point source lamps and provide task-specific illumination, such as under cabinet lighting in kitchens, and accent lighting. However as the domestic lighting market develops, lamps are becoming increasingly amenable for use in both general and directional illumination applications. For example, with the correct reflector, halogen MR-16 lamps are used to provide general illumination when used as ceiling spot lights, or directional illumination in a stand-alone reading light. Therefore within this chapter it has been decided not to attempt to divide lamps into categories, but rather discuss lighting technologies collectively, with reference to the applications in which they are most used.

The lamps most used in the domestic sector are GLS and halogen lamps, a small amount of linear fluorescents, and an increasing number of CFLs.

Table 2.1 provides a summary of the key properties of the technologies currently used, or with the potential to be used in the domestic lighting sector. In this table, efficacy represents the ratio of the light emitted by the lamp compared to the power consumed. The lifetime is the time taken for 50% of a sample batch to fail under test conditions and CRI expresses how accurately coloured surfaces appear under different light sources. Generally, a CRI greater than or equal to 80 is adequate for domestic applications.

Table 2.1 Key Metrics of Technologies Suitable for the Domestic Lighting Sector

	Efficacy (lm/W)	Lifetime (hours)	CRI
Incandescent Lamp	8-17	1,000	95-100 Excellent
Halogen Lamp	10-30	2,000	95-100 Excellent
CFL (integral ballast)	60-75	6,000 – 15,000	70-90 Very Good
Linear Fluorescent Lamp (T5)	90-104	24,000	80-90 Very Good
Linear Fluorescent Lamp (T8)	75-95	24,000 – 70,000	80-90 Very Good
LED Lamp (integral ballast)	40-60	20,000[8]	80 Very Good
Dedicated LED Luminaire	45-65	50,000	80 Very Good
Ceramic Metal Halide	75-90	12,000	80-90 Very Good

Sources: Manufacturer interviews, catalogues and literature, 2009.

2.2.1 Incandescent

Developed originally in the late 1800's, incandescent lamps produce light as a result of passing current through a tungsten filament within an inert atmosphere inside a glass bulb envelope. The current causes the filament to glow producing heat and light.

Tungsten filament incandescent lamps for general lighting service have the highest penetration in UK homes, over 97%, and in volume they represent 33% of active bulbs in homes (Lighting Association, 2008). Incandescent lamps are available in a range of wattages, shapes (candle, round), sizes, colours, and as bayonet or screw cap fittings, which makes them suitable for a wide range of applications. Incandescent lamps have the lowest first cost on a £/lumen basis compared to other lighting technologies in today's market. In addition, incandescent lamps produce a warmer (yellowish-white) coloured light which is preferred by most consumers to the often colder (bluish-white) light of CFLs.

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[8] Lifetime for an LED (i.e., the light-emitting portion of the LED Lamp or Dedicated LED Luminaire) is defined by two parameters – Bx (percent of product) falling below Lx (lumen maintenance). For example, B50 L70 means the point in time when 50% of the product falls below 70% of the initial lumen output.

While efficiency improvements to incandescent lamps may still be possible, for various technical and cost reasons, they have not been commercialised. Thus the efficacies of lamps today have remained relatively stagnant for several decades, ranging from 8 to 17 lm/W, depending on wattage. These poor performance metrics resulted in a proposal from the European Commission in December 2008 to phase out incandescent lamps from the domestic sector. It is estimated that replacing incandescent lamps in homes with more efficient technologies could reduce household electricity consumption by 10-15% (EC, 2008). In March 2009, the European Parliament granted approval for this regulation, phasing out incandescent lamps from the domestic sector under the Ecodesign Framework Directive. The regulation only applies to non-directional (i.e., general illumination) lamps, and a separate regulation on directional lamps is under consideration. The regulation works in conjunction with the European A to G efficiency label for lamps, whereby a particular lamp must meet or exceed a particular letter in order to still be traded in the European markets. Thus, incandescent lamps which are classified as an ‘F’ or a ‘G’ on that scale are phased out when the minimum of ‘C’ becomes effective. The following table summarises the EU regulation on non-directional lamps.

Table 2.2 Summary of EU Regulation of Non-Directional Household Lamps

Lamp Type	Summary of Action	Regulatory Mechanism
Non-clear lamps	All incandescent non-clear lamps to be phased out starting in September 2009	Non-clear lamps will be required to be ‘A’ class. In practice this means non-clear lamps will have to be CFLs.
Clear lamps	All incandescent and some conventional halogen lamps to be phased out progressively starting with the highest wattage (100W) in September 2009 and progressing each year through September 2012.	Clear lamps to be regulated in stages. F and G incandescent lamps are phased out from September 2009, so that only class E incandescent lamps remain. From 2012, classification will be made progressively stricter so that every lamp must reach class C, and by 2016 all lamps must be rated class B except for certain special cap halogen lamps rated class C.

The Commission projects that the new regulations will save nearly 80 TWh of electricity by 2020 (roughly the electricity consumption of Belgium) and about 32 million tonnes of carbon dioxide emissions per annum (Europa, 2009). However, there has been some concern about the impact that the regulation could have on employment in the European lighting sector, as currently most incandescent lamps used in the EU are also manufactured domestically, whereas halogen lamps and CFLs are imported from overseas.

The following list provides a summary of the principal advantages and disadvantages of tungsten filament lamps, which have been the baseline household lamp for many years.

Incandescent Advantages

- Low purchase price
- Excellent colour rendering
- No control gear required
- Easily dimmed
- Universal operating position
- Full lighting level immediately when switched on

Incandescent Disadvantages

- Low efficacy: about 8-17 lm/W
- Short lifetime: 1,000 hours
- High operating costs
- High operating temperature

Tungsten halogen incandescent lamps first appeared on the market in 1959 and represent an improvement over GLS lamps with better efficacy and quality of light as well as longer bulb life of approximately 2000 hours. These lamps, originally developed by GE, contain a small quantity of halogen (iodine or bromine) inside the filament capsule which re-deposits evaporated tungsten back onto the filament, preventing blackening of the glass and increasing the lifetime of the lamp.

Halogen lamps are suitable for a wide range of applications in both directional illumination applications such as reading and desk lights and general illumination applications including up-lighters- it is estimated that 1 in 8 households have an up-lighter, in addition to the recent trend for down-lighting provided by recessed ceiling halogen spot lights, particularly in kitchens, bathrooms and corridors. MR-16 is a standard format for halogen reflector lamps, and is available rated 20 to 50 watts. Halogen lamps that operate at 12 volts instead of line voltage are also available in the market, but must be operated using a transformer. The filament is able to operate at a higher efficacy point at this lower voltage. In the UK, 500W halogen lamps are also commonly found in outdoor flood-light applications, often in conjunction with motion sensors for security for the purpose of providing additional security to properties.

Market studies have found that halogens lamps are a popular light source in households across the UK. Indeed, they have a higher market penetration than CFLs, with an estimated 61 million low wattage halogen lamps in UK homes, compared to 54 million CFLs (Lighting Association, 2008). Sales of halogen reflector lamps have increased rapidly in the last few years, as a result of the shift away from centralised pendant lighting, to the fashionable sparkle of multiple halogen ceiling spot lights for general illumination. However this growth is expected to become saturated in the future, as halogen lamps are replaced with energy efficient LED and CFL solutions.

The following list provides a summary of the principal advantages and disadvantages of halogen lamps, which offer some of the same advantages as incandescent lamps while improving the efficacy.

Halogen Advantages

- Higher efficacy than conventional tungsten filament lamps
- Bright, white light
- Full light output immediately when switched on
- Excellent colour rendering
- Life of 2,000 to 3,000 hours
- Dimmable
- No transformer required for mains voltage models

Halogen Disadvantages

- Transformer required for low voltage lamps
- High operating temperature
- Double-ended types must be used in horizontal position

2.2.2 Compact Fluorescent Lamps and Linear Fluorescent Lamps

Compact fluorescent lamps (CFLs) consist of an electronic ballast which drives current through a tube filled with an inert gas (usually krypton or argon) and a small amount of mercury. When an arc is struck at the tube's electrodes, the mercury atoms emit UV light, which excites a phosphor coating on the inside of the tube and emits visible light. CFLs were developed in response to the 1970's oil crisis, and are essentially a miniature version of a large linear fluorescent lamp fitting. Compared to incandescent lamps, which they were developed to replace, CFLs use approximately 75% less power and last about ten times longer. In today's market, CFLs typically have efficacies of 60 to 72 lumens per watt and operating lifetimes of 6,000-15,000 hours (Energy Federation Inc, 2008).

CFLs are used as replacements for incandescent lamps, but are often cited as being more expensive. While it may be true that CFLs are more expensive than incandescent lamps, they have much lower operating costs, which means on a life cycle basis, they are less expensive to operate. For example, comparing a 100 watt incandescent lamp and an 23 watt CFL (i.e., lamp of equivalent light output), the CFL is approximately ten times more expensive to purchase, however over its lifetime, the CFL would offer net savings of approximately £100 through avoided electricity consumption.

CFLs are best suited to locations in the home where lamp sockets experience heavy use (i.e., more than 4 hours a day). These areas might include living rooms, circulation zones such as hallways, stairways, landings and shared passageways outside buildings. CFLs have a low operating temperature, which makes them suitable for applications where the build up of heat must be avoided such as flush-wall and ceiling fittings. The long lifetimes of CFLs lend them to applications which are not easily accessible e.g., above stairwells, where changing lamps can be a health and safety hazard.

Historically, criticisms of CFLs have included the fact that they're too bulky to install or don't have a pleasing light colour or appearance. Concerns have also been expressed with regard to the mercury content of the lamps, as in the domestic sector, at end-of-life; it is less likely that these lamps will be disposed of properly. Industry continues to work to overcome these barriers, and to support more widespread adoption of energy-efficient CFLs into the domestic market.

The following list provides a summary of the principal advantages and disadvantages of CFLs, which offer some key advantages over incandescent lamps.

CFL Advantages
- Low running costs
- High efficacies: 50-70 lm/W
- Long life: 6,000 to 15,000 hours
- Suitable for replacing tungsten filament lamps
- Very good to excellent colour rendering

CFL Disadvantages
- Control gear required
- Bulky construction may be difficult to install or unattractive appearance
- Dimming requires special ballast
- Mercury content and associated disposal concerns

Linear fluorescent lamps operate in a similar manner to CFLs. Linear fluorescent lamps were introduced into European households in the 1940s, but the 'cooler' light emitted by this technology has restricted their use largely to kitchens, workshops, garages and sheds. T5 linear fluorescent technology, the top-performing linear fluorescent lamp, entered the global lighting market in the 1990s, and offer a premium efficacy lamp, with some units operating at efficacies in excess of 100 lumens per watt and others offering long lifetimes of more than 70,000 hours (Philips, 2009). T5 are 16mm in diameter and are suitable both in small fittings in discrete lighting applications as well as larger fittings providing general illumination. The smaller form-factor of T5 lamps enables better optical management of the light output from the lamp than older, larger fluorescent tubes. Primarily used in the commercial sector, T5 lamps are not found in the domestic sector in 2009, however it is feasible that as households become more energy-aware and T5 costs come down, these lamps could migrate into the domestic sector and displace current fluorescent technology in kitchens, workshops, garages and sheds. In addition, there is the potential for new applications for T5 lamps to be identified, such as up-lighting above kitchen cabinets which may be used in place of halogen down-lights to create an ambient lighting effect.

The following list provides a summary of the principal advantages and disadvantages of linear fluorescent lamps.

Linear Fluorescent Advantages

- Low running costs
- High efficacies: 90-100+ lm/W
- Long life: 24,000-74,000 hours
- Very good to excellent colour rendering

Linear Fluorescent Disadvantages

- Control gear required
- Frequent switching shortens working life
- Dimming requires special dimming ballast and control gear
- Mercury content and associated disposal concerns if used in the domestic sector

2.2.3 Light Emitting Diode Lamp and Dedicated Luminaire

Light emitting diodes (LEDs) are semiconductor devices that produce light. The movement of electrons within the band-gap of the semiconductor causes the emission of visible light through a process called electroluminescence. LEDs tend to emit in very narrow bands of wavelengths, thus they will produce just green, red, blue, or other coloured light. In order to create good quality white light for general illumination, these discrete emissions must either be mixed together or a phosphor be used to distribute discrete emissions across the visible spectrum to create white light. Manufacturers today use both clusters of LEDs in a single housing, as well as multiple LED die in a single encapsulated device. This flexibility of design enables LEDs to be used in everything from directional replacements for MR-16 lamps to high-lumen output street lights.

Recent technical advances have made LEDs more cost-effective in certain niche applications. LED technology is capturing these new applications because it offers a better quality, more cost effective lighting service compared to traditional light sources, such as incandescent. In addition to energy savings, LEDs offer longer operating life, lower operating costs, improved durability, compact size, and faster on/off response times. LED lamps commonly available today have efficacies of approximately 30 to 60 lumens per watt, exceeding incandescent. And, it is widely accepted that as research investments in LEDs continues, these lamps will further improve their efficacy and reduce their price. LED lamps are a promising emerging lighting technology, with many of the lamps grouped into EU lighting label class ‘A’ for energy efficiency.

LEDs can give the kind of in vogue sparkle to kitchens and modern interiors that until now tungsten halogen lamps have provided and already have started entering the domestic lighting market with directional light sources. White-light LED products include LED task lights, down lights, under cabinet lighting, and outdoor lights. LEDs are not simply limited to these applications and are in fact being developed for other applications areas – for example, street lighting - which is enhancing LED research investments. LED replacements for MR-16 lamps are now widely available as well as under-cabinet LED lighting strips and cupboard accent lights. LEDs are also making a significant impact in domestic outside lighting, particularly solar-powered garden lighting and decking lights. As LEDs continue to improve their performance and lower their costs, they will expand their market share of directional light sources and compete for general illumination (i.e., non-directional) applications. LED lamps are cited as having the potential to make more of an impact in the domestic sector than CFLs, which are often criticised for the ‘cold’ appearance of the light.

LED lamps also offer instantaneous full lumen output and dimming potential, which are both technical challenges associated with CFLs (MTP, 2006).

For continued success in the domestic market it is important that LED lamps become a low-cost product, with a lifetime of about 20,000 hours, 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 LED lamps are expected to compete with incandescent light sources. For LEDs to make a major impact into the home a complete change is required in how home lighting is viewed as LEDs could be used in architectural mouldings or window frames and sills.

The following list provides a summary of the principal advantages and disadvantages of LED lamps.

LED Advantages

- Low running costs
- High efficacies of 40-60 lm/W and increasing
- Suitable for replacing directional and potentially non-directional sources.
- Market leading products exhibit good colour rendering
- Very long life: 20,000 hours for integrally ballasted LED lamp and 50,000 hours for dedicated luminaire

LED Disadvantages

- Not a fully mature technology
- More expensive on a first-cost per lumen basis
- Limited testing metric standardisation and information for consumers
- Quality of construction and light output can be poor

2.2.4 Ceramic Metal Halide Lamps

Created in the late 1960s, metal halide lamps produce light by passing an electric arc through a high pressure mixture of metal halides, mercury and argon gas. The correlated colour temperature and light intensity (making the light bluer, or redder, for example) are affected by the mixture of halides used. Metal halide lamps require electrical ballast to regulate the current flow and deliver the voltage to the arc. The argon gas in the lamp is readily ionised, and facilitates striking the arc across the two electrodes when voltage is first applied to the lamp. The heat generated by the arc then vaporises the mercury and metal halides, which produce light as the temperature and pressure increase.

CMH lamps offer a high quality, energy-efficient alternative to halogen lamps, with CRI values in the 80-90 range and CCT values of 3000 – 4100K. The new CMH technology also provides improved lumen maintenance, and is presently offered in wattage ranges starting at 20 watts up through 400 watts. For lower wattages, there is a trend toward using the electronic ballast rather than the magnetic ballast. Electronic ballasts can increase the life of the lamps, and result in smaller, lighter CMH systems that are not much larger than a halogen lamp.

CMH lamps are used in a wide variety of colour critical (i.e. where colour rendering is important) applications due to its high efficacy, high CRI, comparable lumen maintenance, and long lifetime. The retail sector is the largest market at present, as stores and shopping malls often require point-source accent lighting. CMH lamps are used to replace halogen lamps because they are five times more efficient and have a lifetime of approximately three years. Today a 20W CMH offers equivalent light output to a 50W halogen. CMH lamps are also used in offices, and for accent, display, and studio lighting (OSRAM Sylvania, 2002). It is also an excellent alternative as a white-light source in outdoor application, such as street lighting, area lighting, landscape lighting, and floodlighting. Research is currently being conducted to develop a 10 watt lamp, which coupled with the 20 watt lamp, would provide good coverage of typical directional lamp lumen packages in the domestic sector.

Factors that will dominate how quickly the domestic market will absorb the CMH technology will also depend on when manufacturers are able to address technical issues related to re-strike delay time. Instead, CMH systems are being used in the commercial sector today, and may be adopted by the domestic sector in the near future, where an entirely new luminaire is installed. Generally, CMH lamps are better suited to re-design rather than to the direct replacement domestic market.

Many businesses are switching away from the less efficient, lower life halogen lighting systems in favour of CMH lamps, with the efficiency and performance gains becoming visible early on in the replacement process. Current 20W CMH systems (equivalent to 50W halogen systems) are yielding efficiencies of approximately 90 lumens per watt and with the high R&D investments being made by manufacturers this technology is expected to exceed 100 lumens per watt.

Summary of ceramic metal halide lamps:

CMH Advantages

- Excellent colour rendering- CRI 80-90
- High efficacy
- Low running costs

CMH Disadvantages

- Not a fully mature technology – restrike and full brightness warm-up
- High purchase price

2.3 Energy Consumption

Energy consumption by the lighting sector is the electrical energy used by lamps to produce light (and heat) energy. Energy consumption has been found by other LCA studies on incandescent and compact fluorescent lamps to be the most significant environmental impact of all the life cycle stages (Parsons, 2007; Ramroth, 2008). This is because the majority of UK electricity is produced from the combustion of fossil fuels such as coal and natural gas, which result in the emission of carbon dioxide and other air-borne pollutants. The greater the amount of electricity consumed, the greater the amount of carbon dioxide and pollutant emissions produced, and the more significant the impact on environmental issues such as global warming as a result of increasing atmospheric CO_2, and acid rain from SO_2 emissions. Therefore, the importance of improving the efficacy (or lumens per watt) of light sources cannot be overstated from the perspective of providing equal or better lighting service while reducing associated impacts.

Figure 2.1 presents the energy consumption estimates from ‘A Brighter Future’ the Domestic Lighting Report 2008 on the total percentage of electricity used by bulb type inside the average home. Then, multiplying these percentages of consumption by relative efficacy ratios,[9] the approximate lighting service (i.e., lumen-hours of light output) associated with the electricity consumption for each of the lamp types is also calculated.

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[9] By multiplying the percentage of power consumption by the relative efficacies of the light sources, an estimate of the light service provided by technology can be calculated. For these estimates, it was assumed incandescent = 15 lm/W; halogen = 20 lm/W; linear fluorescent = 80 lm/W and CFL = 60 lm/W.

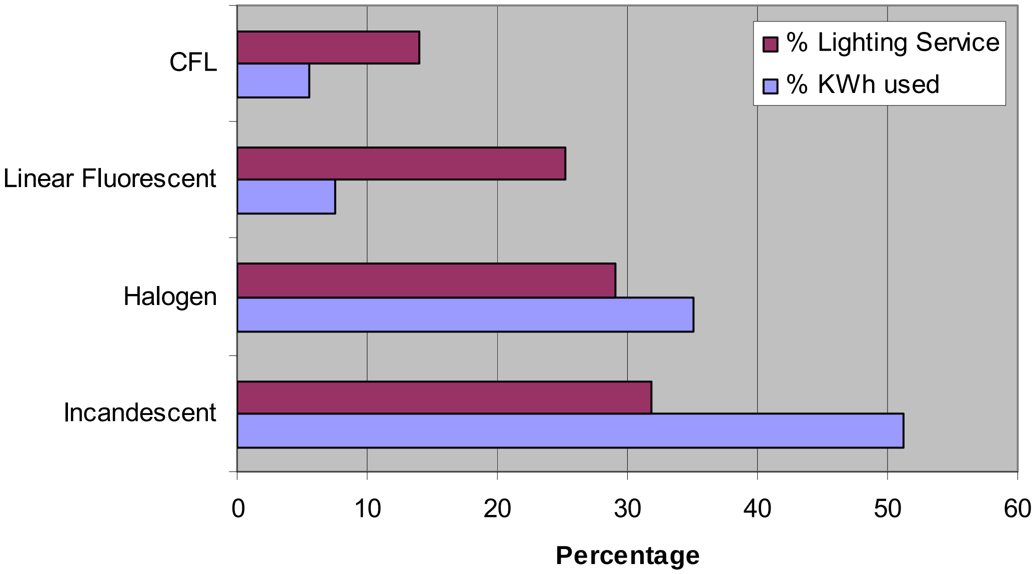

Figure 2.1 Percentage of Lighting Electricity by Source in Average UK Household

It is noticeable that CFLs, linear fluorescents, and to a lesser extent halogen lamps give much greater lighting service for percentage kWh used compared to incandescent lamps. This is attributable to the higher efficacies associated with CFLs, linear fluorescent lamps and halogens, compared to incandescent lamps. The greater efficacies and lighting service output compared to kWh used make CFLs and linear fluorescent lamps more energy-efficient, and consequently more cost-effective lighting technologies for the home.

2.4 Manufacturers

The UK lighting industry is represented by bodies such as the Lighting Industry Federation (LIF) and the Lighting Association (LA). The LIF represents the interests of lamp and luminaire producers that operate principally in the commercial sector. The LA represents the interests of lamp and luminaire producers that operate principally in the domestic sector. Given the fact that some lighting technologies are sold into both sectors, there is some overlap, and some manufacturers are members of both organisations.

Within the UK LED sector there are small businesses who manufacture dedicated LED luminaires, sourcing raw materials locally and overseas. The nature of LEDs enables small manufacturers to develop niche products and compete with larger luminaire manufacturers for market share. In conducting the stakeholder interviews for this study, it transpired that there are many small UK-based companies that manufacture and assemble LED luminaires for the UK and European markets. The LED lighting market is recognised as a high growth area, and consequently the opportunity exists for further future small business start-ups within the UK to enter the market and help meet the growing demand.

The UK is dependent on the international lighting-product industry to meet manufacture its lighting components and often products. The global lighting-product industry consists of a range of manufacturers, from small single product enterprises to large multi-national companies that manufacture a broad range of lighting products. That said, there is a high degree of standardisation across the market, and while the lamp market is highly concentrated and dominated by a limited number of major players, the luminaire market is much more fragmented.

The four market leading lamp manufacturers are: Philips (based in the Netherlands), OSRAM (based in Germany), General Electric (based in the U.S.) and Havells-Sylvania (based in Europe). While these companies are based in either Europe or the United States, the majority of their lamp manufacturing operations are located in China. Dependence on the Chinese lamp manufacturing industry is projected to intensify, as the transition is made away from incandescent lamps, and the uptake of CFLs and LED lamps increases. Traditionally, European lamp manufacturers have supplied EU countries with incandescent lamps produced within the EU, however as incandescent lamps are to be phased out under the Eco Design Framework Directive, concerns have been expressed over the projected job losses associated with demand being met entirely by energy efficient lamps manufactured in China.

Lamp manufacturers within the EU are represented by the European Lamp Companies Federation (ELC). Members of the ELC include: Philips Lighting, OSRAM, GE Lighting, Aura Lighting Group, BLV, Leuci, Narva and Havells Sylvania.

2.5 Retail Distribution

There are many routes to market for domestic lighting products in the UK. Consumers buy luminaires, lamps and fittings from specialist lighting shops such as The Lighting Store, department stores including House of Fraser and John Lewis, do-it-yourself shops such as B&Q and Homebase, and increasingly from supermarkets and over the internet. Twenty-four hour hypermarkets like Tesco Extra and ASDA Walmart sell a wide range of non-food items including electrical appliances and lighting products, and enable retailers to offer reduced prices as a result of leveraging economies of scale that simply are not available to local DIY stores. Similarly, the trend for online shopping provides customers with a large number of retailers including www.directlight.co.uk and www.inspiredbylight.co.uk. Furthermore, online shoppers have the added convenience of not having to leave the house, and their purchases are delivered directly to their home. Current sales figures put the average purchase at two luminaires per house per annum, and the majority of home-owners purchase the lighting product and then install it themselves.

In recent years, growing welfare has resulted in increasing numbers of home owners who employ designers, home decorators, installers or qualified electricians when making modifications to their homes. These professionals not only influence the choice of light source, but also affect where it is purchased from, as the majority use trade suppliers rather than buying from the retail market. Some furniture and appliances manufacturers are now including lighting in their products for example in vanity mirrors, and this market is dominated by the fashionable halogen down lighter reflector lamps. Since 1995 there has been a transition in general illumination practices, from a single pendant lamp or a few incandescent lamps to several halogen reflector lamps configured on the ceiling in down-light fittings.

3 Ultra Efficient Lamp Technology

3.1 Introduction

A wide range of lighting technologies are available today, including many new energy-efficient options. While newer more energy-efficient lamps may initially enter the market in the commercial sector, these technologies are expected to make the transition to the domestic market. Of the four UEL sources considered in this study, none have achieved commercially available product offering 100 lumens per system watt by mid-2009, however they all have the potential of reaching that level by 2014. All of these lighting technologies are found in the commercial sector, particularly in office and retail applications, however they are (at present) rarely used in the domestic sector. Reasons for the lack of domestic market penetration include cost, lumen package and controllability, light quality, lamp availability and fixture requirements and designs.

Although the domestic market penetration is very low for the four lamps being studied in this analysis, all of these technologies are expanding their respective market shares in the commercial sector, and are expected to continue to grow into that sector. Historically, more efficient and expensive light sources have first entered the commercial market, then later made the transition to the domestic market (e.g., T8 linear fluorescent lamps and halogen lamps). For this reason, these four lamp types have been included in the scope of this study, as they are expected to penetrate the domestic sector in the future, albeit in specific niche applications at first.

This section of the report offers a technical review of the four UELs under study: LEDs (both integrally ballasted and a dedicated luminaire), CMH, and T5 linear fluorescent; as well as providing an overview of OLEDs, CFLs, halogens, and incandescent lamps. This section provides 1) a technology overview (examining the operation, developments, and performance characteristics); 2) a complete component breakdown schematic of a typical lamp in each category; and 3) presents results analysed using the evidence gathered both from the literature and stakeholder interviews.

3.2 Light Emitting Diodes Technology Overview

The first practical visible-spectrum light-emitting diode (LED), a Gallium-Arsenide-Phosphide (GaAsP) alloy with a p-n homojunction, was invented at General Electric’s Advanced Semiconductor Laboratory in 1962.[10] This LED, and the ones that were commercialised during the 1960’s, were all red LEDs with extremely low efficacy levels (~0.1 lm/W). Industry continued to research this technology over the next three decades, achieving higher efficiencies and expanding the range of emission wavelengths through the engineering of new III-V alloy systems, developed the wide range of high-brightness LEDs available in the market today.

LEDs are discrete semiconductor devices with a narrow-band emission that can be

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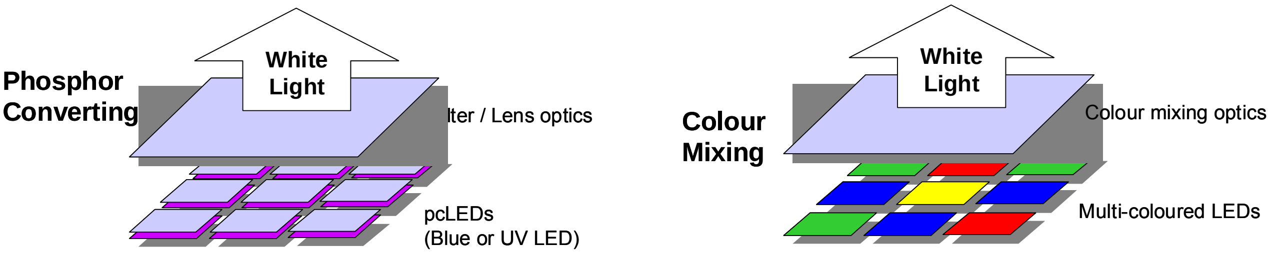
[10] Holonyak and Bevaqcua, Applied Physics Letter, Volume 1, pp.82-83 (1962).

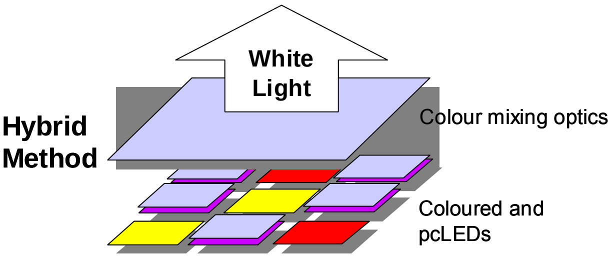
manufactured to emit in the ultraviolet (UV), visible, or infrared regions of the electromagnetic wavelength spectrum. Alone, these LED chips (or 'die') are not well suited for general illumination applications as they do not produce white-light (i.e., a distribution of wavelengths across the visible range of the spectrum that are perceived by the human eye as being 'white'). To generate white-light for general illumination applications, the narrow spectral band of an LED's emission must be converted into white-light, or two (or more) discrete emissions must be mixed. Thus, white-light LED devices are typically based on one of three common approaches: (a) phosphor-conversion LEDs (pc-LEDs); (b) discrete colour-mixing; or (c) a Hybrid method. Figure 3.1 shows these three approaches used for white-light production.

Phosphor-conversion LEDs generally create white-light by blending a portion of the blue light emitted directly from the chip with light emission down-converted by a phosphor. Discrete colour-mixing, on the other hand, starts with discrete coloured sources and uses colour mixing optics to blend together the light output to create white-light emission. The hybrid method uses a combination of pcLEDs and discrete-coloured LEDs to create the desired light output.



(a) Phosphor-Conversion LED

(b) Colour-Mixing



(c) Hybrid Method

Figure 3.1 General Types of White-Light LED Devices

For the phosphor converting blue LED approach, an LED chip emits blue light, generally around 460nm. Some of this light is emitted directly and some of it is down-converted by a phosphor from the 460nm wavelength (blue) to longer wavelengths (e.g. green, yellow, red) with wide-band emissions that blend with the blue to produce white-light. Nichia was the first manufacturer to use this method to produce white-light LED devices on a commercial scale in 1997. It has since been adopted by numerous other manufacturers as a method for generating white-light. Some manufacturers have successfully lowered correlated colour temperature[11] (CCT) and increased the colour rendering index[12] (CRI) by adding a second phosphor to the device, but at a cost to device efficacy. These 'warm-white' devices are currently available in high brightness LEDs with an efficacy of 54 lm/W and a CCT of 3000K.

One of the problems confronting manufacturers of pc-LED devices is the difficulty of maintaining consistent quality white-light due to natural variations in LED (blue or UV) wavelength or in the phosphors. The white-light produced by pc-LEDs is susceptible to variations in LED optical power, peak emission wavelength, phosphor coating, temperature and optical characteristics. Thus, variations in the light appearance can occur from one pc-LED to another, a potentially serious problem for many applications.

Although improvements in phosphor technology will help, the losses associated with adsorbing blue (or UV) light and down-converting it to other wavelengths such as green, yellow and red, are an inevitable limitation to the efficiency. These losses are called "Stoke's loss" and are associated with any phosphor-based down-conversion of light, including the process by which fluorescent tubes emit white-light. Discrete colour-mixing, for this reason, promises to offer the highest efficacy LED device. In colour-mixing, LED devices mix discrete emissions from two or more coloured-light LED chips to generate white light. This approach has its own manufacturing challenges for blending the discrete colours and creating full-spectrum white-light. Analysis has shown, however, that with the colour-mixing approach, high-quality, high-efficacy white-light can be produced. For example, modelling has found that three discrete colour elements can produce white-light with a CCT of 4100K with 80 CRI (similar to the quality of white-light emitted by fluorescent lamps today) at a cumulative efficacy of 200 lm/W, assuming a device efficiency of 56% (see section 1.4.3.1). The principal advantage of the colour-mixing method is that it does not involve phosphors, thereby eliminating phosphor conversion losses in the production of white-light. The largest challenge is the absence of efficient emitters of green light, which significantly limits achievable efficacy. Another drawback is increased complexity. It would require multi-chip mounting and potentially sophisticated optics for blending the discrete colours. It may also require colour control feedback circuitry that could address the different degradation and thermal characteristics of the discrete LED chips.

The third method for generating white light is a hybrid approach that mounts together pc-LEDs and coloured-emission LEDs in the same luminaire to produce the desired light output. For example, some manufacturers are combining pc-LEDs with a higher (bluish-white) CCT with several yellow and red-light emitting LEDs to create a lower (yellow-white) CCT. In this example then, the discrete colour-emitting LEDs are used to change cool-white CCT to a warm-white CCT. The efficacy of this hybrid system approach is dependent on the proportion of the light derived from phosphor-converting LEDs and the direct-emission coloured LEDs. The overall system efficacy will be higher than a pc-LED system, but lower than a colour-mixing system, and will be proportional to the average of the two hybrid component technologies.

In late 2008, the best system efficacies of white-light LED devices were approximately

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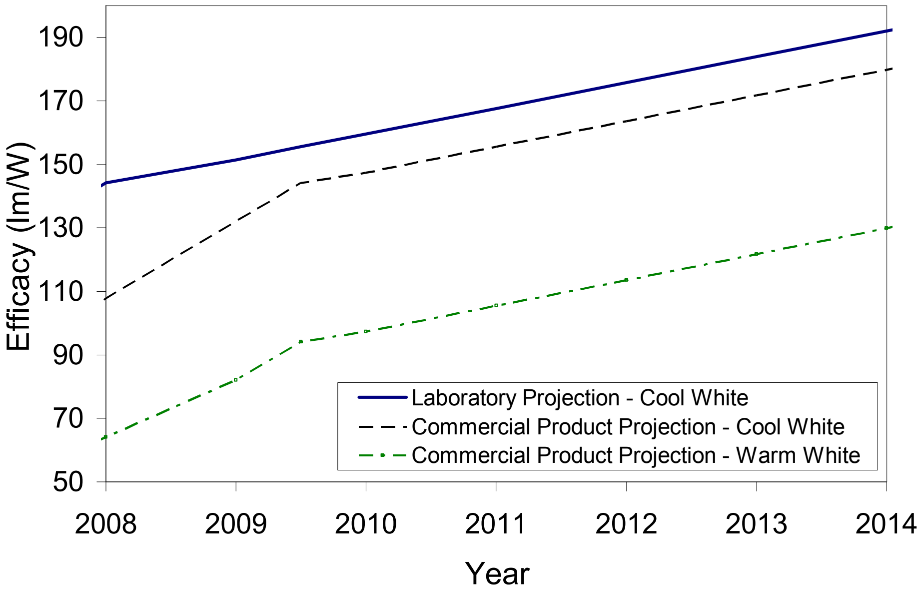
[11] The CCT is the temperature of a blackbody that best matches the colour of a given light source. It describes the colour appearance of the source, measured on the Kelvin (K) scale. Lamps with a CCT below 3500 K are "warm", and appear more yellow-white in colour. Lamps above 4000 K are 'cool' sources, and blue-white in colour.

[12] CRI is the measure of the effect of a light source on the colour appearance of objects in comparison to a reference case with the same CCT.

60 lumens per watt. Some experts estimated that system efficacy is increasing by between 7 and 14 lumens per watt every year. Thus, the market leaders are expected to exceed 100 lumens per watt over the next six years.

As shown in Figure 3.2, laboratory (i.e., not yet commercialised) LEDs are projected to improve from 140 lumens per Watt in 2008 to 190 lumens per Watt in 2014. Commercial production cool white and warm white LEDs are both lower than the laboratory devices, but follow equally as aggressive trends. It is important to note that these efficacy values are for the LED light source, i.e., one component of in the system. Also, they represent performance in an ideal laboratory setting, which cannot be achieved on the production floor. Supply chain issues like volume production, manufacturing line quality control, and supply chain issues can prevent the commercialised lamps from ever achieving the laboratory efficacy levels. Other parts of the system will reduce the overall efficacy of the LED lamp system. That said, changes are also being made to the drivers/ballasts and to the materials, filters and other component parts to enhance overall system efficacy.

Figure 3.2 U.S. DOE Forecasted LED Efficacy Improvements, 2009



In parallel to the efforts to increase LED efficacy, there is also a growing interest to improve the quality of light emitted from the lamp. Manufacturers today are investing millions of pounds of research effort into improving light quality, stability, consistency and maintenance for the LEDs and luminaire devices being manufactured. Ultimately, addressing these technological barriers will position LEDs more competitively in the market, as they become a light source trusted by lighting designers and embraced by consumers seeking the lowest cost of light.

3.3 Ceramic Metal Halide Technology Overview

Originally developed in the 1960's, metal halide lamp technology belongs to the high intensity discharge (HID) family of lamps. These small scale, high light output devices are compact, powerful, efficient, and are widely available in many configurations for the industrial

/ commercial sector as well as the domestic sector.

In high-intensity discharge lamps, light is produced by passing an electric arc through a mixture of gases inside a high-pressure arc tube. In metal halide lamps, the arc tube is filled with a high-pressure gaseous mix, typically including argon, mercury and several metal halides. The argon gas in the arc tube facilitates the striking process across the two electrodes when voltage is first applied to the lamp. The arc generates high temperatures which in turn vaporise the mercury and metal halides, producing light as the temperatures and pressures increase. The combination of metal halides used in the arc tube affects the colour of the light emission (i.e., both the CCT and CRI), which can be modified by using different halides and varying their relative proportions of these halides in the arc tube. The metal halides are dosed into the arc tubes as pellets (i.e., they are solid at room temperature). The typical dose is 5 milligrams per lamp, combining all the halides added.

The CMH lamp is a relatively recent innovation on the traditional metal halide lamp which had an arc tube made from fused silica (quartz). By changing the arc tube material to ceramic enables the lamp to operate at approximately 1,150ºC, whereas quartz metal halide lamps typically operate around 950ºC. This higher operating temperature enables CMH lamps to offer three distinct advantages: higher efficacy, improved colour rendering and better lumen maintenance.

The improved colour from CMH lamps (i.e., CRI of between 80 and 90) enables this technology to compete directly with incandescent and fluorescent light sources. For example, in retail establishments today, CMH lighting systems are regularly installed as a replacement for halogen reflector lamps. The ceramic arc tube improvements offer lamps that can provide CCT values of 3000-4100K, and are guaranteed not to shift by more than 200K over the rated lamp life. The operating life of the lamps is another improvement, typically being specified for 12,000 hours of service whereas the halogen lamps may have been only 3,000. Finally, in addition to these benefits, CMH lamps use less mercury than their quartz counterparts.

CMH lamps, like all metal halide lamps require a ballast to start the lamp and to regulate the flow of the arc current and voltage. This study assumes the CMH lamp is coupled with an electronic ballast for two reasons. First, the electronic ballast represents the most efficient means of operating a CMH lamp, with losses typically only 6% as opposed to 10% for magnetic ballasts. Second, there is a market shift toward use of an electronic ballast with the lower wattage lamps because they can increase the operating life of the lamps and they are smaller and lighter. Indeed, with electronic ballasts, the whole fixture becomes smaller, with a whole CMH system being not much larger than a halogen lamp.

CMH lamps operate with an efficacy of between 80 and 100 lumens per watt (not including losses of the ballast or fitting). These lamps are approximately 10-20% more efficacious than standard MH lamps of equivalent wattage. Taking into account the electronic ballast losses of approximately 6%, the system efficacy drops to between 75 and 94 lumens per watt, just below the threshold performance for an UEL. If a reflector is then incorporated, then a further 20 to 30% of losses should be assumed, lowering the overall performance to approximately 55 to 70 lumens per watt.

Manufacturers are continuing to make investments into improvements to CMH technology. Some of these areas include further improvement to the lamp efficacy, dimming without colour shift, higher CRI values, and reducing the costs. In addition, research is being conducted into instant-on, faster ramp-up to full light output and the ability to conduct hot re-strikes, rather than waiting several minutes for the arc tube temperatures to drop enough to initiate the arc again. Finally, work is being conducted on reducing the mercury content of the lamp as well as finding a more environmentally friendly replacement for the small dose of Krypton-85, an alpha radiation emitter.

3.4 Linear Fluorescent Technology Overview

A fluorescent lamp is a low pressure gas discharge light source that consists of a glass bulb or tube, filled with low pressure mercury vapour and inert gas. The lamp has electrodes sealed onto both ends of the tube, across which an electrical arc is created by causing current to flow between the two electrodes. This arc produces ultraviolet light, which excites phosphors coated on the tube's inner walls, absorbing the ultraviolet light and emitting visible light. The fluorescent lamp has five major components in its construction: glass tube, electrodes, bases, gas fill, and phosphors. In addition to the lamp, a high-efficiency electronic ballast is also part of this LCA analysis, as the lamp requires a ballast to operate.

The tube of a fluorescent lamp is made out of ordinary soda-lime glass, and is produced in different diameters. The "T" in lamp nomenclature represents the tubular shape of the lamp. The "5" in the title connotes the diameter of the lamp as 5/8ths of an inch (1.6 cm). T5 lamps are approximately 40% smaller than T8 lamps, which are one inch in diameter, and almost 60% smaller than T12 lamps, which are 1½" in diameter. Using smaller diameter lamps means that less material (e.g., glass, phosphor, end-caps) is used in manufacturing, reducing the cost of the lamp.

The electrodes of a fluorescent lamp are generally tungsten filaments coated with a mixture of alkaline earth oxides. The purpose of the electrodes is to emit a sufficient number of electrons to ionise the gas and maintain the ultraviolet arc. Electrode coating improvements can improve efficacy and lamp lifetime. Materials that have been used with conventional oxides to coat fluorescent lamp electrodes include Zirconium oxide (ZrO), extending lamp lifetime, and Silicon Carbide (SiC) to more effectively remove electrons from the electrode.

In addition to mercury vapour, which ionises during lamp operation and emits UV light output, the gas fill of a fluorescent lamp usually includes argon and/or a combination of argon and krypton for energy-saver lamps. The lamp fill gas composition can affect efficacy in two ways – 1) the number of collisions between the lamp fill gas and evaporated barium atoms from the electrodes.; and 2) the molecular weight of the lamp fill gas affects the mobility of the Mercury ions and electrons in the lamp plasma. As lighter gases are used, the mobility of mercury ions and electrons increases, allowing them to reach greater velocities which facilitates recombination and improves efficacy.

The phosphors of a fluorescent lamp adsorb ultraviolet light and re-emit that energy as visible light. Fluorescent lamps generally produce spectra with a continuous curve, generated by the phosphors, and superimposed discrete high-output bands, resulting from the mercury discharge. This spectral power distribution determines the colour correlated temperature (CCT) and the colour rendering index (CRI), both important properties to lamp consumers and therefore to manufacturers. The CCT is a measure of the colour of the light emitted, and is measured in degrees Kelvin. Some common fluorescent lamp colour temperatures are 3500k, 4100K, 5000K and 6500K. CRI is a measure of the appearance of colours illuminated by the light, a higher CRI (close to 100) indicates better colour rendering properties of the lamp. T5 fluorescent lamps all have CRI values of 85 or greater. While there are two groupings of phosphors commonly used in fluorescent lamps - halo phosphors and rare-earth phosphors – T5 lamps are only manufactured using rare-earth phosphors.

A T5 fluorescent lamp must be operated in series with a current-limiting device, which for these lamps is always an electronic ballast. In addition to limiting current, ballasts also supply starting and operating voltages as required by the lamp. T5 fluorescent lamps operate in one of three starting methods - preheat (i.e., programmed) start, instant start, or rapid start – each requiring a different type of ballast. In the preheat start method, a current passes through both electrodes in series, heating them and then a voltage is applied across the lamp to induce the arc. In instant start, the lamps are started with a high voltage (400 to 1000V) being applied across the lamp. This voltage causes the ejection of electrons from the electrodes, creating the arc discharge, however this starting method can shorten the operating life of the lamp, particularly if the lamp is installed in a frequently switched application. Once operational, the arc current itself heats the electrodes. In rapid-start, the electrodes are heated for a few milliseconds before initiating the arc. However, once the arc is initiated, the electrodes are continuously actively heated during operation which is unnecessary and reduces the efficiency of the system.

Table 3.1 presents examples of common T5 lamps found in the market in 2008.

Table 3.1. High Efficiency T5 Linear Fluorescent Lamps, 2008

Lamp	Wattage	Nominal Length	CCT	Initial Light Output	CRI	Efficacy
T5	14 W	549 mm	3450 K	1200-1350 lm	85	96
T5	21 W	849 mm	3450 K	1900-2100 lm	85	100
T5	28 W	1149 mm	3450 K	2600-2900 lm	85	104
T5	35 W	1449 mm	3450 K	3300-3650 lm	85	104

Source: Manufacturer catalogues, 2008.

Research is being conducted into methods of further increasing the efficiency of T5 lamps, by changing gas fill and improving the cathodes. It is expected that UEL versions of T5 lamp systems will become available within the next year or two where the lamp is operating at more than 110 lumens per watt. In addition, research is on-going into extending the operating life of the lamp (e.g., up to 75,000 hours for some products – which is more than three times longer than standard fluorescent lamps) and reducing the mercury content.

3.5 Other Lamp Technologies

3.5.1 Compact Fluorescent Lamps

Compact fluorescent lamps (CFL) were designed as a direct replacement for the incandescent lamp. CFLs operate on the same principles as the linear fluorescent technologies, yet they consume about one-quarter as much power as incandescent lamps while having approximately an 8 to 10 fold increase in operating life. While they are more expensive than a standard incandescent lamp in terms of initial cost, they offer electricity savings which more than outweighs their original cost over the life time of the product. As with the family of fluorescent lamps, CFLs have mercury as a critical component which adds to concerns over their end of life disposal.

A typical CFL has an efficacy range between 60 and 72 lumens per watt compared to a standard incandescent lamp which ranges between 8 and 17 lumens per watt (Energy Federation Inc., 2008[13]). Most good quality CFLs have a CRI of 80 or higher and an operating life of 8,000 to 15,000 hours.

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[13] http://www.energyfederation.org/consumer/default.php/cPath/25_44_784

CFLs are the replacement lamp of choice for people switching from incandescent lamps. Due to their great energy savings potential and several market transformation programmes CFLs have achieved a strong foothold in the domestic sector. This is expected to increase as the European Union is phasing out general service incandescent lamps, creating additional market share for technologies like CFLs in the coming starting in late 2009 (Europa, 2008[14]).

3.5.2 Halogen Lamps

Tungsten-halogen lamps are a subgroup of incandescent lamps which use a halogen element such as bromine, chlorine, fluorine, and iodine to help increase lifetime of the lamp. In a tungsten-halogen lamp, small diameter fused quartz envelope filled with a halogen element surrounds the filament. At temperatures above 500 degrees Fahrenheit, when tungsten is evaporated from the filament, the tungsten molecules combine with the halogen into a gaseous compound. This compound circulates within the envelope until it comes into contact again with the filament. The heat of the filament, breaks the gaseous compound, freeing the halogen and re-depositing the tungsten on the filament.

This regenerative process extends the life of incandescent lamps by reducing the loss of tungsten material. Also, because tungsten is not being deposited on the glass surface, bulb darkening over time is greatly reduced. The efficacy of a Halogen lamp ranges from 10 to 30 lumens per watt, with a lifetime of approximately 2000 hours. The CCT is approximately 3000K, just slightly cooler than standard incandescent due to the higher operating temperature.

3.5.3 Incandescent Lamps

Incandescent lamps are a light source in which an electrical current is passed through a filament, thermally exciting electrons which then radiate energy in the form of light and heat (i.e., infrared radiation). Incandescent lamps consist of a bulb, generally composed of glass such as regular lead, soda lime, or borosilicate heat-resisting glass. Sealed to the bulb is an electrical-contact metal base of some type (e.g., screw-base of bayonet-base). Although early incandescent lamps used carbon, osmium, and tantalum filaments, current lamps generally use tungsten filaments. Tungsten's low vapour pressure and high melting point allows for high operating temperatures, and consequently higher lamp efficacies than the older filament materials. Lamp fill gas, though not included in all incandescent lamps, is used to extend the lifetime of the lamp.

Today, incandescent lamps are the leading lamp type found in the domestic sector. These lamps tend to be highly inefficient with efficacies ranging between 8 and 17 lumens per watt, and operating lives of approximately 1,000 hours with a CRI of 100. Incandescent lamps are also the least expensive available lighting solution for the domestic market with a 60W lamp costing approximately £0.40.

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[14] http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/1909&format=HTML&aged=0&language=EN&guiLanguage=en

4 Life Cycle Inventory

4.1 Introduction

In order to quantify the various environmental impacts that occur during all the life cycle stages of the lamp technologies analysed, it is first necessary to build inventories of the various resources (notably raw materials and fuels) that are used, and of the emissions to air, water and soil that occur during those life cycle stages.

Navigant used the evidence matrix established during this project, together with input from the stakeholders and our team's expertise, to prepare an inventory of all the materials and processes used during the life cycle stages of two Light Emitting Diode products, a Ceramic Metal Halide fitting, a T5 linear fluorescent lamp luminaire, an integrally ballasted CFL and an incandescent lamp. These were combined with impact assessment data from the ecoinvent life cycle database in order to determine the environmental impacts of the lighting systems at each life cycle stage.

4.1.1 ecoinvent Database

In this study, Navigant used the ecoinvent life cycle impact assessment database, from the Swiss Centre for Life Cycle Inventories (http://www.ecoinvent.org). This contains environmental impact data on over 4000 manufacturing or related processes, such as the impacts associated with the production of a kilogram of steel or the transoceanic shipping of one tonne of material a distance of one kilometre. For each material or process, the database reports the various impacts through an extensive array of over 250 standard indicators. For example, the database estimates that the global warming potential impacts associated with transoceanic shipping of one tonne of material for one kilometre is 0.0107 kilograms of carbon dioxide equivalents.

This section of the report presents tables giving detail on the inventories of materials and processes associated with each of the luminaire systems studied, together with the names of the processes in ecoinvent that were used to model those materials and processes[15]. Some of the ecoinvent materials and processes are very close matches to the ones in the luminaire systems studied, while others are approximations. The relative significance of these approximations becomes clear when the results are reviewed, and the more critical materials and processes are investigated in more detail in the sensitivity analyses presented in the annexes of the report.

4.1.2 Comparative Basis

Each of the luminaire systems analysed in this study is a little different, having different levels of power consumption, light output, and operating lamp and ballast life time. In order to make a fair comparison between the lamp technologies analysed, it is necessary to

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[15] It should be noted that this is not, in the strict sense, the life cycle inventory of the luminaire systems, since the processes are not broken down further into their constituent elemental flows (the transport is left as transport, rather than converting it into so much steel, plastic, CO_2 emissions, etc). The ecoinvent impact assessment database allows that intermediate step to be avoided, although the detailed life cycle inventory could be produced.

assess the luminaire systems' relative performances over a comparable time period and using a common metric. To achieve this, all of the impacts calculated for the six systems are compared on the basis of lighting service delivered during the analytical time period. The time period is set as the duration of the ballast service life, as this was longer than any of the lamp lives. The quantity of light produced over that time period is calculated as lumen-hours and then used to normalise the impacts making them comparable.

It should be noted that the light levels for these systems were all different, the analytical lifetimes were all different and the number of lamp changes (and thus multiples of lamp-related impacts compounded in the analysis) were different. However, all the analysis culminates in a calculation of megalumen-hours (Mlm-hr) of light over the full use stage of the life cycle analysis. The final results will therefore be in units of, for example, kg of CO_2e per megalumen-hour, in the case of global warming potential. The performance parameters of the lighting systems studied are presented in the following table, including the target efficacies by 2014.

Table 4.1 Performance Parameters for Luminaire Systems

Characteristics	Units	LED int.	LED lum.	CMH	T5	CFL	Incand.
Power Consumption per Lamp	Watts	1	1	20	28	23	100
Number of Lamps per Luminaire	Die / Lamps	10 die	16 die	1 lamp	2 lamps	1 lamp	1 lamp
Power Consumption per Luminaire (including ballast losses)	Watts	12	18	23	59	23	100
System Efficacy (including ballast) in 2009	Lumens per Watt	60	65	77	93	69	16
Projected System Efficacy (including ballast) by 2014	Lumens per Watt	102	143	104	102	76	16
Typical Lamp Lifetime	Hours	20,000	50,000	12,000	24,000	10,000	1,000
Typical Luminaire System Lifetime (i.e., ballast life)	Hours	n/a	50,000	36,000	48,000	n/a	n/a
Total Electricity Consumed	Kilowatt-Hours	240	900	720	2,688	230	100
Total Light Emitted (in 2009)	Mega-Lumen-Hours	14.4	58.5	55.4	263.0	15.9	1.6

In order to put the analytical periods considered for these UEL luminaire systems into perspective, consider the fact that a high-use socket in a domestic setting might be six hours of use per day. At that level of use, a full year of service would total 2,200 hours per year. For the CMH system at 36,000 hours of use, that equates to 16 years of service. For the LED luminaire at 50,000 hours of use, that equates to 23 years of service.

The table shows the relative quantities of light emitted over the analytical periods considered. For the integrally ballasted LED lamp, the total light output over the life of the lamp would be approximately 14.4 megalumen-hours (not accounting for lumen depreciation, and assuming that the LED lamp achieves its other performance targets). Compared to the LED system, the CMH system has approximately four times the lighting service over approximately a longer time period, with around double the power consumption. This differential links back to the difference in system efficacy – a T5 luminaire system today is more efficacious than a LED luminaire today.

4.1.3 Life Cycle Assessment Stages

The impact inventories are broken down into the five life cycle stages, which are (1) raw material production, (2) manufacture, (3) distribution, (4) use / consumption and (5) end-of-life. The LCA work in this report is subdivided into these stages, each of which are briefly described below.

1. Raw Material Production

Many products are made up of multiple components, and nearly all require some form of packaging material in order to protect them during transit to the final customer. This first stage of the life cycle accounts for the emissions and resource usage associated with the production of the various raw materials that go into the final product, and their transportation to the point of manufacture. If it is known that a component or item of packaging is made from recycled materials, it is acceptable to adjust the impacts associated with its production accordingly.

2. Manufacture

The manufacturing phase takes all of the raw materials defined above, as delivered to the point of production, and accounts for the energies used and emissions associated with fabricating the final product. For some products, the manufacturing impacts are dominated by energy usage, while, for others, it is the emissions during manufacturing that are most important.

3. Distribution

The distribution phase covers the transportation of the product from its point of production to its point of installation and use. There might be a tendency when thinking about an LCA to believe that a detailed transport model will be required. However, for many products, transport and distribution form a small part of the overall environmental footprint. Impacts from distribution tend to be much more significant if the product needs to be refrigerated during transit, which obviously isn’t the case for UEL products.

4. Use/Consumption

The use/consumption phase of a product is usually relatively straightforward to define, though it is important that a consistent basis is chosen against which to compare different products. For luminaire systems, the use phase is associated with the consumption of electricity to produce light.

5. End-of-Life

The final stage of a life cycle is ‘end-of-life’, reflecting what happens when things are no longer required. It is far from straightforward to define what is within and without the system boundary at end-of-life, but some rules of thumb exist. As well as accounting for the product itself, the end-of-life phase needs to take account of other integral components, most notably the packaging. That said, aspects such as the handling of transportation vehicles at their end-of-life are usually not explicitly included, as those impacts (together with, for example, the original production impacts) are rolled into the tonne-kilometre impacts associated with transportation during their service life.

There is also the question of whether to give a process credit for any end-of-life recycling. If a cardboard box is recycled at its end of life, this will reduce the need to use virgin pulp. However, if the process were also assigned a reduced impact associated with using recycled cardboard for its packaging, this might constitute double-counting[16]. For this study, any benefits associated with recycling packaging have been excluded from the system boundary, though impacts from land filling the materials are included.

4.2 Raw Material Production

The production of raw materials shows the greatest variation between the UELs analysed, in terms of the processes involved and their associated impacts, thus they are discussed individually by lamp type. The table here provides a summary comparison of the estimated relative weights of the UELs and the two benchmark reference lamps.

Table 4.2 Summary of Component Weights of Luminaire Systems

Component	LEDint	LEDlum	CMH	T5	CFL	Incand.
Base	n/a	0.14 kg	0.16 kg	1.01 kg	n/a	n/a
Ballast	0.21 kg	0.31 kg	0.14 kg	0.31 kg	0.04 kg	0.01 kg
Lamp	0.04 kg	0.03 kg	0.10 kg	0.42 kg	0.01 kg	0.01 kg
Lens	0.02 kg	0.03 kg	n/a	2.02 kg	0.03 kg	0.02 kg
Packaging	0.003 kg	0.003 kg	0.014 kg	0.03 kg	0.004 kg	0.004 kg
Total	**0.28 kg**	**0.52 kg**	**0.41 kg**	**3.79 kg**	**0.095 kg**	**0.03 kg**

The following sections summarise some of the key points associated with the ecoinvent database inputs modelled for the various lighting systems analysed in this study. Detailed tables containing the lists of component parts making up the respective lamp, ballast and fixture for each of the systems are contained in Annex B.

4.2.1 LED Integral Lamp and Dedicated Luminaire Raw Materials

The LED was the simplest of the three technology families to model, because the ecoinvent database includes a process for ‘light emitted diode, LED, at plant’. The LED UEL was assumed that it would need 10 LED die to deliver the required amount of light, so this was factored in to the inventory. Other than that, the inventory included an aluminium heat-sink functioning as a printed circuit board, a plastic base with metal contacts and a lens assembly with a thin film reflective aluminium coating. It was assumed that the lamp would be packaged in a standard cardboard box without the need for a plastic film sleeve.

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[16] Note, however, that this is not definitely double-counting, since it depends on where the box was made and where it was recycled, because cardboard is not a global commodity. In contrast, assigning credit for use of recycled aluminium content during production, and recycling aluminium at end of life, would be double-counting.

4.2.2 Ceramic Metal Halide Raw Materials

The CMH luminaire system consists of a multi-component HID unit in a lens and reflector unit, mounted on plastic base with metal pins as contacts. This is powered by an electronic ballast unit including wires and a switch, capacitors and solder. These are all mounted in a base that comprises plastic and aluminium, with further wiring. It was anticipated that these luminaire systems would be plastic wrapped within their standard cardboard boxes.

4.2.3 T5 Fluorescent Lamp Raw Materials

The T5 fluorescent luminaire system is a relatively large surface-mounted luminaire, as might be used for strip lighting in a kitchen, workshop or garage. The luminaire holds two lamps, each of which consists of a large glass tube with aluminium end caps. These are mounted on a steel base with copper wiring and plastic sockets, covered by a polycarbonate lens diffuser. The electronic ballast contains a PCB, capacitors, luster terminals and solder. It was assumed that the lamps would be individually wrapped in plastic film, and then packed in their cardboard boxes.

4.3 Manufacture

The ecoinvent database does not have a process on the manufacture of lighting fixtures and lamps, so an approximation had to be made. Having examined the available processes, it was decided that a suitable proxy for the manufacture of the lamp, once its various components had been sourced in the raw materials stage, would be that of the assembly of an LCD screen. This surrogate was selected because an LCD screen is also a complex electrical product, involving circuits and components that are assembled, and because the manufacturing impacts are expressed on a basis of kilogram of screen produced. Given that this is a complex product, and assembling a UEL would be easier than constructing an LCD screen, it was presumed to be a conservative approximation. Furthermore, the manufacturing impacts of LCD screens is able to be adjusted in the ecoinvent software to each of the lamps being manufactured by the weight of the product being assembled, adding a degree of flexibility and differentiation. Finally, if the manufacturing life cycle stage were found to have made a significant contribution to the overall impacts, the approximation described would need to be re-examined for accuracy. However, it did not, and therefore this choice was retained for the final analysis.

4.4 Distribution

While there are some exceptions to this rule, in order to consider UELs at volume production and make an assumption that would not underestimate the impact of distribution, Navigant presumed that all UEL systems are sourced from China. In China, it was assumed that they would be transported 500km by lorry (>32 tonne), to the port at Shanghai. They were then assumed to be shipped by transoceanic freight ship from Shanghai to Southampton, and from there by lorry (16-32 tonne) 200km to their final destination.

No transportation was included for the consumer travelling to and from the shop to purchase the luminaire system. This was because it was expected to present an extremely small impact, both in terms of the actual impact of the journey itself, and, in particular, once account was taken that the luminaire system would rarely be the sole purpose for making that journey, and impacts would have to be apportioned according to the rationale behind making the journey. The units for these journeys are represented by tonne-kilometres.

4.5 Use/Consumption

For all UEL systems, the power consumption, light emitted and hours of service were presented earlier in this chapter. To simplify the analysis, it was assumed that there was no diminishing performance during the lamps' lifetimes, so the power consumption and light emitted per watt are constant over the full analytical period. Although this is unlikely to be entirely accurate, the assumption allows us to compare the luminaire systems on a consistent basis, rather than trying to factor in the uncertainty of lumen depreciation curves for each of the technologies.

It was also assumed that the luminaire systems would be powered by electricity from the UK grid, which is produced by a mixture of generating technologies, some of which are more polluting than others. That mixture of generation technologies for the UK electricity supply is presumed to be the same for the lifetimes of all the luminaire systems.

4.6 End-of-Life

The end-of-life of the luminaire system was assumed to occur when the luminaire reached its end of life, as defined in Table 4.1. This ignores the fact that some systems have such long operating lives that they might be replaced before they reach their natural end of life, because of (for example) wider refurbishment of someone's home. At end of life, due to the fact that this study is focused on the domestic sector, it was assumed that the majority of lamps and luminaires considered in this study would not be recycled or disposed of properly. Instead, it was assumed that 80% of the products would simply be land-filled while just 20% would be properly dismantled and recycled. Thus, for all the lighting systems considered in this analysis (both the four UELs and the two reference benchmark lamps), it was assumed that the split between these two fates would be 20:80 (20% recycled, 80% land-filled).

In addition to the luminaire system itself, the fate of its packaging was also considered. All the luminaire systems were assumed to be transported in corrugated cardboard boxes, of which 60% were assumed to be recycled, and the other 40% land-filled. For those that might be expected to be sold also wrapped in a plastic film sleeve, it was assumed that only 10% of those sleeves would be recycled, with the remaining 90% land-filled.

5 Life Cycle Assessment Results

5.1 Introduction

This section of the report presents the results from the life cycle impact assessment. The inventories compiled in Section 4 were combined with impact data from the ecoinvent database, in order to produce levels of environmental impact against a number of indicators selected for this study. The fifteen indicators chosen for this study are presented in the following table.

Table 5.1 Environmental Indicators Chosen for this Study

	Abbr.	Name	Defra Indicator	Ecoinvent Indicator	Units
Air Impacts	GWP	Global Warming Potential	greenhouse gas emissions	global warming potential (GWP100a) [CML2001]	kg CO_2-eq
	AP	Acidification Potential	air pollution	acidification potential [CML2001]	kg SO_2-eq
	POCP	Photochemical Ozone Creation Potential	air pollution	photochemical oxidation [CML2001]	kg O_3 formed
	ODP	Ozone Depleting Potential	air pollution	stratospheric ozone depletion (ODP10a) [CML2001]	kg CFC11-eq
	HTP	Human Toxicity Potential	toxicity	human toxicity (HTP100a) [CML2001]	kg 1,4-DCB-eq
Water Impacts	FAETP	Freshwater Aquatic Ecotoxicity Potential	water pollution	freshwater aquatic ecotoxicity (FAETP100a) [CML2001]	kg 1,4-DCB-eq
	MAETP	Marine Aquatic Ecotoxity Potential	water pollution	marine aquatic ecotoxicity (MAETP100a) [CML2001]	kg 1,4-DCB-eq
	EP	Eutrophication Potential	water pollution	eutrophication potential [CML2001]	kg PO_4-eq
Soil Impacts	LU	Land Use	land use	land use [CML2001]	m^2a
	EDP	Ecosystem Damage Potential	biodiversity impacts	ecosystem damage potential [EDP]	points
	TAETP	Terrestrial Ecotoxicity Potential	soil degradation & contamination	terrestrial ecotoxicity (TAETP100a) [CML2001]	kg 1,4-DCB-eq
Resources	ARD	Abiotic Resource Depletion	resource depletion	depletion of abiotic resources [CML2001]	kg Sb-eq
	NHWL	Non-Hazardous Waste Landfilled	non-hazardous waste	landfilling of bulk waste [EDIP2003]	kg waste
	RWL	Radioactive Waste Landfilled	hazardous waste	landfilling of hazardous waste [EDIP2003]	kg waste
	HWL	Hazardous Waste Landfilled	hazardous waste	landfilling of radioactive waste [EDIP2003]	kg waste

In table 5.1, the right-most column labelled units uses the abbreviation "eq" for equivalents. Equivalent units are used for many of the indicators, particularly where there may be more than one pollutant that can cause a particular impact. For example, global warming is attributed to a number of gases, including carbon dioxide (CO_2) and methane (CH_4); however emissions are reported in units of "kg of CO_2 equivalents." On that basis, CO_2 is said to have a global warming potential (GWP) of one because one kg of CO_2 has the warming potential of itself, but methane has a GWP of 23 (one kg of CH_4 has the warming potential of 23 kg of CO_2). By using equivalent values, it simplifies the outputs of the life cycle analysis and makes studies more comparable. Several other criteria are reported in a similar way, notably the toxicity criteria, which are assessed relative to the toxicity of 1,4-DiChloroBenzene (1,4-DCB), a known carcinogen.

The remainder of this section provides a brief introduction to each of the 15 environmental criteria against which the luminaire systems are assessed.

Indicator: **Global Warming Potential** (GWP)
Measurement Units: kilograms of carbon dioxide (CO_2) equivalents
Description: This indicator is a measurement of activities associated with the life cycle of the product that alter the chemical composition of the atmosphere through the build-up of greenhouse gases, primarily carbon dioxide, methane, and nitrous oxide. As these and other heat-trapping gases increase their concentration, the heat-trapping capability of the earth's atmosphere will also increase, triggering global climate change and associated environmental impacts.

Indicator: **Acidification Potential** (AP)
Measurement Units: kilograms of sulphur dioxide (SO_2) equivalents
Description: This indicator is a measure of the air pollution (mainly ammonia, sulphur dioxide and nitrogen oxides) caused by the product's life cycle which contributes the deposition of acidic substances. The resultant 'acid rain' is best known for the damage it causes to forests and lakes. However, less well known impacts are the ways acidification affects freshwater and coastal ecosystems, soils and even ancient historical monuments. Acid deposition can also increase the environmental mobility of metals, resulting in the pollution of water sources and increased uptake of metals (e.g., mercury) by biota.

Indicator: **Photochemical Ozone Creation Potential** (POCP)
Measurement Units: kilograms of ozone (O_3) formed
Description: This indicator is a measure of the photochemical smog generated during the product's life cycle. Common sources include automobile internal combustion engines, as well as the increased use of fossil fuels for heating, industry, and transportation. These activities lead to emissions of two major primary pollutants, volatile organic compounds (VOCs) and nitrogen oxides. Interacting with sunlight, these primary pollutants convert into various hazardous chemicals known as secondary pollutants – namely peroxyacetyl nitrates (PAN) and ground-level (tropospheric) ozone. These secondary pollutants cause the smog.

Indicator: **Ozone Depleting Potential** (ODP)
Measurement Units: kilograms of CFC-11[17] equivalents
Description: This metric quantifies the ozone depleting potential of the product during its life cycle. Although ground-level ozone is a pollutant, stratospheric ozone is beneficial, protecting the earth from excessive amounts of ultraviolet light. The stratospheric ozone layer is attacked by free radical catalysts, some of which are produced by many man-made chemicals such as chlorofluorocarbons (CFCs) which were used as a blowing agent in aerosols and insulation and as a working fluid in refrigerator compressors. This indicator

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[17] CFC-11 (Chloro-Fluoro-Carbon 11) is Trichlorofluoromethane, CCl_3F.

adjusts all ozone depleting chemicals associated with the UEL to the equivalent level of emissions of these harmful chemicals.

Indicator: **Human Toxicity Potential** (HTP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator attempts to quantify the air, water and soil emissions associated with the product's life cycle that may be detrimental to human health. The toxicological factors are calculated using scientific estimates for the acceptable daily intake or tolerable daily intake of the toxic substances, but are still at an early stage of development, so can only be taken as an indication and not as an absolute measure of the toxicity potential. The measurement units are in equivalents of 1,4-dichlorobenzene, a known carcinogen.

Indicator: **Freshwater Aquatic Ecotoxicity Potential** (FAETP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator is very similar to human toxicity potential, but combines factors associated with the maximum tolerable concentrations of different toxic substances in water by freshwater aquatic organisms.

Indicator: **Marine Aquatic Ecotoxity Potential** (MAETP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator is analogous to FAETP, combining factors associated with the maximum tolerable concentrations of different toxic substances in water, but refers to marine aquatic organisms.

Indicator: **Eutrophication Potential** (EP)
Measurement Units: kilograms of phosphate (PO_4) equivalents
Description: Nitrates and phosphates are essential for life, but increased concentrations in water can encourage excessive growth of algae, reducing the oxygen within the water and damaging ecosystems – a phenomenon known as eutrophication.

Indicator: **Land Use** (LU)
Measurement Units: square meters per year (m^2a), the product of m^2 area and years
Description: Land use is an economic activity that generates large benefits for human society, but it also has negative impacts on the environment. The occupation of a location by an industrial facility precludes the return of that site to a more natural environment, including availability for wildlife. The indicator captures the impact on both the area involved and the number of years over which that occurs.

Indicator: **Ecosystem Damage Potential** (EDP)
Measurement Units: points
Description: Biodiversity has been negatively influenced by intensive agriculture, forestry and the increase in urban areas and infrastructure. This indicator attempts to provide some measure of that impact. It combines land-use and land transformation (both to and from industrial uses), and assigns characterisation factors to account for the relative impact of the land usage.

Indicator: **Terrestrial Ecotoxicity Potential** (TAETP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator is very similar to the previous toxicity potentials, but refers to the maximum tolerable concentrations of different toxic substances by terrestrial organisms.

Indicator: **Abiotic Resource Depletion** (ARD)
Measurement Units: Equivalent kilograms of the scarce element, antimony (Sb)
Description: The current levels of global resource consumption are widely acknowledged to be unsustainable. Abiotic resources are natural, and essentially limited, resources, such as

iron ore, crude oil and natural gas, as opposed to renewable, biotic sources such as biomass. ARD impacts are reported against the remaining global inventory of antimony (Sb), a relatively scarce element.

Indicators: **Non-Hazardous Waste Landfilled** (NHWL), **Radioactive Waste Landfilled** (RWL), and **Hazardous Waste Landfilled** (HWL)
Measurement Units: Kilograms of each of these three land-fill processes
Description: For the products being considered in this LCA, these indicators all seek to quantify the amount of materials sent to landfill, split between three categories – non-hazardous waste, radioactive waste and hazardous waste.

5.2 Relative Impacts Across the Life Cycles

It is possible to assess the results from this study in several different ways. Navigant considered that the first assessment should be which stages of the life cycle of each luminaire system make significant contributions to the overall environmental impacts, and which are negligible. This analysis is important to inform the sensitivity analysis, which investigates significant assumptions and tests whether conclusions drawn are robust to plausible variations in the underlying data.

For each luminaire system, the impacts were separately calculated for the production of four raw material components (the fixture, ballast, lamp and lens), the packaging, transport (by road and by sea), the power consumed during use, and end of life (recycling and disposal).

The following series of tables and figures present the results for each UEL system, broken down into life cycle stages. All values are in the units presented in Table 5.1 above, but normalised by the number of mega-lumen hours emitted by each system during its lifetime. Discussion about these findings follows after this series of tables and figures.

Table 5.2 Life Cycle Impacts of the Integrally Ballasted LED Lamp

LED-int. Components		Air					Water			Soil			Resources			
LCA Stage	**Aspect**	**GWP**	**AP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**EP**	**LU**	**EDP**	**TAETP**	**ARD**	**NHWL**	**RWL**	**HWL**
Raw Material	Fitting	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ballast	2.49E-01	3.34E-03	2.29E-05	2.33E-08	4.70E-01	8.44E-02	3.90E-01	1.37E-04	1.75E-02	1.27E-02	1.96E-04	1.87E-03	1.20E+01	1.22E-04	1.38E-01
	Lamp	3.36E-01	1.67E-03	4.24E-05	2.88E-08	8.18E-02	2.50E-02	1.22E-01	1.71E-04	8.06E-03	6.22E-03	1.06E-04	2.53E-03	7.32E+00	5.37E-05	1.78E-02
	Lens	4.05E-03	2.05E-05	4.30E-07	5.22E-10	2.59E-03	5.47E-04	2.22E-03	2.64E-06	4.07E-04	2.89E-04	6.75E-07	2.98E-05	7.41E-02	6.19E-07	1.37E-03
Manufacture	Packaging	2.39E-04	8.70E-07	4.06E-08	3.51E-11	7.20E-05	2.96E-05	1.27E-04	2.67E-07	4.99E-04	3.17E-04	2.10E-07	1.68E-06	4.85E-03	8.09E-09	2.05E-05
Distribution	Assembly	7.47E-02	3.23E-04	6.93E-06	1.95E-09	2.57E-02	6.12E-03	2.57E-02	1.17E-04	4.22E-03	3.13E-03	1.75E-05	2.42E-04	1.05E+00	6.67E-06	1.36E-02
	Road	1.59E-03	7.46E-06	2.17E-07	2.26E-10	3.23E-04	9.40E-05	4.47E-04	1.17E-06	2.89E-05	2.02E-05	4.14E-07	1.20E-05	7.34E-02	1.33E-07	2.01E-04
	Sea	3.69E-03	8.17E-05	4.87E-07	3.76E-10	2.11E-03	8.99E-05	2.86E-03	6.86E-06	2.76E-05	3.05E-05	7.07E-07	2.45E-05	2.11E-01	4.89E-08	3.59E-05
Use	Power	9.70E+00	3.31E-02	5.23E-04	2.76E-07	8.24E-01	1.70E-01	1.54E+00	2.43E-03	2.20E-01	1.65E-01	1.05E-03	7.53E-02	1.02E+02	2.52E-04	1.33E-01
End of Life	Recycling	1.60E-04	8.00E-07	1.79E-08	1.16E-11	8.65E-05	1.50E-05	1.05E-04	6.79E-08	8.70E-06	6.52E-06	7.74E-08	1.18E-06	4.18E-03	7.78E-09	2.95E-05
	Disposal	1.54E-02	9.27E-06	2.62E-07	1.44E-10	8.25E-03	2.83E-02	9.06E-02	2.03E-06	2.64E-05	1.85E-05	5.93E-07	8.39E-06	7.35E+00	1.88E-07	3.93E-04
	Total	**1.04E+01**	**3.86E-02**	**5.97E-04**	**3.32E-07**	**1.41E+00**	**3.14E-01**	**2.18E+00**	**2.87E-03**	**2.51E-01**	**1.88E-01**	**1.38E-03**	**8.00E-02**	**1.30E+02**	**4.35E-04**	**3.05E-01**

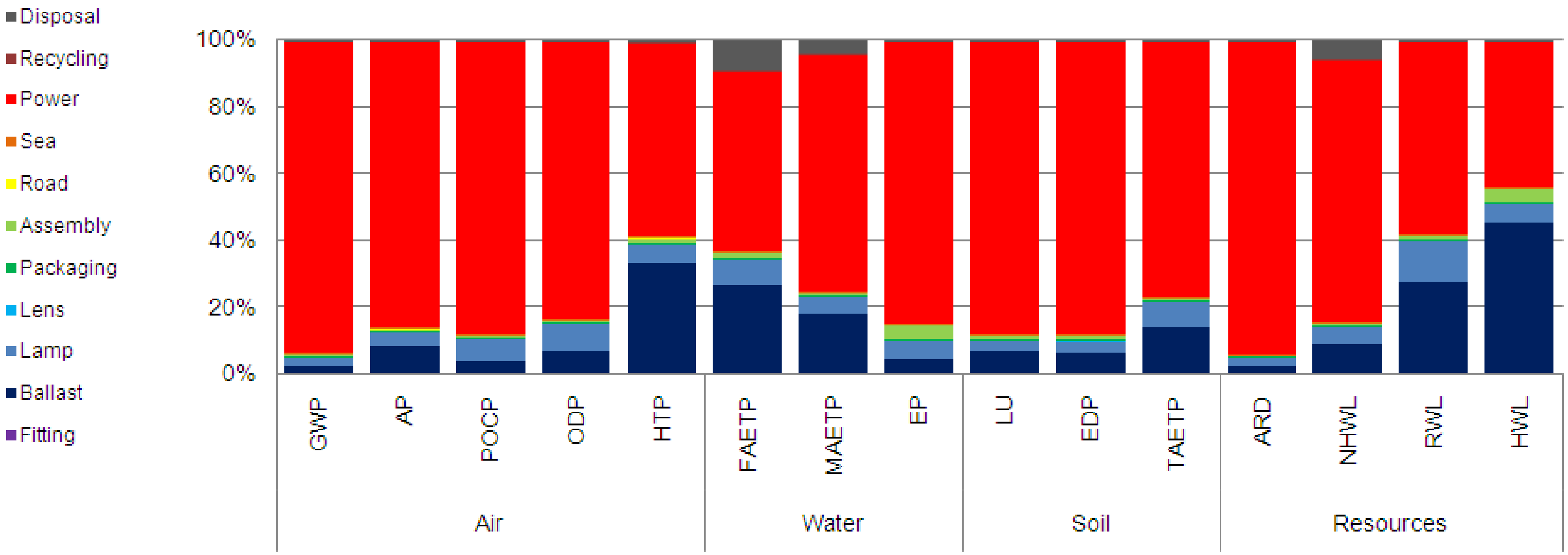

Figure 5.1 Share of Life Cycle Impacts in the Integrally Ballasted LED Lamp

Table 5.3 Life Cycle Impacts of the Dedicated LED Luminaire System

Dedic. LED Components		Air					Water			Soil			Resources			
LCA Stage	**Aspect**	**GWP**	**AP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**EP**	**LU**	**EDP**	**TAETP**	**ARD**	**NHWL**	**RWL**	**HWL**
Raw Material	Fitting	2.63E-02	1.41E-04	1.73E-06	1.90E-09	1.17E-01	1.18E-02	4.69E-02	1.10E-05	6.81E-04	5.33E-04	8.40E-06	1.65E-04	6.93E-01	2.39E-05	4.22E-03
	Ballast	7.71E-02	8.60E-04	6.54E-06	6.79E-09	1.86E-01	2.82E-02	1.23E-01	3.95E-05	4.45E-03	3.25E-03	5.03E-05	5.53E-04	3.26E+00	4.44E-05	3.49E-02
	Lamp	1.22E-01	5.99E-04	1.52E-05	1.05E-08	2.88E-02	8.97E-03	4.38E-02	6.18E-05	2.85E-03	2.20E-03	3.82E-05	9.12E-04	2.63E+00	1.77E-05	6.46E-03
	Lens	1.39E-03	7.04E-06	1.49E-07	1.82E-10	6.82E-04	1.69E-04	6.95E-04	9.17E-07	1.43E-04	1.02E-04	2.27E-07	1.03E-05	2.51E-02	1.70E-07	4.77E-04
Manufacture	Packaging	5.51E-05	2.01E-07	9.37E-09	8.09E-12	1.66E-05	6.83E-06	2.93E-05	6.15E-08	1.15E-04	7.31E-05	4.85E-08	3.89E-07	1.12E-03	1.87E-09	4.72E-06
Distribution	Assembly	1.20E-02	5.19E-05	1.11E-06	3.14E-10	4.13E-03	9.83E-04	4.12E-03	1.87E-05	6.78E-04	5.02E-04	2.81E-06	3.89E-05	1.68E-01	1.07E-06	2.19E-03
	Road	7.34E-04	3.44E-06	9.98E-08	1.04E-10	1.49E-04	4.33E-05	2.06E-04	5.39E-07	1.33E-05	9.33E-06	1.91E-07	5.54E-06	3.38E-02	6.14E-08	9.24E-05
	Sea	1.70E-03	3.76E-05	2.25E-07	1.73E-10	9.75E-04	4.14E-05	1.32E-03	3.16E-06	1.27E-05	1.40E-05	3.26E-07	1.13E-05	9.73E-02	2.25E-08	1.65E-05
Use	Power	8.96E+00	3.06E-02	4.83E-04	2.55E-07	7.60E-01	1.57E-01	1.42E+00	2.25E-03	2.03E-01	1.52E-01	9.73E-04	6.95E-02	9.45E+01	2.33E-04	1.23E-01
End of Life	Recycling	7.43E-05	3.71E-07	8.30E-09	5.37E-12	4.01E-05	6.95E-06	4.86E-05	3.15E-08	4.03E-06	3.02E-06	3.59E-08	5.47E-07	1.94E-03	3.61E-09	1.37E-05
	Disposal	7.13E-03	4.29E-06	1.12E-07	6.65E-11	3.82E-03	1.31E-02	4.20E-02	9.28E-07	1.22E-05	8.53E-06	2.75E-07	3.89E-06	3.41E+00	8.72E-08	1.63E-04
	Total	**9.21E+00**	**3.23E-02**	**5.08E-04**	**2.75E-07**	**1.10E+00**	**2.20E-01**	**1.69E+00**	**2.38E-03**	**2.12E-01**	**1.59E-01**	**1.07E-03**	**7.12E-02**	**1.05E+02**	**3.20E-04**	**1.71E-01**

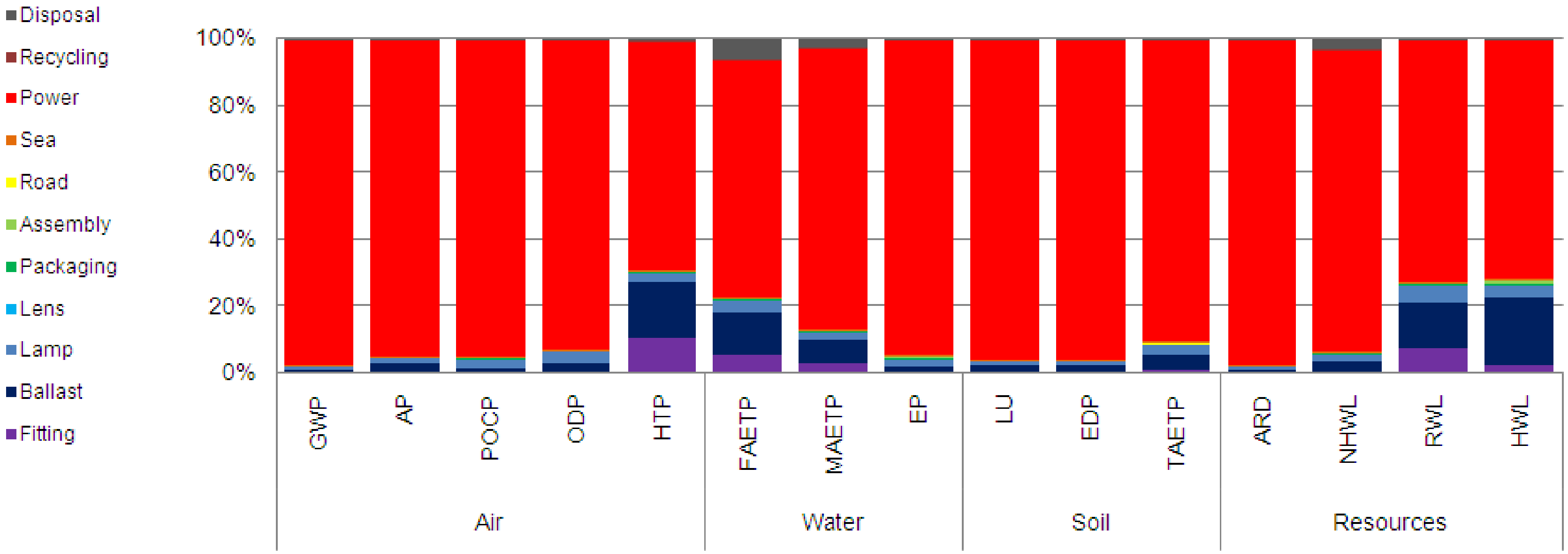

Figure 5.2 Share of Life Cycle Impacts in the Dedicated LED Luminaire System

Table 5.4 Life Cycle Impacts of the CMH Luminaire System

CMH Components		Air					Water			Soil			Resources			
LCA Stage	**Aspect**	**GWP**	**AP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**EP**	**LU**	**EDP**	**TAETP**	**ARD**	**NHWL**	**RWL**	**HWL**
Raw Material	Fitting	1.64E-02	1.76E-04	1.55E-06	1.12E-09	1.18E-01	6.57E-03	3.83E-02	8.97E-06	1.11E-03	8.09E-04	1.26E-05	1.27E-04	4.72E-01	2.72E-05	2.55E-03
	Ballast	3.48E-02	2.39E-04	3.98E-06	4.69E-09	3.35E-02	1.01E-02	5.06E-02	2.32E-05	2.38E-03	1.70E-03	4.13E-05	2.58E-04	2.11E+00	1.07E-05	3.21E-02
	Lamp	4.90E-03	2.33E-05	5.60E-07	4.45E-10	2.79E-03	1.62E-03	6.46E-03	2.79E-06	3.09E-04	2.21E-04	5.16E-05	3.50E-05	1.83E+00	3.00E-06	1.31E-03
	Lens	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Manufacture	Packaging	3.15E-04	1.10E-06	4.66E-08	3.13E-11	6.73E-05	2.84E-05	1.21E-04	2.51E-07	4.26E-04	2.71E-04	1.85E-07	3.20E-06	4.86E-03	2.34E-07	1.91E-05
Distribution	Assembly	3.50E-02	1.51E-04	3.24E-06	9.13E-10	1.20E-02	2.86E-03	1.20E-02	5.45E-05	1.97E-03	1.46E-03	8.19E-06	1.13E-04	4.91E-01	3.12E-06	6.37E-03
	Road	5.93E-04	2.78E-06	8.07E-08	8.42E-11	1.20E-04	3.50E-05	1.67E-04	4.36E-07	1.08E-05	7.55E-06	1.54E-07	4.48E-06	2.74E-02	4.97E-08	7.48E-05
	Sea	1.37E-03	3.05E-05	1.82E-07	1.40E-10	7.89E-04	3.35E-05	1.07E-03	2.56E-06	1.03E-05	1.14E-05	2.64E-07	9.15E-06	7.87E-02	1.82E-08	1.34E-05
Use	Power	7.56E+00	2.58E-02	4.08E-04	2.15E-07	6.42E-01	1.32E-01	1.20E+00	1.90E-03	1.72E-01	1.29E-01	8.21E-04	5.87E-02	7.98E+01	1.96E-04	1.04E-01
End of Life	Recycling	5.85E-05	2.92E-07	6.53E-09	4.23E-12	3.16E-05	5.47E-06	3.82E-05	2.48E-08	3.17E-06	2.38E-06	2.82E-08	4.31E-07	1.52E-03	2.84E-09	1.08E-05
	Disposal	5.69E-03	3.40E-06	1.16E-07	5.26E-11	3.01E-03	1.04E-02	3.33E-02	7.78E-07	1.00E-05	6.98E-06	2.17E-07	3.07E-06	2.70E+00	6.88E-08	2.27E-04
	Total	**7.66E+00**	**2.64E-02**	**4.17E-04**	**2.23E-07**	**8.12E-01**	**1.64E-01**	**1.34E+00**	**1.99E-03**	**1.78E-01**	**1.33E-01**	**9.36E-04**	**5.92E-02**	**8.75E+01**	**2.41E-04**	**1.46E-01**

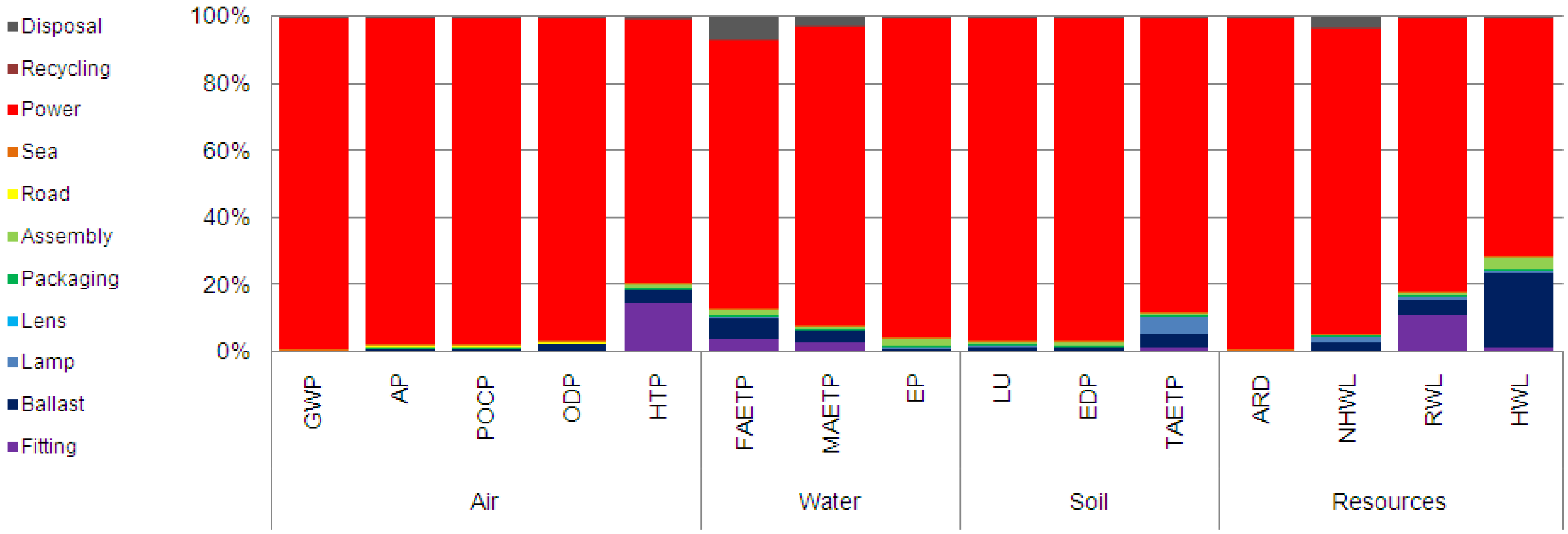

Figure 5.3 Share of Life Cycle Impacts in the CMH Luminaire System

Table 5.5 Life Cycle Impacts of the T5 Luminaire System

T5 Components		Air					Water			Soil			Resources			
LCA Stage	**Aspect**	**GWP**	**AP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**EP**	**LU**	**EDP**	**TAETP**	**ARD**	**NHWL**	**RWL**	**HWL**
Raw Material	**Fitting**	1.45E-02	5.81E-05	5.30E-06	1.06E-09	1.89E-02	8.51E-03	3.05E-02	8.48E-06	7.47E-04	5.30E-04	1.70E-05	1.16E-04	9.02E-01	1.58E-06	3.43E-03
	Ballast	3.97E-02	2.71E-04	4.58E-06	5.31E-09	8.92E-02	1.76E-02	7.86E-02	2.64E-05	2.68E-03	1.92E-03	3.31E-05	2.89E-04	1.88E+00	6.92E-06	4.03E-02
	Lamp	6.28E-03	3.06E-05	5.57E-07	7.05E-10	2.83E-03	6.96E-04	3.29E-03	3.29E-06	4.64E-04	3.33E-04	4.27E-05	3.97E-04	1.51E+00	9.05E-07	1.48E-03
	Lens	3.45E-02	1.26E-04	5.63E-06	2.74E-09	1.24E-02	2.30E-03	1.29E-02	2.80E-05	1.65E-03	1.22E-03	1.02E-05	3.81E-04	6.38E-01	3.59E-05	2.39E-03
Manufacture	**Packaging**	2.25E-04	7.49E-07	2.70E-08	8.78E-12	2.29E-05	1.05E-05	4.40E-05	8.73E-08	9.28E-05	6.00E-05	4.88E-08	3.17E-06	2.08E-03	3.72E-07	6.43E-06
Distribution	**Assembly**	3.72E-02	1.61E-04	3.45E-06	9.71E-10	1.28E-02	3.04E-03	1.28E-02	5.80E-05	2.10E-03	1.56E-03	8.70E-06	1.20E-04	5.21E-01	3.32E-06	6.77E-03
	Road	1.34E-03	6.27E-06	1.82E-07	1.90E-10	2.72E-04	7.91E-05	3.76E-04	9.84E-07	2.44E-05	1.70E-05	3.48E-07	1.01E-05	6.17E-02	1.12E-07	1.69E-04
	Sea	3.10E-03	6.87E-05	4.10E-07	3.16E-10	1.78E-03	7.56E-05	2.41E-03	5.77E-06	2.32E-05	2.56E-05	5.95E-07	2.06E-05	1.78E-01	4.11E-08	3.02E-05
Use	**Power**	6.26E+00	2.14E-02	3.37E-04	1.78E-07	5.31E-01	1.10E-01	9.95E-01	1.57E-03	1.42E-01	1.06E-01	6.80E-04	4.86E-02	6.60E+01	1.63E-04	8.59E-02
End of Life	**Recycling**	1.35E-04	6.76E-07	1.51E-08	9.79E-12	7.31E-05	1.27E-05	8.85E-05	5.74E-08	7.35E-06	5.51E-06	6.54E-08	9.97E-07	3.53E-03	6.57E-09	2.50E-05
	Disposal	1.30E-02	7.82E-06	1.95E-07	1.21E-10	6.97E-03	2.40E-02	7.68E-02	1.68E-06	2.24E-05	1.57E-05	5.01E-07	7.09E-06	6.24E+00	1.59E-07	3.48E-04
	Total	**6.41E+00**	**2.21E-02**	**3.58E-04**	**1.90E-07**	**6.77E-01**	**1.66E-01**	**1.21E+00**	**1.70E-03**	**1.50E-01**	**1.12E-01**	**7.93E-04**	**4.99E-02**	**7.80E+01**	**2.12E-04**	**1.41E-01**

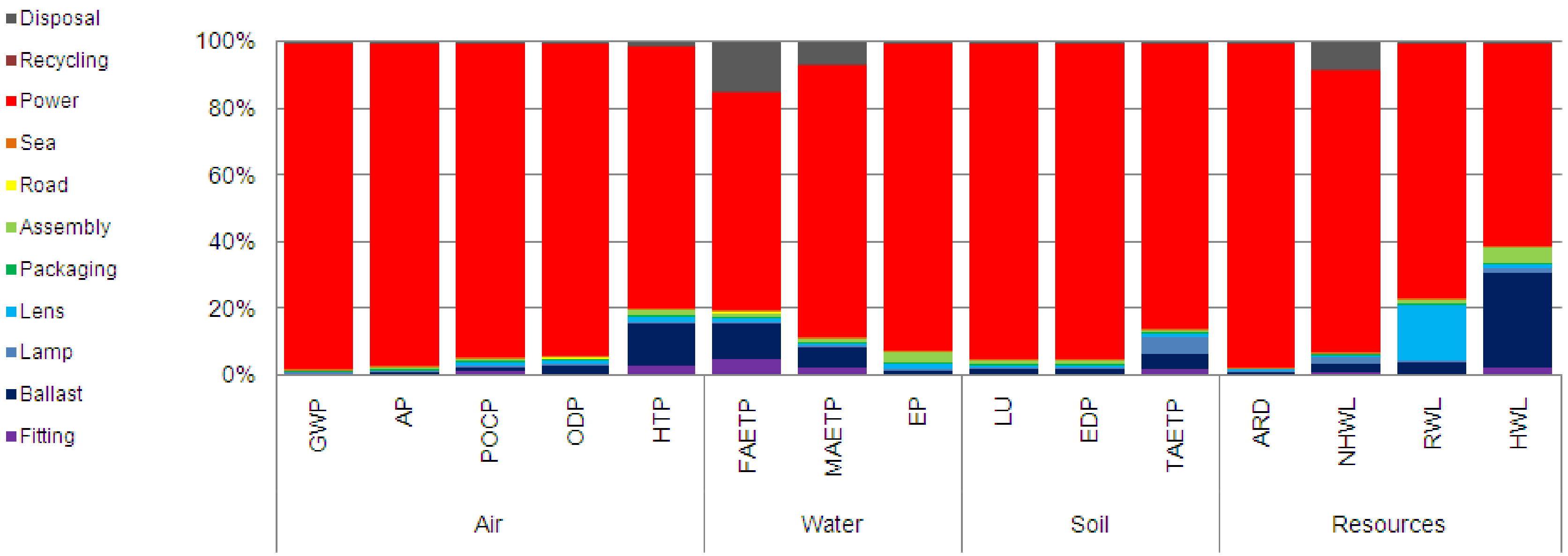

Figure 5.4 Share of Life Cycle Impacts in the T5 Luminaire System

Table 5.6 Life Cycle Impacts of the Integrally Ballasted Compact Fluorescent Lamp

CFL Components		Air					Water			Soil			Resources			
LCA Stage	**Aspect**	**GWP**	**AP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**EP**	**LU**	**EDP**	**TAETP**	**ARD**	**NHWL**	**RWL**	**HWL**
Raw Material	**Fitting**	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ballast	1.64E-01	9.94E-04	1.63E-05	2.37E-08	1.10E-01	4.02E-02	2.25E-01	1.13E-04	1.36E-02	9.62E-03	1.65E-04	1.21E-03	9.46E+00	5.03E-05	2.18E-01
	Lamp	8.56E-03	1.59E-04	8.42E-07	7.84E-10	2.17E-02	1.21E-03	8.07E-03	8.06E-06	6.26E-04	4.57E-04	1.32E-04	7.31E-05	4.63E+00	2.76E-07	6.72E-04
	Lens	5.22E-03	2.66E-05	5.80E-07	7.09E-10	9.76E-04	4.96E-04	2.10E-03	3.55E-06	5.74E-04	4.07E-04	8.19E-07	3.91E-05	9.20E-02	3.19E-07	1.86E-03
Manufacture	**Packaging**	2.94E-04	1.07E-06	5.00E-08	4.32E-11	8.88E-05	3.65E-05	1.57E-04	3.29E-07	6.15E-04	3.91E-04	2.59E-07	2.08E-06	5.98E-03	9.98E-09	2.52E-05
Distribution	**Assembly**	1.85E-02	7.99E-05	1.72E-06	4.83E-10	6.36E-03	1.51E-03	6.35E-03	2.88E-05	1.04E-03	7.74E-04	4.33E-06	5.99E-05	2.59E-01	1.65E-06	3.37E-03
	Road	5.30E-04	2.48E-06	7.21E-08	7.52E-11	1.08E-04	3.13E-05	1.49E-04	3.90E-07	9.64E-06	6.75E-06	1.38E-07	4.00E-06	2.44E-02	4.44E-08	6.68E-05
	Sea	1.23E-03	2.72E-05	1.62E-07	1.25E-10	7.05E-04	2.99E-05	9.53E-04	2.29E-06	9.19E-06	1.01E-05	2.36E-07	8.17E-06	7.03E-02	1.63E-08	1.19E-05
Use	**Power**	8.44E+00	2.88E-02	4.55E-04	2.40E-07	7.16E-01	1.48E-01	1.34E+00	2.12E-03	1.91E-01	1.44E-01	9.16E-04	6.55E-02	8.90E+01	2.19E-04	1.16E-01
End of Life	**Recycling**	5.17E-05	2.58E-07	5.78E-09	3.74E-12	2.79E-05	4.84E-06	3.38E-05	2.19E-08	2.81E-06	2.10E-06	2.50E-08	3.81E-07	1.35E-03	2.51E-09	9.53E-06
	Disposal	5.08E-03	3.01E-06	1.21E-07	4.66E-11	2.66E-03	9.15E-03	2.93E-02	7.17E-07	8.87E-06	6.19E-06	1.93E-07	2.72E-06	2.38E+00	6.09E-08	2.03E-04
	Total	**8.64E+00**	**3.01E-02**	**4.75E-04**	**2.66E-07**	**8.59E-01**	**2.00E-01**	**1.61E+00**	**2.27E-03**	**2.08E-01**	**1.55E-01**	**1.22E-03**	**6.69E-02**	**1.06E+02**	**2.72E-04**	**3.40E-01**

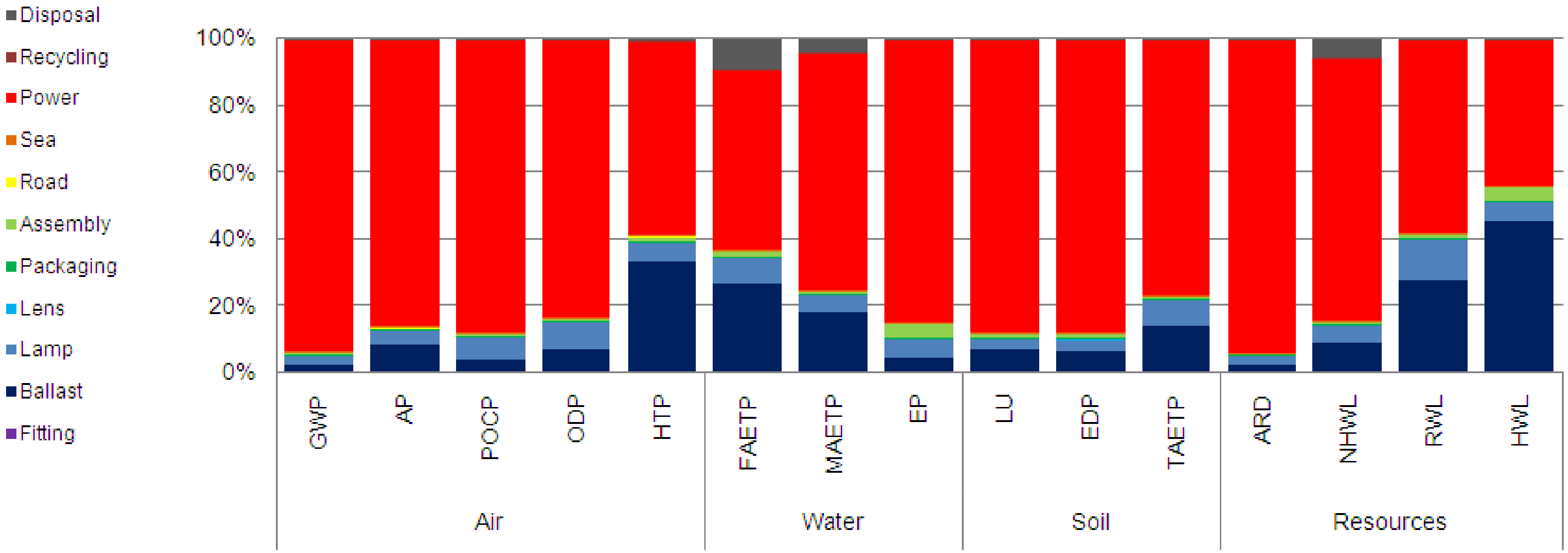

Figure 5.5 Share of Life Cycle Impacts in the Integrally Ballasted Compact Fluorescent Lamp

Table 5.7 Life Cycle Impacts of the General Service Incandescent Lamp

Incand. Components		Air					Water			Soil			Resources			
LCA Stage	**Aspect**	**GWP**	**AP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**EP**	**LU**	**EDP**	**TAETP**	**ARD**	**NHWL**	**RWL**	**HWL**
Raw Material	**Fitting**	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ballast	2.99E-03	8.16E-06	2.46E-07	5.04E-10	6.44E-04	1.99E-04	8.77E-04	9.23E-07	3.08E-04	2.24E-04	2.64E-07	2.33E-05	2.36E-02	1.89E-07	2.82E-04
	Lamp	1.99E-02	4.30E-04	2.19E-06	1.66E-09	6.29E-03	1.65E-03	7.88E-03	2.31E-05	1.74E-03	1.25E-03	5.35E-06	1.77E-04	5.26E-01	6.55E-07	1.77E-03
	Lens	2.99E-02	1.53E-04	3.33E-06	4.07E-09	5.60E-03	2.85E-03	1.21E-02	2.04E-05	3.29E-03	2.33E-03	4.70E-06	2.24E-04	5.28E-01	1.83E-06	1.07E-02
Manufacture	**Packaging**	2.92E-03	1.06E-05	4.96E-07	4.29E-10	8.81E-04	3.62E-04	1.55E-03	3.26E-06	6.10E-03	3.88E-03	2.57E-06	2.06E-05	5.93E-02	9.90E-08	2.50E-04
Distribution	**Assembly**	5.31E-02	2.29E-04	4.92E-06	1.39E-09	1.83E-02	4.35E-03	1.82E-02	8.28E-05	3.00E-03	2.22E-03	1.24E-05	1.72E-04	7.45E-01	4.74E-06	9.67E-03
	Road	1.68E-03	7.87E-06	2.29E-07	2.38E-10	3.41E-04	9.92E-05	4.72E-04	1.24E-06	3.06E-05	2.14E-05	4.37E-07	1.27E-05	7.75E-02	1.41E-07	2.12E-04
	Sea	3.89E-03	8.62E-05	5.15E-07	3.97E-10	2.23E-03	9.49E-05	3.02E-03	7.24E-06	2.91E-05	3.22E-05	7.47E-07	2.59E-05	2.23E-01	5.16E-08	3.79E-05
Use	**Power**	3.64E+01	1.24E-01	1.96E-03	1.04E-06	3.09E+00	6.37E-01	5.79E+00	9.13E-03	8.26E-01	6.19E-01	3.95E-03	2.82E-01	3.84E+02	9.45E-04	4.99E-01
End of Life	**Recycling**	1.48E-04	7.41E-07	1.66E-08	1.07E-11	8.01E-05	1.39E-05	9.70E-05	6.29E-08	8.06E-06	6.04E-06	7.17E-08	1.09E-06	3.87E-03	7.20E-09	2.74E-05
	Disposal	1.55E-02	8.83E-06	7.00E-07	1.36E-10	7.64E-03	2.64E-02	8.45E-02	2.63E-06	2.87E-05	1.98E-05	5.63E-07	7.91E-06	6.85E+00	1.76E-07	1.30E-03
	Total	**3.65E+01**	**1.25E-01**	**1.97E-03**	**1.05E-06**	**3.13E+00**	**6.73E-01**	**5.91E+00**	**9.27E-03**	**8.40E-01**	**6.29E-01**	**3.98E-03**	**2.83E-01**	**3.93E+02**	**9.53E-04**	**5.24E-01**

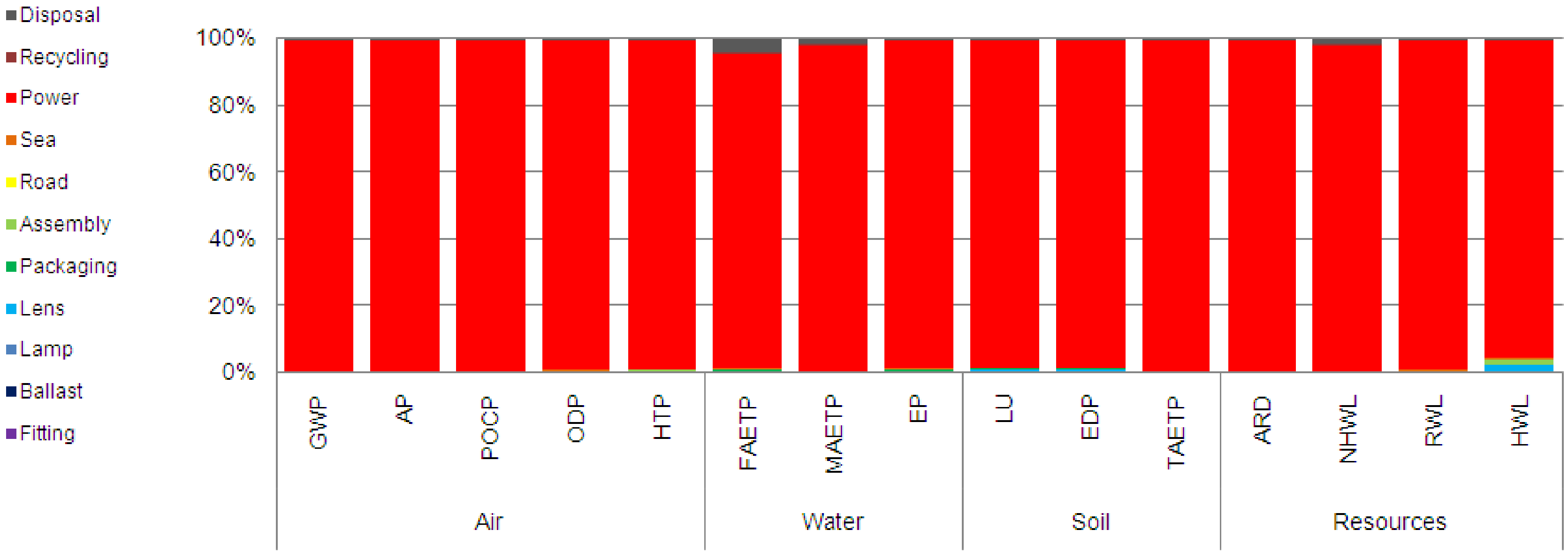

Figure 5.6 Share of Life Cycle Impacts in the General Service Incandescent Lamp

5.2.1 Discussion of Life Cycle Assessment Results

Looking at the six sets of results in the preceding pages, it becomes clear that the use stage, during which the power is consumed, is the dominating factor for the majority of environmental indicators for all lighting systems analysed. This is particularly true for the incandescent lamp, where energy in use constitutes 95% or more of all the impacts over the lifetime of that lamp. After energy in use, the four LCA impacts that have the most significant impact are human toxicity potential, freshwater aquatic ecotoxicity, radioactive waste landfill and hazardous waste landfill. These factors are important because of the materials used in the construction of these lamps.

The integrally ballasted LED lamp did not score well on hazardous waste landfill and radioactive waste landfill because of its abbreviated operating life assumption (i.e., 20,000 hours). That is, compared to the dedicated LED luminaire, which contains similar parts and components, the dedicated LED luminaire has a smaller impact due to its ability to amortise the impacts over a longer operating life. Also, while the energy in use phase had the dominant impact relative to all other life-cycle assessment stages, the aluminium heat sinks in the two LED products contributed to their relatively poor scores in human toxicity and freshwater aquatic ecotoxicity impacts.

The ceramic metal halide and T5 fluorescent lamp systems both did not score well in hazardous waste landfill due primarily to its in use energy consumption and secondarily because of the printed circuit board (which is assumed to be sent to the landfill 80% of the time).

Some of the other life cycle phases were found to make very little contribution to the environmental impacts of the luminaire systems. For all four UELs analysed, the production of the packaging and the distribution by road and by sea all contribute less than 1% to the total impact.

For comparative purposes, an 100 watt incandescent lamp and 23 watt integrally-ballasted compact fluorescent lamp were also evaluated for their relative impacts. Normalising for light output, it was found that the impacts of the incandescent lamp far out-weighed the impacts of each of the four UELs evaluated, and indeed, that of the integrally-ballasted CFL as well. The impacts for the incandescent lamp were driven almost exclusively by the energy in-use phase, which represented between 95% and 99.9% of the impacts across the fifteen life-cycle assessment categories. Looking at a few specific indicators of interest, it was found that:

- comparing the performance of an incandescent lamp to a T5 fluorescent lamp, the incandescent produces 5.7 times more carbon dioxide per unit of delivered light;
- the integrally ballasted CFL had a similar general profile to that of the integrally-ballasted LED, although the LED had slightly higher impacts in all categories due to the aluminium content in the heat sink; and
- the incandescent lamp is the worst performing light source evaluated in this analysis due to its high energy consumption per unit of light produced.

The other life cycle stage that makes a noticeable contribution to a number of the environmental indicators, particularly for the LED luminaire system, is the aluminium heat sink. For the LED and the CMH systems, the largest contributor from the ballast components is the printed circuit boards, while, for the T5 luminaire system, it’s the printed circuit board and the inductive coil. Creating a positive feedback loop, efficacy improvements for LED systems will not only reduce the energy consumption per lumen delivered, but will also enable manufacturers reduce the size of the heat sink, and thus the environmental impacts associated with it.

5.3 Comparative Results Between Luminaire Systems

As well as understanding which parts of the life cycle are the main contributors to the overall environmental impacts of each luminaire system, it is also necessary to assess which system has the smallest overall impact. The results of that analysis are presented in Table 5.8, below.

Table 5.8 Relative Environmental Impacts of the Different Luminaire Systems

Air	Global Warming kg CO_2-Eq per MLm-hr	Acidification kg SO_2-Eq per MLm-hr	Photochemical Oxidation kg formed O_3 per MLm-hr	Stratospheric Ozone Depletion kg CFC-11-Eq per MLm-hr	Human Toxicity kg 1,4-DCB-Eq per MLm-hr
LED-integ.	10.39	0.039	0.00060	3.32E-07	1.41
LED-lumin.	9.21	0.032	0.00051	2.75E-07	1.10
CMH	7.66	0.026	0.00042	2.23E-07	0.81
T5 Fluor.	6.41	0.022	0.00036	1.90E-07	0.68
CFL-integ.	8.64	0.030	0.00047	2.66E-07	0.86
Incand. GLS	36.52	0.125	0.00197	1.05E-06	3.13

Water	Freshwater Aquatic Ecotoxicity kg 1,4-DCB-Eq per MLm-hr	Marine Aquatic Ecotoxicity kg 1,4-DCB-Eq per MLm-hr	Eutrophication kg PO_4-Eq per MLm-hr
LED-integ.	0.31	2.18	0.0029
LED-lumin.	0.22	1.69	0.0024
CMH	0.16	1.34	0.0020
T5 Fluor.	0.17	1.21	0.0017
CFL-integ.	0.20	1.61	0.0023
Incand. GLS	0.67	5.91	0.0093

Soil	Land Use m^2a per MLm-hr	Ecosystem Damage points per MLm-hr	Terrestrial Ecotoxicity kg 1,4-DCB-Eq per MLm-hr
LED-integ.	0.25	0.19	0.0014
LED-lumin.	0.21	0.16	0.0011
CMH	0.18	0.13	0.0009
T5 Fluor.	0.15	0.11	0.0008
CFL-integ.	0.21	0.16	0.0012
Incand. GLS	0.84	0.63	0.0040

Resources	Abiotic Resource Depletion kg antimony-Eq per MLm-hr	Non-Hazardous Waste Landfill kg waste per MLm-hr	Radioactive Waste Landfill kg waste per MLm-hr	Hazardous Waste Landfill kg waste per MLm-hr
LED-integ.	0.080	130.42	0.00044	0.30
LED-lumin.	0.071	104.81	0.00032	0.17
CMH	0.059	87.48	0.00024	0.15
T5 Fluor.	0.050	77.99	0.00021	0.14
CFL-integ.	0.067	105.94	0.00027	0.34
Incand. GLS	0.283	392.91	0.00095	0.52

Considering the numerical findings of the fifteen LCA impact indicators presented in the four sub-tables under in Table 5.8, the incandescent lamp lamp has the highest impacts of any of the other systems studied. This finding would be due to the fact that the incandescent lamp has the lowest efficacy (16 lm/W), while all the other light sources considered had efficacies that were at least four times greater. The best performing of the four systems is T5, with the lowest impact scores, scoring significantly lower than incandescent and lower than the LED systems in all categories considered.

In the air category, the incandescent GLS lamp has the highest impact across all five LCA analyses considered. In global warming potential, the incandescent lamp is between three and six times more intensive than all the other sources considered for its emissions of greenhouse gases. In acidification, photochemical oxidation and stratospheric ozone depletion, the range is approximately the same, as these are all primarily driven by the energy in use category. In the human toxicity category, LED-integrated has just half the impact of the incandescent lamp, when it was about a third of all the other impacts considered. This is primarily due to the large aluminium heat sink used in this device and the short operating life, both of which increase the human toxicity per unit light output. The same is true for the dedicated LED luminaire, which was approximately one-fourth the emissions of incandescent in every category but human toxicity, where it is approximately one-third.

In the water category, the incandescent lamp is the light source with the highest impact of those analysed. For freshwater aquatic ecotoxicity, the more efficient light sources were from 50 to 75 percent lower than the incandescent source. For marine aquatic ecotoxicity and eutrophication, the range was approximately 65 to 80 percent lower. The slightly lower reduction in freshwater aquatic ecotoxicity for the more efficacious lamps is due to their aluminium content, which contributes to this impact.

In the soil category, the incandescent lamp is again the most environmentally damaging light source per unit light emission. For this category of impacts, including land use, ecosystem damage and terrestrial ecotoxicity, the reductions over incandescent for each of the more efficacious lamps are relatively consistent. Compared to incandescent, the integrated-ballast LED lamp ranges from a 65 to 70 percent reduction, the dedicated LED luminaire ranges from 73 to 75 percent, the ceramic metal halide ranges 76 to 79 percent, the T5 reduces impacts by 80 to 82 percent and the CFL reduces impacts from 69 to 75 percent. Overall, substituting any one of the four UELs or the CFL for an incandescent lamp will generate a reduction in soil impacts of between 65 and 82 percent.

In the resources category, the dominant impact is still the incandescent lamp, however there is more variance in this category, particularly for hazardous waste landfill, and to a lesser extent, radioactive waste landfill. For abiotic resource depletion, the four UELs and the CFL all represented between 72 and 82 percent reduction over incandescent lamps. A similar trend is observed in the non-hazardous waste landfill, with between 67 and 80 percent savings over incandescent. However, for radioactive waste landfill, the two LED UELs have a reduced savings potential due to the aluminium heat sinks contained in the lamps. In other words, the savings for the integrally ballasted LED over the incandescent lamp is just 54% and that of the dedicated LED luminaire (which operates for 50,000 hours) is just 66% savings. The other light sources analysed range between 71 and 78 percent savings. For hazardous waste, the integrally ballasted LED and the integrally ballasted CFL both have markedly lower savings potentials, with just 42% and 35% savings respectively, over incandescent. This is primarily due to the aluminium content of the LED and the printed circuit board. The other three sources considered offer between 67 and 73 percent savings over incandescent. In total then, all the light sources considered offer resource impact savings potential over incandescent, typically of approximately 60 to 80 percent.

Compared against all the other sources, the T5 system has the most attractive profile, with the lowest impacts in all categories, although CMH is close for Hazardous Waste Landfill and Freshwater Aquatic Ecotoxicity. From this analysis, we would therefore conclude that, on the basis of the data considered, the T5 is the best system of the four UEL technologies investigated in 2009.

To enable simpler interpretation, the results are also presented in a 'spider graph' in Figure 5.7. Each radius on the chart represents a different environmental impact, and the impacts are grouped into four categories – air (orange), water (blue), soil (green) and resources (yellow). For each impact, whichever luminaire system has the largest impact is plotted at the outer circumference, and the other products are then normalised to that impact, so the distance from the centre denotes the severity of the impact relative to that worst performer. The relative position of the points for the other lighting system demonstrates their relative environmental impact to that maximum. Therefore, the closer each point is to the centre of the plot, the smaller that particular impact. Those lamps with most of their plotted impacts close to the centre of the web are the best performers from an environmental perspective.

It is clear from Figure 5.7 that the incandescent lamp has the highest impact per unit lighting service of all the sources considered (it occupies all of the outermost points on the chart). This result is intuitive because this lamp has the lowest efficacy of the four UELs and two reference lamps considered.

The next worst performer is the integrally ballasted LED, followed by the integrally ballasted compact fluorescent lamp. Apart from the incandescent lamp, these two sources had the shortest analytical period, and therefore had a smaller amount of lighting service over which to amortise the environmental impacts. The best performer was the linear fluorescent T5 system, which had an impact, in total, of just 20% that of the incandescent lamp. From this analysis, we would therefore conclude that, on the basis of the data considered, the T5 UEL is the best of the lighting technologies investigated in 2009.

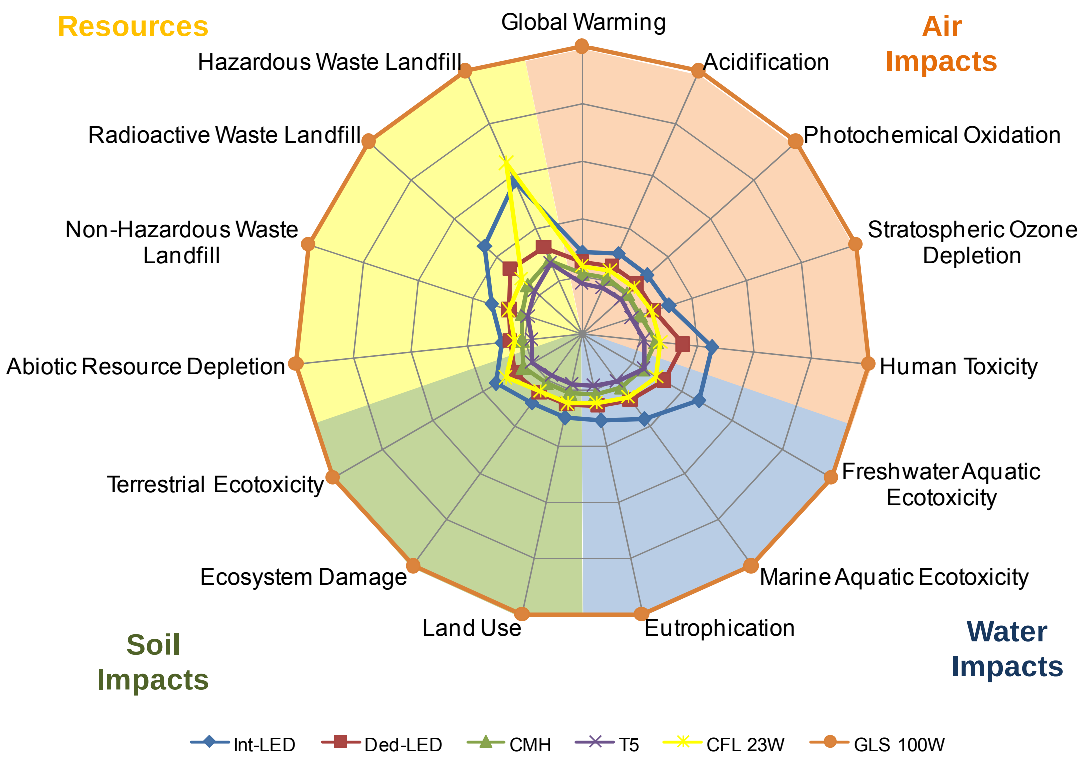

Figure 5.7 Relative Life-Cycle Assessment Impacts of the Lamps Analysed

5.4 Analysis of How Results Might Change in the Future

The results above present the performance of the luminaire systems as they are anticipated to be in the next few years. If we look further into the future, the relative performances of these UELs are expected to change, as they develop along their respective technology maturity curves.

For LEDs in particular, there are considerable investments being made in research and development to improve the efficacies of the lamps. This work is expected to result in higher lumens per watt for LED-based UELs. Since the luminaire systems themselves will be expected to deliver roughly the same amount of light, we can expect that the main change that the consumer will see is that the power consumption will decrease as the efficacy increases.

As an extra study, Navigant reworked the results, to see what would happen if the system efficiencies of the UELs changed as follows:

- Integrally ballasted LEDs improve by 70%, going from 60 lm/W to 102 lm/W
- Dedicated LED Luminaire improve by 120%, going from 65 lm/W to 143 lm/W
- CMH improve by 35%, going from 77 lm/W to 104 lm/W
- T5 improve by 10%, going from 93 lm/W to 102 lm/W
- CFL improve by 10%, going from 69 lm/W to 76 lm/W
- Incandescent GLS assumed to have no improvement in efficacy

The results of this hypothetical ("future") analysis are presented in Figure 5.8 below. The use phase has already been demonstrated to be the most significant for the majority of the environmental impacts, so it was expected that improving the efficacies of the UELs would change their relative environmental performance, and so it proved. The UELs all improved their performance, and as such, moved closer to the centre of the web, reducing their associated environmental impacts. The dedicated LED source was found to be the best performing in this future scenario, with the smallest surface area covered in the spider plot. If the anticipated efficacy improvement in LED is realised, it would enable this UEL to outperform or match the other luminaire systems for every one of the environmental indicators, with the exception of hazardous waste landfill. With the efficacies very close in this scenario, the T5 and CMH impacts are similar.

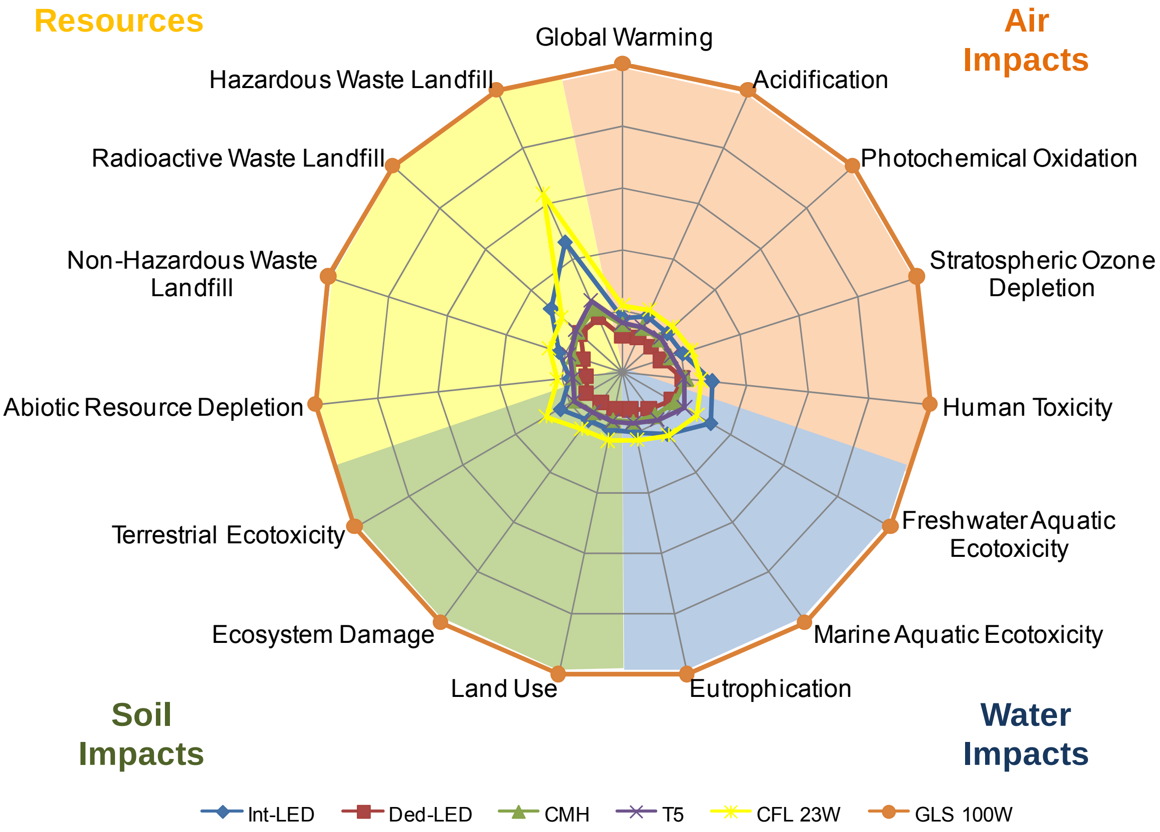

Figure 5.8 Future Relative Life-Cycle Assessment Impacts of the Lamps Analysed

The important finding from these graphs is not necessarily the minor relative differences between the four different UELs analysed, but instead the great reduction in environmental impacts that will result from any of the four UELs (or indeed, the CFL) replacing an incandescent lamp. Environmental impact reductions on the order of 4 to 5 times are possible through transitioning the market to these new, more efficacious sources. Because of the dominant role of energy consumption in driving the impacts, continued focus on efficacy targets and incentives is worthwhile. Furthermore, the greatest environmental impact after energy in-use for the LED sources is the aluminium heat sink, which would be reduced as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat).

6 Data Gaps and Limitations

6.1 Introduction

This report has been prepared with guidance from Defra under the product roadmap programme and the LCA has been conducted in accordance with ISO 14062. Despite best efforts to ensure that the report is of the highest possible standard, it is recognised that there are limitations. The aim of this section is to identify any data gaps in the literature research, present the findings of a sensitivity analysis detailed in Appendix D and discuss assumptions made within the model.

6.2 Data Gap Analysis

The content of the literature reviewed was assessed both in terms of its applicability to life cycle assessment and its specific relevance to the ultra efficient lamps included in the scope of this study.

Major gaps in relation to life cycle assessment are as follows:

- **LCA Analyses -** there is a lack of information relating to the life cycle assessment of LED and ceramic metal halide lamps. In one of the stakeholder interviews a manufacturer indicated that they had conducted an LCA of LED lamps, but that this had not yet been published. It is possible that this absence of readily available LCA data is due to these technologies being in the early stages of development, whereas several life cycle assessments relating to the more mature lamp technologies (fluorescent and incandescent lamps) are included in the research matrix that accompanies this report.

- **Production, Transport and End of Life -** there is a broad range of literature available on the raw materials of lamps, and most of the LCA studies focus on the energy consumed in the ‘use’ phase, but less detail is provided on the production, transport and end of life phases. Where possible, literature findings have been supplemented with stakeholder input to try and address all aspects of the life cycle.

6.3 Sensitivity Analysis

When modelling a complex process like the LCAs of the UELs in this report, not all the parameters are precisely known. One option for dealing with this uncertainty is simply to make a ‘best guess’ of the unknown parameters. This is a pragmatic approach to arrive at an answer, but creates uncertainty about the reliability of the results. When comparing the performance of two or more processes, it is entirely possible that the conclusions about which are ‘best’ may be a direct result of the estimated values of these unknown parameters. Sensitivity analysis aims to address this problem, by exploring the sensitivity of the results and conclusions to these underlying assumptions, and thereby provide comment on the confidence in the results.

In order to increase the robustness of the conclusions drawn from the modelling, it was decided that the key parameters should be subjected to sensitivity analysis using a Monte Carlo simulation. Annex D to this report explains the theory and methodology and then presents the results of this work.

It is usual when modelling a complex process that not all the parameters are known precisely. One option for dealing with this uncertainty is simply to make a 'best guess' of the unknown parameters. This is a pragmatic approach to arriving at an answer, but creates uncertainty about the reliability of the results. When comparing the performance of two or more processes, it is entirely possible that the conclusion about which is 'best' may hang on the estimated values of these unknown parameters. Sensitivity analysis aims to explore the sensitivity of the results and conclusions to these underlying assumptions, and thereby provide comment on the confidence in the results.

Two simulations were run; the first modelling the current performance of the lighting systems, and the second looking at the predicted performance in the future, using the efficiencies presented (and assuming incandescent bulbs do not improve). For each simulation, 10,000 calculations were performed.

The general form of the results is depicted in Figure 6.1 which shows the predicted future global warming potential of the six luminaire systems. The incandescent lamp (GLS 100 watt), in orange, has normal-looking distribution with a mean at about 38 kg CO_2-eq per million Lumen hours; this is the most likely global warming potential from the incandescent bulbs. Furthermore, because the distribution does not overlap any of the other luminaire systems, we can conclude that the incandescent lamp is definitely the worst performer. Considering the plots for the other luminaire systems, the other chief conclusion from the plot is that, using the incandescent bulb as a benchmark, all of the others represent a significant improvement. While this is presented for global warming, this same result also holds true for all fifteen indicators.

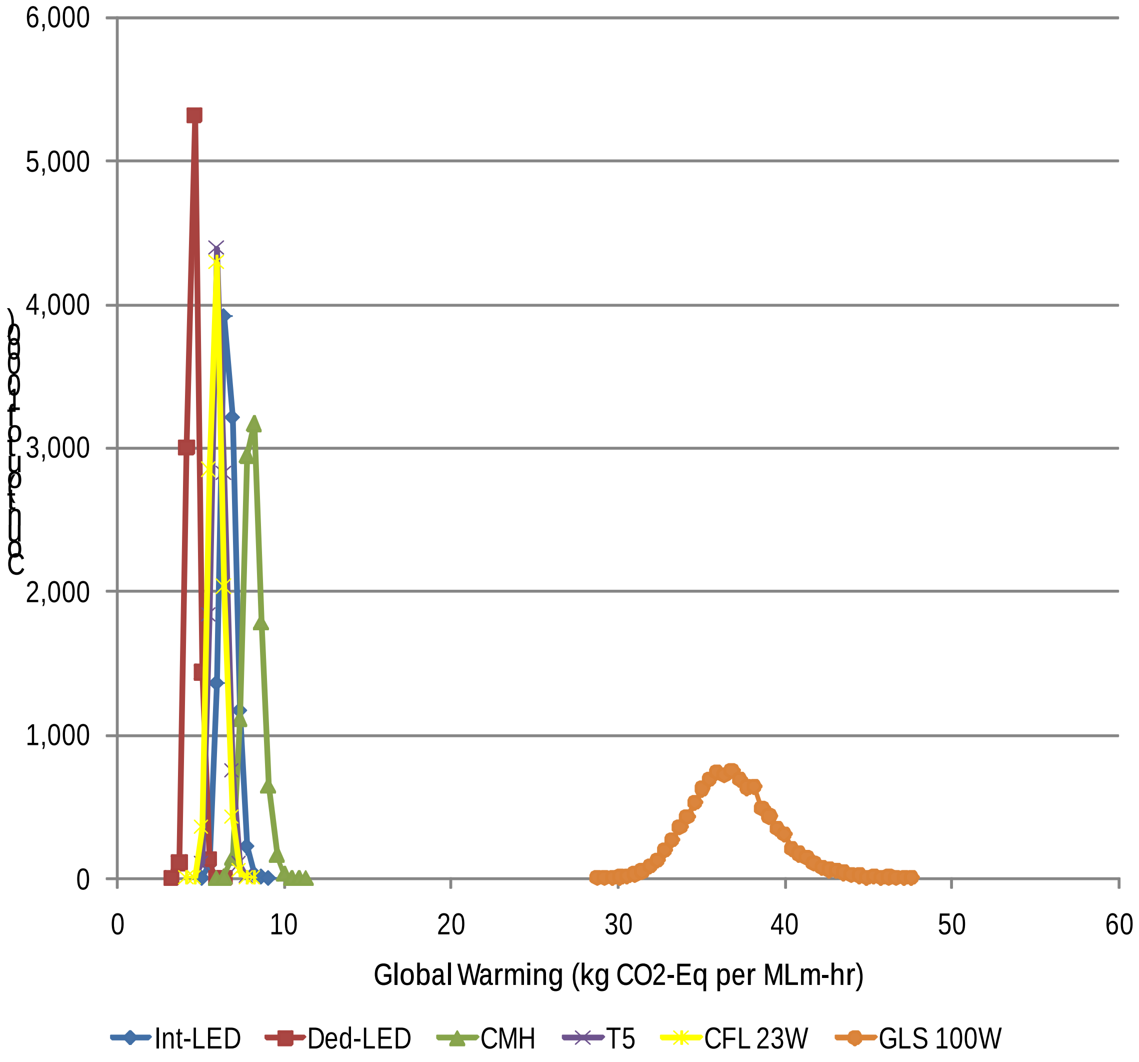

Figure 6.1 Histogram of Results for Monte Carlo Analysis of Global Warming Potential

In conclusion, the Monte Carlo sensitivity analysis shows that the incandescent lamp is, by a considerable margin, the least preferred luminaire system; changing to any other form of lighting represents a definite improvement in performance against all indicators. At the other end of the scale, the LED with dedicated luminaire is, overall, the most preferred option, but there are certain indicators against which it is either not the best, or its margin of preference is small.

6.4 Analysis of the Model

6.4.1 Matching Database Events

The impacts associated with each of the five life cycle stages were estimated using a database programme called ecoinvent. There are two limitations to the approach taken:

- For each UEL included within the scope, one product was selected to be used in the model. The product modelled was selected because it was felt to be a reasonable representation of the products available in the market. However it is recognised that other products on the market may have different degrees of impact than the lamp modelled, because they will be of a different design and performance. However, upon review of the relative proportion of resulting impacts, it was felt that the discrepancy in environmental impacts across the product range for a lamp type is likely to be minimal, and therefore should not have a significant impact on the robustness of the results.

- In some instances the exact product or component of a lamp could not be found in the ecoinvent database, so a close alternative was used in the model. For example, the assembly process for an LCD TV was used to represent the assembly of an LED lamp, which was not available in the ecoinvent database. While this would only approximate the assembly of an actual UEL, this process is for assembly of another electrical product and in the ecoinvent database, is a weight-dependent variable, so it can be tailored to each UEL individually.

6.4.2 Gaps in the LCA Stages

Key gaps or assumptions made at each stage of the LCA are discussed in this section.

- **Raw Materials/Manufacturing:**

  Much of the information on these lifecycle stages was obtained from stakeholders, and so is specific to their product and is dependent on their understanding of the product and its manufacture. The environmental impacts of these stages will be determined by how the raw material is obtained, whether it is sourced locally or internationally and if all components are manufactured on site or purchased in a condition ready for assembly. There is some degree of uncertainty as to whether these variables have been fairly represented by the stakeholder, and therefore whether they are accurately accounted for in the model.

- **Transport**

  It has been found that the majority of UEL products are shipped from China for sale in the UK market. Due to the small / niche size of some markets, a few manufacturers are using air freight as a means of transportation, but this has not been included in the LCA as the view is that in the long term, as volumes increase, all lighting products will be shipped to minimise transport costs.

- **Use**

  In the model it is assumed that the UEL systems achieve their specified operating life and are used until they fail. A long lifetime of a lamp is a positive attribute because it reduces the cost and environmental impact[18] associated with replacing bulbs, and is something that designers and manufacturers have sought to increase in developing new lighting technologies. LED lamps are now achieving lifetimes of 50,000 hours, which is approximately 50 years of service life, assuming an average daily use of 3 hours per day. LED lamps are therefore likely to out-live changing interiors and even changes in home ownership. It is therefore uncertain whether, in practice, UELs will be used for the full duration of their lifetime. As a consequence, the environmental impacts associated with replacement may be incurred more frequently than has been modelled. In addition, the energy in use would be less significant.

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[18] This statement is generally true, however for UELs that are experiencing a rapid period of research and development (e.g., LEDs), the efficacy of these devices is increasing every few months. If a socket is occupied by a very long life lamp, that socket will not available to be replaced for a long period of time, foregoing energy savings that could have been captured by installing a premium-efficiency lamp.

- **End of Life**

  Many of the materials used in UELs have the potential to be recycled or recovered at end of life. The manner in which domestic waste is collected in the UK at present does not allow for a high degree of recycling or recovery, and it was assumed that this would not change significantly over the next five years. Thus, for the analysis presented in this report, it was assumed that just 20% of the material from the UELs analysed is recycled in the future, with the balance (80%) being put into the standard municipal waste stream. This assumption is considered reasonable any lamp sold today will be in service at least 20 years, and by 2029, the domestic waste collection systems should be sophisticated enough for this level of materials recovery.

7 Market Interventions

7.1 Introduction

In this chapter of the report, the focus turns to providing an analysis of the market interventions which the government may wish to consider in order to reduce the overall environmental impacts associated with UELs sold in the domestic sector. This chapter provides a range of practical actions for intervention with the scope of improving the efficiency and sustainability performance of the lighting products entering the domestic market. It starts with a review of the existing programmes aiming to change behavioural patterns across the supply chain and then considers a range of new proposals to complement the existing initiatives identified.

7.2 Existing Programmes

Policy Programmes EU:

- ***Energy using Products (EuP) Directive:*** This Directive is being prepared for the domestic lighting sector. The process involves examination of the environmental impacts of Energy-using Products such as domestic lighting: energy consumption, natural resource depletion, generation of waste, release of hazardous substances, and so on. This programme aims to integrate these environmental factors at the early stages of design in order to improve the environmental performance of the lamps. The framework provides a coordinated set of measures that take a holistic view of the product at all life cycle stages with scope to produce a maximal reduction in environmental impacts.

- ***European Community Directive on Energy End Use Efficiency and Energy Services[19]:*** The purpose of this Directive is to enhance the cost-effective improvement of energy end-use efficiency from member states. This can be achieved by creating conditions to promote and develop the energy services market and provide other energy-saving programmes; and/or establish targets, incentives, and the institutional, financial and legal frameworks needed to eliminate market barriers and imperfections that prevent efficient end use of energy.

- ***Energy Performance of Buildings Directive (EPBD[20]):*** This Directive accounts for the lighting energy demand in the overall building energy balance (i.e., non-domestic buildings). It allows trade-offs with heating and cooling energy demands. This method provides internal lighting loads and can be used as a design tool, making it possible to optimise lighting energy requirements in a holistic approach integrating artificial lighting, daylighting and control systems. The EPBD is also intended to promote energy efficient artificial lighting systems and the efficient use of daylight.

- ***Restriction of the use of certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive:*** Since 1st July 2006, this Directive banned new electrical and electronic equipment from entering the European market if it

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[19] http://www.mtprog.com/spm/download/document/id/631

[20] http://www.buildingsplatform.eu/epbd_publication/doc/P091_EN_CENSE_EN_15193_p3245.pdf

contained lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants.

- ***The Waste Electrical and Electronic Equipment (WEEE) Directive:*** The WEEE together with the Restriction of Hazardous Substances (RoHS) Directive set collection, recovery and recycling targets for electrical goods. This includes lighting equipment such as fluorescent lamps (80% recycle/re-use of the lamp weight). Producers are financially responsible for recycling at the end of life of the lamp.

Product Information EU:

- ***European Framework Directive for Energy Labelling (98/11/EC on lighting).***This type of labelling was enforced on the 1st of January 2001 for domestic lamps. Label ranking covers A-G with A being the best practice lamps (e.g. CFLs) and E-G being incandescent performance. However, this does not provide the necessary ranking distinction at the highest performing spectrum when ultra efficient lamps such as LEDs emerge full scale onto the domestic market.

- ***Energy Efficiency Requirements for Ballasts for Fluorescent Lighting Directive 2000/55/EC:*** This Directive aims to improve the efficiency of the systems by limiting the ballast losses. CELMA developed a classification method that takes both parts of the system into account (lamp and ballast).

Policy Programmes UK:

- ***Government Sustainable Procurement Action Plan:*** This plan came into effect in March 2007 with a scope to re-instate the government procurement to push forward the agenda for energy efficient products in the market. Mandatory standards approaches are being reviewed by the Centre of Expertise for Sustainable Procurement.

- ***Application of the Building Regulations:*** This guidance supports 'Part L' of the Building Regulations for new dwellings which sets out the number of light fittings designed to be compatible with low energy lamp designs, similarly the same principle applies to re-wired existing dwellings. April 2006 saw the inclusion of one dedicated energy light fitting per 25m^2 of floor area or if greater one in four fittings to be energy efficient compatible. 'Part L' is reviewed every five years (next in 2010).

- ***Energy Savings Recommended Scheme:*** The Energy Savings Trust (EST) has an Energy Saving Recommended (ESR) scheme that updates criteria for lamps and dedicated energy efficiency luminaires. The ESR scheme endorses the most efficient lighting products. It serves to recognise manufacturers' efforts towards efficiency best practice. Established in 2001 as a consumer label it is reviewed on an annual basis.

- ***Carbon Emission Reduction Target (CERT):*** The Energy Efficiency Commitment (EEC) scheme has passed on the requirement for energy suppliers to meet improvement targets in the energy efficiency market for household customers. Previous phases have resulted in millions of CFLs being promoted and supplied. The current phase is the 2008-2011 Household Energy Supplier Obligation called CERT looking at supplying 55 million CFLs through direct sales and retailers.

- ***International Task Force for Sustainable Products (ITFSP):*** the UK government has established the ITFSP in order to provide a vehicle through which international product standards are increased having the positive effect of offering UK consumers a greater range of efficient products to choose from.

- ***Domestic Energy Efficient Luminaires (DEELS):*** Came into force in October 2004 it has successfully been adopted and assist the manufacture of energy efficient products across the lighting component spectrum (fixture, fitting, lamp, etc). The Lighting Association (LA) which pioneered this programme has enabled a levelling of the market competition between more expensive energy efficient technologies and the existing conventional incandescent target fixtures.

7.3 New Initiatives

The use stage was found to have the most significant impacts with respect to the life cycle assessment of UELs. After energy-in use, the next most significant contributor was the use of aluminium in the various UELs, particularly LED which incorporated relatively large heat-sinks made out of aluminium. Thus, improvements in efficacy will not only reduce impacts associated with energy-in use, but for the LED products, will reduce the size of the heat sink, and thus the second most significant impact identified in this study.

For this reason, new or refocused initiatives to mitigate environmental impacts associated with UELs should focus two aspects:

1) encouraging the research and development of premium efficiency UELs to reduce energy consumed during the use stage; and

2) promoting market adoption of the most efficacious UELs.

Research / Market Support:

- Sponsorship of basic science research to advance the UK-knowledge base on the fundamental technologies underpinning UEL technologies. This research would be pre-competitive / pre-commercialisation, with a medium-term to long-term benefit horizon.

- Co-sponsorship of competitively awarded contracts focused on incremental improvements to the efficacy of UELs. These contracts would set targets and award millions of pounds of research investment to companies who commit to producing results. UK-based research should be pre-requisite, to strengthen the existing UK-knowledge base. Intellectual property rights must be handled carefully, to ensure this remains with the manufacturer(s) who are awarded the contracts.

- Establish a business incubator that actively works to encourage and nurture small and medium size enterprises entering the UEL supply chain, either as a manufacturer or component supplier. Assist existing small businesses with the transition to medium-sized companies, including financial support to rapidly scale-up manufacturing of premium-efficiency products.

Market Enforcement / Monitoring:

- CALiPER Program (U.S.): As Solid-state lighting (SSL) is developing at increasingly fast rates, the market is flooded with a wide range of product performance. The US DOE has initiated the CALiPER program that tests and reports (objectively) the product performance of commercially available products in order to protect consumers against exaggerated manufacturer claims. This programme is based on the concept of 'name and shame,' and in the U.S. has resulted in products being withdrawn from the market. A similar programme to this in the UK could help remove sub-standard producers and false performance claims which are tarnishing segments in the lighting industry.

Improved Labelling:

- Continue to support the Energy Savings Recommended consumer label in the UK which allows customers to have a choice in selecting the highest performing products in the industry. This has the 'trickle down effect' of encouraging manufacturers particularly at the lower end of the energy efficiency spectrum to invest and produce the highest performing products in order to achieve the energy star rating.
- Move away from the typical wattage labelling system common to incandescent lamps, to be more reflective of the higher performance emerging UELs.
- Provide lamp selection and compatibility guide at purchasing outlets, essentially educating them on the new available features of more efficient technologies.

Sustainable Procurement:

- Use the purchasing power of the UK government to draft terms for a lighting supply contract that is beyond current performance levels (i.e., it should constitute a stretch for manufacturers), particularly in terms of efficacy. Note that the US Department of Defence made a bulk purchase of LED down lights in 2008, installing thousands of retrofit lamps from CREE.

- Work cooperatively with CERTS and any interested utilities to develop a bulk procurement contract with performance metrics that are beyond those of the current market. The emphasis should be on both higher efficacy and high quality (to maintain consumer satisfaction). These bulk procurement contracts should be updated every 6 to 12 months, to ensure only the most efficient in the market are included in the programme.

Affordability Incentives:

- Provide coupons or other means of reducing the first-cost of UELs to consumers. Given current market pricing, it is expected that the top-performing UELs will also be the most expensive, which is likely to inhibit market adoption.

Fiscal Instruments:

- Cut/reduce the European levies on imported lamp products that make them more expensive than other efficient lamp types.

Better Regulation:

- Support the development of harmonised international testing standards and cooperation around regulatory standards.

7.4 Market Transformation Programme Design

Navigant Consulting has developed a methodology to evaluate barriers and design market transformation programmes for energy efficient products. This methodology is called the 5 A's framework and it is designed to enable government, utilities, efficiency advocates and other stakeholders to identify and characterise market barriers. In essence, this methodology is designed to build on previous market transformation research and programmes and to enable the participants to rank barriers and design effective market solutions.

The 5 A's framework considers all the steps in the value chain from manufacturer through to the end user. The 5 A's stand for:

- **Availability:** Does the technology exist?
- **Awareness:** Does the market know about the technology?
- **Accessibility:** Does the market have easy access to the technology?
- **Affordability:** Is the technology affordable?
- **Acceptance:** Are the form, fit and function of the technology acceptable to the market?

Each **A** in the framework represents a critical step along the path of new technology adoption in the market place.

After barrier classification, programmatic solutions are developed to overcome the barriers to a particular product or technology. There are four key advantages that the 5 A's framework offers the energy efficiency community, these are:

1. The structure of the framework requires workshop participants to look broadly at all potential barriers, and not simply focus on the one or two primary barriers.
2. It is flexible and can accommodate a broad range of comments from the most obvious to the 'eureka' type that are often exposed during brainstorming sessions.
3. It can benefit integrated markets, barrier discussions and programmatic solutions to address these barriers can benefit organisations operating in these integrated markets.
4. The methodology is logical, and offers individuals involved in a variety of technologies and programmes, a clear, consistent framework through which to understand technologies and unique market drivers for those targeted technologies.

To date the 5 A's method has been used to facilitate discussions at stakeholder workshops on lighting, commercial refrigeration, air handling and many other technologies. It has demonstrated a sound, workable framework in these instances, and it has facilitated market transformation programme design and evaluation.

Annex A: Glossary of Terms

Ballast - a device used to obtain the necessary electrical conditions to start and operate an electric lamp. Also referred to as “electronic driver” for LED devices.

Colour rendering index (CRI) - the measured degree of colour shift objects undergo when illuminated by a light source as compared with the colour of those same objects when illuminated by a reference source of comparable colour temperature. A perfect rendering with respect to the reference source is subjectively given a maximum value of 100. The changes (or shifts) in chromaticity are averaged and a single CRI value is determined scaled to the maximum value. A limitation of this metric is that it is only applicable to light sources of the same correlated colour temperature (CCT). In other words, CRI values of two light sources with different CCT cannot be compared. For example, comparison of the CRI of a “cool” lamp and a “warm” lamp provides no useful information. However, the metric does allow for comparison of lamps across different source technologies. For example, the CRI values for a 5000K LED can be compared to a 5000K fluorescent lamp.

Correlated colour temperature (CCT) - the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source. The metric for colour is CCT, given in degrees Kelvin (K). Lower temperatures (less than 3200K) are referred to as being “warm” in colour, while higher temperatures (in excess of 4000K) are referred to as being “cool” in colour.

Efficacy - the measured lumen output of a lamp in lumens divided by the measured lamp electrical power input in watts expressed in units of lumens per watt (LPW). Efficacy provides a metric to compare the performance of white-light sources. In this study, lamp efficacies take into account the lamp losses (exclusively) and system efficacies take into account the losses associated with the lamp and ballast together.

Fixture – (also referred to as a “fitting”), it represents the housing into which a lamp and ballast are installed to create a finished luminaire. The fixture protects the lamp, and usually manages source light distribution.

Lamp - a generic term for a source created to produce optical radiation. By extension, the term is also used to denote sources that radiate in regions of the spectrum adjacent to the visible. Through popular usage, a portable luminaire consisting of a lamp with shade, reflector, enclosing globe, housing, or other accessories is also sometimes called a lamp. In such cases, in order to distinguish between the assembled unit and the light source within it, the latter is often called a bulb or tube, if it is electrically powered.

Lamp lumen depreciation (LLD) - the intrinsic reduction in light output from start to finish of lamp. Many factors, such as the fixture construction and application, affect this reduction in light output. For example, the accumulation of dust on the lamp (and fixture) will contribute to the reduction in light output over time.

Light - radiant energy that is capable of exciting the retina and producing a visual sensation. Since the energy at each wavelength does not stimulate the human visual system equally, to go from radiant energy to light, it is necessary to factor the contribution of radiant energy from each wavelength by the visibility function of the human eye. That function is defined by the CIE as the photopic visibility function. This effectively limits the useful radiant energy to a very small range in the electromagnetic spectrum called the visible spectrum (wavelengths between 380 and 780 nanometres). Since it is the distribution of the converted electrical energy in the visible spectrum that determines the efficacy of a light source, a highly efficient source capable of converting electrical energy to radiant energy may not necessarily be a source of high efficacy.

Lumen (lm) - the SI (metric) unit of luminous flux. Radiometrically, it is determined from the radiant power as in luminous flux. Photometrically, it is the luminous flux emitted within a unit solid angle (1 steradian) by a point source having a uniform luminous intensity of 1 candela.

Luminaire - a complete lighting unit consisting of a lamp or lamps and ballast(s) (when applicable) together with a fixture (housing and parts) designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

System efficacy - measurement of energy efficiency for lamp-ballast combinations. All of the lighting systems considered in this report must be used with a ballast. The application of system efficacy is the same as for lamp efficacy, except that it takes into account the contribution of the ballast as it delivers power to the lamp from the main.

Annex B: Component Lists for Systems Analysed

B.1 Raw Material Production

The production of raw materials shows the greatest variation between the UELs analysed, in terms of the processes involved and their associated impacts, thus they are discussed individually by lamp type. The table here provides a summary comparison of the estimated relative weights of the UELs.

Table B.1 Summary of Component Weights of Luminaire Systems

Component	LEDint	LEDlum	CMH	T5	CFL	Incand.
Base	n/a	0.14 kg	0.16 kg	1.01 kg	n/a	n/a
Ballast	0.21 kg	0.31 kg	0.14 kg	0.31 kg	0.04 kg	0.01 kg
Lamp	0.04 kg	0.03 kg	0.10 kg	0.42 kg	0.01 kg	0.01 kg
Lens	0.02 kg	0.03 kg	n/a	2.02 kg	0.03 kg	0.02 kg
Packaging	0.003 kg	0.003 kg	0.014 kg	0.03 kg	0.004 kg	0.004 kg
Total	**0.28** kg	**0.52** kg	**0.41** kg	**3.79** kg	**0.095 kg**	**0.03 kg**

Following raw materials, the remaining LCA stages are similar, thus they are not presented separately by technology. Work proceeded on the basis that, if these assumptions led to life cycle stages that were significant contributors to the overall impacts of any of the luminaire systems, the assumptions would be revisited and tested in the sensitivity analysis (see Annex D).

B.1.1 LED Raw Materials – Integrally Ballasted and Dedicated Luminaire

The LED was the simplest of the four technologies to model, because the ecoinvent database includes a process for ‘light emitted diode, LED, at plant’. The LED UEL was assumed that it would need 10 LED die to deliver the required amount of light, so this was factored in to the inventory. Other than that, the inventory included an aluminium heat-sink functioning as a printed circuit board, a plastic base with metal contacts and a lens assembly with a thin film reflective aluminium coating. It was assumed that the lamp would be packaged in a standard cardboard box without the need for a plastic film sleeve. The following table provides a list of all the raw materials that were assumed are used in the LED UEL system.

Table B.2 Raw Material Inventory for the integrated LED Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	Foam	polyurethane, rigid foam, at plant	0.003	kg
Raw Material	Ballast	Inductor	cast iron, at plant	0.006	kg
Raw Material	Ballast	Inductor	copper, at regional storage	0.004	kg
Raw Material	Ballast	Zener Diodes	diode, unspecified, at plant	0.0001	kg
Raw Material	Ballast	Capacitors	aluminium, production mix, at plant	0.005	kg
Raw Material	Ballast	Resistors	resistor, unspecified, at plant	0.010	kg
Raw Material	Ballast	Transistor	transistor, unspecified, at plant	0.003	kg
Raw Material	Ballast	PCB (Aluminium machined tooled block)	aluminium, production mix, at plant	0.100	kg
Raw Material	Ballast	Wiring	copper, at regional storage	0.002	kg
Raw Material	Ballast	Solder Paste	solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant	0.001	kg
Raw Material	Ballast	Housing (Polypropylene)	polypropylene, granulate, at plant	0.035	kg
Raw Material	Ballast	Integrated Circuit	integrated circuit, IC, logic type, at plant	0.001	kg
Raw Material	Ballast	PET Film	polyethylene terephthalate, granulate, amorphous, at plant	0.002	kg
Raw Material	Lamp	Black Glass Insulation	foam glass, at plant	0.006	kg
Raw Material	Lamp	Tinplate Base	steel, low-alloyed, at plant	0.003	kg
Raw Material	Lamp	Copper pins	copper, at regional storage	0.0001	kg
Raw Material	Lamp	Base contacts	copper, at regional storage	0.0004	kg
Raw Material	Lamp	Base contacts	solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant	0.0002	kg
Raw Material	Lamp	Plastic Base	polyvinylchloride, at regional storage	0.016	kg
Raw Material	Lamp	LED	light emitting diode, LED, at plant	0.019	kg
Raw Material	Lens	Glass	glass tube, borosilicate, at plant	0.020	kg
Raw Material	Lens	Coating	aluminium, production mix, at plant	0.001	kg
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at plant	0.003	kg

Table B.3 Labour to Process Raw Material for the Integrated Ballast LED Lamp

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Lamp	Tinplate Base	tin, at regional storage	0.001	kg
Raw Material	Lamp	Plastic Base	injection moulding	0.016	kg
Raw Material	Ballast	Inductor	wire drawing, copper	0.004	kg
Raw Material	Ballast	Capacitors	sheet rolling, aluminium	0.005	kg
Raw Material	Ballast	PCB (Aluminium machined tooled block)	aluminium product manufacturing, average metal working	0.100	kg
Raw Material	Ballast	Wiring	wire drawing, copper	0.002	kg
Raw Material	Ballast	Housing (Polypropylene)	injection moulding	0.035	kg
Raw Material	Ballast	PET Film	extrusion, plastic film	0.002	kg
Raw Material	Lamp	Tinplate Base	tin, at regional storage	0.001	kg
Raw Material	Lamp	Plastic Base	injection moulding	0.016	kg
Raw Material	Ballast	Inductor	wire drawing, copper	0.004	kg
Raw Material	Ballast	Capacitors	sheet rolling, aluminium	0.005	kg
Raw Material	Ballast	PCB (Aluminium machined tooled block)	aluminium product manufacturing, average metal working	0.100	kg
Raw Material	Ballast	Wiring	wire drawing, copper	0.002	kg

Table B.4 Raw Material for the Dedicated LED Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	Foam	polyurethane, rigid foam, at plant	0.003	kg
Raw Material	Ballast	Inductor	cast iron, at plant	0.006	kg
Raw Material	Ballast	Inductor	copper, at regional storage	0.004	kg
Raw Material	Ballast	Zener Diodes	diode, unspecified, at plant	0.0001	kg
Raw Material	Ballast	Capacitors	aluminium, production mix, at plant	0.005	kg
Raw Material	Ballast	Resistors	resistor, unspecified, at plant	0.010	kg
Raw Material	Ballast	Transistor	transistor, unspecified, at plant	0.003	kg
Raw Material	Ballast	PCB (Aluminium machined tooled block)	aluminium, production mix, at plant	0.200	kg
Raw Material	Ballast	Wiring	copper, at regional storage	0.002	kg
Raw Material	Ballast	Solder Paste	solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant	0.001	kg
Raw Material	Ballast	Housing (Polypropylene)	polypropylene, granulate, at plant	0.035	kg
Raw Material	Ballast	Integrated Circuit	integrated circuit, IC, logic type, at plant	0.001	kg
Raw Material	Ballast	PET Film	polyethylene terephthalate, granulate, amorphous, at plant	0.002	kg
Raw Material	Fitting	Base	aluminium, production mix, at plant	0.100	kg
Raw Material	Fitting	Metal Clips	aluminium, production mix, at plant	0.030	kg
Raw Material	Fitting	Wiring	copper, at regional storage	0.010	kg
Raw Material	Lamp	Copper pins	copper, at regional storage	0.0001	kg
Raw Material	Lamp	Base contacts	copper, at regional storage	0.0004	kg
Raw Material	Lamp	Base contacts	solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant	0.0002	kg
Raw Material	Lamp	LED	light emitting diode, LED, at plant	0.030	kg
Raw Material	Lens	Glass	glass tube, borosilicate, at plant	0.030	kg
Raw Material	Lens	Coating	aluminium, production mix, at plant	0.001	kg
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at plant	0.003	kg

Table B.5 Labour for Processing the Raw Material for the Dedicated LED Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	Inductor	wire drawing, copper	0.004	kg
Raw Material	Ballast	Capacitors	sheet rolling, aluminium	0.005	kg
Raw Material	Ballast	PCB (Aluminium machined tooled block)	aluminium product manufacturing, average metal working	0.200	kg
Raw Material	Ballast	Wiring	wire drawing, copper	0.002	kg
Raw Material	Ballast	Housing (Polypropylene)	injection moulding	0.035	kg
Raw Material	Ballast	PET Film	extrusion, plastic film	0.002	kg
Raw Material	Fitting	Base	aluminium product manufacturing, average metal working	0.100	kg
Raw Material	Fitting	Metal Clips	aluminium product manufacturing, average metal working	0.030	kg
Raw Material	Fitting	Wiring	wire drawing, copper	0.010	kg

B.1.2 Ceramic Metal Halide Raw Materials

The CMH luminaire system consists of a multi-component HID unit in a lens and reflector unit, mounted on plastic base with metal pins as contacts. This is powered by an electronic ballast unit including wires and a switch, capacitors and solder. These are all mounted in a base that comprises plastic and aluminium, with further wiring. It was anticipated that these luminaire systems would be plastic wrapped within their standard cardboard boxes. The following table provides a list of all the raw materials that were assumed are used in the CMH UEL system.

Table B.6 Raw Material Inventory for the CMH Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	PCB	printed wiring board, surface mounted, unspec., Pb free, at plant	0.007	kg
Raw Material	Ballast	Housing	steel, electric, un- and low-alloyed, at plant	0.036	kg
Raw Material	Ballast	Gear Tray	steel, electric, un- and low-alloyed, at plant	0.065	kg
Raw Material	Ballast	Wiring	copper, at regional storage	0.001	kg
Raw Material	Ballast	Connectors	polypropylene, granulate, at plant	0.003	kg
Raw Material	Ballast	Switch	polypropylene, granulate, at plant	0.006	kg
Raw Material	Ballast	Coil	aluminium, production mix, at plant	0.017	kg
Raw Material	Ballast	Capacitor	aluminium, production mix, at plant	0.002	kg
Raw Material	Ballast	Capacitor	epoxy resin insulator (SiO2), at plant	0.001	kg
Raw Material	Ballast	PET Film	polyethylene terephthalate, granulate, amorphous, at plant	0.001	kg
Raw Material	Ballast	Solder Paste	solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant	0.001	kg
Raw Material	Fitting	Plastic	polypropylene, granulate, at plant	0.053	kg
Raw Material	Fitting	Clips	aluminium, production mix, at plant	0.053	kg
Raw Material	Fitting	Wiring	copper, at regional storage	0.053	kg
Raw Material	Lamp	Pins	steel, low-alloyed, at plant	0.002	kg
Raw Material	Lamp	Pins	copper, at regional storage	0.0001	kg
Raw Material	Lamp	Pins	chromium, at regional storage	0.0001	kg
Raw Material	Lamp	Pins	nickel, 99.5%, at plant	0.0001	kg
Raw Material	Lamp	Base	polycarbonate, at plant	0.011	kg
Raw Material	Lamp	HID capsule	mercury, liquid, at plant	0.000006	kg
Raw Material	Lamp	HID capsule	argon, liquid, at plant	0.0000003	kg
Raw Material	Lamp	HID capsule	krypton, gaseous, at plant	0.0000003	kg
Raw Material	Lamp	HID capsule	rare earth concentrate, 70% REO, from bastnasite, at beneficiation	0.000009	kg
Raw Material	Lamp	HID capsule	aluminium oxide, at plant	0.023	kg
Raw Material	Lamp	Reflector & Lens	glass tube, borosilicate, at plant	0.060	kg
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at	0.005	kg

LCA Stage	Aspect	Further Information	Name	Amount	Units
			plant		
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at plant	0.005	kg
Raw Material	Packaging	Plastic	polyethylene, LLDPE, granulate, at plant	0.003	kg

Table B.7 Labour to Process Raw Material for the CMH Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	Housing	steel product manufacturing, average metal working	0.036	kg
Raw Material	Ballast	Gear Tray	steel product manufacturing, average metal working	0.065	kg
Raw Material	Ballast	Wiring	wire drawing, copper	0.001	kg
Raw Material	Ballast	Connectors	injection moulding	0.003	kg
Raw Material	Ballast	Switch	injection moulding	0.006	kg
Raw Material	Ballast	Coil	wire drawing, copper	0.017	kg
Raw Material	Ballast	Capacitor	sheet rolling, aluminium	0.002	kg
Raw Material	Ballast	PET Film	extrusion, plastic film	0.001	kg
Raw Material	Fitting	Plastic	injection moulding	0.053	kg
Raw Material	Fitting	Clips	aluminium product manufacturing, average metal working	0.053	kg
Raw Material	Fitting	Wiring	wire drawing, copper	0.053	kg
Raw Material	Lamp	Pins	chromium steel product manufacturing, average metal working	0.002	kg
Raw Material	Lamp	Base	injection moulding	0.011	kg
Raw Material	Lamp	Reflective Coating	aluminium, production mix, at plant	0.002	kg
Raw Material	Packaging	Plastic	extrusion, plastic film	0.003	kg

B.1.3 T5 Fluorescent Lamp Raw Materials

The T5 fluorescent luminaire system is a relatively large surface-mounted luminaire, as might be used for strip lighting in a kitchen, workshop or garage. The luminaire holds two lamps, each of which consists of a large glass tube with aluminium end caps. These are mounted on a steel base with copper wiring and plastic sockets, covered by a polycarbonate lens diffuser. The electronic ballast contains a PCB, capacitors, luster terminals and solder. It was assumed that the lamps would be individually wrapped in plastic film, and then packed in their cardboard boxes. The following table provides a list of all the raw materials that were assumed are used in the T5 fluorescent lamp system.

Table B.8 Raw Material Inventory for the T5 Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Lamp	Glass	glass tube, borosilicate, at plant	0.38858	kg
Raw Material	Lamp	Caps	aluminium, production mix, at plant	0.0126	kg
Raw Material	Lamp	Phosphor	rare earth concentrate, 70% REO, from bastnasite, at beneficiation	0.0084	kg
Raw Material	Lamp	Gases	argon, liquid, at plant	0.0042	kg
Raw Material	Lamp	Gases	krypton, gaseous, at plant	0.0042	kg
Raw Material	Lamp	Mercury	mercury, liquid, at plant	0.00002	kg
Raw Material	Fitting	Base	steel, low-alloyed, at plant	1	kg
Raw Material	Fitting	Wiring	copper, at regional storage	0.001114798	kg
Raw Material	Fitting	Sockets	polypropylene, granulate, at plant	0.01	kg
Raw Material	Ballast	PCB	printed wiring board, surface mounted, unspec., Pb free, at plant	0.031	kg
Raw Material	Ballast	Housing	steel, converter, chromium steel 18/8, at plant	0.1581	kg
Raw Material	Ballast	PET Film	polyethylene terephthalate, granulate, amorphous, at plant	0.0062	kg
Raw Material	Ballast	Solder Paste	solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant	0.0031	kg
Raw Material	Ballast	Coil	aluminium, production mix, at plant	0.0868	kg
Raw Material	Ballast	Metal Film Capacitor	aluminium, production mix, at plant	0.0093	kg
Raw Material	Ballast	ELKO Component	aluminium, production mix, at plant	0.0062	kg
Raw Material	Ballast	Luster Terminal	polypropylene, granulate, at plant	0.00465	kg
Raw Material	Ballast	Luster Terminal	steel, converter, chromium steel 18/8, at plant	0.00465	kg

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Lens	Polycarbonate	polyethylene terephthalate, granulate, bottle grade, at plant	2.02	kg
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at plant	0.0082253	kg
Raw Material	Packaging	Plastic	polyethylene, LLDPE, granulate, at plant	0.02	kg

Table B.9 Labour to Process Raw Material for the T5 Luminaire System

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Lamp	Caps	sheet rolling, aluminium	0.0126	kg
Raw Material	Fitting	Base	steel product manufacturing, average metal working	1	kg
Raw Material	Fitting	Wiring	wire drawing, copper	0.001114798	kg
Raw Material	Fitting	Sockets	injection moulding	0.01	kg
Raw Material	Ballast	Housing	sheet rolling, chromium steel	0.1581	kg
Raw Material	Ballast	PET Film	extrusion, plastic film	0.0062	kg
Raw Material	Ballast	Coil	aluminium product manufacturing, average metal working	0.0868	kg
Raw Material	Ballast	Metal Film Capacitor	sheet rolling, aluminium	0.0093	kg
Raw Material	Ballast	ELKO Component	sheet rolling, aluminium	0.0062	kg
Raw Material	Ballast	Luster Terminal	injection moulding	0.00465	kg
Raw Material	Ballast	Luster Terminal	sheet rolling, chromium steel	0.00465	kg
Raw Material	Lens	Polycarbonate	injection moulding	2.02	kg
Raw Material	Packaging	Plastic	extrusion, plastic film	0.02	kg

B.1.4 Integrally Ballasted CFL Raw Materials

The integrally ballasted CFL raw materials were extracted directly from a life-cycle assessment published by the Rocky Mountain Institute in 2008 (RMI, 2008). The materials and weights were taken from this study, but the materials were then matched to the Ecoinvent database which was used for assessing the four UELs in this study. This approach ensures a consistent, comparable dataset, with the LCA for all lamps discussed in this report based off of the same environmental impact database. The following table provides a list of all the raw materials that were assumed are used in 23 watt CFL.

Table B.10 Raw Material Inventory for Integrally-Ballasted CFL

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	Foam	polyurethane, rigid foam, at plant	0.003	kg
Raw Material	Ballast	Plastic base (PVC)	polyvinylchloride, at regional storage	0.017	kg
Raw Material	Ballast	Printed board	printed wiring board, surface mounted, unspec., Pb free, at plant	0.004	kg
Raw Material	Ballast	PBA - other caps	polypropylene, granulate, at plant	0.004	kg
Raw Material	Ballast	PBA - inductor	cast iron, at plant	0.006	kg
Raw Material	Ballast	PBA - inductor	copper, at regional storage	0.004	kg
Raw Material	Ballast	PBA - transistor	acrylonitrile-butadiene-styrene copolymer, ABS, at plant	0.001	kg
Raw Material	Ballast	PBA - transistor	aluminium, production mix, at plant	0.003	kg
Raw Material	Ballast	PBA - resistors, diodes, HV capacitor	integrated circuit, IC, logic type, at plant	0.001	kg
Raw Material	Ballast	PBA - torus magnet	cast iron, at plant	0.001	kg
Raw Material	Lamp	Electrode assembly - gases	mercury, liquid, at plant	0.000004	kg
Raw Material	Lamp	Electrode assembly - capsule	chromium, at regional storage	0.002	kg
Raw Material	Lamp	Copper pins	copper, at regional storage	0.002	kg
Raw Material	Lamp	Tin plate base	tin, at regional storage	0.005	kg
Raw Material	Lamp	Black Glass Insulation	foam glass, at plant	0.005	kg
Raw Material	Lens	Tube glass	glass tube, borosilicate, at plant	0.034	kg

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at plant	0.004	kg
Raw Material	Ballast	Foam	polyurethane, rigid foam, at plant	0.003	kg

Table B.11 Labour to Process Raw Material for Integrally-Ballasted CFL

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Ballast	Plastic base (PVC)	injection moulding	0.017	kg
Raw Material	Ballast	PBA - electrolytic cap	aluminium, production mix, at plant	0.004	kg
Raw Material	Ballast	PBA - other caps	injection moulding	0.004	kg
Raw Material	Ballast	PBA - inductor	wire drawing, copper	0.004	kg
Raw Material	Ballast	PBA - transistor	injection moulding	0.001	kg

B.1.5 Incandescent Lamp Raw Materials

The incandescent lamp raw materials were extracted directly from a life-cycle assessment published by the Rocky Mountain Institute in 2008 (RMI, 2008). The materials and weights were taken from this study, but the materials were then matched to the Ecoinvent database which was used for assessing the four UELs in this study. This approach ensures a consistent, comparable dataset, with the LCA for all lamps discussed in this report based on the same environmental impact database. The following table provides a list of all the raw materials that were assumed are used in 100 watt general service incandescent lamp.

Table B.12 Raw Material Inventory for Incandescent Lamp

LCA Stage	Aspect	Further Information	Name	Amount	Units
Raw Material	Lamp	Tin plate base	tin, at regional storage	0.002	kg
Raw Material	Lamp	Tungsten filament	chromium, at regional storage	0.00002	kg
Raw Material	Ballast	Black Glass Insulation	foam glass, at plant	0.002	kg
Raw Material	Lamp	Internal glass	glass tube, borosilicate, at plant	0.002	kg
Raw Material	Lens	Globe (glass)	glass tube, borosilicate, at plant	0.020	kg
Raw Material	Ballast	Internal filler	foam glass, at plant	0.001	kg
Raw Material	Packaging	Card	packaging, corrugated board, mixed fibre, single wall, at plant	0.004	kg

B.2 Manufacture

The ecoinvent database does not have a process on the manufacture of lighting fixtures and lamps, so an approximation had to be made. Having examined the available processes, it was decided that a suitable proxy for the manufacture of the lamp, once its various components had been sourced in the raw materials stage, would be that of the assembly of an LCD screen. This surrogate was selected because an LCD screen is also a complex electrical product, involving circuits and components that are assembled, and because the manufacturing impacts are expressed on a basis of kg of screen produced. Given that this is a complex product, and assembling a UEL would be easier than constructing an LCD screen, this was presumed to be a good approximation. In addition, the manufacturing impacts of LCD screens are able to be adjusted in the ecoinvent software to each of the lamps being manufactured by their respective weights. If the manufacturing life cycle stage were found to have made a significant contribution to the overall impacts, the approximation described would need to be re-examined for accuracy. However, it did not, and therefore this choice was retained for the final analysis. The following table provides the manufacturing activities that were assumed for the four UEL systems and two baseline reference lamps. It should be noted that the weights of manufacture do not include the weight of the base and the weight of the lens. Thus, although the incandescent lamp as a total weighs approximately 30 grams, the portion of the lamp that is actually assembled on-site weighs just 4 grams.

Table B.10 Manufacturing Processes for the Lamps Analysed

UEL	Activity	Name	Amount	Units
Int. Ballast LED	Assembly	assembly, LCD screen	0.044	kg
Ded. LED	Assembly	assembly, LCD screen	0.031	kg
CMH	Assembly	assembly, LCD screen	0.096	kg
T5 FL	Assembly	assembly, LCD screen	0.418	kg
CFL	Assembly	assembly, LCD screen	0.013	kg
Incandescent	Assembly	assembly, LCD screen	0.004	kg

B.3 Distribution

While there are some exceptions to this rule, in order to consider UELs at volume production and make an assumption that would not underestimate the impact of distribution, Navigant presumed that all four UEL systems are sourced from China. In China, it was assumed that they would be transported 500km by lorry (>32 tonne), to the port at Shanghai. They were then assumed to be shipped by transoceanic freight ship from Shanghai to Southampton, and from there by lorry (16-32 tonne) 200km to their final destination.

No transportation was included for the consumer travelling to and from the shop to purchase the luminaire system. This was because it was expected to present an extremely small impact, both in terms of the actual impact of the journey itself, and, in particular, once account was taken that the luminaire system would rarely be the sole purpose for making that journey, and impacts would have to be apportioned according to the rationale behind making the journey. The units for these journeys are represented by tonne-kilometres. The following table provides the transport and distribution activities that were assumed for the four UEL systems and two baseline reference lamps.

Table B.11 Transport Inventory for the Lamps Analysed

UEL	Aspect	Activity	Further Information	Amount	Units
Int. Ballast LED	Road	Transport to Chinese dock	transport, lorry >32t, EURO4	0.14	tkm
Int. Ballast LED	Sea	Shipping China to UK	transport, transoceanic freight ship	5.30	tkm
Ded. LED	Road	Transport to Chinese dock	transport, lorry >32t, EURO4	0.26	tkm
Ded. LED	Sea	Shipping China to UK	transport, transoceanic freight ship	9.82	tkm
Ded. LED	Road	Transport to UK retail	transport, lorry 16-32t, EURO4	0.10	tkm
CMH	Road	Transport to Chinese dock	transport, lorry >32t, EURO4	0.20	tkm
CMH	Sea	Shipping China to UK	transport, transoceanic freight ship	7.81	tkm
CMH	Road	Transport to UK retail	transport, lorry 16-32t, EURO4	0.08	tkm
T5	Road	Transport to Chinese dock	transport, lorry >32t, EURO4	1.89	tkm
T5	Sea	Shipping China to UK	transport, transoceanic freight ship	72.24	tkm
T5	Road	Transport to UK retail	transport, lorry 16-32t, EURO4	0.76	tkm
CFL	Road	Transport to Chinese dock	transport, lorry >32t, EURO4	0.05	tkm
CFL	Sea	Shipping China to UK	transport, transoceanic freight ship	1.82	tkm
CFL	Road	Transport to UK retail	transport, lorry 16-32t, EURO4	0.02	tkm
Incandescent	Road	Transport to Chinese dock	transport, lorry >32t, EURO4	0.02	tkm
Incandescent	Sea	Shipping China to UK	transport, transoceanic freight ship	0.58	tkm
Incandescent	Road	Transport to UK retail	transport, lorry 16-32t, EURO4	0.01	tkm

B.4 Use/Consumption

For all UEL systems, the power consumption, light emitted and hours of service were presented earlier in this chapter. To simplify the analysis, it was assumed that there was no diminishing performance during the lamps' lifetimes, so the power consumption and light emitted per watt are constant over the full analytical period. Although this is unlikely to be entirely accurate, the assumption allows us to compare the luminaire systems on a consistent basis, rather than trying to factor in the further uncertainty of deterioration curves.

It was also assumed that the luminaire systems would be powered by electricity from the UK grid, which is produced by a mixture of generating technologies, some of which are more polluting than others. That mixture of technologies was assumed to be the same for the lifetimes of all the luminaire systems. The following table provides the energy consumption estimates that were assumed for the four UEL systems and two baseline reference lamps analysed.

Table B.12 Electricity Use Inventory for Four UEL Systems

UEL	Activity	Name	Amount	Units
Int. Ballast LED	Power- Electricity	electricity mix	240	kWh
Ded. LED	Power- Electricity	electricity mix	900	kWh
CMH	Power- Electricity	electricity mix	828	kWh
T5	Power- Electricity	electricity mix	2832	kWh
CFL	Power- Electricity	electricity mix	230	kWh
Incandescent	Power- Electricity	electricity mix	100	kWh

B.5 End-of-Life

The end-of-life of the luminaire systems was assumed to occur when the luminaire reached its end of life, as defined in Table 4.1. This ignores the fact that these systems have such long operating lives that they might be replaced before they reach their natural end of life, because of (for example) wider refurbishment of someone’s home. At end of life, it was assumed that some luminaire systems would be properly dismantled and recycled, where possible, while others would simply be put in a landfill. For all the luminaire systems, it was assumed that the split between these two fates would be 20:80 (20% recycled, 80% landfilled).

In addition to the luminaire system itself, the fate of its packaging was also considered. All the luminaire systems were assumed to be transported in corrugated cardboard boxes, of which 60% were assumed to be recycled, and the other 40% landfilled. For those that might be expected to be sold also wrapped in a plastic film sleeve, it was assumed that only 10% of those sleeves would be recycled, with the remaining 90% landfilled. The following table provides estimates of end-of-life activities assumed for the four UEL systems and two baseline reference lamps analysed.

Table B.13 End of Life Inventory for Four UEL Systems

UEL	Activity	Name	Further Information	Amount	Units
Int. Ballast LED	Recycling	Light	shredding, electrical and electronic scrap	0.220	kg
Int. Ballast LED	Disposal	Light	disposal, electronics for control units	0.055	kg
Int. Ballast LED	Recycling	Card Pkg	recycling of packaging material	0.002	kg
Int. Ballast LED	Disposal	Card Pkg	disposal, packaging cardboard, 19.6% water, to sanitary landfill	0.001	kg
Int. Ballast LED	Recycling	Plastic Pkg	recycling of packaging material	-	kg
Int. Ballast LED	Disposal	Plastic Pkg	disposal, plastics, mixture, 15.3% water, to sanitary landfill	-	kg
Ded. LED	Recycling	Light	shredding, electrical and electronic scrap	0.410	kg
Ded. LED	Disposal	Light	disposal, electronics for control units	0.102	kg
Ded. LED	Recycling	Card Pkg	recycling of packaging material	0.002	kg
Ded. LED	Disposal	Card Pkg	disposal, packaging cardboard, 19.6% water, to sanitary landfill	0.001	kg
Ded. LED	Recycling	Plastic Pkg	recycling of packaging material	-	kg
Ded. LED	Disposal	Plastic Pkg	disposal, plastics, mixture, 15.3% water, to sanitary landfill	-	kg
CMH	Recycling	Light	shredding, electrical and electronic scrap	0.317	kg
CMH	Disposal	Light	disposal, electronics for control units	0.079	kg
CMH	Recycling	Card Pkg	recycling of packaging material	0.006	kg
CMH	Disposal	Card Pkg	disposal, packaging cardboard, 19.6% water, to sanitary landfill	0.004	kg
CMH	Recycling	Plastic Pkg	recycling of packaging material	0.0003	kg
CMH	Disposal	Plastic Pkg	disposal, plastics, mixture, 15.3% water, to sanitary landfill	0.003	kg

UEL	Activity	Name	Further Information	Amount	Units
T5	Recycling	Light	shredding, electrical and electronic scrap	3.007	kg
T5	Disposal	Light	disposal, electronics for control units	0.752	kg
T5	Recycling	Card Pkg	recycling of packaging material	0.005	kg
T5	Disposal	Card Pkg	disposal, packaging cardboard, 19.6% water, to sanitary landfill	0.003	kg
T5	Recycling	Plastic Pkg	recycling of packaging material	0.002	kg
T5	Disposal	Plastic Pkg	disposal, plastics, mixture, 15.3% water, to sanitary landfill	0.018	kg
CFL	Recycling	Light	shredding, electrical and electronic scrap	0.018	kg
CFL	Disposal	Light	disposal, electronics for control units	0.073	kg
CFL	Recycling	Card Pkg	recycling of packaging material	0.002	kg
CFL	Disposal	Card Pkg	disposal, packaging cardboard, 19.6% water, to sanitary landfill	0.002	kg
CFL	Recycling	Plastic Pkg	recycling of packaging material	0	kg
CFL	Disposal	Plastic Pkg	disposal, plastics, mixture, 15.3% water, to sanitary landfill	0	kg
Incandescent	Recycling	Light	shredding, electrical and electronic scrap	0.005	kg
Incandescent	Disposal	Light	disposal, electronics for control units	0.021	kg
Incandescent	Recycling	Card Pkg	recycling of packaging material	0.002	kg
Incandescent	Disposal	Card Pkg	disposal, packaging cardboard, 19.6% water, to sanitary landfill	0.002	kg
Incandescent	Recycling	Plastic Pkg	recycling of packaging material	0	kg
Incandescent	Disposal	Plastic Pkg	disposal, plastics, mixture, 15.3% water, to sanitary landfill	0	kg

Annex C: Manufacturing an LED

The LED is composed from a small semiconductor chip also known as a “die.” It is fabricated from several different elements that help to form the thin layers of crystalline material. Typically, the crystalline material structures are grown directly onto a more durable substrate or they are transferred to the substrate at a later stage. The substrate material (wafer) is chosen to be matched with the crystalline material elements.

There are four key stages to manufacturing the completed LED Chip. These manufacturing processes are identified below:

1) Making the Wafer: In order to make the wafer, a crystalline semiconductor is grown in a high temperature, pressure chamber, forming what is referred to as a cylindrical crystal ingot. This ingot is then cut into very thin slices (≈10mm) of semiconductor. The wafers are then polished to remove any surface defects and to prepare the semiconductor surface for further processing. The final stage is to clean the individual using a series of physical (ultrasonic) and chemical (solvents) processes to achieve a high quality end result.

2) Depositing epitaxial layers on the substrate: At this stage of the manufacturing process, a monocrystalline film is grown on the substrate prepared surface. Liquid phase epitaxy can be used to grow a high quality uniform layer of crystal material with the same structure as the substrate from a molten alloy with an appropriate dopant mix. It is often required to provide additional dopants to shape the characteristics of the diode in order to achieve the desired colour and efficiency levels. This process is performed in a high temperature furnace which is sealed and contains a doped gas atmosphere.

3) Forming the Metal Contacts: At this stage, the electrical current pathway leads are set into the wafer. The exact orientation of these electrodes and their placement is dependent on the end use of the chip (i.e., whether the die will be used on its own or in combination with other die). Contact patterns are set and a light-sensitive compound is used to cover the wafer which is then baked at a low temperature. The set template pattern is then correctly orientated and the wafer is exposed to UV light. This is followed by washing away the exposed area, and then forming the electrode by heating the contact metal to vaporising point, causing the vaporised metal to bond to the exposed areas of the wafer. The wafer is then cleaned and annealed to harden the metal contacts. The contact metals used include gold, geranium, zinc, aluminium, titanium and nickel.

4) Encapsulant: The encapsulant provides a level of protection from the operational environment. This often takes the form of a silicon, epoxy or acrylic as they tend to have a high refractive index therefore allowing the LED die to be exploited to their maximum potential.

There are three key areas for potential environmental concern during the manufacture of the semiconductor wafer - chemical emissions, worker health and an energy-intensive process. The occupational health issues associated with working in the wafer manufacturing lines are of concern due to the long-term risks associated with chemical exposure. Finally, the high material and process intensity of fabricating semiconductors, results in high electricity requirements followed by a significant global warming impact.

Annex D: Monte Carlo Sensitivity Analysis

Introduction

In order to increase the robustness of the conclusions drawn from the modelling, it was decided from the start that the key parameters should be subjected to sensitivity analysis, using a Monte Carlo simulation. This annex/appendix explains the theory and then presents the results of this work.

It is usual when modelling a complex process that not all the parameters are known precisely. One option for dealing with this uncertainty is simply to make a ‘best guess’ of the unknown parameters. This is a pragmatic approach to arriving at an answer, but creates uncertainty about the reliability of the results. When comparing the performance of two or more processes, it is entirely possible that the conclusion about which is ‘best’ may hang on the estimated values of these unknown parameters. Sensitivity analysis aims to explore the sensitivity of the results and conclusions to these underlying assumptions, and thereby provide comment on the confidence in the results.

If we take the example of the luminaire systems in this study, one key parameter was their typical lifetimes. A simple form of sensitivity analysis involves using extreme values to see if the results are unchanged by large perturbations. Navigant used a lifetime of 1000 hours for incandescent bulbs, the least favoured; what if it were ten times higher? The answer is that they’re still least favoured, so we could conclude that uncertainties about the lifetime of incandescent bulb are not significant to the conclusions drawn. This method is good for weeding out which parameters have little effect on the results, but does not reveal anything about the critical parameters, apart from that they are critical.

A similar ‘test to destruction’ technique involves changing the parameter until the results change, and then assessing the likelihood of that result being true. Again, this technique can filter out the parameters that have no great impact on the results, but does not reveal any answers about the key parameters.

An alternative sensitivity analysis varies parameters by a plausible range – if we think the incandescent bulb lasts for 1000 hours, what would happen if it were actually 800 or 1200 hours. This can provide more certainty about the results, since it operates in plausible ranges, but will often simply highlight that the results depend on the values assumed for certain parameters.

Monte Carlo analysis takes the last option a step further, by picking possible values from the range, and seeing what the results are each time. Furthermore, rather than choosing any value in the range 800-1200 with equal probability (a flat distribution), it allows the user to stipulate a distribution (e.g., normal). The user stipulates which parameters will be variables, and specifies the distribution for each of those parameters. The Monte Carlo analysis then performs multiple calculations, each time guessing a value from within the range and using it to generate the results. The output, instead of a point result, is a distribution of results. By plotting histograms of the distributions for the different luminaire systems, it is possible to determine, by the amount of overlap, a level of confidence in the results.

Method

The calculations were performed in the Microsoft Excel workbook that had been created, using the Oracle Crystal Ball software plug-in. Table D.1 presents the parameters chosen for the simulation. All were modelled using a normal distribution, and the means and standard deviations of the distributions are also presented.

Table D.1 Input Parameters Adjusted for UEL Sensitivity Analysis

Lighting Technology	Parameter	Units	Mean	St Dev	Comment
Integrally-Ballasted LED	Lifetime	years	20,000	1,333	6-sigma = ± 20%
	PCB Weight Scalar (*)	-	1	0.07	6-sigma = ± 20%
	Future Efficiency Increase	%	170%	17%	10%
LED with Dedicated Luminaire	Lifetime	years	50,000	3,333	6-sigma = ± 20%
	PCB Weight Scalar (*)	-	1	0.07	6-sigma = ± 20%
	Future Efficiency Increase	%	220%	22%	10%
Ceramic Metal Halide	Lifetime	years	36,000	2,400	6-sigma = ± 20%
	Future Efficiency Increase	%	135%	13.5%	10%
T5	Lifetime	years	48,000	3,200	6-sigma = ± 20%
	PCB Weight Scalar (*)	-	1	0.07	6-sigma = ± 20%
	Future Efficiency Increase	%	110%	11%	10%
CFL 23W	Lifetime	years	10,000	667	6-sigma = ± 20%
	Future Efficiency Increase	%	110%	11%	10%
GLS 100W	Lifetime	years	1,000	67	6-sigma = ± 20%

Two simulations were run; the first modelling the current performance of the lighting systems, and the second looking at the predicted performance in the future, using the efficiencies presented (and assuming incandescent bulbs do not improve). For each simulation, 10,000 calculations were performed.

The general form of the results is depicted in Figure D.1, which shows the predicted future global warming potential of the six luminaire systems. The incandescent lamp (GLS 100W), in orange, has normal-looking distribution with a mean at about 38 kg CO_2-eq per million Lumen hours; this is the most likely global warming potential from the incandescent bulbs. Furthermore, because the distribution does not overlap any of the other luminaire systems, we can conclude that the incandescent lamp is definitely the worst performer. Considering the plots for the other luminaire systems, the other chief conclusion from the plot is that, using the incandescent bulb as a benchmark, all of the others represent a significant improvement. While this is presented for global warming, this same result also holds true for all 15 indicators.

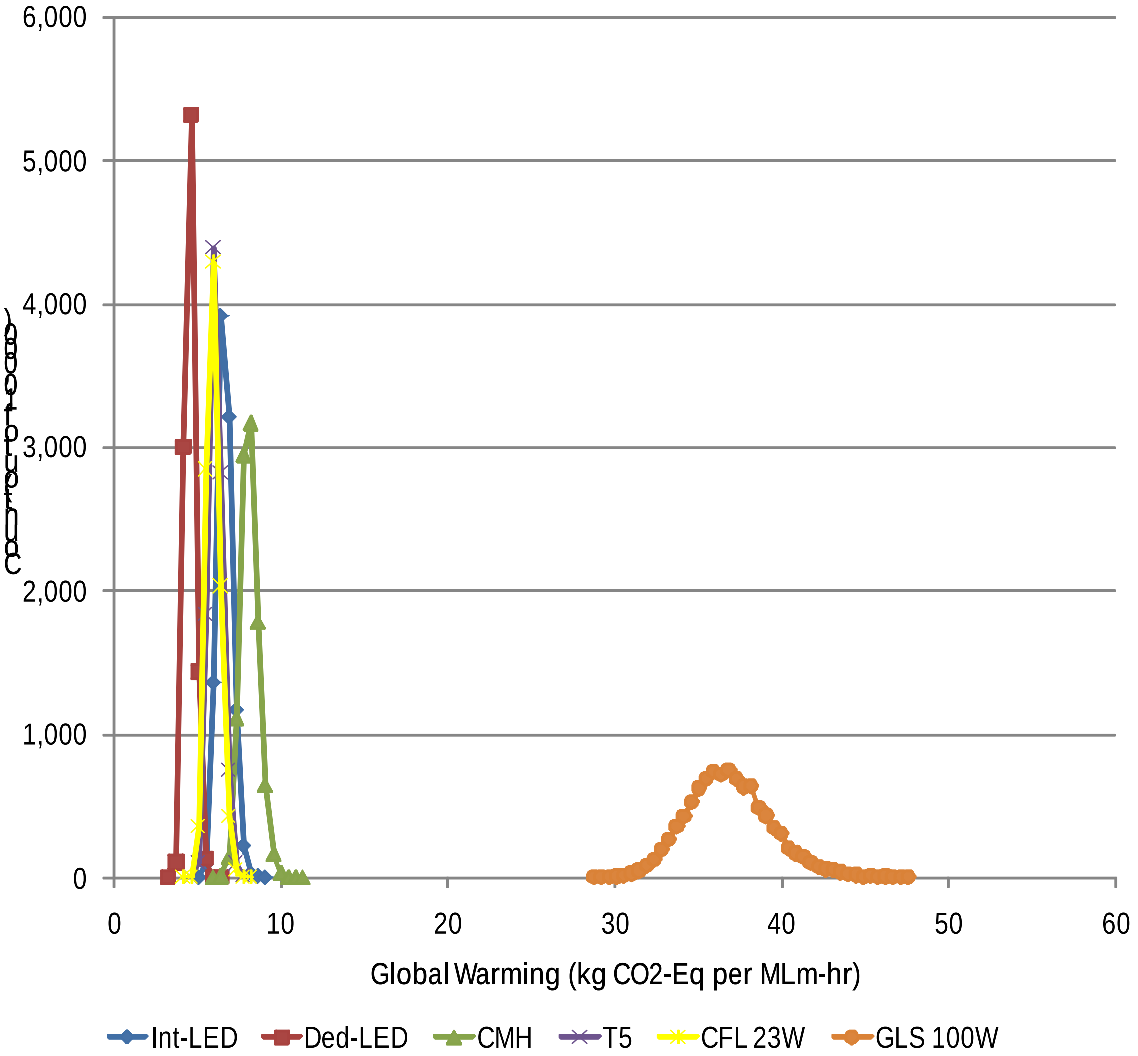

Figure D.1 – Histogram of Results for Monte Carlo Analysis of Global Warming Potential

If we remove the incandescent bulb from the plot and rescale, the result is Figure D.2. We can now see that, of the other technologies, the LED with dedicated luminaire is significantly better than the others, on the basis, again, that its distribution hardly overlaps the four remaining systems. This luminaire systems proves to be as convincingly the most preferred option for six other indicators, namely Eutrophication, Land Use, Ecosystem Damage, Terrestrial Ecotoxicity, Abiotic Resource Depletion and Non-Hazardous Waste Landfill. For another five indicators (Acidification, Photochemical Oxidation, Stratospheric Ozone Depletion, Marine Aquatic Ecotoxicity and Hazardous Waste Landfill), the LED with dedicated luminaire still has the lowest peak, but other distributions begin to overlap it more significantly. For the remaining indicators, it is equal to or worse than some of the others.

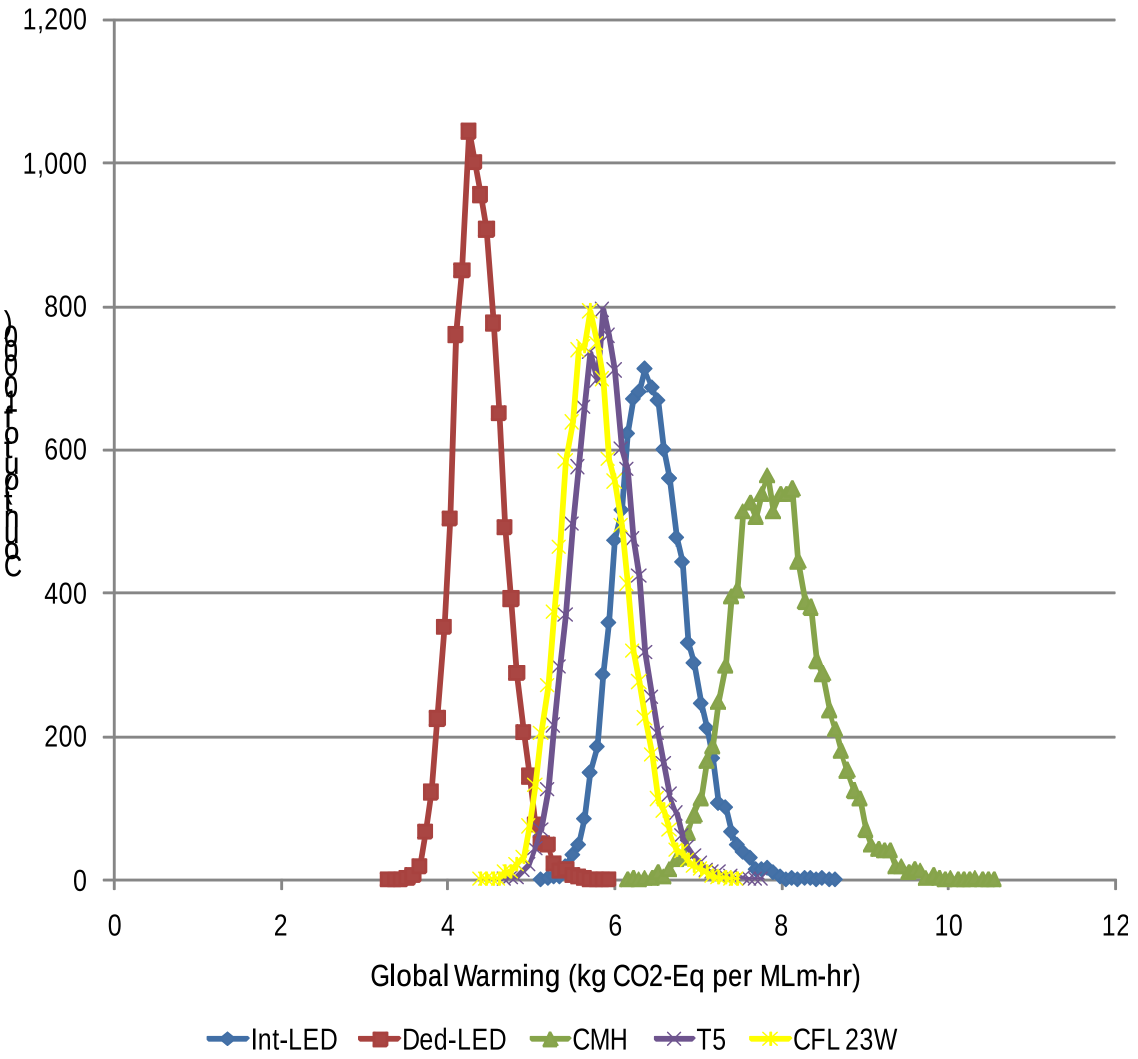

Figure D.2 – Histogram of Results for Monte Carlo Analysis of Global Warming Potential (without GLS 100W)

In conclusion, the Monte Carlo sensitivity analysis shows that the incandescent lamp is, by a considerable margin, the least preferred luminaire system; changing to any other form of lighting represents a definite improvement in performance against all indicators. At the other end of the scale, the LED with dedicated luminaire is, overall, the most preferred option, but there are certain indicators against which it is either not the best, or its margin of preference is small.

Annex E: References

ANON., 2009. White Paper- Towards a Just and Sustainable Solar Energy Industry.

APISITPUVAK, W.,2007. LCA of Spent Fluorescent Lamps in Thailand at Various Rates of Recycling. Journal of Cleaner Production

ASHDOWN, B.G., et al., 2004. Assessing Consumer Values and Supply-Chain Relationships for Solid-State Lighting Technologies. Oak Ridge National Laboratory.

BAKRI, S.N.S., 2008. A Case Study of Life Cycle Assessment (LCA) on Ballast for Fluorescent Lamp in Malaysia. International Symposium of Electronics and the Environment.

BARDSLEY, J.N., 2001. International OLED Technology Roadmap: 2001-2010. US Department of Energy.

BRABER, W., 2009. LED: Working Principles, Electric, Thermal and Optical Characteristics. Future Lighting Solutions.

CARLIN, J.F., 2007. U.S. Geological Survey, Mineral Commodity Summaries Indium.

CELMA., 2005. Guide for the Application of Directive 2000/55/EC on Energy Efficiency Requirements for Ballasts for Fluorescent Lighting. CELMA: Federation of National Manufacturers Associations for Luminaries and Electrochemical Components in Luminaries in the European Union.

CONNER, M., 2008. LED’s Bring New Applications and Standards. EDN Europe.

CORAZZA, A., et al., 2009. Environmental Issues Related to Mercury in Fluorescent lamps. SAES Getters S.P A-Italy.

DEFRA, 2008. Policy Brief: Improving the energy performance of domestic lighting products. Department for Environment, Food and Rural Affairs, July 2008.

DOWDELL, E.A., 2003. Technology Migration and Disruption. A Case Study of the Solid State Lighting Industry. Massachusetts: Massachusetts Institute for Technology.

DU, S., 2008. Replacement Technology- LEDs. General Electric.

DUAN, H. et al., 2008. Life Cycle Assessment Study of a Chinese Desktop Personal Computer. Science of the Total Environment

DUBBERLEY, et al., A. Life-cycle Assessment of an Intelligent Lighting System using a Distributed Wireless Mote Network. California: Department of Mechanical Engineering University of California.

ENERGY FEDERATION INCORPORATED, 2008. ASK ARIS

ENERGY SAVINGS TRUST., 2004. Energy Efficiency Best Practice in Housing, Energy Efficient Lighting, Guidance for Installers and Specifiers.

EUROPA, 2009., Commission adopts two regulations to progressively remove from the market non-efficient light bulbs. Available from: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/09/411]

EUROPEAN LAMP COMPANY FEDERATION, 2003. “Let there be Light”- Policies for Energy Efficiency Lighting.

EUROPEAN LAMP COMPANIES FEDERATION, 2006. Eco Profile High Intensity Discharge Lamps for General Lighting Applications. Available from: http://www.elcfed.org/documents/061106_Ecoprofile%20HID.pdf 2006

FROST & SULLIVAN,2007. Advancements in Solid State Lighting. Technical Insights.

FROST & SULLIVAN, 2008. European Energy Efficient Lighting Markets. Market Engineering Research.

FTHENAKIS, V.M., 2005. Life Cycle Assessment of Photovoltaics: Perceptions, Needs and Challenges. IEEE Photovoltaics Specialists Conference.

GEIBIG, J.R. AND SOCOLOF, M.L., 2005. Solders in electronics: A life cycle assessment summary. United States Environmental Protection Agency.

GYDESEN, A. AND MAIMANN, D., 1991. LCA of integral compact fluorescent lamps and incandescent lamps. Available from: http://www.iaeel.org/IAEEL/Archive/Right_Light_Proceedings/Proceedings_Body/BOK1/200/1411.PDF

HARISON TOSHIBA LIGHTING., 2008. Environmentally conscious products Mercury free HID lamps for automotive headlamps. Harison Toshiba Lighting Environmental Report.

HOFF, C. Life cycle concepts and assessments. Krishna: Krishna Institute of Engineering and Technology.

IESNA, 2002. Rea, M. S., The IESNA Lighting Handbook: Reference and Application, 9th Edition. 2002, New York: Illuminating Engineering Society of North America.

JUNGBLUTH, N., 2005. Life Cycle Assessment of Crystalline Photovoltaics in the Swiss ecoinvent Database. Progress in Photovoltaics, 13(5), pp.429-446

JUNGBLUTH, N., 2005. Life Cycle Assessment for Emerging Technologies: Case Studies for Photovoltaic and Wind Power. The International Journal of Life Cycle Assessment, 10.

KEMNA, R., et al., 2005. Methodology Study Eco-Design of Energy-Using Products Final Report. European Commission.

KLIOPOVA, I. AND LAUKYTE, N., 2006. Evaluation of possibilities to introduce lead-free technology in electronics industry. Environmental research, engineering and management.

KLOPFFER, W., 2006. Proceedings on the Workshop on Nanotechnology and Life Cycle Assessment. International Journal of Life Cycle Assessment.

KORTMAN, J.G.M., 1997. A Life Cycle Assessment of the Environmental Impacts of Photovoltaic Streetlight Systems. Right Light 4(1).

KRUMMAC, B.C., 2009. Efficiency analysis of organic light-emitting diodes based on optical simulation. Organic Electronics.

MARKET TRANSFORMATION PROGRAMME., 2006. Light Emitting Diodes: Eco-design Innovation Roadmap. Available from: www.mtprog.com

MATTHEWS, H.S., et al. 2009. Life Cycle Assessment of Solid State Lighting Applications.

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION, 2005. Fluorescent and other mercury-containing lamps and the environment. National Electrical Manufacturers Association.

NAVIGANT CONSULTING, 2003. Energy Savings Potential of SSL in General Illumination Applications. Available from www.ntis.gov

NAVIGANT CONSULTING, 2009. Solid State Lighting Research and Development Plan.

NERI, P., Life Cycle Assessment of an Emergency Lamp Manufactured by the Firm Beghelli. Available from: http://www1.coe.neu.edu/~smgupta/4193-17-SPIE.PDF

OPTOELECTRONICS INDUSTRY DEVELOPMENT ASSOCIATION., 2002. Organics light emitting diodes (OLEDs) for general illumination.

PARSONS, D., 2006. The Environmental Impacts of Compact Fluorescent Lamps and Incandescent Lamps for Australian Conditions. The Environmental Engineer, 7 (2).

PHILIPS, G., et al., 2007. Indium and Gallium Supply Sustainability.

PHILIPS LUMILEDS., 2007. Binning and Labeling (Luxeon Product). Philips Lumileds Lighting Company.

PHYLIPSEN, G.J.M. AND ALSEMA, E.A., 1995. Environmental life cycle assessment of multicrystalline silicon solar cell modules. The Netherlands Agency for Energy and the Environment (NOVEM) Department of Science, Technology and Society. Utrecht University

RAMROTH, L., 2008. Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp. Rocky Mountain Institute. Available from: www.rmi.org/images/PDFs/Climate/C08-02_CFL_LCA.pdf

SLOCUM, A., 2006. A Technology Assessment of Light Emitting Diode Solid State Lighting For General Illumination.

SUSTAINABLE MATERIALS AND MANAGEMENT INITIATIVE., 2009. Progress report of SMM case study on critical metals.

TALLIN., 2005. Energy Using Product Directive. European Lamp Companies Federation.

TECHATO, K., 2009. Life Cycle Analysis of Retrofitting with High Energy Efficiency Air-Conditioner and Fluorescent Lamp in Existing Buildings. Energy Policy 37(1).

THE ECONOMIST. 2009. A Brilliant Approach. Available from http://www.economist.com/science/displaystory.cfm?story_id=13315818

THE EUROPEAN COMMISSION, 2008. Phasing Out Incandescent Bulbs in the EU Technical Briefing.

THE LIGHTING ASSOCIATION, 2008. A Brighter Future.

TIBI, N. AND RAMAHI, A., 2005. The Effect of Energy Efficient Lighting on the Environment a Pilot Project in Palestine. The journal of Clean Technology and Environmental Policy.

TURNER, R.K., MORSE-JONES, S. AND FISHER, B., 2007. Perspectives on the Environmental Limits Concept. Department for Environment and Rural Affairs.

UEMURA, K., et al., 2000. Improved Characteristics of Inductively Coupled Electrodeless Metal Halide Lamps. Journal of Light and Visual Environment, 84(5). Available from:://www.jstage.jst.go.jp/article/jlve/26/2/26_2_1/_article

US DEPARTMENT OF ENERGY. Carbon Dioxide Emissions from the Generation of Electric Power in the United States. US Department of Energy.

US DoE., 2004. Energy Efficiency Program for Commercial and Industrial Equipment: High-Intensity Discharge Lamps Analysis of Potential Energy Savings.

VAN TICHELEN, P., 2007. Preparatory Studies for Eco-design Requirements for EuPs: Final Draft Lot: 9: Public Street Lighting. VITO.

VAN TICHELEN, P., et al., 2007. Preparatory Studies for Eco-design Requirements of EuPs: Final Report, Lot 8: Office Lighting. VITO

VISSER, P., 2008. OLED Technology also the Ultimate Lighting Solution? Potential and Status of a Promising Technology.

VITO., 2008. Preparatory Studies for Eco-design Requirements of EuPs: Lot 19: Domestic Lighting, Part 1- Non-directional Light Sources [draft].

WAIDE, P., et al., 2006. Barriers to Technology Diffusion. The case of Compact Fluorescent Lamps. International Energy Agency – Organisation for Economic Cooperation and Development.

WALL, R. AND CROSBIE, T., 2009. Potential for Reducing Electricity Demand for Lighting in Households. An exploratory Socio-Technical Study. Energy Policy, 37(3), pp.1021-1031.

WILLIAMS, E.,2000. Global Production Chains and Sustainability: The case of High-Purity Silicon and its Applications in IT and Renewable Energy. United Nations University.

WILLIAMS, E. 2004. Environmental Impacts of Microchip Manufacture.

XIE, R.J., HIROSAKI, N. AND MITOMO, M., 2007. Oxynitride/nitride Phosphors for White Light-Emitting Diodes (LEDs). Journal of Electroceramics.

ZHANG, Z., et al., 2006. High Efficiency Fluorescent White Organic Light-Emitting Diodes with Three Red, Green, and Blue Separately Monochromatic Emission Layers. Organic Electronics.

ZHU, T., 2004. Life Cycle Assessment in Designing Greener Semiconductor. Thesis. Department of Chemical and Environmental Engineering, University of Arizona, Arizona.