The Life Cycle of LED
A review by IIIEE & Lighting Metropolis

Thomas Lindhqvist & Mikael Backman
International Institute for Industrial Environmental Economics
(IIIIEE) Lund University
Lighting the paths for Eco Design: Life Cycle Assessment of light sources

Malgorzata Lekan
Rongyu Veneta Tzeng
MESPOM 11
December 2016
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
LCA!
So...what is LCA?
‘Life Cycle Assessment (LCA) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle’

(ISO 14040:2006)
MAIN PHASES OF LCA

Goal & Scope Definition

Life Cycle Inventory Analysis

Life Cycle Impact Assessment

INTERPRETATION of results

(ISO 14040:2006)
LCAs of light sources: Overview
Key factors affecting LCA results & their comparison

- type of a body conducting a LCA (purpose of LCA) & data providers

- lack of established rules to conduct a detailed LCA

- diverse shapes and sizes
- material composition (electronic components!)
- diverse uses
- rate of development

- (overly?) simplified nature of simplified LCA models
LCAs for LEDs since 2009

**Academic institutions & Scholars**
Carnegie Mellon University & UC Berkeley

**Producers**
Philips, OSRAM

**Gov.**
US Department of Energy

**Private bodies**
Navigant Consulting, Inc. & Athena Sustainable Material Institute

**Inter-gov. Organization**
International Energy Agency
Purpose of LCAs for LEDs
Aid policy-makers

Compare energy consumption levels of various lighting sources

Identify hazardous materials

Estimate lifetime & design EoL treatments

Provide suggestions for conducting LCA

Demonstrate benefits to the market
Key factors affecting LCA results & their comparison

- type of a body conducting a LCA (purpose of LCA) & data providers
- lack of established rules to conduct a **detailed** LCA
  - diverse shapes and sizes
  - material composition (electronic components!)
  - diverse uses
  - rate of development
- (overly?) **simplified** nature of simplified LCA models
Bulb shapes and sizes are... diverse!

(Source: bestlightingbuy.com)
Key factors affecting LCA results & their comparison

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Material composition of non-directional lamps used in households

(Tähkämö et al. 2014)
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Average lighting efficacy (light output per unit of energy consumed) & cost per bulb

[Graph showing lumens/watt and dollars over time for different types of bulbs: light-emitting diode (LED), compact fluorescent lamp (CFL), incandescent/halogen]

(eia 2014)
Key factors affecting LCA results & their comparison

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(OVERLY?) SIMPLIFIED LCA MODELS

Simple

Extensive

Functional Unit

Lumen-hours

Case-specific

Life cycle stages

Fewer (M & U)

More (R, M, U & EoL)

Envi impacts

Only one (e.g. GWP)

Several (GWP, AP, EP)

Energy source (use stage)

Primary energy

Actual energy production

(Tähkämö 2015)
Use & Manufacturing phase account for the highest share of total environmental impacts during life cycle
Energy consumption (MJ/20 million lumen-hours):

- Incandescent (~22 lamps)
- Halogen (use only) (~27 lamps)
- CFL (~3 lamps)
- LED (2011) (~1 lamp)
- LED (2015) (~0.6 lamps)

Life Cycle Energy of lighting sources

(DOE 2012)
LEDs and CFLs consume primary energy significantly less (~ 900 MJ/functional unit) than incandescent lamps (~ 15 100 MJ/functional unit)

LEDs & CFLs win in terms of luminous efficacy (SI: lumens/watt)

(Tähkämö 2015)
Characteristics of LEDs’ life cycle stages

Raw material acquisition
Manufacturing
Distribution & Use
End-of-Life
Minor impact

Aluminum for heatsinks
(DOE, 2012)
Major impact

Energy consumption

• The only phase out-winning other lighting sources
• Increasing significance - complex lighting technology
• LED package
  Varies significantly from case to case (0.1-27% of LCI) (DOE, 2012)
• Tradeoffs (energy efficiency rate vs. metal components)

Data unavailability

LCA doesn’t consider premature failure of LEDs
## Major impact

<table>
<thead>
<tr>
<th>Life cycle impacts per MmWh</th>
<th>Global warming (kg CO₂-eq.)</th>
<th>Abiotic (resource) depletion (kg sb-eq.)</th>
<th>Acidification (kg SO₂-eq.)</th>
<th>Eutrophication (kg PO4-eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>European electricity</td>
<td>9.4</td>
<td>0.070</td>
<td>0.040</td>
<td>0.0029</td>
</tr>
<tr>
<td>French electricity</td>
<td>2.0</td>
<td>0.013</td>
<td>0.011</td>
<td>0.00056</td>
</tr>
</tbody>
</table>
Minor impact

Material restoration & Complex structures
(Silver, nickel, gold, antimony, copper, recyclable plastic components & ALUMINUM)

NOTE: restoration levels vary from one country to another!
WHAT IS NEXT...?
TAKE-AWAY

DATA BLACK BOX

ENERGY SOURCE

HAZARDOUS WASTE

USER BEHAVIOUR

‘Do I call the police? Next door have got a halogen bulb on again’
References

- Interview with IKEA (November 14th, 2016)

Raw Materials Use in LEDs

Elizabeth Drachenberg, Darja Mihailova, Sai Siddhartha Nandamuri
Agenda

• Materials used
• Rare earth elements (REEs)
• Environmental and social impacts
• Future recycling potential REEs
What are LED lights made out of?

Surprisingly difficult to find out for a number of reasons…

1. Diversity of materials used by different LED producers
2. Reluctance to share trade secrets
3. Opacity of supply chains
Materials used
Materials used

- Sapphire
- Silica
Materials used

- Sapphire
- Silica
- Gold
- Silver
Materials used

- Sapphire
- Silica
- Gold
- Silver
- Gallium nitride
- Gallium arsenide
- Substrate layer
- LED Chip
- p-contact
- n-layer
- n-contact
- p-layer
- p-n junction
- Semiconductor materials
- Electricity current flow
Materials used

- Aluminium
- Plastic
LED vs CFL

Figure 7-6. Life-Cycle Assessment Impacts of the CFL and LED Lamps Analyzed (Detail)
LED vs CFL

Figure 1-2. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to CFL
LED vs CFL

Yttrium
Europium
Cerium
Lanthanum
Terbium
“While extent of industry use of REEs is uncertain, there is an association in the public mind of LEDs with REEs. For this reason, it is important to take into account the social and environmental impacts associated with their extraction and refining.”
Mining and Extraction
Mining and Extraction

Photo by Sandor H. Szabo / Keystone
Environmental impacts

Water

- Acidic wastewater, ammonia and nitrogen levels above safety level in REE extraction
- Cyanide leaching into groundwater and soil for gold production
- Smelting and chemical leaching in silver mining
Environmental impacts

Water

Air

Toxic fluorine gas, flue dust from REEs production
Environmental impacts

Water

Air

Land

Landscape degradation

Soil contamination
Case study: Bayan Obo Mine

Bayan Obo Rare Earth Mines
Baotou, Inner Mongolia, China
Case study: Bayan Obo Mine

Photo by Liam Young/BBC
Social impacts

- Human health
- Social and economic restructuring
Social impacts

- Human health
  - Water contamination
  - Air contamination
  - Radioactive waste
Social impacts

- Human health
- Social and economic restructuring
Social impacts

Mine development
Mine operation
Mine closure

Social and economic restructuring
Recycling REEs--A potential goldmine?

- LEDs a 26 billion $ industry -- Europe accounts for a quarter of this
- China controls most of the supply of REEs -- in 2009, export restrictions were placed

<table>
<thead>
<tr>
<th>Element</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tbody>
<tr>
<td>Lanthanum oxide</td>
<td>3.2</td>
<td>8.2</td>
<td>4.6</td>
<td>21.1</td>
<td>97.9</td>
<td>23.7</td>
<td>7.5</td>
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<tr>
<td>Cerium oxide</td>
<td>2.8</td>
<td>4.3</td>
<td>3.7</td>
<td>20.3</td>
<td>95.9</td>
<td>23.2</td>
<td>7.8</td>
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<tr>
<td>Europium oxide</td>
<td>304.9</td>
<td>453.5</td>
<td>464</td>
<td>527</td>
<td>2674.9</td>
<td>2337.9</td>
<td>1093.4</td>
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<tr>
<td>Terbium oxide</td>
<td>555.6</td>
<td>678.3</td>
<td>340.5</td>
<td>525.1</td>
<td>2196.3</td>
<td>1910.8</td>
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Source: Golev, Scott, Erskine, Ali, & Ballantyne, 2014; 2016 values obtained from mineralprices.com
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Recycling REEs--A potential goldmine?

Figure: Historical prices of REE

Source: Brumme, A., 2014
“Recycling rates for REEs have remained at less than 1 per cent.”
Recycling LEDs--Why?
Recycling LEDs--Bottlenecks
Future: Is recycling viable?

- Recovery quantities
- Modelling studies
- Legislative support
- Price
Thank you!
Manufacturing of LED and Lamp systems

Strategic Environmental Development (SED)

Ritika Jain
Robyn Kotze
Sunanda Mehta
Contents

• Manufacturing Process Of LED
• Energy And Material Consumption
• Key Issues of LED Production
• Environmental Aspects
• Social Aspects
• New Challenges
Manufacturing of LED

Substrate Production
- Raw materials
- Growing ingots
- Slicing
- Polishing

LED Die Fabrication
- Layering
- Masking / lithography
- Etching
- Die singulation

Packaged LED Assembly
- Die testing
- Die attach
- Encapsulation and optics
- Test and binning
## Energy and Material Consumption

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<th>Substrate Production</th>
<th>LED Die Fabrication</th>
<th>LED Packaging Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Consumption</strong></td>
<td>18.3 kWh/wafer</td>
<td>42.57 kWh/wafer</td>
<td>0.03 kWh/wafer</td>
</tr>
<tr>
<td><strong>Material Consumption</strong></td>
<td>4</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td><strong>Water Consumption</strong></td>
<td>105.3 liters/wafer</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Key issues of LED Production
Environmental Aspects
Uncertainty over energy consumption

- Navigant Consultant Incorporated, 2012 -

Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products
Part 2: LED Manufacturing and Performance
<table>
<thead>
<tr>
<th>Study</th>
<th>Product(s)</th>
<th>Component(s) Analyzed</th>
<th>Data provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quirk (2009)</td>
<td>EarthLed A19 lamp</td>
<td>LED package&lt;sup&gt;1&lt;/sup&gt;, Bulk lamp material</td>
<td>Primary energy</td>
</tr>
<tr>
<td>OSRAM (2009)</td>
<td>Osram Golden Dragon Plus (LED package); Parathom LED lamp</td>
<td>LED package, Bulk lamp material</td>
<td>Primary energy</td>
</tr>
<tr>
<td>Navigant (2009)</td>
<td>A19 LED lamp</td>
<td>LED package&lt;sup&gt;2&lt;/sup&gt;, Bulk lamp material</td>
<td>Global warming potential (GWP), lamp component masses</td>
</tr>
<tr>
<td>Carnegie Mellon (2010)</td>
<td>LED Spotlight; LED Floodlight; A19 LED lamp</td>
<td>Bulk lamp material</td>
<td>Lamp component masses</td>
</tr>
<tr>
<td>Carnegie Mellon/Booz Allen (2010)</td>
<td>LED package</td>
<td>LED package</td>
<td>Primary energy</td>
</tr>
</tbody>
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2. Uses the manufacturing of an LED indicator light as a proxy for an LED package.
Uncertainty over energy use for manufacturing 1 LED Package
# Life-Cycle Manufacturing Primary Energy

<table>
<thead>
<tr>
<th>Product Analyzed</th>
<th>Studies</th>
<th>Primary energy consumption (MJ/LED Package)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
</tr>
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<td>EarthLed A19 Lamp</td>
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<td></td>
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<tr>
<td>A19 LED Lamp</td>
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</tr>
<tr>
<td>LED Package</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Environmental contribution depending upon the electricity mix

Source: Tähkämö et al. 2013a
<table>
<thead>
<tr>
<th>Environmental impact category</th>
<th>French electricity mix (%)</th>
<th>European electricity mix (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-hazardous waste (NHW)</td>
<td>~78</td>
<td>~20</td>
</tr>
<tr>
<td>Inert Waste (IW)</td>
<td>~16</td>
<td>~4</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>~17</td>
<td>~2</td>
</tr>
<tr>
<td>Acidification Potential (AP)</td>
<td>~17</td>
<td>~3</td>
</tr>
<tr>
<td>Air Pollution (AiP)</td>
<td>~23</td>
<td>~4</td>
</tr>
<tr>
<td>Ozone Depletion Potential (ODP)</td>
<td>~22</td>
<td>~3</td>
</tr>
</tbody>
</table>
Cleanroom requirements for production

Manufacturing semiconductor requires ultraclean environment - high levels of purity
Controlled environment - Low level of pollutants, dust, microbes, aerosols, chemicals vapours

Massive amounts of energy to operate Accounts for 46% of electricity consumption in fabrication facilities

Trend: make large sections of the process line or entire process line operate in vacuum.

Increasing energy costs of high maintenance
IKEA recalls PATRULL nightlight for risk of electric shock hazard

Osram Sylvania recalls LED-based T8 tubes for potential burn hazard

Published on: September 2, 2015
By Maury Wright
Editor in Chief, LEDs Magazine

Cree recalls recently launched fluorescent-replacement LED T8 lamps

Published on: June 9, 2015
By Maury Wright
Editor in Chief, LEDs Magazine
Safety standards ignored at the time of manufacturing

Fake CE mark
Social Aspects Of LED Production
Bever Innovations

- **Social involvement**
  Supportive environment to people physically or mentally challenged
- 2 social factories - 200 people
- ISO 9001 certification (Quality)

Trilux

- **Trilux:** OHSAS certified
- **ZVEI Code of Conduct for social responsibility**

Aura Light

**Code Of Conduct:**

- International Labour Organization's Declaration of Fundamental Principles & Rights at Work
- UN Global Compact
- OECD´s guidelines

IKEA’s Code of Conduct

- Working conditions
- Prevention of Child labour
- Environment

Based on International conventions

**No child labour** in its own business or in the supply chain.

Employees in Risk Areas given **Special Check-ups**
Upcoming LED-Integrated Products: New Challenges

- New materials
- Ease of manufacturing

Modular Philips luminous textile:
Luminous textile integrates multi-coloured LEDs within textile panels

LED powered shoes

Bed by French furniture designer Philippe Boulet

Sources

• BBC. (2014). Fake Britain. Retrieved from https://www.youtube.com/watch?v=M0fqceT9n5Q&t=107s


Sources

- Chepesiuk, R. (1999). Where the chips fall: environmental health in the semiconductor industry. Environmental Health Perspectives, 107(9),
DISTRIBUTION & USE PHASE OF LED LIGHTS

Marula Tsagkari & Brayton Noll
Electricity mix

Distribution

Life-time

Rebound effect & Energy savings possibilities

OUTLINE
The distribution phase of LED lights is a small proportion of the total environmental footprint (0.09% of the total impact).

(US Department of Energy, 2012)
Electricity mix

- The main environmental impact is caused by energy consumption in the use phase.
- The future role of renewable energy?
- Trend of decarbonisation
## Electricity Mix

<table>
<thead>
<tr>
<th>Case (Region)</th>
<th>Assessment Method</th>
<th>Percentage of Manufacturing Phase Impact</th>
<th>Percentage of Use Phase Impact</th>
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</thead>
<tbody>
<tr>
<td>Road lighting (EU)</td>
<td>CML-IA</td>
<td>13%</td>
<td>87%</td>
</tr>
<tr>
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<td>86%</td>
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<td>63%</td>
<td>36%</td>
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<tr>
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<td>48%</td>
<td>51%</td>
</tr>
<tr>
<td>LED downlight (France)</td>
<td>SimaPro LCA Software*</td>
<td>23%</td>
<td>76%</td>
</tr>
<tr>
<td>LED downlight (EU)</td>
<td>SimaPro LCA Software*</td>
<td>7%</td>
<td>93%</td>
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**Norway:** 99% Hydropower, 1% Fossil fuels

**Denmark:** 51% Wind, 34% Fossil Fuels, CHP 13%, Solar 2%

**Sweden:** 41% Hydropower, 43% Nuclear, 7% Wind, 9% CHP and Fossil Fuels

**France:** 77% Nuclear, Hydro and Solar 15%, Fossil Fuels 8%
Electricity Mix

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Improving the technology and efficiency in LEDs will continue to be the most significant and environmentally beneficial modification that producers can upgrade in the Life Cycle of an LED.
LIFETIME OF LEDs

● WHAT IS IT?

“The time the product is expected to operate as supposed, under a defined set of environmental and mechanical parameters” (Next Generation Lighting Industry ALliance and US. Department of Energy, 2011)

● WHY IS IT IMPORTANT?

Consumers are willing to pay a higher value for a more efficient but also long-lasting product (Maitre-Ekern and Dalhammar, 2016).
LIFETIME OF LEDS

- A high quality LED will normally last 70,000 hours -or longer (US Department of Energy, 2016).
- The crucial time of an LED, is the point after which the LED light puts out only 70% of its initial light, although this does not mean total failure- $L_{70}$ = minimum 50,000 hours

<table>
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<tr>
<th>Operation hours per day/lifetime hours</th>
<th>50.000h</th>
<th>100.000h</th>
</tr>
</thead>
<tbody>
<tr>
<td>24h</td>
<td>5.7 years</td>
<td>11.4 years</td>
</tr>
<tr>
<td>15h</td>
<td>9.1 years</td>
<td>18.3 years</td>
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<td>8h</td>
<td>17 years</td>
<td>34.2 years</td>
</tr>
<tr>
<td>4h</td>
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OTHER PARAMETERS THAT CAN AFFECT THE LIFETIME OF LEDs

- Use scenario
- Product type & quality
- Rapid technologic development - quick replacement

(Bennich et al. 2015)
OTHER PARAMETERS THAT CAN AFFECT THE LIFETIME OF LEDs

- Use scenario
- Product type & quality
- Rapid technologic development- quick replacement
- Failures

A “failure” is an event which ends the life of a specific product or component” (Next Generation Lighting Industry Alliance and US. Department of Energy, 2011)
Most common failures appeared in a family of outdoor LEDs, from one manufacturer. The lights were operating for 34 million hours.

Source: Appalachian Lighting Systems, Inc

Data from Chang et al. 2012 and OSRAM 2013
The Rebound Effect

The Energy Savings Estimated by the Technological Improvements

Actual Energy Savings

- Indirect Rebound Effects
- Direct Rebound Effects

The Rebound Effect
Policy Possibilities for Electricity Providers

- Majority of Utility Companies provide more than one service
- Water and Heating sector most promising, but long payback period – waste and energy reductions up to 25%
- Policy can direct funding from electricity savings to fund innovation in these sectors
GLOBAL LIGHTING CHALLENGE
A Clean Energy Ministerial Campaign

“A Campaign to Deploy 10 Billion High Efficient Bulbs”

“Energy Justice”
Conclusions

- Energy mix is important – but only in extreme cases does it bring manufacturing's significance close to that of the use phase

- Further testing under real life, non-optimal conditions could further understanding of how long LEDs last and what affects them

- Organizations that seek to promote LED use should use (in part) a policy approach to effectively utilize the fiscal and energy savings and consider “energy justice”
REFERENCES


Next Generation Lighting Industry ALliance and US. Department of Energy (2011)


Tähkämö, L. 2013. Life cycle assessment of light sources – Case studies and review of the analyses. Aalto University. Finland


After-Light: The Today and Tomorrow of LED End-of-Life Management

Savannah Carr-Wilson
Gabrielle Freeman
Sandeep
Outline

- Introduction
- LED End-of-Life Today
- Nordic Recycling AB: A Company’s Perspective
- Looking to the Future
- Reflection on literature
- Conclusion
Introduction

● Growth of LED sales & waste stream over past decade

● Countries & companies just starting to think about recycling LEDs

● Role of research institutes

● Role of companies (i.e. Nordic Recycling AB)

Data from Gassmann et. al, 2016
LED End-of-Life Today

- Most collection and recycling schemes for lamps are driven by legislation (WEEE Directive in Europe) and generally have low-end uses for recovered materials.

- LEDs are collected with other lamps, which may lead to mercury contamination from broken fluorescent lamps.

- If LEDs are recycled, current recycling processes cannot recover valuable elements such as printed circuit board with critical metals and rare earth metals.

- Separate collection and recycling of LEDs recommended.

- Processes and technologies to recover valuable materials in LEDs are still at the research or pilot phase of development.
LEDs’ End-of-Life Values

Environment
- Avoided toxic materials in nature/landfill/incineration
- Avoided primary material extraction and production

Consumers
- Civic duty fulfilment
- Used product sale
- Product/component reuse/repurposing

Society
- Domestic job opportunities in reuse/recycling activities
- Resource efficient and circular economy
- Secure supply of critical metals

Network Actors
- Recycled material value
- Legal compliance
- Corporate social responsibility
- Resilient supply chains
- Product/component reuse value

Richter, 2016
Nordic Recycling AB:
A Company’s Perspective

- Among top three lamp recycling companies in the world
- Yearly recycling capacity: 3600 tonnes or 30-40 million lamps
- Recycles: 100% lamps from Sweden, Norway & 30% from Denmark
Role of Players

IKEA, Philips → El-Kretsen AB → Nordic Recycling AB
Visit to Nordic Recycling AB
LED Recycling in Nordic Recycling AB

- One Year Ago: LED in Waste Stream = 0.8%
- Six Months Ago: LED in Waste Stream = 2%
- Now: LED in Waste Stream = 3.5%
The Process

- Crushing All lamps (problematic)
- Mercury Separation
- Recycling Glass, Metals, Plastic
Innovation in LED Recycling

- Chalmers University of Technology in Gothenburg
- European Union’s project ‘Illuminate’

Peter Arnesson, General Manager, Nordic Recycling AB
The Company’s Future

- Presorting of lamps
- Using a prototype from Italy
- Recycling LEDs separately
Looking to the Future

- LED recycling = new, active area of research and learning
- Several research institutes are pursuing innovative LED recycling methods
- Companies are also involved in improving LED end-of-life
Recovering LED Critical Metals

- **CycLED Project**

- Consortium of partners led by the Germany-based Fraunhofer Institute for Reliability and Microintegration IZM

- Need for mechanical pre-treatment to remove critical metals in a technically and economically feasible way

- CreaSolv

Photo credit: authors
The Shockwave Method

- Uses an "electrohydraulic" process to break LED lamps into their constituent parts.

Illustration of the electrohydraulic fragmentation (EHF) method

Photo credit: ©Fraunhofer Project-Group IWKS
Improving LED Design

- Another approach
- Hendrickson, Matthews, and Ashe
- Philips “SlimStyle” bulb

Photo credit: Net of Everything
http://netofeverything.blogspot.se/2014_02_11_archive.html
Lighting as a Service

- Aka "pay per lux"

- Philips
  - Amsterdam’s Schiphol Airport
  - National Union of Students office in the UK
  - Amsterdam based RAU Architects office
  - Washington DC Metro
Reflection on literature

- Everyone agrees we have to determine how to recycle LEDs, but work is still at preliminary stages.

- Overall, lack of academic work in this area (so lack of literature for agreement/disagreement).

- Need for more literature in this area profiling & considering feasibility of different methods in LED recycling.

- Relied on many primary sources:
  - Site visit to Nordic Recycling AB
  - Institute & project websites
  - Company websites
  - Conference papers
Conclusion

● Finding an efficient and economical way to recycle LEDs is both a challenge and an opportunity

● Continued work by academics, research institutes, and companies is needed to determine how to optimise LED end-of-life

● Grassroots developments?

● Most promising developments include improving design to close material loops, product as a service, and recycling to recover valuable critical metals
Thank you!
References


References


