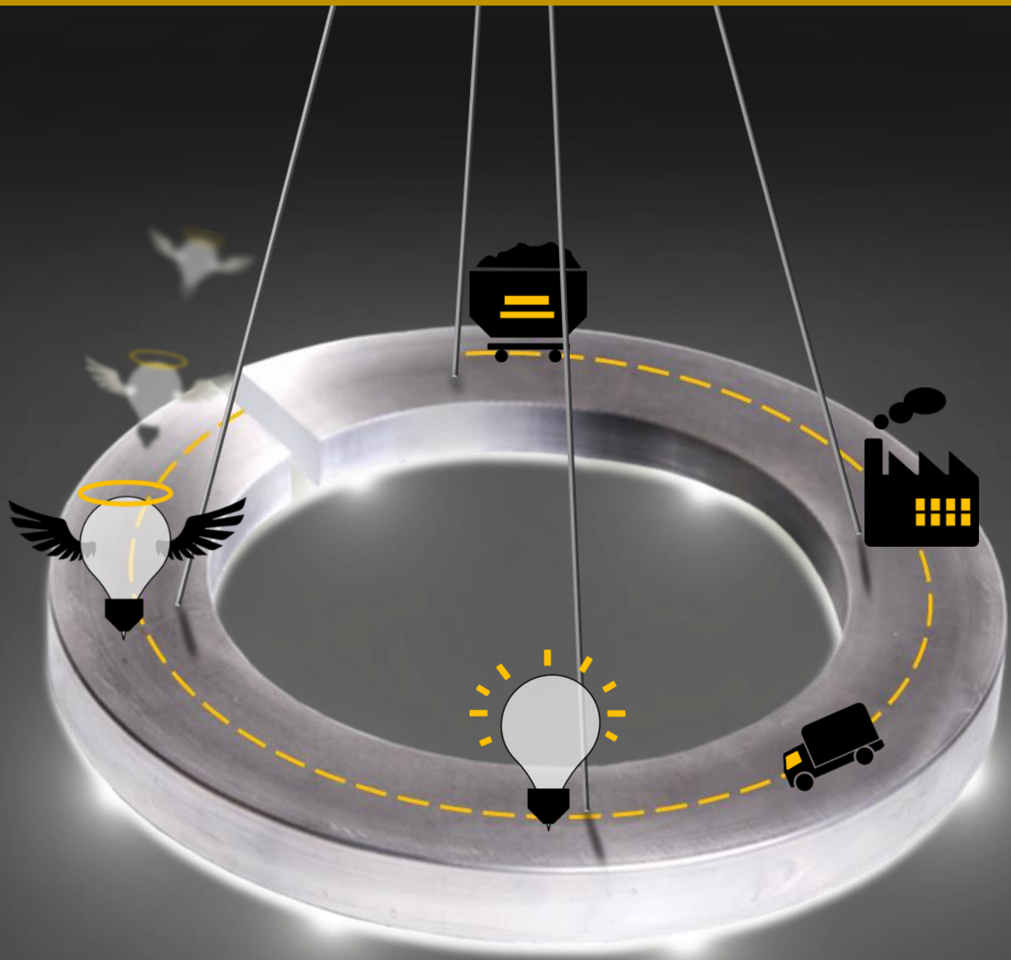
Circle of Light

The impact of the LED Lifecycle



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CONTENTS

Introduction

Why a Life Cycle Approach to LEDs is Needed

This report *Circle of Light. The impact of the LED Lifecycle* uses a life cycle framework to explore the different phases of Light-Emitting Diode (LED) lights. The information presented in the report will be useful to public and private stakeholders as they get ready to invest in transformative LED solutions. The research was done in the framework of the Lighting Metropolis Project.

By presenting data and information for each stage of a LED's life cycle, the report can inform stakeholders of the most relevant issues related to LED technology. Which phase of the LED life cycle has the most impact? What should we be concerned about as we choose LED technologies? The rapid uptake of LED technology has brought about a transformation in the lighting industry. This transformation also raises questions about its impacts on the environment and society. While LEDs are publicly perceived to be environmentally friendly, a look at it from a life cycle approach offers an in-depth perspective.

By following a LED light through its life cycle, some concerns regarding the sustainability of such products, often founded in a lack of knowledge, can be addressed. This report addresses impacts from the four stages: raw material extraction, manufacturing, use and distribution, and end-of-life. Ultimately, *Circle of Light* sets the stage for recommendations and guidelines to be elaborated in 2017.

For the past 11 years, Professors Mikael Backman and Thomas Lindhqvist have worked with students in the Masters programme in Environmental Science, Policy and Management (MESPOM) studying at the International Institute for Industrial Environmental Economics (IIIEE) at Lund University to apply sustainability concepts and strategies to real world challenges. Backman, Lindhqvist, and the Institute's MESPOM students have been commissioned by numerous organisations to produce reports exploring a variety of topics from energy efficiency to sustainable cities.

Lighting Metropolis is the first and most important step toward turning the whole Öresund region into the world's leading living lab for human centric and smart urban lighting. The project aims to create better light for people in cities and buildings. Light supports security, accessibility, identity, health, and learning and intelligent solutions that create energy savings, efficient and user-friendly cities and new services.

Lighting Metropolis

Some important terms in brief:

Light Emitting Diode (LED): A semiconductor device that emits light when an electric current is passed through it.

Life Cycle Assessment (LCA): A tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle.

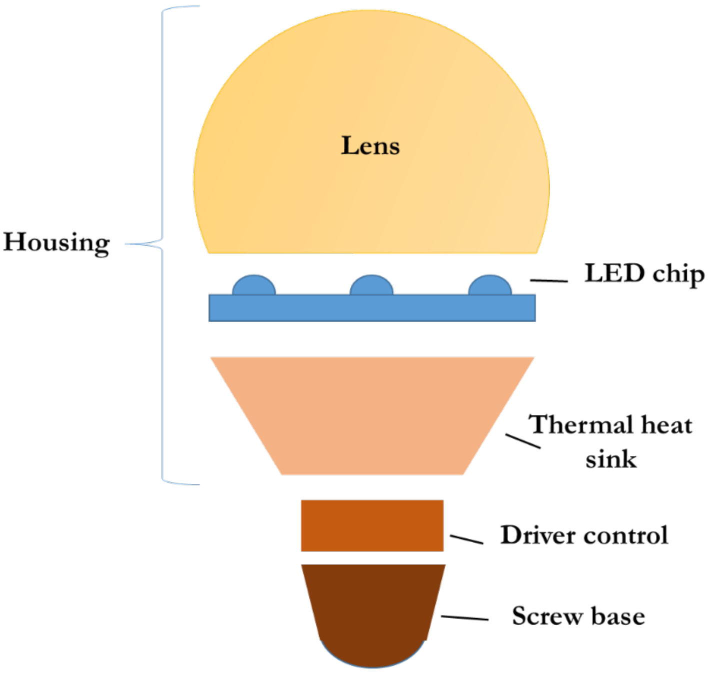
Semiconductor: A substance, usually a solid chemical element or a compound, that can conduct electricity under specific conditions, making it a good medium for the control of electrical current.

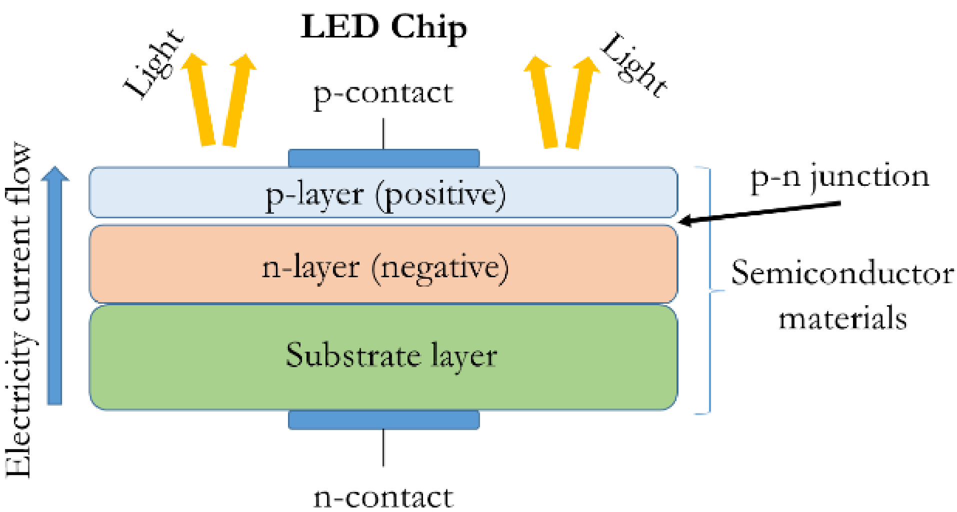
End-of-life: Term indicating that the product is in the end of its useful life.

Extended Producer Responsibility (EPR): A policy approach under which producers are given a significant responsibility for the treatment or disposal of post-consumer products.

Rare earth elements (REEs): A group of 17 elements with unique properties that make them useful in a number of technological products.

LED package: The LED die is mounted within the package – a combination of lens, and heat sink – which allows for electrical connection and assembly.





Lighting the Paths for Eco-Design

Life Cycle Assessment of Light Sources

Malgorzata Lekan & Rongyu Veneta Tzeng

Did you know that…

"Today light emitting diodes (LEDs) cut electricity consumption by over 85% compared to incandescent light bulbs and around 40% compared to fluorescent lights"

"It is projected that the efficacy of LEDs is likely to increase by nearly 50% compared to fluorescent lamps by 2020"

\- *Goldman Sachs, 2015*

The above statements leave no doubt that light-emitting diodes (LEDs), being the first-entirely commercialised low carbon technology, are currently the most rapidly developing type of energy efficient light source globally. They are not only becoming increasingly affordable, widely applicable and help to reduce overall energy consumption costs, but also last longer (minimum 5 years of continuous use) and provide a good quality of light.

In order to evaluate environmental performance of LEDs and relate it to other light sources, it is common to use the Life Cycle Assessment (LCA) approach, which brings into light a 'bigger picture' of environmental impacts occurring during a given product's entire lifespan. By reviewing different LCAs of light sources, this article will highlight that the most significant environmental impacts are associated with the use phase where a great amount of energy is being used by a consumer who has control of the product. The use phase is then followed by the manufacturing phase, which includes component processing, product assembly and packaging. Even though the raw materials extraction phase (e.g. mining bauxite to produce aluminium) as well as the distribution and end-of-life phases account for the lowest share of total environmental impacts throughout the entire life cycle of LEDs, more complex data is required to unravel and potentially magnify the actual impacts occurring within these phases.

About LCA

LCA is a technique for the 'systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle' (ISO 14040:2006), starting from the raw material acquisition stage and moving toward manufacturing, packaging and distribution, use and ultimately end-of-life stage (EoL). The last stage contains various ways of handling the end-product, e.g. recycling or landfill disposal. Consequently, LCA shows both upstream and downstream trade-offs in relation to environmental pressures, human health and resource consumption over a product's lifecycle.

The ISO standards (ISO 14040:2006 and ISO 14044) distinguish four main phases of a conventional process-based LCA, which reflect the complex, macro-scale interactions between a given product and the environment:

1. **Goal definition and scope**, which includes: main assumptions, limitations, sys-

tem boundaries, functional unit and allocation methods;

2. **Life Cycle Inventory (LCI)**, which includes large amounts of data on environmental inputs and outputs in electronic form;
3. **Life Cycle Impact Assessment (LCIA)**, which includes the following impact categories:

Global Warming Potential (GWP)
Relative measure of how much heat a greenhouse gas traps in the atmosphere

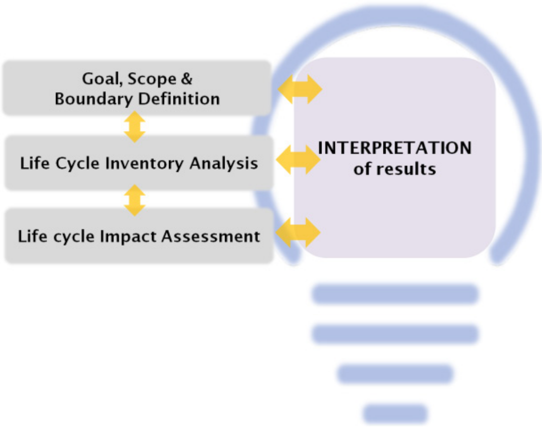
Human toxicity Potential (HTP)
Quantitative toxic equivalency potential to express the potential harm of a unit of chemical released into the environment

Abiotic Resources Depletion Potential
Decreasing availability of one particular natural resource in relation to another

Energy use:
Amount of energy consumed in a process or system

4. **Interpretation of results**, which includes various checks to ensure that the 'results, data collection methods, assumptions and limitations are transparent and presented in sufficient detail' so that informed decisions can be made).

Standardised LCA Framework



Created by Authors

Even though LCA does not provide a comprehensive overview of local and socio-economic impacts associated with a product's production, use and disposal phases, it helps to complement other approaches aimed at identifying of environmental hotspots and potential improvement areas in order to promote sustainable development.

LCA of various lighting sources

The EU Eco-design Directive (2009/125/EC) and its implementing measures are based on a lifecycle approach and impose requirements on lighting sources, such as energy efficiency and functionality. Consequently, LCA is especially common in the EU lighting sector.

The following section discusses the main factors, which influence LCA results and their consecutive comparison. Based on these factors, key findings of LCAs will be presented.

Types of bodies conducting LCAs, purposes of LCAs and data providers

Following the review of the published LCAs of **LEDs**, it can be concluded that LCAs have been mainly carried out by:

- Academic institutions (Carnegie Mellon University & UC Berkeley, US, 2010; and scholars such as: Tähkämö,L., 2015; Hadi, S.A. *et al.*, 2013; Dale, A.T. *et al.*, 2013; Quirk, 2009)
- Consultancy firms (Navigant Consulting, Inc., 2009; which also helped to produce LCA for the U.S. Department of Energy (DOE, 2012) and Department for Environment: Food & Rural Affairs (DEFRA), 2009)
- Intergovernmental organisations (International Energy Agency, 2014);
- Producers (Osram, 2009; Philips, 2013).

In relation to **data** providers, the most common are:

- Academic institutions (Carnegie Mellon University & UC Berkeley, US and Aalto University in Finland);
- Consultancy companies (Navigant Consulting, Inc.);
- Governmental bodies (U.S. Department of Energy (DOE));

There are also more than 10 software tools that further help to conduct a LCA (e.g. Gabi, SimaPro or Ecoinvent).

Depending on the type of a body conducting a LCA, the main **purposes** associated with LCA are as follows:

- To aid policy-makers in making decisions related to lighting sources (IEA 2014);
- To examine and compare energy consumption levels of different lighting sources; to identify hazardous materials; to estimate the lifetime of lighting sources to design relevant EoL treatments (Carnegie Mellon University, US, 2010; Navigant Consulting Europe, Ltd., 2009);
- To guide environmental decisions and demonstrate market benefits (Philips, 2013; Osram, 2009);
- To provide suggestions for conducting LCA of lighting sources by comparing different LCAs (Tähkämö, L. 2015).

While numerous LCAs of various lighting sources have been conducted starting in the 1990's,[1] the overview of LCAs of LEDs shows that LCAs of LEDs were carried out in a relatively systematic manner over the past 6 years (2009-2015).The overview of the published LCAs in the lighting sector also reveals that the vast majority of LCAs have been concerned with LEDs, compact fluorescent lamps (CFL) and incandescent lamps. Other lighting sources such as halogen lamps, fluorescent lamps and luminaires, high pressure sodium lamps, (ceramic) metal halide lamps and induction lamps, high pressure mercury vapour lights (which were equally banned from the European Union market in 2015) ((EU) 2015/1428) have received little attention.

In general, not many detailed LCAs have been carried out for light sources globally. Given that the availability and quality of data determines not only the quality of LCA but also the ability to conduct it, the lack of publicly available data (particularly related to the private industry manufacturing processes) constitutes a great problem[1].

'The devil lies in detail': conducting a detailed LCA

Even though there are various standards, which provide different sets of procedures for conducting a LCA (e.g. ISO 14040:2006 and ISO 14044:2006), it is difficult to obtain transparent and comparable results that are necessary to carry out a profound LCA - the initial data and assessment methods can vary significantly[2]. The following inherent characteristics of lighting sources further affect the LCA results and their comparison:

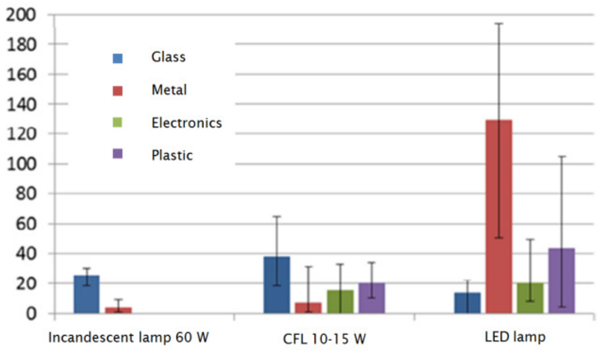
Diverse shapes and sizes

Different lighting sources come in various shapes and sizes. It is difficult to make generalisations and comparisons of different light sources when there is a wide variety of lighting sources available in the market[3].

Material composition

Different lighting sources have different material compositions which are presented in the form of a graph below. Interestingly, the graph is based on the research which showed that the data for the material composition (of non-directional lamps used in households) vary greatly, depending on the applied methodological approach[1]. However, the graph clearly illustrates that while LEDs are largely composed of metals; both LEDs and CFLs contain electronic components. The presence of these components might substantially impede the evaluation of environmental impacts due to the limited availability of data in Life Cycle Inventory Analysis for specific geographical locations. Contrary to halogens, LEDs have a more complex structure and not all the materials used are easily recycled[2].

Initial data for the material composition of non-directional lamps used in households



Source: Tähkämö et al., 2014

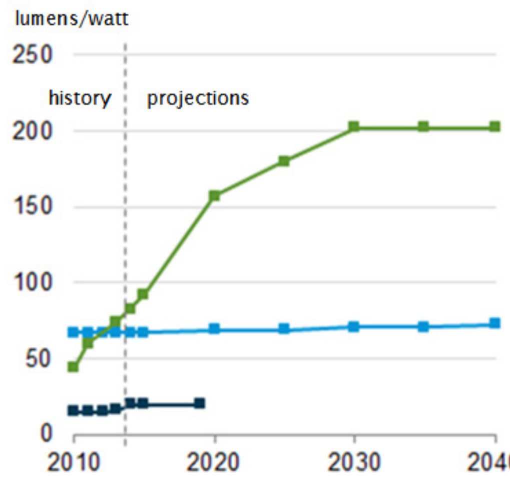
Diverse uses

Diverse uses translate into different levels of electricity consumption. While fluorescent lights and luminaires are designed for industrial applications (e.g. warehouses), electronic LEDs have multiple uses ranging from sport facilities to tunnels. In terms of different use patterns, LEDs, contrary to halogen lights, do not have a fixed set of use patterns. In result, it is challenging to make a comparative analysis2.

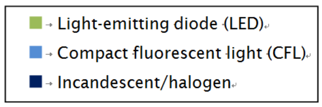
Rate of development

Following the introduction of innovative and quickly evolving LED chips that have revolutionised design of luminaires and lights, there has been a significant increase in the lighting efficacy (from approx. 50 lumen in 2010 and 60 lumen in 2014) and dramatic decrease in prices of LEDs (from approx. USD65 per bulb in 2010 to USD10 per bulb in 2014). Consequently, the overall rate of development of LEDs, contrary to CFLs and halogen lights, is immense. While the lighting efficacy is projected to further increase, the costs per bulb are expected to further decrease in the near future. Given that conducting a detailed LCA is a very lengthy process, such a quick rate of development makes it difficult to ensure that LCAs are based on the most recent data[4]. The trends are illustrated in figures below.

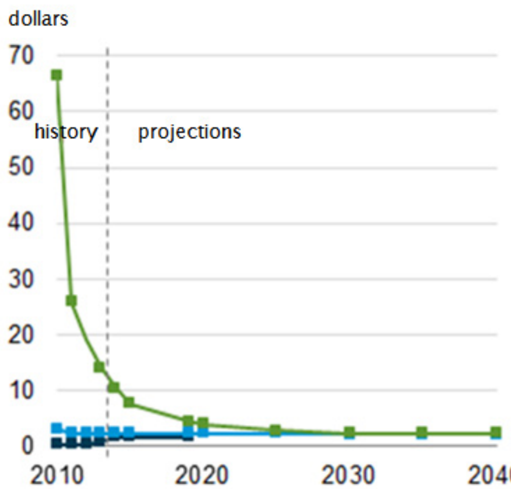
Average lighting efficacy (light output per unit of energy consumed)



Source: EIA, 2014



Costs per bulb



Source: EIA, 2014

It can be also noted that the ever increasing efficiency and broad applicability of LEDs make them a very competitive source of light in the market and have the potential to influence users' behaviour. Users, incentivised by energy savings, might actually offset these benefits (thus, change LCA results) by significantly increasing the use of LEDs and replacing the old models with the newest ones, before they expire.

Other aspects such as: functional unit, life cycle stages, environmental impacts and energy source in use stage, which further affect the ability to conduct a detailed LCA and compare results; and which are correlated to the above mentioned characteristics, are explained in relation to 'Simplified LCA models' in the next sub-section

(Over?) Simplified LCA models

In order to enable a rapid comparative analysis of LCAs of various light sources in such a rapidly evolving market and in the absence of valuable data, some studies have relied on two simplified models: simple and extensive model, which prioritise qualitative comparative analysis of LCA results. Both models encompass **key parameters** of the LCA so that all major environmental aspects are considered[2]. The table below illustrates the main characteristics of both models.

Simplified models for a LCA of light sources

EXTENSIVE MODEL	SIMPLE MODEL
Functional unit	
Case-specific, related to the function of the light source in a specific application (indoor/outdoor)	Lumen-hours (incl. burning hours and luminous flux, e.g., Mlmh)
Life cycle stages	
Raw material acquisition Manufacturing Use End-of-Life	Manufacturing Use
Environmental impacts	
Several impact categories, e.g. Global Warming Potential (GWP), waste (hazardous, nonhazardous), etc.	Only one impact category, e.g. Global Warming Potential (GWP)
Energy source in use stage	
Actual energy production, and high- and low emission energy production	Primary energy

Data source: Tähkämö, 2015

Functional unit: 'a measure of the performance of the functional outputs of the product system and a reference to which the inputs and outputs can be related'

(ISO 14040:2006)

However, these two models might be perceived as too narrow in scope, and hence oversimplified. By referring to the functional unit of simple model (lumen-hours),not all of the published LCAs are concerned with lumen depreciation (quantity of the energy from a light lost over time) over light source's life span. For instance, even though incandescent lights display a constant luminous flux over their lifetime, the luminous flux depreciates over the lifespan of LEDs and fluorescent lights. In addition, the lumen-hour do not reflect the 'actual illumination but rather the quantity of light (luminous flux and time)'[1].In case the functional unit is 'case-specific', the requirement to fulfill all lighting design criteria for outdoor lighting is hardly feasible due to high costs. [5]

Regarding the **life cycle stages**, by not taking into account the 'Raw material acquisition stage' in case of the simple model, it is impossible to prove that this stage accounts for the higher share of total environmental impacts in case of LEDs when compared to conventional light sources.

On the one hand the simple model shows that the evaluation of the environmental performance of various light sources is highly impeded if many important **environmental impact categories**, which can be weighted for importance, are excluded from assessment. On the other hand, if several impact categories are taken into account, it is difficult to compare results as they are presented in various units and there is no commonly used single scale index. Interestingly, there is also no single environmental impact category, which addresses the impacts of the light itself (e.g. light pollution that can affect fauna and flora).[5]

In relation to **energy source** in use stage, it is estimated that while approximately half of the LCAs rely on primary energy, the remaining studies do not inform whether they consume primary energy(energy sources that can be used directly, e.g. coal or wood), or secondary energy (energy carriers, which come from the conversion of primary energy, e.g. electricity). In result, the comparison of energy uses is very challenging.

Key findings

Regardless of a multitude of LCA approaches, which cover various aspects of light sources, the comparative analysis of various LCAs clearly reveals that the most significant environmental impacts are associated with the use phase where a great amount of energy is being consumed. Interestingly, by taking into consideration several characteristics of light sources, the studies found out that the dominant use stage was especially discernible when luminous efficacy and manufacturing efforts were at low levels as well as when high emission energy sources were used.[1,2]

The dominant use stage is followed by the manufacturing stage, whose importance might increase in case a notable transition toward more energy-efficient light sources occurs, and more comprehensive assessments of processes at manufacturing-level are conducted. While the transport has the overall minimal impact on the environment, the impacts associated with EoL stage can vary in relation to specific environmental impact categories such as hazardous waste[2]. One of the LCA studies based on the 'simple model' have also demonstrated that CFLs and LEDs tend to consume significantly lower amount of primary energy (approx. 900 MJ/functional unit) than incandescent lights (approx. 15100 MJ/functional unit), thus ranking them as the most environmentally friendly light sources[5].The energy consumption trends related to specific light sources are depicted in figure below.

Both CFLs and LEDs (together with fluorescent lights and induction luminaires) have also scored high in terms of the luminous efficacy of the light source, which determines environmental performance of the light source[2].

In relation to 'useful life' LED lights are estimated to last for approx. 20 000 h and CFL lights up to 12 000 h.[1] However, due to the unavailability of detailed data and the lack of detailed LCAs of light sources, including LEDs, the total life cycle impacts remain unknown.

Characteristics of LEDs' life cycle stages

As the previous section revealed, LEDs constitute a promising alternative to other available light sources. The table on next page provides an overview of important aspects of LED's life cycle stages and highlights how significant are their consequent levels of environmental impacts.

★★★	Significant total environmental imp act
★★	Major total environmental impact
★	Minor total environmental impact

RAW MATERIALS ★★★

This stage has low data availability and is only included in few LCA reports.

- Aluminum is used to make heatsink (a heat exchanger that is used to absorb and disperse excess heat from the LED diode) in a LED light and acquisition of aluminium makes the LED exceed the CFL in the life cycle impact category of hazardous waste to landfill.
- The development and use of ceramic heatsinks help to alleviate environmental impact from heatsinks.[1]

MANUFACTURING ★★

Total environmental impact results related to energy usevary from 1%-24%[3, 4,6]

This stage has low data availability (manufacturing data are regarded as confidential and complex due to intellectual property rights of suppliers for materials like yttrium, cerium, etc.)[1].

- The only stage that surpasses other lighting sources.
- Impacts (energy use category) are mainly associated with: driver (average 40% of total environmental impacts), LED array (28% of total impacts), LED components, silicone covering sheet, and aluminum reflector and heatsink.[3]
- Material composition of a (5 mm) LED chip is not devoid of hazardous materials.[7]
- Materials used in LEDs like copper, lead, chromium are hazardous if occur in high concentrations.[8]
- Energy consumption is becoming more significant due the complex lighting technology.
- There are tradeoffs between energy efficiency rate and amount of metal containing components.[3]
- LCAs don't consider the premature failure at LED (as well as other electronic equipment).

DISTRIBUTION ★

This stage has low data availability and is only included in few LCA reports.

There is minimal insight into calculation assumptions regarding distance of transport, type of transportation vehicle and the estimated capacity of the vehicle.

- Transporting of a packaged light from the manufacturing facility to the retail outlet.

USE ★★★

Total environmental impact results related to energy consumption vary from 76% to 98%.[2,3,6]

- Since LEDs are categorised as energy-related product (ErP) (2009/125/EC), various energy sources render different results in different geographical regions (e.g. French electricity has lower impacts in relation to many environmental aspects such as GWP and resource depletion, than the European average).[3]
- LED's "long life"makes it difficult to measure its whole life cycle (uncertainty). [3]

END-OF-LIFE ★

Total environmental impact results are minor yet remain highly under-investigated (lack of recycling statistics, recycling process data)

- LED's End-of-life solutions are environmentally and economically beneficial as they help to recycle plastic components and retrieve valuable materials such as silver, nickel, gold, antimony, and copper.[5]
- The standard waste recycling is not able to recover LEDs' materials due to complex structures and diverse material use.[1]
- It is recommended to conduct assessments for toxicity and resource depletion potentials in the earliest stages of LEDs' development. The relevant policies, which have the capacity to influence the development of technologies, such as REACH Directive, RoHS Directive or WEEE Directive, should become stricter.

Conclusions

Given that electric lighting is a major source of electricity consumption globally, the lighting sector has been always at the center of technological innovations, which help to improve the quality of lighting and minimise environmental impacts by enhancing energy efficiency.

Even though LCAs give different results in relation to different factors (such as functional unit or system boundaries), which are greatly determined by data providers and the purpose for conducting a LCA, the published LCAs of light sources demonstrate that LEDs are currently the most promising and competitive source of light on the rapidly growing market.

Moreover, considering the fact that all light sources consume a significant amount of energy in the use phase, the main LCA results (such as the dominance of the use stage in terms of the highest share of total environmental impacts over entire life cycle), are not going to be notably affected[5].

Regardless of the inherent uncertainties and various drawbacks associated with various methodological approaches for conducting a LCA, it cannot be denied that both models, be it detailed or simplified, cast a light on important issues related to light sources such as: luminous efficacy, lighting quality, longevity, safety or package (especially in case of LEDs), and help to identify key bottlenecks for future improvement.

Nonetheless, it is necessary to conduct a more detailed LCA of LEDs that would cover the entire lighting system, including under investigated EoL phase and raw material phase. The future LCA should also introduce more criteria for lighting quality and luminous features (e.g. glare, light pollution or photochemical effect), which are additionally influenced by many other aspects such as daylight availability or use of the area. Even though the results are likely to be case-specific and might seem to be less detailed once the bigger picture is concerned, they would become less uncertain and could help to address important issues such the biological impacts of light sources.

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Digging for Truth

Raw Material Extraction and Future Potential for LEDs

By Elizabeth Drachenberg, Darja Mihailova & Sai Siddhartha Nandamuri

The manufacturing of LEDs requires a combination of sector-specific materials like rare earth elements and more widely used elements like gold and silver. However, the impacts of the raw materials phase, or mining and extraction of these key materials, have been largely unexamined.

This gap in the life cycle represents a dangerous question mark for consumers and producers alike. What are the impacts, social and environmental, of mining and refining the elements needed to make a LED? How do these impacts compare to other stages in the life cycle? If most rare earth elements are sourced from China, what practices should buyers be concerned about?

This ambiguity opens industry to a wide range of potential vulnerabilities: radioactive tailings from rare earth extraction, health impacts on workers in Chinese refineries, groundwater contamination, and more. This can be clearly seen in the case of the largest rare earth deposit in the world, the Bayan Obo mining area in China, where serious environmental pollution runs unchecked by regulation.

To limit potential negative impacts, LED manufacturers and EU regulators can consider implementing stricter procedures for sourcing raw materials (e.g. from countries with strict social and environmental regulations) or using substitute materials. One interesting possibility for EU regulators is to examine internal sources of material: specifically, material recycling from waste electronics. This has the potential to offset many of the impacts associated with extracting virgin material and assist in efforts to close the resource loop.

The Data Problem

There is very little data on material extraction and refining for LEDs. This is due to several factors, including the diversity of materials used by different LED producers, reluctance by manufacturers to share trade secrets, and opacity of supply chains.

Without this data, it can be extremely difficult for a Life Cycle Assessment (LCA) to correctly categorise the relative importance and impacts of the raw materials extraction phase of LED lights. Because of this, most LCAs have excluded the raw materials phase from their calculations completely.

In 2012, the United States Environmental Protection Agency published a three-part review of LED LCAs. In their review, the EPA analysed the results from 25 different LCAs and combined raw material extraction, refining of raw materials into usable product, manufacturing, and assembly into one large category. In 2014, the International Energy Agency (IEA) conducted a similar review of nine different LCAs and chose to exclude raw material extraction and refining from their scope entirely due to lack of data.

Using the data available, this analysis aims to present the materials used in LED lights with the highest environmental and social impacts in the raw material extraction and refining stage of the life cycle.

Materials Used in LEDs

Following the format of a life cycle assessment, this section focuses on some of those elements that are the most high profile in the raw materials phase of the LED lifecycle. While the elements discussed here are by no means exhaustive, they are some of the better known by consumers.

First, sapphire is used to grow the crystalline substrate for LED wafers. A LED dye is then added to the substrate to produce the light's colour. The first LED devices were infrared and red devices made with LED dyes like gallium arsenide, but LEDs have evolved over time and more colours are now available, using LED dye combinations such as gallium aluminium phosphide (produces green), aluminium gallium arsenide (red and infrared), silicon carbide (blue), and zinc selenide (blue).[1] Once the LED dye is added, the substrate is doped with chemicals to create a charge in the p-n junction, which leads to the light emission.

Rare earth elements (REEs) are a group of seventeen elements, some of which are used in the production of LED products. Rare earth elements have unique characteristics that make them an attractive element in a number of technological products like hard drives, fuel cells, and, of course, lighting products.[2] For a phosphor-based LED light, the rare earth element yttrium is combined with aluminium and oxygen to produce yttrium aluminium garnet (YAG).[3] White light LEDs are built on a combination of blue-emitting gallium nitride (GaN) or indium gallium nitride (InGaN) and yellow-emitting cerium-doped yttrium aluminium garnet (YAG) phosphor.[4]

In contrast to the tiny quantities of rare earth elements used in the creation of the diodes and semiconductors, aluminium is a substantial portion of a LED light when used as the heat sink. The Parathom Classic A bulb produced by OSRAM, for example, contains 40% aluminium, almost half of the mass of the 175 g bulb.[5] That same model bulb had only 3% of other non-ferrous metals, likely including materials like gold and silver that are used to form the metal reflector and contacts in the LED light.

Rare Earth Elements: How Significant Are They?

The prominence of REEs in LED lighting can be difficult to determine. When looking at a LED light bulb, the amount of REEs used in terms of total volume and weight can easily be described as miniscule, but industry information is murky at best. For example, the Parathom Classic A bulb mentioned earlier is listed on the OSRAM website as containing 16.85% electronic components (29.5 g).[5] While it is likely that the diode chip (where the REEs is used) is included in this number, there is no information on the weight of the diode chips or the amount of REEs used per gram. This is typical of the LED industry, where the exact construction of the wafers and diodes are generally kept closely guarded, making it difficult to tell what elements are used and in what quantities.

Supply chain uncertainties have pushed manufacturers to limit their usage of REEs and to explore alternative materials. The lighting industry is no exception.[6] For example, a new process of combining more common metals with organic luminescent molecules to produce white light phosphors can reduce the dependence on yttrium, the REE typically used in the process.[7] But while "rare earth free" LEDs are possible, whether they can maintain similar efficiency remains to be seen.

While industry use of REEs may or may not be decreasing, there is an association in the public mind of LEDs with REEs. For this reason, it is important to consider the social and environmental impacts associated with their mining and refining.

Comparison to Compact Fluorescent Lights

Just like LEDs, compact fluorescent lights (CFLs) have been pushed as a more energy-efficient alternative to incandescent bulbs. They create light by sending an electrical charge through argon and mercury vapour. Like LEDs, they can use up to 80% less energy than incandescent lights, though LEDs have longer lifetimes and lower power consumption.[8] Although LEDs are more energy-efficient, it is important to consider the impact of the raw materials stage when deciding which type of light is most environmentally friendly. This short analysis finds that CFLs may be more detrimental than LEDs in the raw materials stage.

CFLs and LEDs both utilise REEs, though CFLs use larger amounts of the rare elements for production of coloured lights. The REEs yttrium, europium, cerium, lanthanum, and terbium are used in phosphors of CFLs to produce red, green, and blue lights.[9]

Not only do CFLs use significantly more REEs, they also use hazardous materials like mercury. While LEDs come with their own slew of hazardous materials like lead and small quantities of arsenic, the large quantities of REEs in fluorescents mean the CFL has more of an environmental impact compared to LEDs.[6] In the U.S. Department of Energy's 2012 LCA comparing traditional incandescent bulbs with CFLs and LEDs, CFLs and LEDs scored substantially better in their environmental impacts compared to traditional bulbs, but CFLs had much more of a negative impact on soil, air, and water for variables like ozone depletion, acidification, and terrestrial eco-toxicity than LEDs.[4]

Mining

It is important to note that materials like REEs, aluminium, and gallium are not mined individually. REEs are often present in complex combinations in relatively small quantities. To produce aluminium, an ore called bauxite is mined and then refined into the metal.

Similarly, gallium does not exist in its pure form in nature and is a by-product of bauxite mining. A considerable portion of gallium is also recycled from waste produced during electronic manufacturing and then re-used to produce the semiconductors for LEDs.[10]

Many of these materials are recovered through open-cast or open-pit mining. While the visual impact of these giant holes in the ground is significant and landscape degradation is clear, tangible environmental impacts also occur in the extraction and refining processes and from the by-products produced.

Extraction and Refining

After the extraction of ore from the ground, the next step is refining. Once the raw material is crushed, it goes through several processing stages. These processing methods can vary depending on the chemical makeup of the unprocessed earth, the desired end-product, and the country practices of the refinery. Different types of extraction include electrolysis, heating, and chemical solutions. Indium and gallium, for example, are extracted using hydrochloric acid. Gold processing uses a cyanide extraction process.

Once the desired elements have been extracted from the raw earth, the remaining material becomes waste. This waste is called tailings, and it is usually deposited into tailings heaps or ponds near the refineries. Tailings are a very problematic source of environmental pollution, and must be managed very carefully to prevent negative impacts. While an open-cast mine may eventually be re-filled, tailings do not degrade.

This means that proper management of tailings must last for decades afterwards.

REE tailings are particularly significant for several reasons. REEs, while not actually "rare" in the earth's crust, are usually present in very small quantities. This means that extraction creates huge amounts of tailings. For perspective, take the example of bauxite processing (during which aluminium and gallium might be extracted). For every tonne of bauxite produced, there might be 1-1.5 tonnes of tailings. In stark contrast, estimates for REE suggest that for every tonne of end material, 2 000 tonnes of tailings are produced.[11] The quantity of tailings produced by REE refining is astronomical. These figures are compounded by the fact that REE tailings often contain thorium, making the tailings radioactive.

Potential Impacts

The negative environmental impacts of refining processes and poor tailings management are well known. LEDs use many high-value materials like REEs, silver, gold, and sapphire. The economic value of these materials means that social and environmental considerations are sometimes not considered. This is particularly true for materials sourced from developing countries.

Water Contamination

Much of the environmental impact of mining for REEs lies in its effect on water. Producing one tonne of rare earth ore creates 200 cubic metres of acidic wastewater.[12] In the Zudong mining area in China, ammonia and nitrogen levels are well above safety standards, impacting the groundwater in the area.[12] Gold and silver extraction, particularly for industrial uses, also uses large amounts of water.[3] Water used in the refining process (for cooling, rinsing, etc.) often becomes contaminated with toxic chemicals and acids and ends up in tailings ponds. In addition to the high water use for extraction, improperly managed tailings can leach toxins into nearby water supplies.

Air Pollution

According to data from the Chinese Society of Rare Earths, processing one tonne of REEs can generate 8.5 kg of toxic fluorine gas and 13 kg of flue dust. The amounts of air emissions produced during refining can be extremely high, with one tonne of production leading to 9 600 to 12 000 cubic metres of gas contaminated with flue dust, sulfuric acid, and other toxic components.[13]

Landscape Degradation

Ecosystem degradation and landscape restructuring are common side effects of open-cast mining which is used for gold, rare earth elements, and bauxite. This impact is easily visible to the naked eye, as shown in the image on the next page.

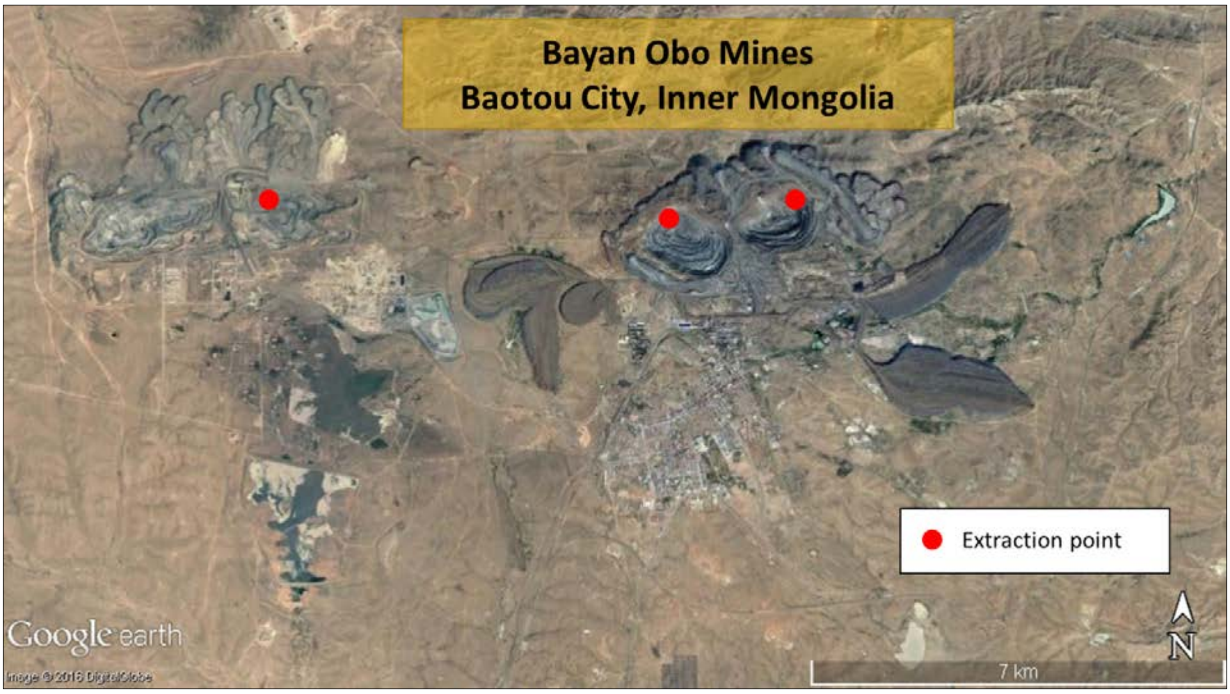
Refineries and tailings can also cause serious soil contamination, especially when improperly managed. Heavy metal contamination and radioactivity from REE tailings are both potential impacts.

Human Health

Emissions to water, soil, and air are not only environmental problems; they also have serious negative impacts on human health. Contaminated air and water can both lead to serious health concerns.

REEs are particularly worrying in terms of human health due to the production of radioactive waste. Estimates suggest that for every tonne of refined REEs, one tonne of radioactive waste is produced.[13] Moreover, workers working with yttrium are at risk of breathing complications and cyanosis.[14]

Working conditions in these mines and refineries may not meet international standards, compounding these impacts.



Economic Restructuring

The economic development associated with mines and refineries can have positive effects. Mine development reroutes communities, creating space for new roads, energy and water supply systems, and new facilities like schools and hospitals. However, these benefits to regional development can be dampened by the negative consequences such as relocation of indigenous people and unequal distribution of the economic benefits of mining. A migration of new workers into the area may occur, altering existing social structures. The closing of mines leads to unemployment in the area and a need for repurposing buildings and infrastructure.[15]

The Case of Bayan Obo

The Bayan Obo mining area is located near Baotou, in the Inner Mongolia region of China, and can be seen in the image above. It is the largest rare earth element mineral deposit in the world. The town of Baotou processes the minerals extracted from these mines. The mining operations and extraction processes together create enormous amounts of waste. The tailings dam alone covers more than 11 km^2, holding 150 million tonnes of tailings, about nine million tonnes of which are rare earth tailings. Analysis of these tailings shows levels of radioactivity 30% higher than normal radiation for the area.[16]

A toxicological study of the derelict land surrounding the mines and tailing areas at Bayan Obo showed serious contamination with heavy metals like copper, chromium, cadmium, lead, and zinc.[17] The same study concluded that the contamination was enough to pose risks to both the environment and to the health of residents in Baotou. However, these toxicity levels are well within the National Environmental Quality Standards for Soil in China. This means that despite the potential health risks and negative environmental impacts, these toxicity levels are not illegal in China.

Electronics Waste Recycling in Europe: An Alternative Resource Stream?

The Global Market Context

The global market size for LEDs was expected to reach almost EUR 24 billion by 2015. Europe is the single largest lighting market for

LEDs, accounting for about a quarter of the world's total market. This figure is growing despite lack of subsidies and possibly due to high electricity prices.[18]

REEs are almost exclusively mined and produced in China, which has placed export restrictions on these metals. These restrictions were increasing every year between 2005 and 2010. During this period, export quotas were reduced by more than 50% from 65 000 tonnes to 30 000 tonnes.[19] Consequently, prices of REEs increased between 500 - 2 000% due to the limitations on exports.[2]

However, China has not always been the leading producer of REEs. The Mountain Pass mine in California, USA was one of the largest sources and caused positive price shocks when it opened due to its scale. It was only in the 1990s that China expanded production significantly and at much lower costs compared to other mines, thereby achieving a competitive advantage. In fact, China was mostly mining REEs for magnets, but managed to produce the other elements as by-products and subsequently became the market leader for them as well.[20]

This monopolistic stance has led to a situation where other countries that require these raw materials are forced to develop their own sources. This usually means opening of new mines around the world to diversify supply chains. The EU is also an importer of REEs, although not a major one, accounting for just 8% of the world total. But, 90% of this supply is coming from one supplier alone: China. This means that volatility in cost cannot be offset easily because other sources are not available.

Most of the REEs that enter the EU are in the form of finished products that are manufactured outside the EU.[21] Ultimately, the key driver for recovery of REEs from waste streams will be dependent on demand and prices of metals and will be influenced by new sources (mines) coming online. In 2013, prices of REEs came down from their 2011 highs to a range comparable to their pre-2009 levels, as can be seen in Table 1.[21,22] In September of 2016, prices for the elements shown in the table had decreased below 2007 levels.[23] However, China has maintained its monopoly over these minerals, necessitating the development of alternate sources.

Recycling Potential: The EU Scenario

Europe generates about 12 million tonnes of waste electrical and electronic equipment (WEEE) per annum. Revenues of all recyclers in Europe are about EUR 1 billion, which is expected to increase to EUR 1.5 billion by 2020.[21] Most of these are focused on recovering metals from WEEE, while recycling rates for REEs have remained less than 1%.[24] Most of this recycling is taking place for pre-consumer scrap, not post-consumer waste.[21] Precious metals like gold and silver perform

Element	2007	2008	2009	2010	2011	2012	2013	2016
Lanthanum oxide	3.2	8.2	4.6	21.1	97.9	23.7	7.5	2.0
Cerium oxide	2.8	4.3	3.7	20.3	95.9	23.2	7.8	2.0
Europium oxide	304.9	453.5	464	527	2 674.9	2 337.9	1 093.4	150.0
Terbium oxide	555.6	678.3	340.5	525.1	2 196.3	1 910.8	916.4	400.0

Table 1 Prices of rare earth oxides (EUR/kg). Data from Golev et al, 2014

better with a recycling rate above 50%.[25]

From an environmental perspective, we have already established that mining and processing of REEs has many environmental impacts. This is also because many deposits occur naturally with radioactive elements like uranium and thorium. In this context, recovering and recycling of REEs from WEEE becomes at least free of radioactivity and does not involve the complicated and polluting procedures of setting up new mines.

Outlook for Recycling in the EU

Arsenic, gallium and indium are the main non-REEs used for manufacturing of substrate material for LED wafers. Currently, cerium, europium, gadolinium, lanthanum, terbium and yttrium are the REEs used in LED manufacture, whether as dopants or phosphors. Gold and silver are used in the metal contacts of the LEDs. Due to the rapidly evolving nature of the industry and development of new materials, this may not be the case within the coming decade. Additionally, LEDs contain very small quantities of critical metals within them, making the cost of recovery high.[26]

In terms of economics, REEs for phosphors and luminescence constitutes about 32% of the total economic value of REEs used.[21] The EU's WEEE Directive requires that lamps and luminaires placed on the market should be recycled.[27] This means that LEDs must also meet the targets set out by the directive in terms of collection and recycling rates. It presents an opportunity for recovery of REEs and evolution of the industry sector on to a larger scale.

Only small amounts of LEDs currently enter the waste stream because they have only just been adopted in mainstream lighting solutions and have long lifetimes. However, this situation is expected to change in the future and they are expected to form a significant portion of waste arising from lighting.

An important question about the potential for recycling to replace primary supply remains. One analysis conducted in 2015 considered three end-of-life recycling rates (mainly fluorescent lamps) of low, medium and high ambition corresponding to 7%, 19% and 53%. The medium scenario has the potential to meet more than 25% of the demand for phosphors by 2020. In the most optimistic scenario, secondary supply has the potential to satisfy about 75% of the total demand by 2020. It is important to remember that fluorescent lamps are considered to be dominant in the market in 2015, whereas LEDs are expected to be dominant in 2020, which will require a revision of these projections after 2020. The authors also concluded that for recycling to form a significant portion of phosphor supply, legislative support is also important in addition to market conditions.[28]

Market prices of primary raw materials play a major role in the economic viability of the recycling process. Historically, prices of raw REEs have been low and the concentrations used in products are extremely low, making recovery costly. However, if the price increases seen in the recent past are maintained, and proper regulatory support is given, it is possible to make the process viable.[20]

Nevertheless, recovering REEs from WEEE has its own set of problems. Currently, the process is very energy intensive and requires large quantities of chemicals. It also generates sizeable quantities of waste chemicals as well as wastewater. However, not enough literature is currently available to properly quantify these impacts. Further studies are required to assess the potential scale and revenues from recycling. In case of damaged lamps, there is also a major problem with the collection of mercury before recycling.[23] From a policy context, only lamps are ready to be prepared for phosphor recycling due to the WEEE directive which necessitates their collection for recovery of mercury. This waste stream is therefore the one closest to reaching full-scale industrial development.[21]

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LED MANUFACTURING

A Take on the Technology and its impacts

By Ritika Jain, Robyn Kotze & Sunanda Mehta

The world of LED lighting is constantly changing at a fast pace. Claimed to be the most environmentally friendly lighting product, LEDs are transforming the industry. The manufacturing process, a significant part of the LED lifecycle, is highly complex due to the number of components, chemicals and processes that go into the production. When evaluating LED manufacturing and the associated environmental impacts difficulties arise owing to challenges in obtaining information and confidentiality.[1]

Out of the three basic stages occurring in the LED manufacturing, LED die fabrication is the most energy and resource-intensive while the substrate production has a lower energy consumption, however associated with the largest water consumption. Finally, LED packaging assembly is the least energy intensive stage. This illustrates where the most environmental impacts occur and where manufacturers should focus their mitigation measures.

How LEDs are manufactured and the related environmental and social impacts are presented in detail in the following chapter. Attention will be paid to the energy consumption, as well as, the production and social practices at the manufacturing sites.

Manufacturing Process

Figure 1 illustrates a simplified version of the LED manufacturing process. The LED manufacturing process can be divided into three stages - substrate production, LED die fabrication (epitaxial growth, front end of line processes and back end of line processes) and packaged LED assembly.[1]

Substrate Production	**LED Die Fabrication**	**Packaging Assembly**
Raw materials Growing ingots Slicing Polishing	Layering Masking/ lithography Etching Die singularisation	Die testing Die attach Encapsulation & optics Test & binning
STAGE 1	STAGE 2	STAGE 3

Figure 1. LED manufacturing proess.[2] Created by authors.

Substrate Production

The first stage of LED manufacturing is the **production of substrate wafers** alternatively known as semiconductors.[3] The main substrate utilised in the production of LEDs is sapphire, gallium arsenide, or silicon carbide. The substrates are used to produce a crystalline boule using the Czochralski method. Once the boule is created sapphire cores of appropriate diameter are created by drilling with diamond tools. Each sapphire core is then sliced into thin wafers by a diamond internal diameter saw with deionised cool water. The wafers are then subject to two to three polishing treatments using a progressively finer slurry of polycrystaline diamond, which removes irregularities to make the wafer completely flat.

The last step in producing the wafers is the final cleaning, which removes trace metals, residues and particles. The cleaning makes use of acids such as ammonium hydroxide (NH_4OH), dilute hydrogen fluoride (HF) acid, hydrogen chloride (HCl) and hydrogen peroxide (H_2O_2) followed by a deionised water rinse.[1]

The energy consumption associated with producing a three inch sapphire wafer is 18.3 kWh per wafer, which is the second most energy-intensive process of the LED manufacturing process. This stage utilises a large quantity of water (105.3 liters/wafer) but only utilises a few number of resources (alumina, cleaning chemicals and diamond slurry) compared to the second stage (LED die fabrication).

Die Fabrication

Next the LED undergoes **die fabrication**. The LED die fabrication process is divided into epitaxial growth and other front-end processes. **Epitaxial growth** is when additional layers of semiconductor crystal layers are grown on the surface of the wafer. This is done by mounting the substrate wafer into a metal organic chemical vapour deposition (MOCVD) reactor. This reactor conducts the nitrification of the substrate wafer at a high temperature in a hydrogen and ammonia atmosphere. Next the substrate wafer undergoes the deposition of the nucleation layer, the n-type layer, the active layers (multi-quantum well) and finally the p-type layer.[3]

The temperature is dropped to approximately 550 °C to grow the buffer layer. This is a thin amorphous film of gallium, just 50 to 100 atoms thick, grown directly on the wafer. The wafer is then heated up until the gallium forms a smooth, mirror-like layer of gallium nitride (GaN).

Next, a layer of negatively doped gallium nitride is deposited, with silane (SiH_4) as the electron-donating dopant. The temperature is dropped from 1 200 °C to 750-850 °C to grow an indium gallium nitride (InGaN) quantum well. This will include 20 angstroms (1 angstrom is equivalent to 0.1 nanometre) of InGaN and 100 angstroms of GaN. This process is repeated to grow several wells.[1]

After growing the last combination of InGaN + GaN, the wafer is heated back up and a confining layer of positively doped aluminium gallium nitride AlGaN is deposited. The positively doped layer confines the charge carriers in the active layer. At the end of this phase, the wafer is referred to as an LED epitaxial wafer.[1]

The LED epitaxial wafer then undergoes **front end of line (FEOL) processes** which involves the wafers going through cleaning, lithography, etch, metallisation, deposition, and anneal.[1] These steps create the LED mesa-structure, and result in visible LED dies on the wafer.[1]

Next, the LED epitaxial wafer proceeds to **back end of line (BEOL) processes** where the substrate is separated from the LED dies, and they are then cut (known as die singulation) and tested according to their performance.[1] At the end of this stage, the LED dies are ready to be packaged. The energy consumption for the LED die fabrication stage is 42.57 kWh per wafer, which makes it the most energy-intensive stage of the manufacturing process.[1]

Packaging Assembly

The last stage of LED manufacturing is the **packaging** of the LED device. It is important to be aware that this is not the packaging of LED into their saleable packaging. It involves taking the LED die and mounting it in housing, making electrical connections, applying phosphor, encapsulant and optics.

It also involves testing and binning the LED into the correctly classified product.[1]

STEP	DESCRIPTION & MATERIAL CONSUMPTION
Packaging element building	Ceramic substrate is prepared for the mounting of the LED chip 13.5 mm^2 alumina/LED
Stud bumping	The wire bonding process where gold is bonded to the die pad 0.004 mm^3 gold/LED
Reflow stage	LED is heated to a temperature above the melting point of the solder
LED and protective die attachment	The LED is attached to the package element, incorporating protection against electrostatic discharge (ESD) 0.220 mm^2 ESD diode (silicon)/LED
Addition of the under filling	An organic polymer and inorganic filler that provides support to the solder ball interconnect 0.05 mm^3 underfill /LED
Addition of (cerium) Ce_3 + (yttrium aluminium garnet) YAG phosphor coating	A portion of the blue light emission from the LED die is converted to longer wavelengths which gives the packaged LED emission the appearance of white light 0.192 mm^3 phosphor/LED
Addition of optical lens	Len gathers and directs the light in the appropriate beam angle for the desired application 8.400 mm^3 silicon/LED
Anneal	Package is heated to anneal together the polymer, phosphor and lens into one cohesive unit
Substrate dicing	Substrate is cut into the individual packaged LEDs for use

Table 1. Steps in the packaging stage of LEDs.[1]
Created by authors

Table 1 illustrates the steps involved in the packaging stage of LED and materials associated. The total energy consumption for this stage is 0.03 kWh per wafer, which makes it the least energy intensive stage.

Final points

There is little available literature on the evolution of the LED manufacturing process or potential measures to improve manufacturing processes to achieve energy and resource efficiency. This, however, is not indicative of the experimental research that is taking place in this field, as there are several new budding technologies being explored for improving the manufacturing process.[17]

Environmental & Social Issues

Uncertainty Over Energy Consumption

LED lamp system manufacturing is a more complicated process than manufacturing for both CFL and incandescent lamps. The amount of energy required for manufacturing of LED packages is dependent on the size and the design of the package.[1] While the size dictates the number of die that go on the package, the design defines the shape, size and the light distribution. The data from the two LCA studies presented in Table 2, on the following page, demonstrates the difference in energy consumption values for the manufacturing process.

The study by Carnegie Mellon (2010) uses data from a previous study by the university in 2009 as foundation to perform a more comprehensive analyses based on energy consumed for LED die fabrication, substrate production, packaging as well as upstream material extraction and processing. It ranges between 0.3 MJ (0.08 kWh) to 121 MJ (33.6 kWh) is in complete

Table 2. Differences in energy consumption during manufacturing LED lamps. Created by authors

Product Analysed	Studies	Primary energy consumption (MJ/ LED Package)		
		Minimum	Average	Maximum
EarthLed A19 Lamp	Quirk (2009)	18.3	19.5	20.6
LED Spotlight LED Floodlight A19 LED Lamp	Carnegie Mellon/ Booz Allen (2010)	0.3	60.4	121

contrast with the values presented by the Quirk (2009) study.

While the study performed by Quirk also analyses the same stages of LED manufacturing as the Carnegie study, it arrives at very different results. One likely reason behind this disparity may be that different products are being analysed in the studies.

The Carnegie study looks at the energy consumption during the manufacturing of 'LED Spotlight, Floodlight, A19 LED Lamp' while the Quirk study looks at 'EarthLed A19 Lamp'. All products are different in size and design, which results in different values for energy consumption during manufacturing. Therefore, there is no one figure for the total energy consumed for the manufacturing phase.

Environmental Impact Due to Electricity Mix

Studies suggest that the total energy consumption during the manufacturing phase can vary between 0.1 to 27 % of the life cycle.[1] This has a direct impact on the environmental contribution of this stage. Additionally, depending upon the electricity mix at the site of manufacturing, it is possible that this stage can also dominate the life cycle impacts.[3] To demonstrate the sensitivity of the environmental impacts during LED manufacturing, Tähkämö *et al.* (2013) undertook an LCA study where they analysed the impacts of the various life cycle stages of a LED for the French and European electricity mix. Table 3 displays the percentage share of the environmental impacts due to the manufacturing stage arranged in descending order of magnitude between the impact using the French mix and the European mix.

As the French electricity mix is cleaner than the European one (since it is primarily dominated by nuclear, hydro and natural gas power), the environmental impact of the use phase reduces in percentage and as a result the share of the impact from the manufacturing phase increases to more than that of the European mix.[4]

The end result was that for the European mix the manufacturing stage contributed to only 7% and the use stage 93% of the total impacts. Whereas, for the French mix the contribution

Environmental impact category	French electricity mix (%)	European electricity mix (%)
Non-hazardous waste (NHW)	~78	~20
Water Potential (WaP)	~38	~3
Eutrophication potential (EP)	~40	~5
Photochemical Ozone creation potential (POCP)	~39	~15
Ozone Depletion Potential (ODP)	~22	~3
Hazardous waste (HW)	~38	~18
Air Pollution (AiP)	~23	~4
Abiotic depletion potential (ADP)	~18	~2
Acidification Potential (AP)	~17	~3
Global Warming Potential (GWP)	~17	~2
Inert Waste (IW)	~16	~4

Table 3. Percentage share of environmental impact of manufacturing stage. Figures estimated (~) from LCA study by Tähkämö et al. 2013A. Created by authors.

of the manufacturing stage increases to as much as 22% of the total life cycle impacts.[4]

Environment Requirements for Production

The manufacturing of semiconductor requires an ultraclean environment to obtain high levels of purity, which are vital to ensure that the semiconductor can act as a circuit even at the atomic level.[4]

The clean room is typically used in manufacturing or research, and is a controlled environment that has a low level of pollutants, dust, microbes, aerosols and chemicals vapours. Cleanroom use and keeping the cleanrooms clean requires massive amounts of energy to operate and accounts for 46% of electricity consumption in fabrication facilities.[6] There is a trend towards making large sections of the process line or the entire process line to operate in vacuum. However, it is important to consider the increasing energy costs of such high maintenance.[7]

Malpractices at the Site of Manufacturing

In order to become more price competitive and attract consumers to cheaper priced goods, SMEs and recently large enterprises such as Philips, GE, Osram and Cree have started shipping LEDs manufactured in China. These LEDs are priced at less than 10 cents/1 W LED package, which allows the enterprises to sell the final products at very low prices.[8]

To achieve these low prices at the manufacturing sites in China, several malpractices are followed that go unchecked due to lack of regulatory control.[8] Substituting expensive raw materials like gold with copper for the connections in the LED chip is a common practice that significantly reduces the production cost. Similar practices are followed for other parts of the bulb as well such as its exterior casing, which may use poor quality aluminum scraps or plastic to keep the overall cost low.[8]

The result is inferior quality bulbs that provide substandard performance and in some cases even be hazardous to the consumers, as their safety standards have not been checked. Examples of such potentially harmful products include the night lamps that IKEA ordered and shipped from China in 2014. Due to the lack of any regulatory checks at the time of manufacturing, there were no means of identifying the potential electric shock hazard that the bulbs presented. It was only when several complaints from consumers who had been subjected to shocks started flowing in that this hazard was identified and IKEA had to issue to a large scale recall.[9]

Another malpractice followed by the manufacturers is the use of the 'CE Mark' which is awarded to products that meet the EU quality standards for electronic products when being placed on the EU market.[10] Manufacturers make use of false marks on all fake LEDs without quality testing. As a result, these LEDs are easily integrated into the market along with products that have actually been tested and cannot be told apart from the latter. As suppliers and consumers alike assume them to be safe, these fraud products find themselves in homes, schools, workspaces etc.

Social Issues

The LED industry enjoys a good image in the market due to the highly advertised environmental benefits of their products – being mercury free and energy efficient.[11] However, not much information can be found for social issues in the industry. As the semiconductor production is a light manufacturing industry (industry that does not require high capitalisation or heavy machinery), worker illness or injuries that may occur day-to-day, are not as severe as in the case of heavy industries. The main health concern is long-term chemical exposure, which can increase rates of birth defects and cancer.[12] But, the extent of this risk to workers is still unclear as connections between long-term exposure and illness are quite difficult to prove.[6]

LED manufacturers such as the Beaver Innovations have taken positive steps to indulge in good social practices and provide supportive employment to physically or mentally challenged people.[12] Some other companies are OHSAS certified and follow a Code of Conduct for social responsibility in their operations. Aura Light's Code of Conduct is based on UN Global Compact and International Labour Organisations Declaration of Fundamental Principles and Rights at Work.[14] IKEA's IWAY policy also prioritises social and sustainability issues.[15] This may offer assurance that LED manufactures are taking steps to be more responsible towards their workers and the society.

Upcoming LED-Integrated Products: New Challenges

A number of products integrated with LEDs are now available on the market, ranging from LED powered shoes, E-textiles (clothes) and Luminous textile ©Philips - which integrates multi-coloured LEDs within textile panels for room interior decoration.[16] Such products have become possible due to the ease of integration of LEDs with other materials. In the future, issues related to LED lighting should take into consideration the manufacturing of such products as well as the added challenges they offer in terms of their production, use and disposal.[17]

Photo by Takumi Sano, ISAC Tokyo Bureau, CC 2.0.

LED lights in jackets. (photograph by author)

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This Little Light of Mine

Use and Distribution of LEDs

By Dann Moreno, Brayton Noll & Marula Tsagkari

The use phase of LED lights has the most significant environmental impact, making this phase and the factors influencing it, critical to study. Electricity mix in the country of use, the lifetime of the product, and side effects resulting from increased energy efficiency that LEDs provide, all affect the use phase of a LED. These factors are analysed in this section with the aim of providing recommendations as to how to lower the impact.

Distribution is also mentioned, but because of the small influence (less than 1%) it has on the overall emissions, it is not discussed in detail. Our findings suggest because of the long life time and unique external factors directly affecting modern LEDs, additional research, accurately portraying the use phase, paired with the enactment of specific legislation, are essential for a sustainable lighting future.

Case (Region/ Country)	Assessment Method	Percentage of Manufacturing Phase Impact	Percentage of Use Phase Impact
Road lighting (EU)	CML-IA	13%	87%
Road lighting (EU)	Eco-Indicator 99	14%	86%
Road lighting (Norway)	CML-IA	63%	36%
Road lighting (Norway)	Eco-Indicator 99	48%	51%
LED downlight (France)	SimaPro LCA Software*	23%	76%
LED downlight (EU)	SimaPro LCA Software*	7%	93%
LED downlight (UK)	SimaPro LCA Software*	N.A.	94%

Table 1. A comparison of the environmental impact in different stages of LCAs. The table shows seven case studies of lighting in different regions and how the energy makeup of different areas affects the two most impactful LCA phases: manufacturing and use. In the cases presented above, the manufacturing phase included raw material extraction to some degree.

**This is a software capable of running multiple Assessments Methods, however the LCAs did not specify what assessment method was used.*

Electricity Mix

According to the majority of the literature on the topic, the electricity consumed by the LEDs in the use phase is responsible for the largest environmental impact.[1,2] However, the magnitude of environmental impact in this phase is directly dependent on the source of the electricity consumed.[3] As would be expected, low-emission electricity generating sources (e.g. hydro, wind, etc.) reduce the environmental impact of the use phase by supplying cleaner electricity to the device. In lowering the effect that emissions have during the use phase, other phases – most notably the manufacturing phase – makes up a larger proportion of the overall percentage.

Today, in almost every country, the use phase is still the most impactful phase, meaning that making LEDs more efficient is still the most environmentally friendly alteration that the light source can undergo.[2] However, with Scandinavian countries rapidly showing preference towards renewable electricity generation, this section examines different energy mixes in this region, to understand how much will renewable energy affect the significance of the two LCA phases.

From the literature review, over thirty cases were analysed.[1,2,4] Table 1 summarises seven of the cases where a lighting source was analysed, the assessment method was explicitly stated, and the relative significance of the environmental impact of the manufacturing and use phase was calculated.

The Case of Norway

The majority of the cases calculated that the largest environmental impact is caused by the consumption of electricity, regardless the energy mix used, with one notable exception. Road lighting in Norway was studied; a country where 99% of the energy mix comes from hydropower. In one of the studies, the environmental impact of manufacturing overtook the use phase (63% manufacturing vs. 36% use phase).[2] However, in another case study of Norway's road lighting, using a different method of analysis, the manufacturing and use phases were found to be almost equal, with the use phase still having slightly more significance.[2]

The assessment methods used to quantify the impact to the environment can vary in their conclusions, due to the utilisation of slightly different methodologies. While there is slight percentage disagreement between the two methods of analysis, what can be determined from this case study is that the energy mix has to supply almost all renewably generated electricity before the manufacturing phase even has the potential to have a similar impact as the use phase.[2,4]

Denmark and Sweden

Worldwide, the electricity share produced from coal and oil has decreased over roughly the last 40 years, from over 63% in 1971 to about 45% in 2014.[5] In Europe, the mean fossil fuel use for electricity generation percentage is lower, averaging 35% between all the nations.[6] This has resulted in a decreasing trend in the emission intensity of the electric sector.[6,7]

Currently, Denmark is experiencing a relatively fast energy mix transition. From 2010 to 2015 fossil fuels have decreased from 70% to less than 50%, and the trend is expected to continue.[8,9] Sweden's energy mix, on the other hand, is dominated by hydropower and nuclear power, supplying 41% and 43% respectively. A further 7% came from wind power, and the final 9% is mainly from combined heat, power plants and other fossil fuel sources.[10] Similarly to Denmark, increasing electricity production from renewable sources is expected.[10, 11]

Coal and other fossil fuels are expected to play a substantial role in Denmark's electricity mix through 2025;[9] ensuring that the use phase in a LED's lifetime will continue to have a substantially greater impact than manufacturing. An up-to-date LCA of any lighting in Sweden could not be found, however France, like Sweden, relies heavily on nuclear power and uses a similar percentage of fossil fuels. France's nuclear use percentage is about one third higher than in Sweden. Therefore, using the LCA on French lighting to infer about the significance of the lifecycle phases in Sweden, we have to account for nuclear being a more environmentally impactful source of renewable energy. However, even taking this into consideration, it is apparent that despite the relatively low use of fossil fuels in Sweden (less than 10%), the manufacturing phase is unlikely to overtake the use phase without a substantial decrease in the use of fossil fuels (Table 1).[4]

The electricity mix for countries is an important consideration in the LCA of lighting options. Yet even in countries such as Norway, where renewable energy makes up almost all of their power, the results are inconclusive as to what lifecycle stage (use or manufacturing) has the largest environmental impact. Thus, even with a greater shift towards renewables, it is expected that in the future the use phase of LEDs will continue to have a proportionally large environmental impact.

Distribution of LED

The distribution phase includes the transportation from the manufacturer to the final user of the product. The journey of a LED generally begins in Asia and from there it is often transported on cargo boats, and in the scope of this analysis, ends in Scandinavia. From there, the LEDs are sent to one of the final retailers. Alternative destinations include distribution warehouses, where they are then sold to smaller business.

Overall the distribution phase of LEDs is a small proportion of the total environmental footprint, roughly 0.09% according to one LCA.[3] Other LCAs[12,] support this notion with less specific numbers, simply noting that this stage's impact makes up less than one percent. The reason this stage is likely to remain constant is that any substantial improvement in this category need to come from stricter regulations in maritime transport in regards to fuel types and minimising air emissions.

Lifetime of LED

Nowadays, as the use and applications of LEDs is expanding, one of the main concerns for producers and consumers, is the lifetime, as this is highly influential on the use phase.[13,14] When we refer to the "lifetime" of a LED we refer to "the time the product is expected to operate as supposed, under a defined set of environmental and mechanical parameters."[15] Lifetime is an important consideration for the consumers who are willing to pay a higher value for a more efficient, but also long-lasting product.[16] The issue of durability is becoming more important in cases in which LED bulbs

Operation hours per day/lifetime hours	10 000 h	50 000 h	100 000 h
24 h/day	1.1 years	5.7 years	11.4 years
15 h/day	1.8 years	9.1 years	18.3 years
10 h/day	2.7 years	13.7 years	27.4 years
8 h/day	3.4 years	17 years	34.2 years
4 h/day	6.8 years	34.2 years	68.5 years

Table 2. Expected Lifetime (years) of different LED products based on their standardised lifetime (hours) and use (hours per day).

are not easily detached from the other components, or it is difficult in terms of cost and effort to replace them (e.g. public lighting).

The lifetime of a LED is significantly longer than that of incandescent, fluorescent or High Intensity Discharge (HID) lamp sources as a high quality LED will normally last 50 000 hours or longer.[17] The "critical time" of an LED's life, is the point after which the LED light emits only 70% of its initial light, not when it totally fails. This point is called the L70 and is standardised by the industry as L_{70} = minimum 50 000 hours. The amount of light produced from the light source at a defined time frame is referred to as "the Lamp Lumen Maintenance Factor", or LLMF.[18]

Currently there are some products on the market with lifetime better than the industry standard, where 80% (LLMF = 0.8) of the luminaire – or more – can remain after 50 000 hours of life. Thus, when it comes to the lifetime of LEDs, one of the interesting characteristics is that they do not die instantly as other light sources do, but they slowly dim down.

To illustrate the long lifetime of a LED, briefly consider that a LED with an estimated lifetime of 100 000 h, used for an average of 8 hours per day is expected to last over 30 years; while if it used for 15 h it will last for more than 18 years. Table 2 shows the expected lifetime (in years) of different LED products based on their standardised lifetime and use.

Nowadays, there is a vast number of different types of products on the market, with a lifetime that can vary from less than 10 000 hours to more than 100 000 hours[17] with price fluctuations between EUR 15 and EUR 120. Thus, consumers can choose the one that best fits their needs and budget. However, it is important to bear in mind that the life expectancy is also affected by the use scenario and the product quality. Life expectancy is easier to estimate in the case of standardised use (e.g. lights in the cities) but can differ in other uses (e.g. household products). Additionally, for some uses, like decorative, a light level below 70% may not be a problem.[19]

However, the lifetime ratings are limited in the expected lumen degradation of the LED package under ideal conditions, and little other information is available in the package. In an effort to increase the accuracy in the description of LED product lifetimes, and to increase consumers' confidence, new international standards related to LED lifetimes have been designed. The new standards (IEC 62717 and IEC 62722-2-1) relate to performance requirements for LEDs and standardise the test time to 6 000 hours in which the luminaire is recorded every 1 000 hours. [17]

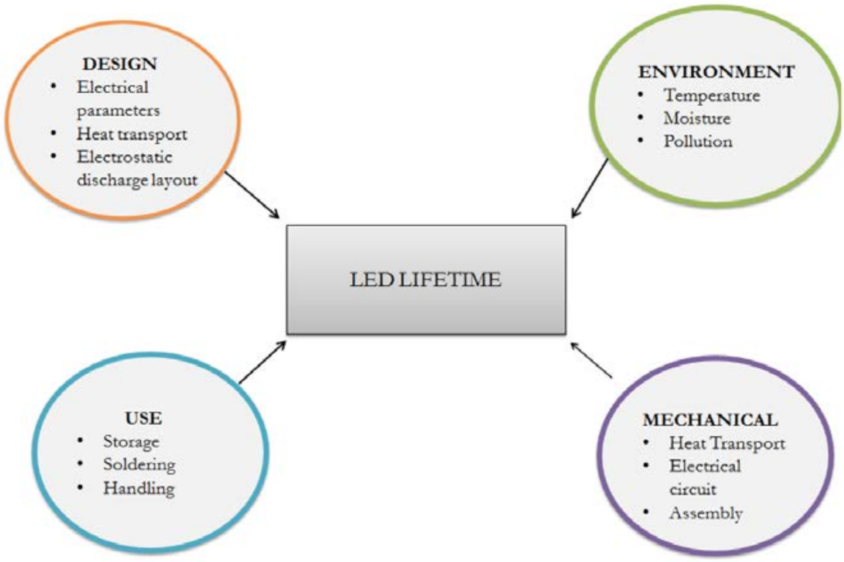

Figure 1. Shows the factors that can affect the lifetime of an LED package and potentially lead to unexpected failures. These factors are related with 4 different areas such as LED design, use, mechanical application and environment. Data from Chang et. Al. (2012); OSRAM (2013).

LED Failures

Despite recent legislative standards passed on LED lifetimes quality testing, LEDs do occasionally fail. While luminaire degradation is expected in LEDs after a certain number of hours, there are other causes of LED failure. Often, damage to the driver, the housing, or other components of the package can result in a catastrophic failure.

The lifetime of LEDs and the other components should be the same. In the recent increase in the lifetime of LEDs the driver technology is lagging and is often a major reason for failure. Other reported failures are related to thermal management components as they accumulate dirt, power supply failures, and corrosion of electrical connection. It has been reported that in environments with high temperature and high levels of moisture leads to the faster degradation of the LED components.

Factors that affect the lifetime of a LED light can be seen in Figure 1. In this context, the SSL Quality Advocates research group reported the cause of 29 field failures from 5 400 outdoor luminaires from one manufacturer. Although only a small proportion of the LEDs tested failed, the most common reasons for failure were: drivers (59%), housing problems (31%) and LED package (10%).[15] These parameters should be taken into account when discussing the installation of LEDs, especially on a larger scale, in order to gain the confidence of the consumers who expect that the products they are buying are well designed and will perform to their expectations.

The aforementioned failures of some components of the LED package, before the actual end of lifetime, has led many scholars to discuss the issue of serviceability of LEDs in order to prolong the use phase. According to the U.S. Department of Energy in 2016; "a serviceable product has components that are replaceable or repairable by regular maintenance personnel."[17]

However, some of the important issues raised include: which parts will be replaceable, what will be the cost, how complex is the replacement, and how one will define when replacement is needed.

A final important issue when it comes to the lifetime of LED lights is the rapid development of technology as new LED products enter the market. This can potentially lead to big changes in the use phase and reduce the use phase as people will replace the LED lights before the end of their lifetime.

Rebound Effects

The consequences or by-products of technological improvement are a well-researched topic and have shown, that increased energy efficiency generally brings about increased consumption known as, the "rebound effects."[21] There are two types of rebounds that occur: when the percentage of the energy consumed is still less than the overall savings (the rebound effect) and when the overall energy used is greater than the savings (the backfire effect).[21,22] The concept of increased consumption of energy resulting from increased efficiency has been around for over a century. As early as 1866, scholars began to explore these two ef-

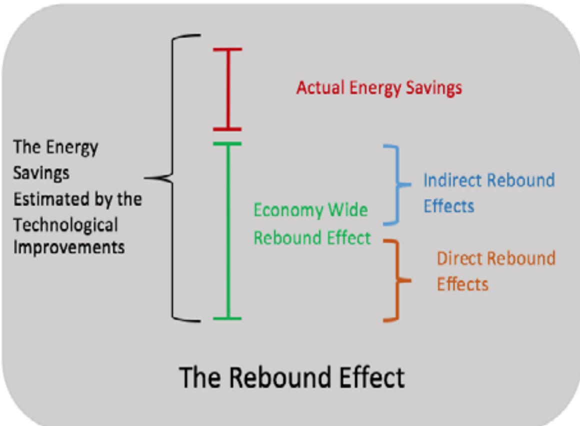

Figure 2 Shows the Rebound Effects broken down into its components: The direct and indirect rebound effect.

fects in reference to coal machinery efficiency in that increased efficiency leads to increased consumption.[23]

Rebound effects can manifest themselves in two different ways on a national level: direct and indirect.

- Direct rebound effect in switching to LED lighting would be increased use of light due to its cheaper cost, overall resulting in greater energy consumption.
- Indirect rebound effect could be that the money saved over time in switching to LED light was spent for a plane ticket for a vacation that otherwise would not have been taken.

If you add the "direct rebound effect" to the "indirect rebound effect" you get the "economy wide rebound effect" (Figure 2).[24]

One study conducted on the rebound effect claims that despite many campaigns to reduce energy use over 25 years (1981-2006) in the Global North energy consumption has continued to rise.[25] To combat this, the author does not suggest that innovation should be stopped, rather that legislation should be implemented, (e.g. carbon taxes) to decouple innovation with additional energy use. Other scholars, have reached a similar conclusion: the necessity of policy to be paired with increases in energy efficiency.[21,22,23]

This type of legislation can also be effective at an institutional level. As utility companies continue to employ more efficient and long-lasting lighting in cities, they will have increased capital resulting from the energy savings. Almost all of the electrical utility companies in Scandinavia provide additional services such as gas, heating, and water.

Real World Policy Potential

A World Bank study in 2014 discovered that utility companies are generally unaware of potential innovations and of benefits that can result from improvements, especially in the water and heating sectors.[26] Innovations to these systems can lead to substantial waste and energy reductions (up to 25%). However, because the payback period is long term, these types of innovations often require legislative or economic instrument implementation. A policy that mandated the fiscal savings from the energy sector, be passed along to these utility sectors, would have substantial short-term environmental impacts and would result in long-term financial savings.[26]

While water and heating improvements are identified as having the potential to greatly benefit the environment, lighting innovation is expected to have similarly positive impacts as well. Some scholars believe that with projected technological advances in lighting such as laser source lighting and more efficient LEDs, there could be overall global reduction in the GHG emissions from lighting sources, despite continued growth in the sector, as early as 2030.[27]

The energy, environmental and financial benefits of LEDs are numerous. However, universally supporting the installation of LEDs wherever possible may trigger rebound effects. The Global Lighting Challenge (GLC) is the largest collective global project currently promoting the growth of global LED lighting through a consortium of 14 governments, a number of businesses and NGOs. This organisation, formed in 2015 at the COP 21 meeting in Paris has embarked to deploy 10 billion high-efficiency (LED) bulbs. Their philosophy is that technology improvement when it comes to lighting will ultimately lead to energy savings despite any rebound effects that may occur. The GLC's goal, to employ "50% more lighting globally while consuming 50% less energy compared to today," leaves issues unaddressed.[29]

The concept of energy equity or "energy justice,"[28] between the global north and south is not discussed, despite international involvement from an array of countries. Secondly, the additional infrastructure required for the

LEDs, and the waste generated from replacing older lighting systems is not accounted for when the GLC discusses energy savings.[29] Finally, depending on the energy mix of the country, replacing older lighting systems with new LEDs should be of low priority due to the minimal and at times even non-existent emissions savings that result from the change.[30] LEDs and continuing to improve lighting efficiency is undeniably the future, but, it is important that all factors are taken into account and contextualised with the surroundings when promoting their use.

Conclusions

Our research touches on the complexity of the use phase in lighting. New lighting projects involve an array of factors that need to be taken into consideration when designing a project. Our analysis suggests that designers should better report lifetime standards, publish more data and information about product lifetimes under various operating conditions, and conduct broader testing on the products. Consumers should aim to be more responsible and purchase products from quality producers. We believe that the additional analysis will reveal potential failures that have historically occurred under conditions of stress and real life conditions. With this additional testing and information provided by the manufacturer, consumers could correctly choose the LED to fit their needs, thus optimising the lifetime and performance the lighting system.

The use of LEDs and other energy-efficient lighting systems are the future of global lighting. However, the process in which this future is actualised, is of great importance if access to lighting and electricity for all is to be achieved in an environmentally sustainable way. Effective policy at all levels and the continued fostering of innovation in lighting technology are the keys to a bright future.

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THE AFTER-LIGHT

The Today and Tomorrow of LED End-of-Life Management

By Savannah Carr-Wilson, Gabrielle Freeman & Sandeep

Over the past decade, the use of light emitting diodes (LEDs) has grown rapidly, and its waste stream is keeping pace. However, countries have not yet implemented economical and scalable solutions for managing LEDs' end-of-life.

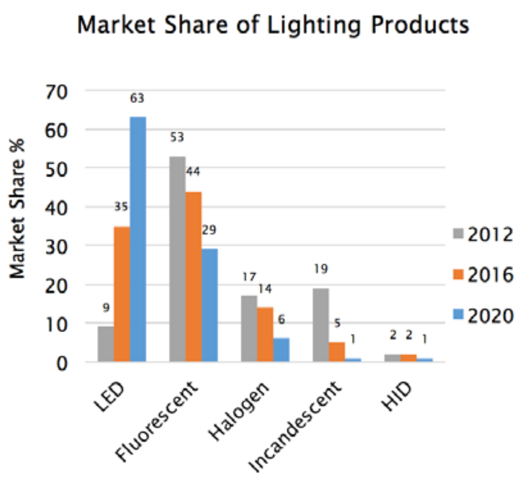
While several studies have shown that LEDs use phase has the largest environmental impact from a life cycle point of view, effective LED end-of-life treatment is important for European countries like Sweden for economic and geopolitical reasons. Today, China is a global leader in the mining of critical metals used in LEDs. In order for Europe to be less dependent on Chinese and other foreign exports and mitigate their supply risks, finding ways to better recycle LEDs and recover these critical metals is indispensable.

Currently, exciting developments in LED end-of-life that could help address the critical metal question and improve LEDs from an overall life cycle perspective are on the horizon. Some research projects in Europe are trying to develop methods for effectively recycling LEDs and retrieving their critical metals. Just how valuable these critical metals are remains to be seen, as researchers and companies learn more about the cost-effectiveness of their extraction. These projects are still at the experimentation stage.

Beyond research institutes, some companies like Sweden's Nordic Recycling AB are experimenting with using presorting machines to introduce LED recycling, while other companies such as Philips are innovating at the design stage.

LED End-of-Life Today

Although LED lighting products have significantly longer lifetimes than any other comparable lighting product on the market, like any other device they eventually reach their end-of life and must be disposed of or recycled. The rapidly growing amount of LEDs on the market is accompanied by an increasingly urgent need for their effective end-of-life management.



Current and projected market share from the lighting industry.[1,2]

As shown in the chart, although LEDs' share of the global lighting market has recently increased dramatically – from 9% in 2012 to 36% in 2016 – fluorescent lamps still dominate the market.[1,2] However, given that LEDs have surpassed other lighting products in the product portfolios of manufacturers and distributors, LED products are predicted to dominate the lighting market in the near future.[1]

Anticipating Tomorrow's Need for LED Recycling

The multi-functionality of LED technology, along with the potential to integrate it into current trends of smart homes and smart city concepts, makes it very attractive for both producers and consumers. The technology found in LEDs makes it an electronic product as well as a lighting one. Therefore, LEDs are not limited to illumination but have multiple potential functions (dimming, colour changing, etc.) including the ability to work with other electronics, such as mobile phones and speakers.

While there is no exact time frame to determine when LEDs will actually reach a dominant position in different lighting market segments (private homes, public areas, industry, transportation, etc.), replacing other lamps with LEDs will require an estimated 2.3 billion LED lamps for Europe alone.[3,4] This may be a conservative estimate considering other factors, such as the need to replace broken products, and cases where LEDs are retired prematurely.[1] How all of these products should be effectively and economically dealt with at their end-of-life is currently an unanswered question.

Current LED End-of-Life

Given that LEDs contain many valuable elements such as rare earth metals and other critical metals such as gallium and indium, there is incentive to develop recycling technologies and processes for LEDs. However, today, LED-specific recycling processes are currently limited to research activities and new patents.[3,4]

In general, collection and recycling of lamps is driven by legislation. The estimated global collection rate ranges from an optimistic high of 40% to a low-end estimate of 15%.[12] The typical recycling process used today to treat lamps, such as compact fluorescent lamps in private households or mercury vapour lamps for street lighting, involves crushing and separating the main components of lamps. The focus is on recovering glass, metals, and plastics. LEDs, on the other hand, contain complex electronic components such as printed circuit boards that are integrated into their design and that cannot be adequately recovered using these recycling processes.[1]

Since the cost of collection and recycling of lamps is relatively high compared to the value of the product, most recycling is driven by legislation in order to deal with the toxic mercury found in fluorescent lamps.[5] In Europe, the Waste Electrical and Electronic Equipment Directive, or WEEE Directive (EU 2002/96/EC and recast 2012/19/EU) covers the management of end-of-life lamps, implementing Extended Producer Responsibility (EPR) and effectively banning them from being landfilled.

The WEEE Directive sorts different products into distinct categories for reporting purposes. Article 5 of the WEEE Directive categorises fluorescent lamps as a priority for collection because they contain toxic mercury. It also sets a standard to recycle 80% of the gas discharge lamps collected (Annex V) and requires the removal of mercury in the treatment process (Annex VII).[12]

End-of-life lamps have certain characteristics that make their collection and recycling particularly challenging. Fluorescent lamps contain mercury, a hazardous waste, and special care must be taken to collect them in a safe way to avoid breaking their fragile glass. LED lamps have been recently classified under Category 5b.

LED lamps and fluorescent lamps are collected together, leaving the recycler with the task of separating the waste streams.[1] While joint collection of lamps is more convenient and straightforward for consumers, it also creates the risk of cross contaminating all lamps with mercury if one or more fluorescent lamp breaks during the collection or transportation process; as a result, all lamps have to be treated as hazardous waste. Since this creates unnecessary costs for recyclers, separate collection of LED lamps should be a priority for their effective recycling.

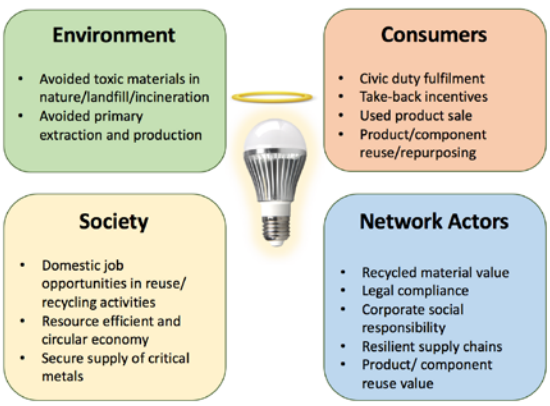
Currently, most lamp recycling facilities use dry separation processes to recover the main materials found in lighting products. Glass is the main material making up most lamps and its recovery provides the most of bulk volume in recovered materials but provides little to no value for recyclers. Metals and plastics are separated with metal providing the most value. The phosphors layer of fluorescent lamps, which produces white light, contains rare earth metals. A wet-chemical method is used to clean the phosphors of mercury before it can be recovered, but the small amount means that this process is not economic and rarely used. Mercury must be disposed of in hazardous waste landfills.[1]

In terms of best practices, the Nordic countries have been recognised for going beyond European standards in the area of end-of-life management of WEEE. However, even they have opportunities for further improvement, such as improving the way recovered materials are used.[5] Even leading companies in lamp recycling, such as Nordic Recycling AB in Sweden, currently use recovered glass to cover landfills and incinerate recovered plastic for energy.

Low-end uses for recovered materials in lamps do not provide enough incentive to significantly improve current collection and recycling schemes for lamps and drive innovation in their end-life-management. However, as illustrated, there are many different types of values that can be derived from a LED's end-of-life.

As the lighting market moves rapidly towards more LEDs, their effective end-of-life management, and especially recycling, will be important for recovering valuable secondary materials, such as critical metals. In addition, conserving resources at end-of-life may be a more feasible policy than trying to target the diffuse social and environmental impacts of the raw material stage of LED production.[12]

Improving end-of-life management for LEDs is both an opportunity and a challenge even for today's best performers in lamp recycling, shown by the following case study on Nordic Recycling AB in Sweden.



LED end-of-life values, adapted from Richter.[12]

Nordic Recycling AB: A Company's Perspective

Located in Hovmantorp, about 200 km from Lund, Nordic Recycling AB is one of the top three lamp recycling companies in the world. It is Sweden's only lamp recycling company, and is responsible for recycling all the lamps in the country. Other than processing lamps from Sweden, all the lamps collected in Norway are also recycled by the company.

Thirty percent of collected lamps from Denmark and a small fraction of lamps from Lithuania are also recycled at Nordic Recycling AB.

The company is accepting all types of lamps: fluorescent tubes, compact fluorescent lamps, or LEDs. In a year, the company recycles an average of 3600 tonnes of lamps – which is about 30-40 million lamps. In Sweden, the lamps are collected from 650 different collection points, set up by a producer organisation, El-Kretsen, that works for lamp manufacturing companies. As part of EPR, manufacturing companies like Philips, IKEA and others have contracted El-Kretsen to collect the used lamps, and bring them to Nordic Recycling AB's premises in Hovmantorp in yellow collection boxes for recycling.

Visit to Nordic Recycling AB

As part of this research project on end-of-life treatment of LEDs, graduate students and professors from Lund University's International Institute for Industrial Environmental Economics (IIIEE) visited the recycling facility of Nordic Recycling AB in Hovmantorp on October 24, 2016. The group spoke with Mr. Peter Arnesson, General Manager, Nordic Recycling AB, about the current status of LED recycling in Sweden, and future challenges. Apart from the discussion, the group also conducted a site visit of the recycling facility, and learned about the different processes involved in the lamp recycling process.

Mr. Arnesson informed the group that the use of LEDs is growing fast, and effectively recycling them will be a big future challenge. He told us that about a year ago, Nordic Recycling AB conducted a detailed analysis of the generated waste stream they received, and found that the percentage of waste from LEDs was 0.8%.

The company conducted a similar analysis again six months ago, and found that the amount of LEDs in the waste stream had increased to 2%. At the time of our visit, the results from the latest waste stream analysis had just come out, showing that LEDs now constitute 3.5% of the waste stream Nordic Recycling AB receives.

Explaining the significance of the results, Mr. Arnesson said, "LEDs are still a small part, but they are growing fast. That's why dealing with LEDs is very important now, and will be even more important in the future."

Innovation in LED Recycling

Mr. Arnesson informed the group that currently, Nordic Recycling AB does not presort the different types of lamps in their facility. However, they are working with the Chalmers University of Technology in Gothenburg to develop a presorting line for lamps. In addition, Nordic Recycling AB is also a partner in the European Union's project 'Illuminate', which aims to create a sealed presorting unit for LEDs.[6] The company plans to bring in their first presorting machinery from Italy soon, where a prototype is being tested. Mr. Anderson said, "We want to test the presorting machine here to see whether it is working or not. If it works, we will install a bigger presorting machine in the future."

The Company's Future Objectives

The company's prime objective is to separate LEDs from the other lamps before the recy-

Post-recycled lamps in piles of shredded plastic (left) and metal (right) at Nordic Recycling AB. Photo credit: Sandeep cling process starts. The advantage of having a presorting line is that the LED waste could be recycled separately, making it easier to recycle the LED lamps and recover valuable components such as critical metals. "These rare earth materials have high value, and could be an additional income for our company," Mr. Arnesson told the group while explaining the presorting projects.

Currently, in the absence of any presorting technique, all the lamps are treated unsorted using an oxidation process. In the oxidation process, all the lamps are crushed together, and cleaned in a liquid that oxidises and binds the mercury. Then the mercury is separated from the glass, metal, plastic, and other materials. The recovered glass is reused to make new glass items, and so is the metal. The plastic is burned. The mercury is sent to another company that specialises in dealing with hazardous waste, who stabilises it and buries it in a mine.

Mr. Arnesson explained that the issue with not having a presorting provision is that all the lamps are crushed together, and the mercury spreads all over the other lamps. Moreover, it is hard to extract rare earth metals from the mixture of lamps, Mr. Arnesson added.

"Right now our company is doing well, but we will be in the front when we will have the new sorting line. Once we have that in place and we develop it, we will be the number one lamp recycler in the world," Mr. Arnesson said at the end of our visit.

Looking to the Future

This case study makes it clear that recycling LEDs is a new and emergent area. Countries are still discovering how best to manage it, and it represents an active area of research and learning. Currently, several European research institutes are pursuing innovative ways of recycling LEDs that have yielded promising results. Companies are also innovating in the area of LED end-of-life, with implications for improvements in the whole LED life cycle.

Recovering LED Critical Metals

The CycLED project is one excellent example of an advance in LED recycling driven by a research institute.[4] This 2012-2015 European Union funded project was the joint effort of a consortium of partners led by the Germany-based Fraunhofer Institute for Reliability and Microintegration IZM. The project as a whole aimed to reduce the amount of critical metals used in LED lights, and to enable recycling of these metals.

The institute defines critical metals as those that are "indispensable in modern key technologies," particularly "low carbon energy & transport technologies," such as solar cells, mobile phones, and LEDs. The project refers to these critical metals as "target metals," and they include gallium, indium, cerium, europium, lutetium, yttrium, gold, silver, and tin.

In the aspect of the project that deals with recycling LEDs, Fraunhofer IZM analysed target metals in 50 retrofit LED lamps. This research revealed that, on average, there are only low concentrations of target metals in the lamps. The institute concluded that with such low concentrations of target metals, it wouldn't be technically feasible or economically worthwhile to recover these metals using the typical "shredding and mechanical separation" process used to recycle lamps, as that process spreads the target metals out in the shredded materials. Therefore, they concluded that it would be necessary to "pre-treat" LED products by removing the LED diode prior to shredding, as this component contains the majority of the target metals. This pre-treatment can be done by hand, but the Institute found that using a manual method for extracting the LED diodes was prohibitively costly. They concluded that it would be necessary to develop a mechanical pre-treatment method.

The Shockwave Method

The good news is that around the time the CycleLED project concluded, another research group, the Fraunhofer Institute for Silicate Research ISC's Project Group for Materials Recycling and Resource Strategies IWKS, developed a mechanical pre-treatment method. Their method, called the "shockwave method," uses an "electrohydraulic" process to break LED lamps into their constituent parts by literally shocking them with electricity in a water bath.[7] After the shockwave treatment, the separated LED diodes can be recycled separately to recover the target metals. One way of doing this is to use a method the CycleLED project came up with, which recycles the diodes using a chemical solvent called CreaSolv. CreaSolv helps to separate the various elements in the LED diode and concentrate the rare earth metals.[8]

These research developments suggest it may become easier to recycle LEDs and recover critical metals in the future. Whether this will be economically feasible for recyclers is another question that remains to be worked out.

Improving LED Design

While these research findings may indicate the future direction of LED recycling, some academics and companies are focusing on LEDs from another, equally important perspective. They are interested in improving LED design to optimise end-of-life, make reuse and reman-

Illustration of the electrohydraulic fragmentation (EHF) method: (a) shows waste lamps before EHF, (b) shows the waste lamps in (a) after EHF, and (c) shows fractions obtained after EHF of one retrofit LED lamp and subsequent manual sorting.[1,7]
Photo credit: ©Fraunhofer Project-Group IWKS

ufacturing, in addition to recycling, easier, and reduce the overall amount of raw materials and other resources consumed in LED life cycles.

For example, in a 2010 study, researchers Hendrickson, Matthews, and Ashe outlined several ways LEDs could be designed for easier end-of-life management.[9] One of their suggestions was to minimise the use of different types of material and colours of plastic in LED bulbs and luminaires so that it is easier to disassemble and separate them for recycling.

However, it's not only academics focusing on better LED design. Global electronics company Philips has also taken initiative to improve LED design for end-of-life. One of their design initiatives is the development of an LED light bulb, the "SlimStyle LED bulb," that is designed for recyclability and falls apart during shredding.[3] Currently, the SlimStyle bulb is not available in Europe. However, it serves as an example of the type of progress that can be made in LED end-of-life from the design side.

Lighting as a Service

Philips has also started to offer lighting as a service, as opposed to a product, further optimising LED use and end-of-life. Lighting as a service means that Philips rents its lighting products to customers, but maintains ownership during the contract. The customer pays for light, as a service, as opposed to purchasing a lighting product. If a lighting product needs replacement or repair during the contract, Philips takes care of this. Philips also takes back the lighting product stock at the end of the contract.

Philips has already started to offer this service in Europe, entering into a contract in 2015 with Amsterdam's Schiphol Airport to provide LED lighting as a service in the airport's terminal buildings.[10] Philips will remain the owner of the lighting fixtures and installations, and Schiphol Airport will pay for the lighting service. Philips along with energy services company Cofely is responsible for maintaining the lighting equipment during the contract period, and at the end will upgrade the fixtures and use them elsewhere, maximising their utility. Philips has entered into similar contracts, often termed "pay per lux," with the National Union of Students office in the UK, the Amsterdam based RAUArchitects office, and the Washington DC metro.[11]

Conclusion

LEDs represent both an increasing market share and an increasing waste stream. They also present potential business opportunities for recycling companies such as Nordic Recycling AB, if appropriate and cost-effective techniques are developed for recycling valuable components such as critical metals. Much of the work on LED recycling is currently being done by academics and in research institutes, although companies are also creating innovative LED designs to optimise recycling at end-of-life.

The future holds many possibilities for LED recycling. We may see improved LED recycling processes for extracting valuable components, improved LED design for end-of-life from multiple manufacturers, and even a change in the way businesses and individual consumers think about lighting, moving from lighting products to lighting as a service.

We may also see grassroots developments. LEDs have a much longer lifetime than other light bulbs, and are often integrated into their luminaries. However, style and taste change over time. We may see a second hand market for LED bulbs and luminaries pop up, allowing people to trade their light sources and find one that better suits their needs. LEDs integration into luminaires may also present new recycling challenges in the future, and require new methods to recycle these integrated products.

Overall, LED end-of-life management is at an early stage. Major players such as governments, research institutes, and companies see a need for improved LED recycling on the horizon, and are conducting research and driving innovation in this area. However, we do not have all the answers about how to best deal with LEDs at end-of-life. Further work is needed to shine light on the best way to manage LEDs, after life.

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This year the MESPOM cohort of 2015-2017, ventured into analysing the impacts of various life cycle phases of LEDs – material extraction, production, use and the end-of-life. This insightful journey took us from gathering all possible scientific and published literature, studies and data collected through field visits to create a picture of the existing situation, the measures taken by various actors to address the issues in various life cycle phases of LED, and finally propose actions for the future.

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MESPOM
Masters in Environmental Science, Policy, and Management

The International Institute for Industrial Environmental Economics (IIIEE)

Established in 1994 by the Swedish Parliament, the International Institute for Industrial Environmental Economics (IIIEE) is a leading international research and teaching institution pursuing strategic preventative solutions in sustainable development. As part of Lund University, the IIIEE offers graduate and postgraduate programmes in a multidisciplinary environment, focusing on pragmatic approaches to foster the transition towards an environmentally conscious society.

The IIIEE seeks to facilitate this transition by engaging in education and research activities, with a focus on connecting academia and practice. The IIIEE, with its international students, faculty and staff, is proud of its multidisciplinary and multicultural approaches to sustainability. By collaborating with other departments at Lund University and universities worldwide, the Institute explores and advances knowledge in design, application and evaluation of strategies, policies and tools for addressing global environmental challenges.

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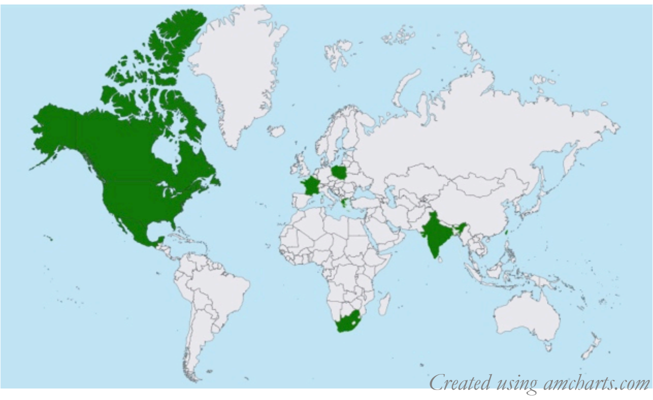
The Authors

This report was compiled by the students of the masters course in Environmental Sciences, Policy and Management (MESPOM). MESPOM is a two-year Erasmus Mundus programme supported by the European Commission and operated by four European and two North American universities.

Students study in at least three out of six consortium universities: Central European University (Hungary); University of the Aegean (Greece); Lund University (Sweden); Manchester University (United Kingdom); Middlebury Institute of International Studies at Monterey (United States); and University of Saskatchewan (Canada).



MESPOM batch 11 consists of 21 students from 12 different countries. The 14 authors of this text are studying at the International Institute of International Economics (IIIEE) at Lund University during the autumn 2016 semester. These 14 students represent Canada, France, Greece, India, Mexico, Poland, South Africa, Taiwan, and United States.

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