The Life Cycle of LED

A review by IIIEE & Lighting Metropolis

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Lighting Metropolis

Interreg
Öresund-Kattegat-Skagerrak
European Regional Development Fund

EUROPEAN UNION

Lighting the paths for Eco Design :

*L*ife *C*ycle *A*ssessment 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"

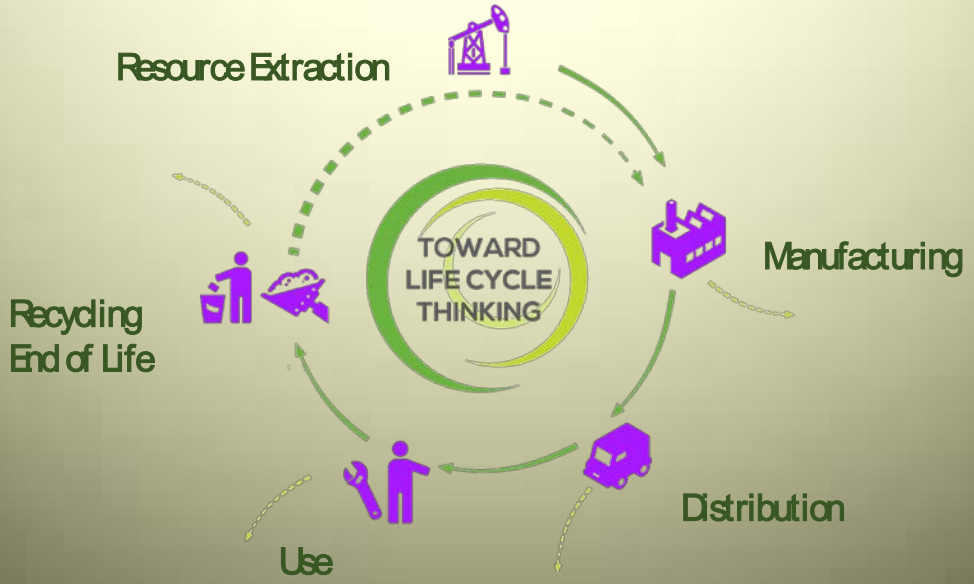
Goldman Sachs, 2015

LCA !

So…what is LCA?

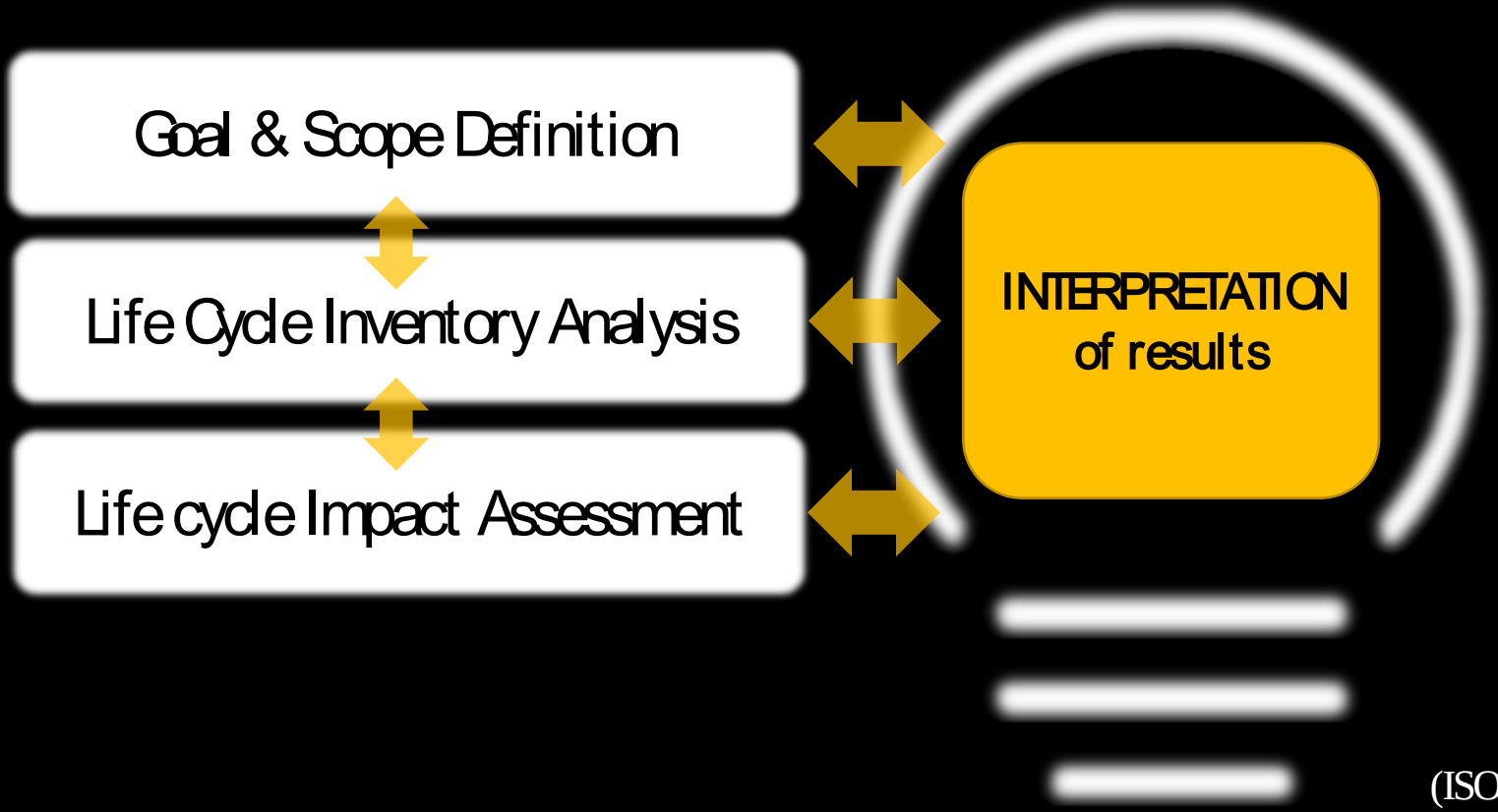
'Life Cycle Assessment (LCA) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle'

(ISO 14040:2006)



(Source: avnir.org)

MAIN PHASES OF LCA



(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 Berkely

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

Producers
Philips, OSRAM, =

Gov.
US Department of Energy

Inter-gov. Organization
International Energy Agency

Purpose of LCAs for LEDs

Aid policy- makers

Provide suggestions for conducting LCA

Identify hazardous materials

Compare energy consumption levels of various lighting sources

Estimate lifetime & design EoL treatments

Demonstrate benefits to the market

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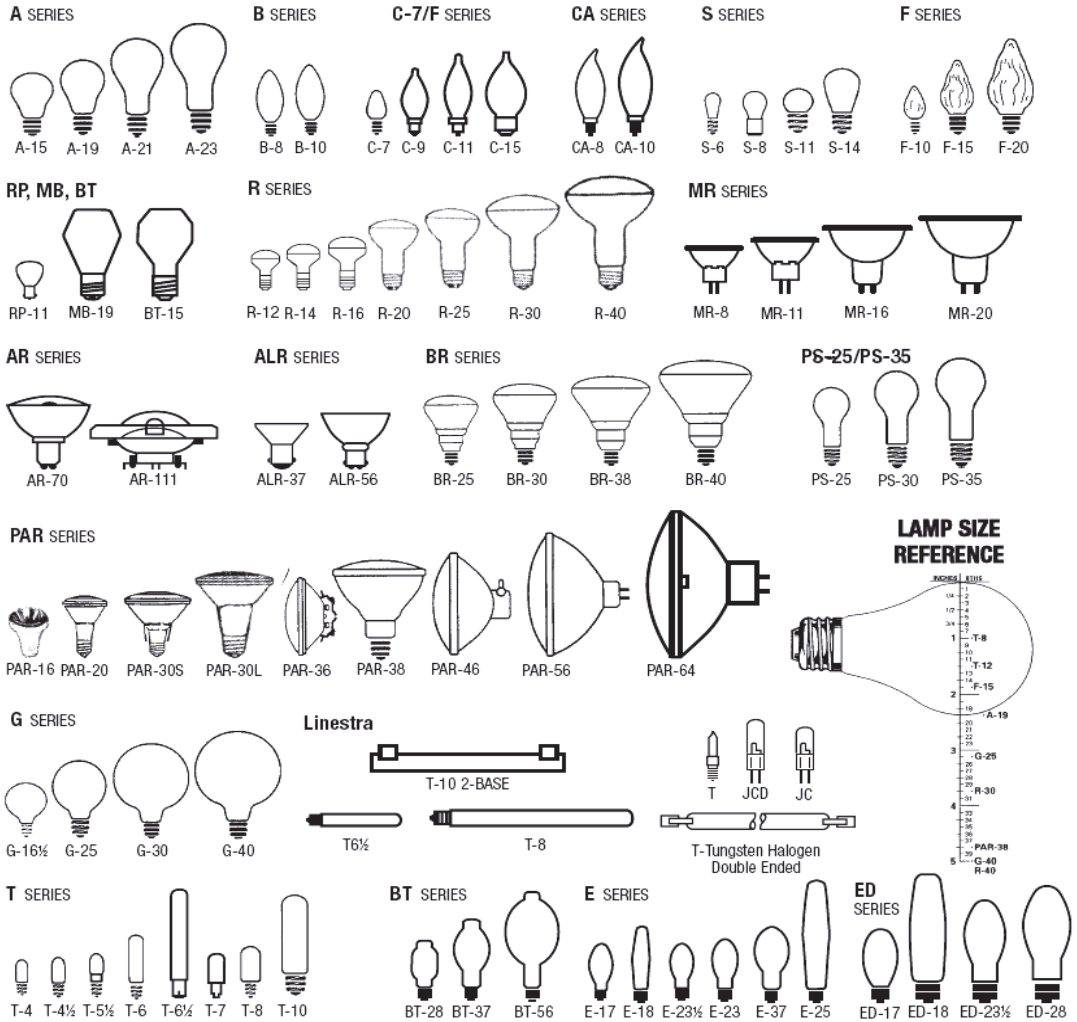
Bulb shapes and sizes are…

…DIVERSE!



(Source: bestlightingbuy.com)

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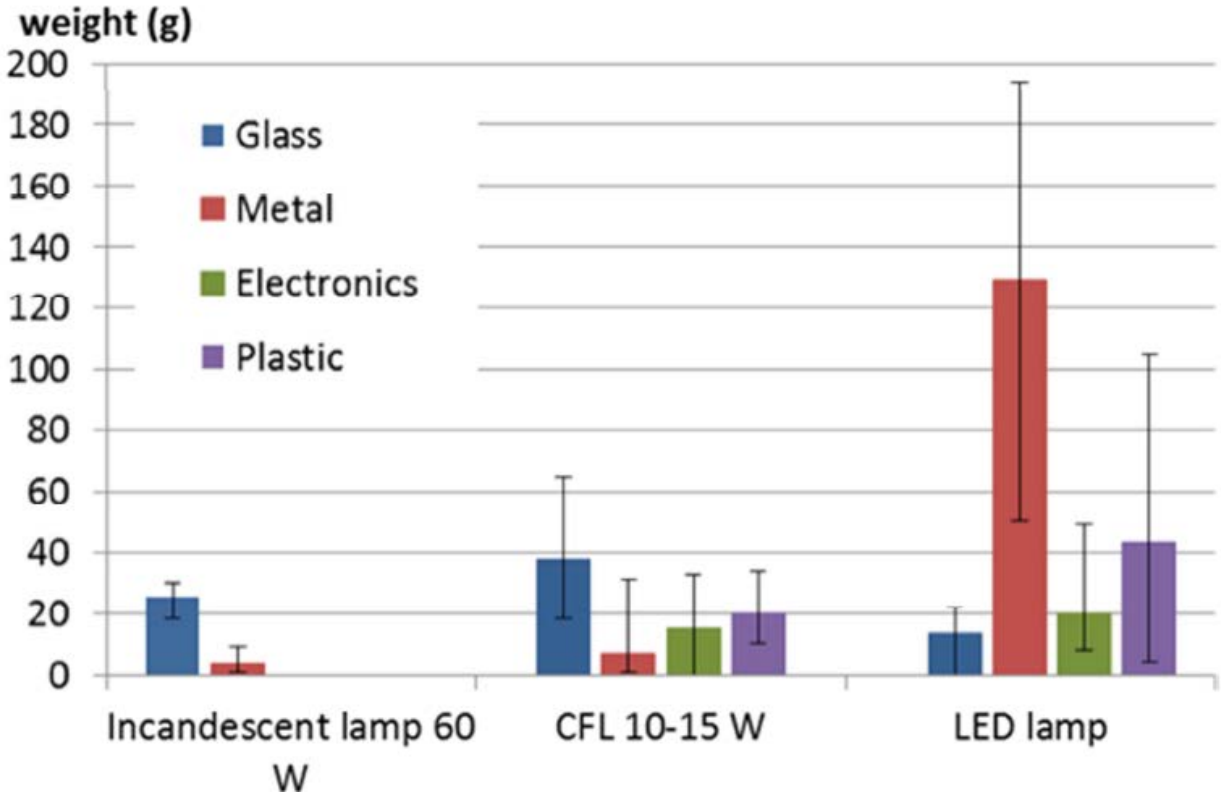
Material composition of non-directional lamps used in households



(Tähkämö et al. 2014)

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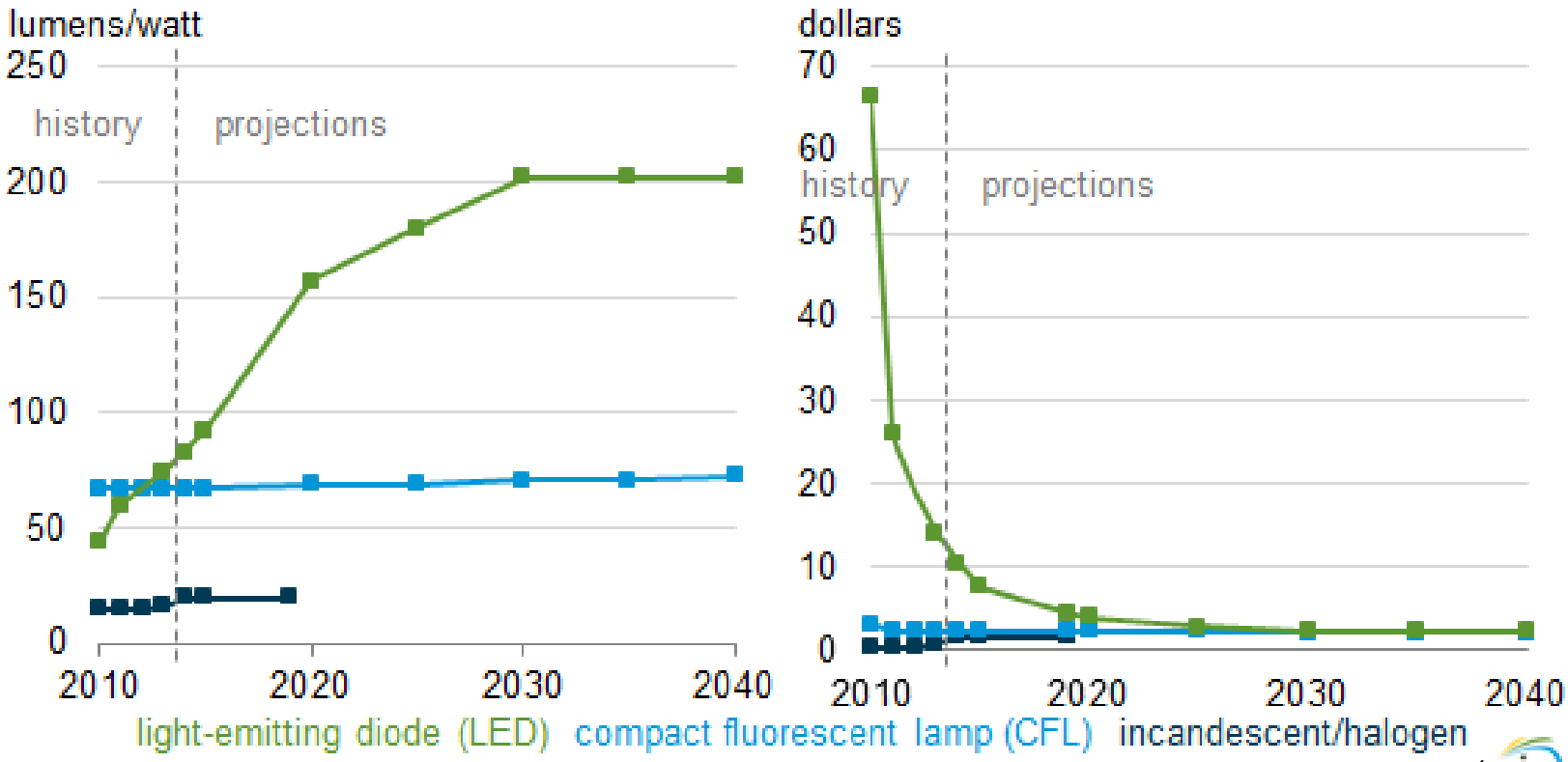
Average lighting efficacy (light output per unit of energy consumed) & cost per bulb



(eia 2014)

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(OVERLY?)

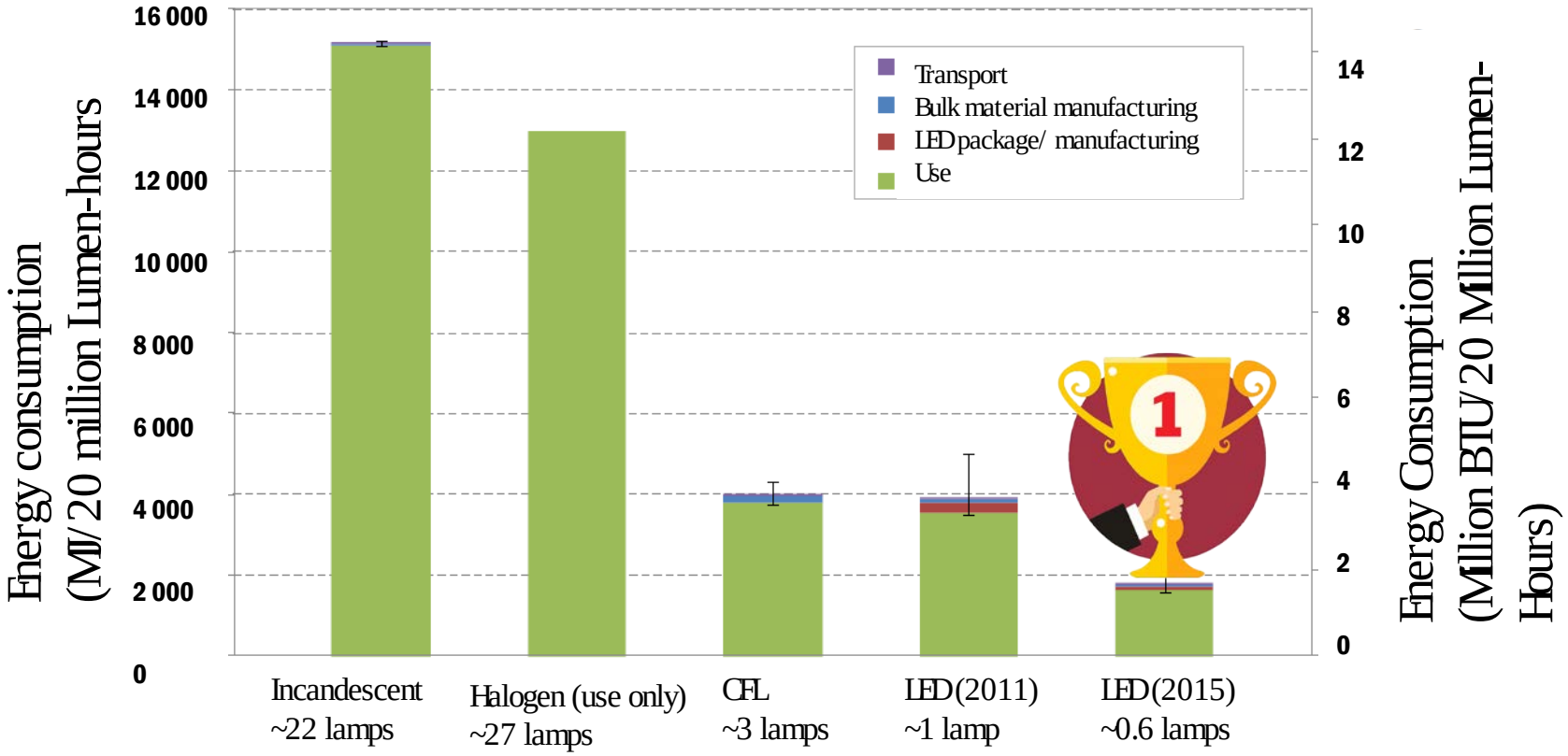
SIMPLIFIED LCA MODELS

	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)

LCAs of light sources: Key findings 1/2

- Use & Manufacturing phase account for the highest share of total environmental impacts during life cycle



Life Cycle Energy of lighting sources

(DOE 2012)

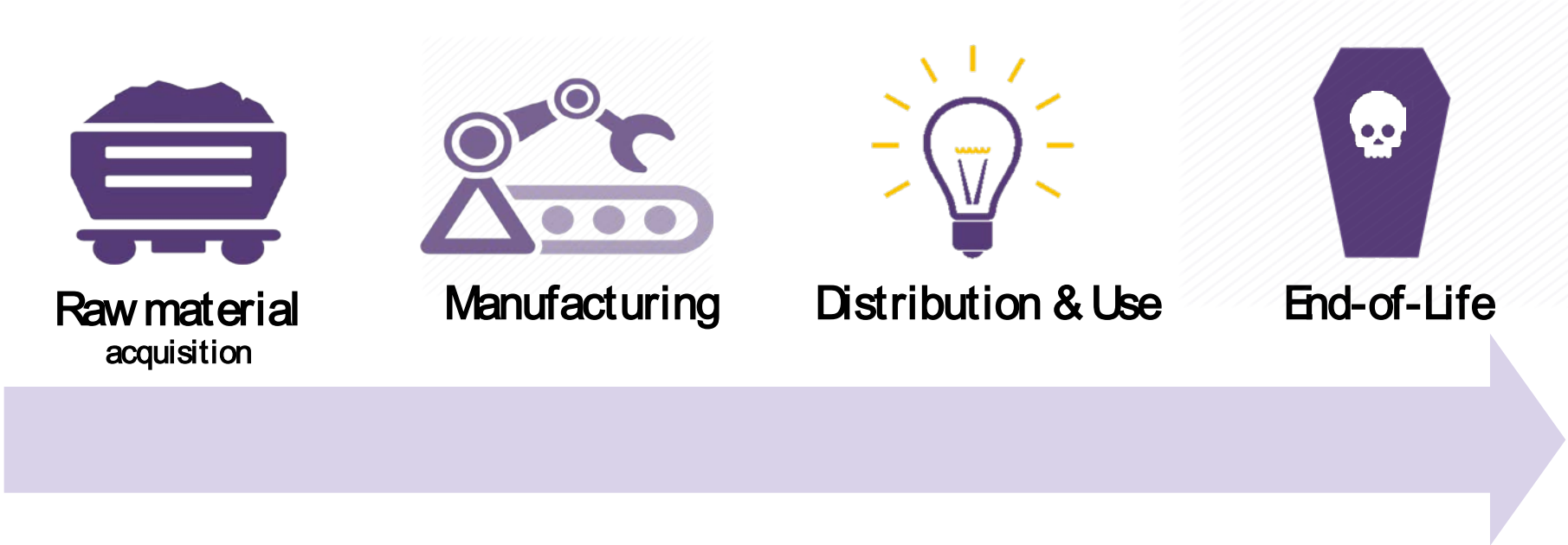
LCAs of light sources: Key findings 2/2

- 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



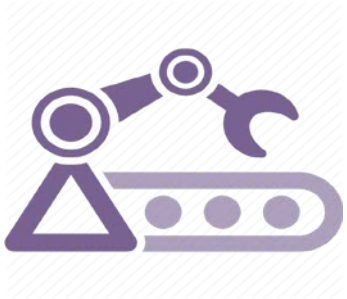
Minor impact

Aluminum for heatsinks

(DOE, 2012)

RAW MATERIAL ACQUISITION

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

MANUFACTUTURING

Major impact

	Impact category (unit)			
Life cycle impacts per Mmh	Global warming (kg CO_2-eq.)	Abiotic (resource) depletion (kg sb-eq.)	Acidification (kg SO_2-eq.)	Eutrophication (kg PO_4-eq.)
European electricity	9.4	0.070	0.040	0.0029
French electricity	2.0	0.013	0.011	0.00056

USE & DISTRIBUTION

Minor impact

Material restoration & Complex structures

(Silver, nickel, gold, antimony, copper, recyclable plastic components & ALUMINUM)

NOTE: restoration levels vary from one country to another!

(Tähkämö et al. 2013)

END-OF-LIFE

WHAT IS NEXT..?

TAKE-AWAY

DATA BLACK BOX

Functional unit
Data source
Lighting source

ENERGY SOURCE

Region
Country
Energy mix

HAZARDOUS WASTE

REACH
RoHS 1
WEEE

USER BEHAVIOUR


WINNER

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Raw Materials Use in LEDs

Elizabeth Drachenberg, Darja Mihailova,
Sai Siddhartha Nandamuri

Agenda

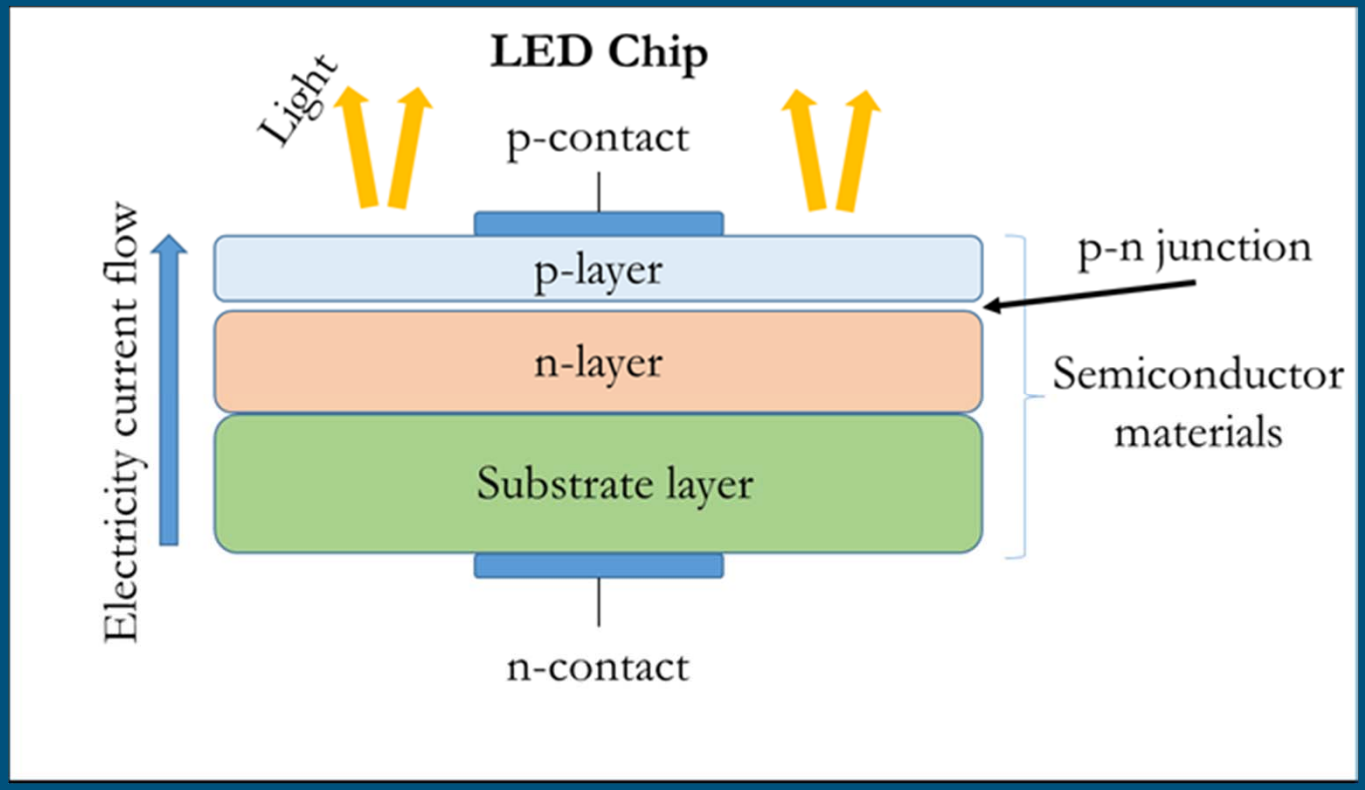
- Materials used
- Rare earth elements (REEs)
- Environmental and social impacts
- Future recycling potential REEs

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



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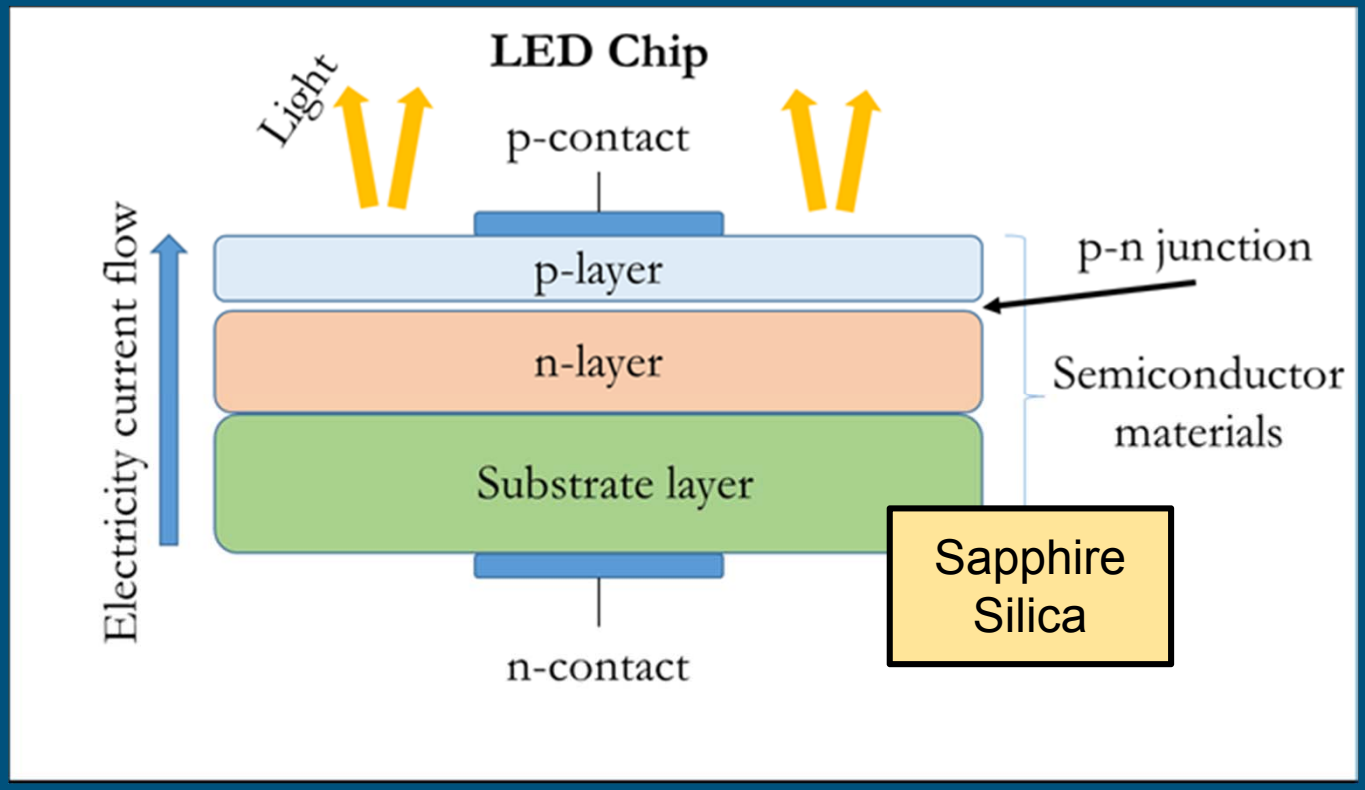

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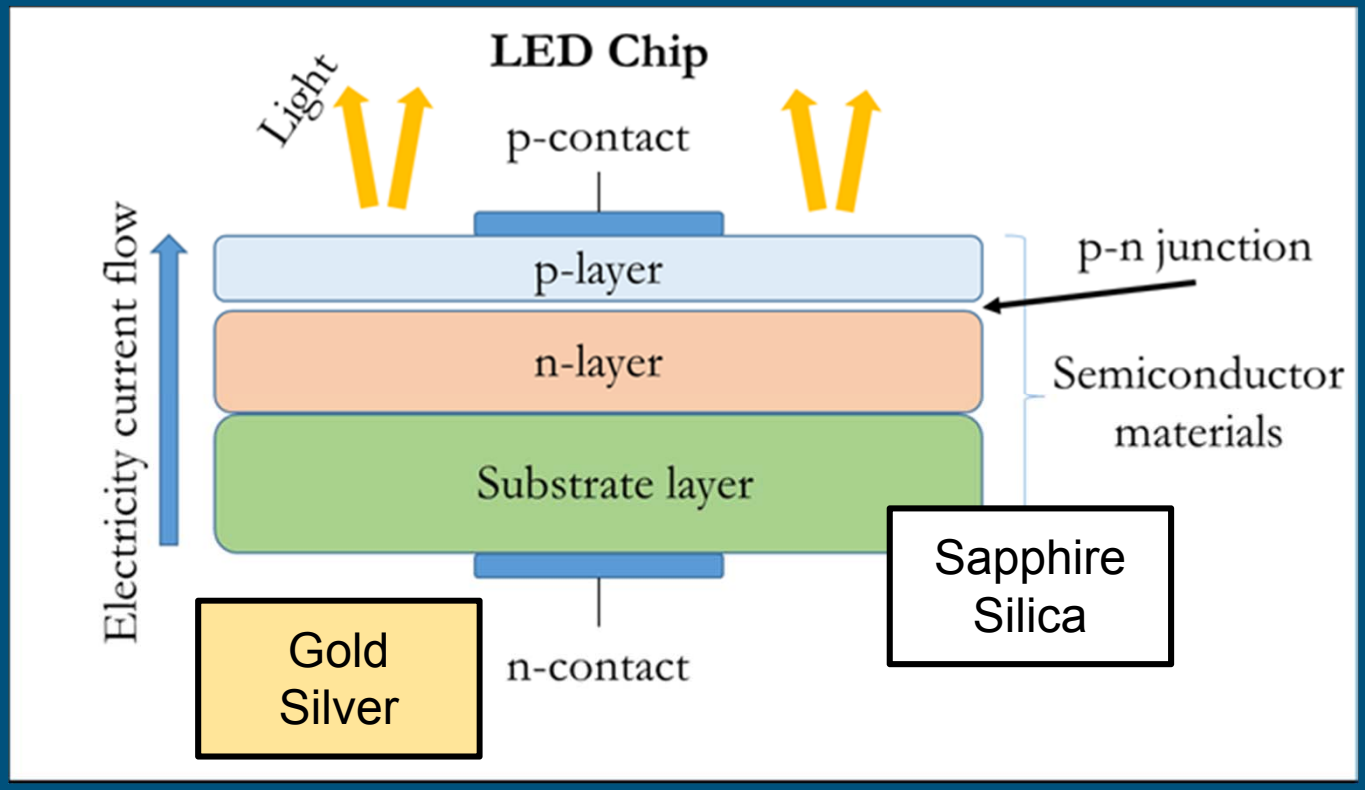

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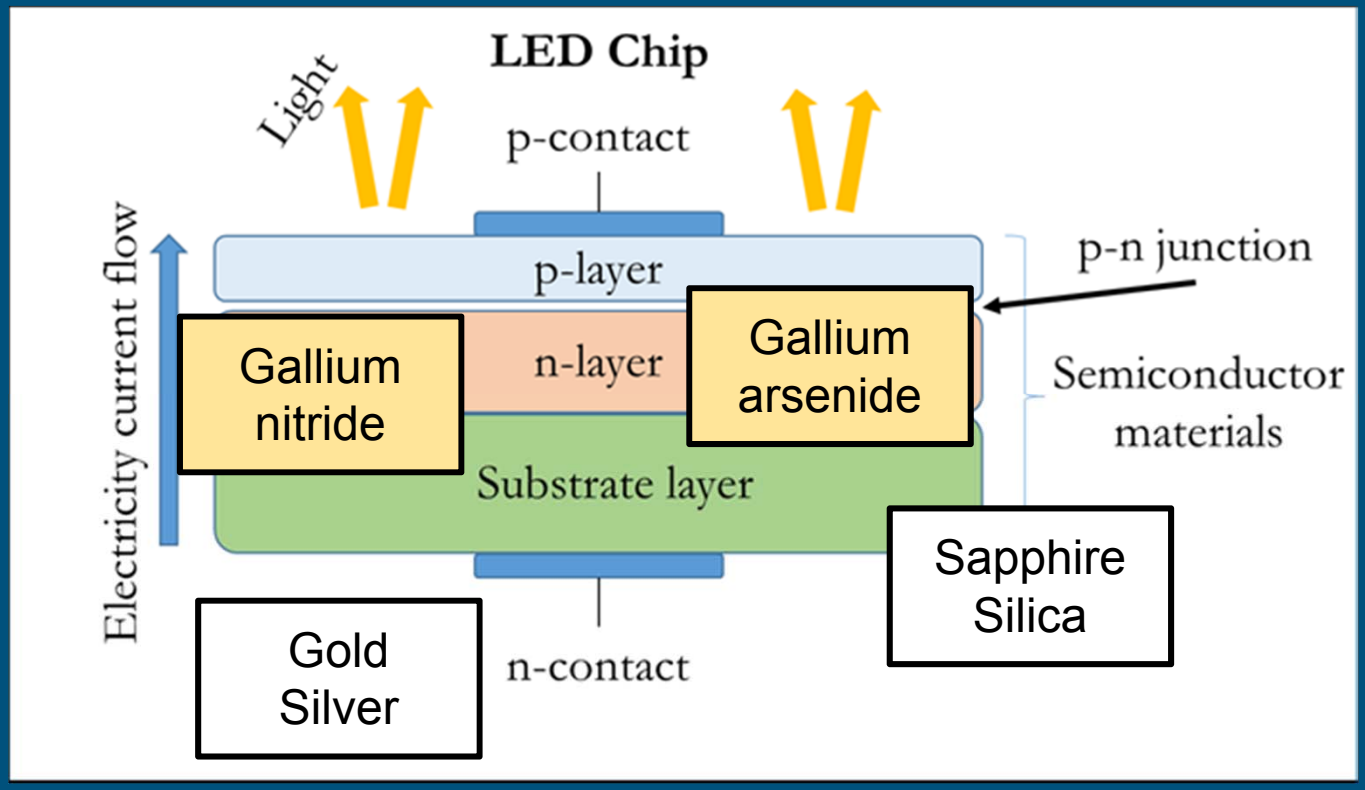

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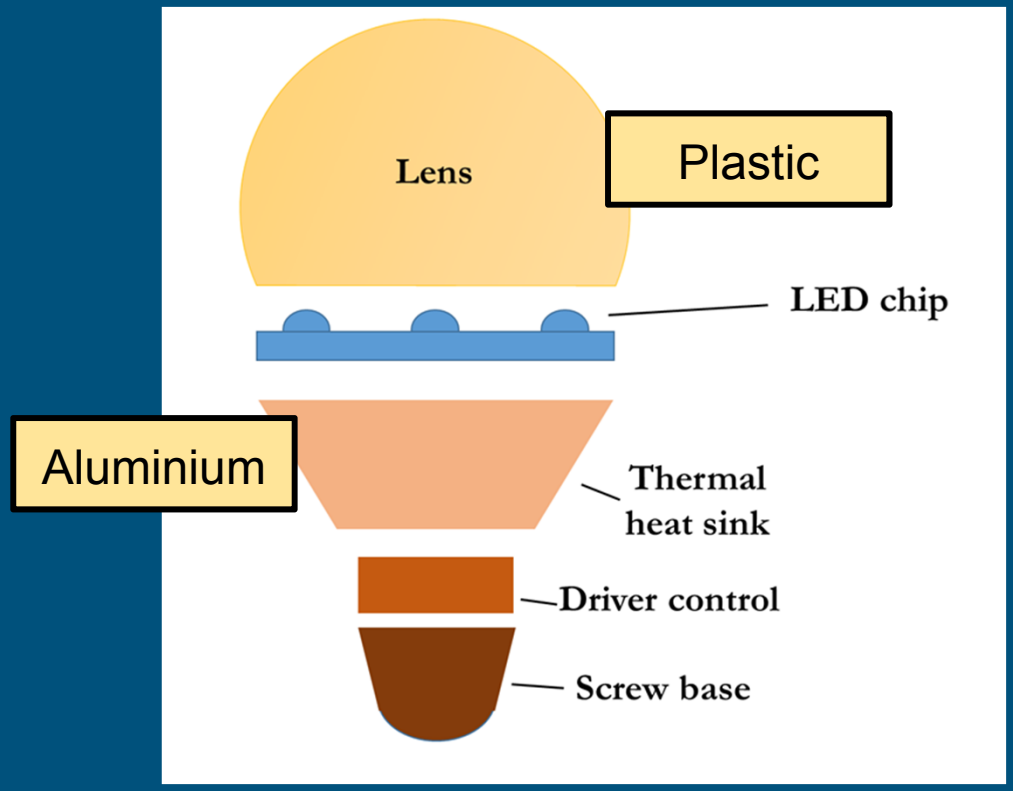

LED vs CFL

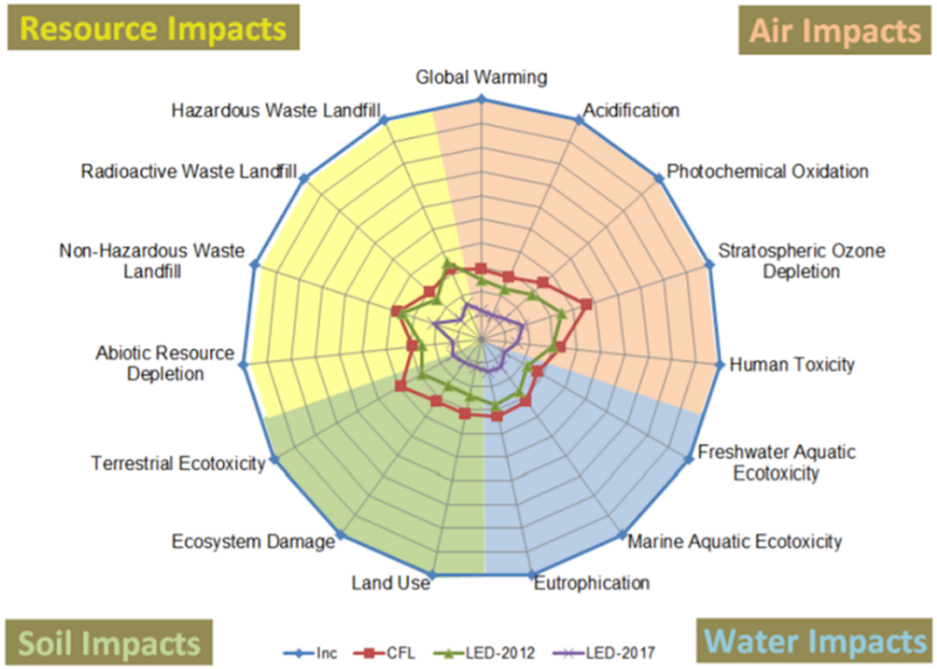

Figure 7-6. Life-Cycle Assessment Impacts of the CFL and LED Lamps Analyzed (Detail)

LED vs CFL

CFL

Mercury

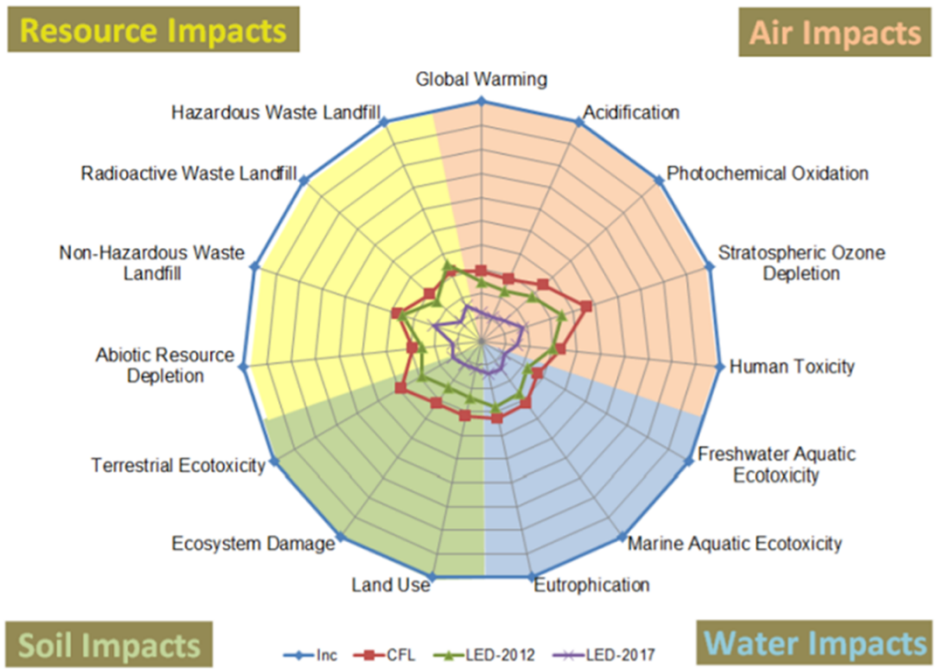

Figure 7-6. Life-Cycle Assessment Impacts of the CFL and LED Lamps Analyzed (Detail)

LED

Lead

Arsenic

LED vs CFL

Yttrium

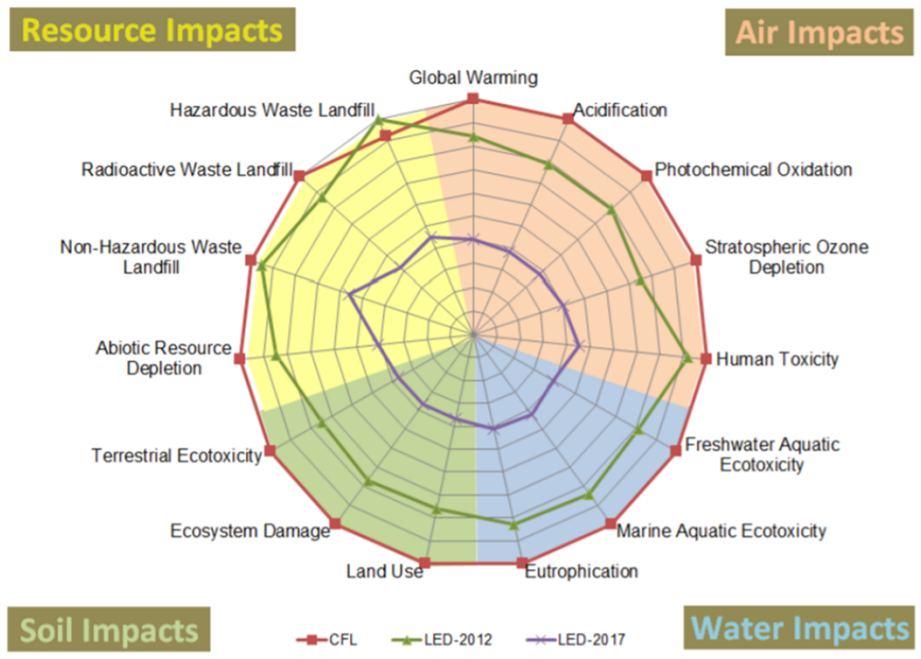

Figure 1-2. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to CFL

LED vs CFL

Yttrium

Europium

Cerium

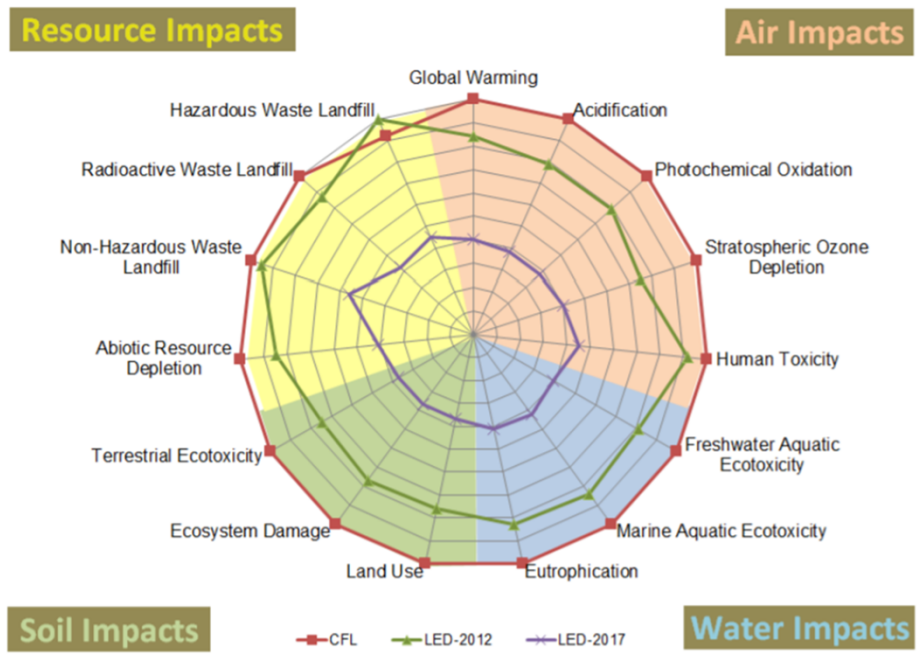

Figure 1-2. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to CFL

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

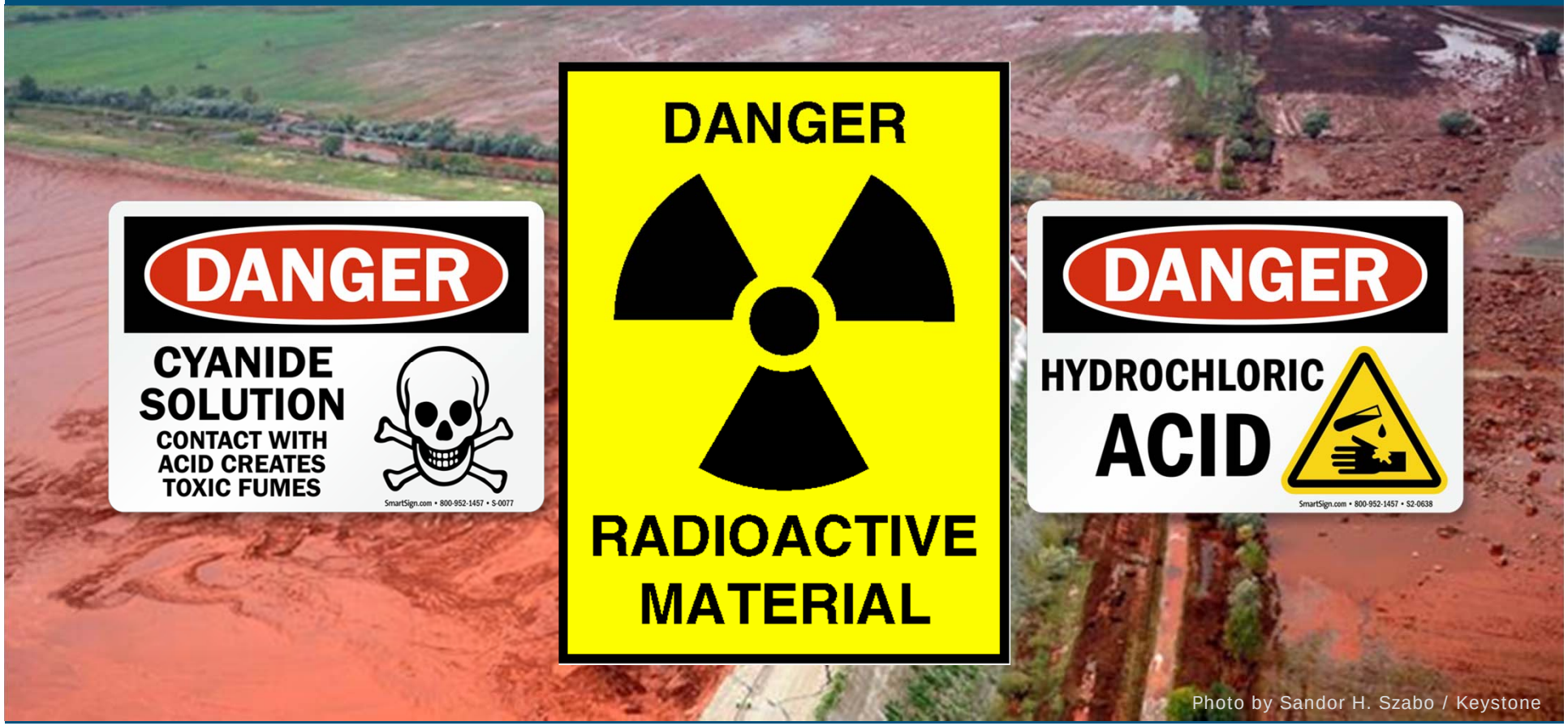

Photo by Sandor H. Szabo / Keystone

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

Toxic fluorine gas, flue dust from REEs production

Environmental impacts

Landscape degradation

Soil contamination

Case study: Bayan Obo Mine

Case study: Bayan Obo Mine

Photo by Liam Young/BBC

Social impacts

Human health

Social and economic restructuring

Social impacts

Social impacts

Human health

Social and economic restructuring

Social impacts

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: Prices of Rare Earth Oxides (EUR/kg)

Element	2007	2008	2009	2010	2011	2012	2013
Lanthanum oxide	3.2	8.2	4.6	21.1	97.9	23.7	7.5
Cerium oxide	2.8	4.3	3.7	20.3	95.9	23.2	7.8
Europium oxide	304.9	453.5	464	527	2674.9	2337.9	1093.4
Terbium oxide	555.6	678.3	340.5	525.1	2196.3	1910.8	916.4

Source: Golev, Scott, Erskine, Ali, & Ballantyne, 2014; 2016 values obtained from mineralprices.com

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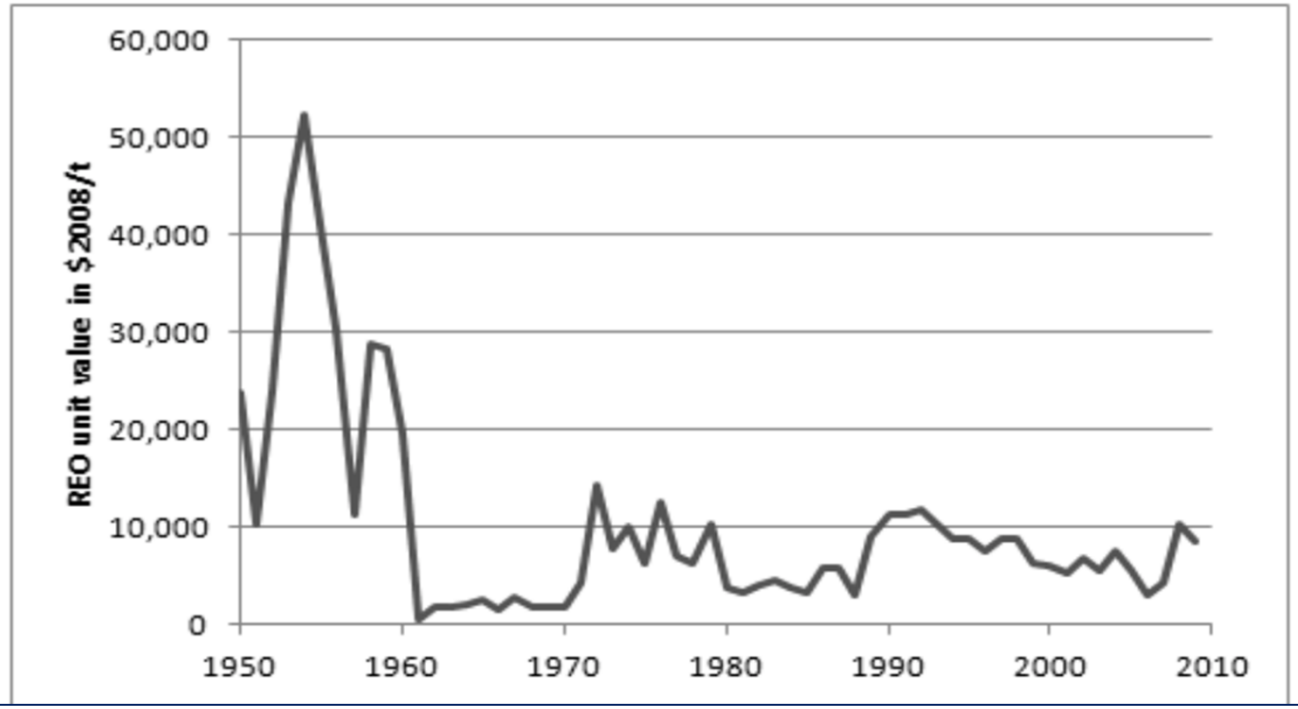
Source: Golev, Scott, Erskine, Ali, & Ballantyne, 2014; 2016 values obtained from mineralprices.com

Recycling REEs--A potential goldmine?

Figure: Historical prices of REE



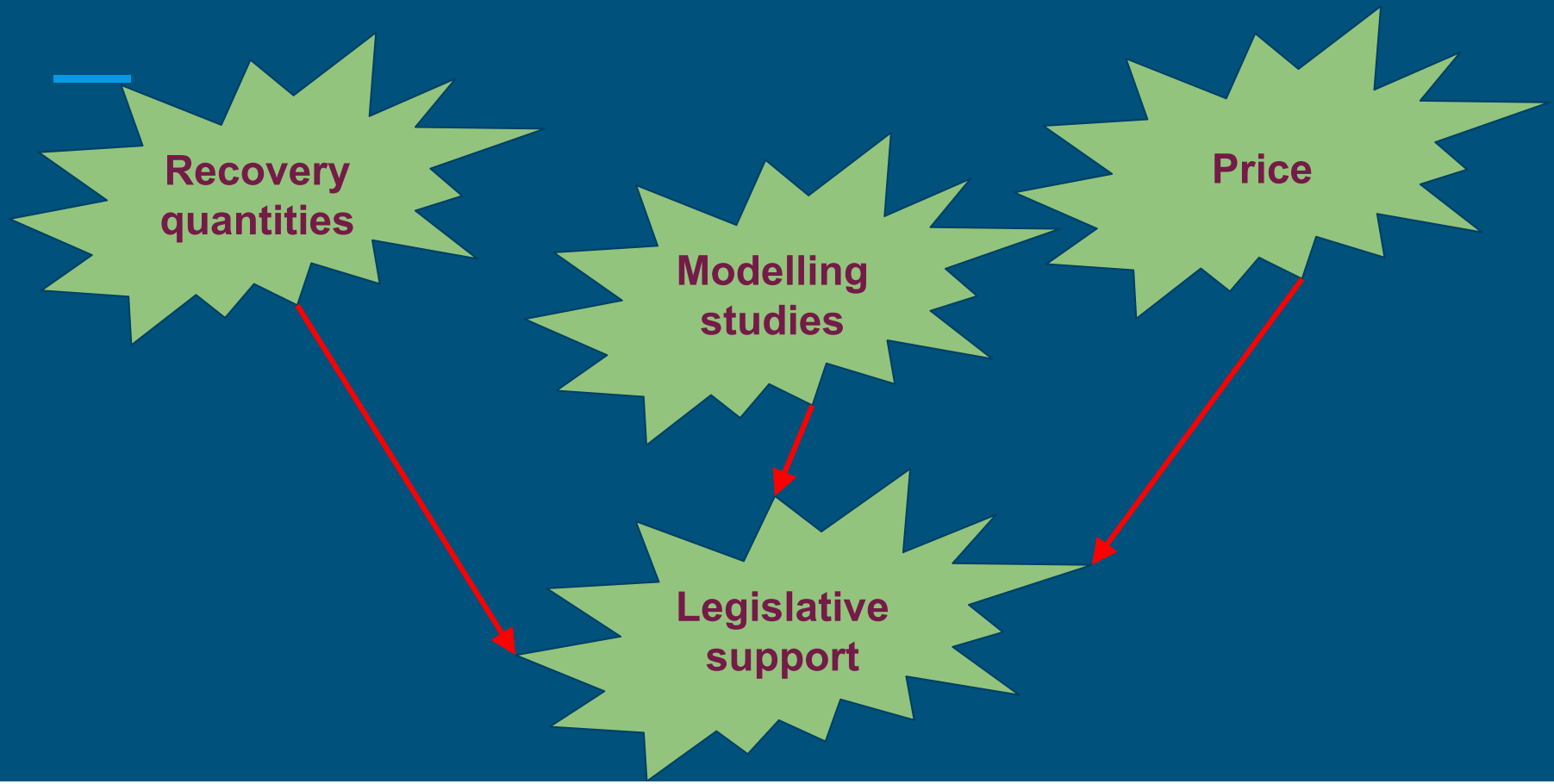
Source: Brumme, A., 2014

“Recycling rates for REEs have remained at less than 1 per cent.”

Recycling LEDs--Why?

Recycling LEDs--Bottlenecks

Future: Is recycling viable?



Thank you!

Manufacturing of LED and Lamp systems

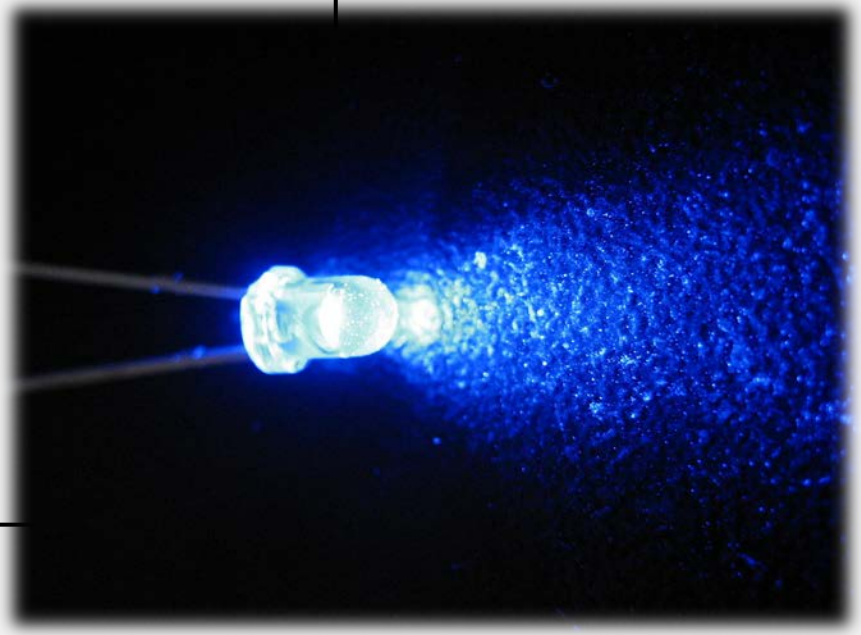
Strategic Environmental Development (SED)

Ritika Jain

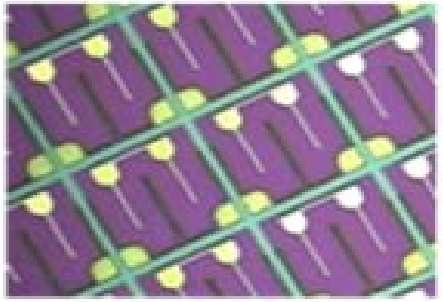
Robyn Kotze

Sunanda Mehta

Contents



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

	Substrate Production	**LED Die Fabrication**	**LED Packaging Assembly**
Energy Consumption	18.3 kWh/wafer	42.57 kWh/wafer	0.03 kWh/wafer
Material Consumption	4	24	6
Water Consumption	105.3 liters/wafer	0	0

Key issues of LED Production

Environmental Aspects

Uncertainty over energy consumption

- Navigant Consultant Incorporated, 2012 -


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

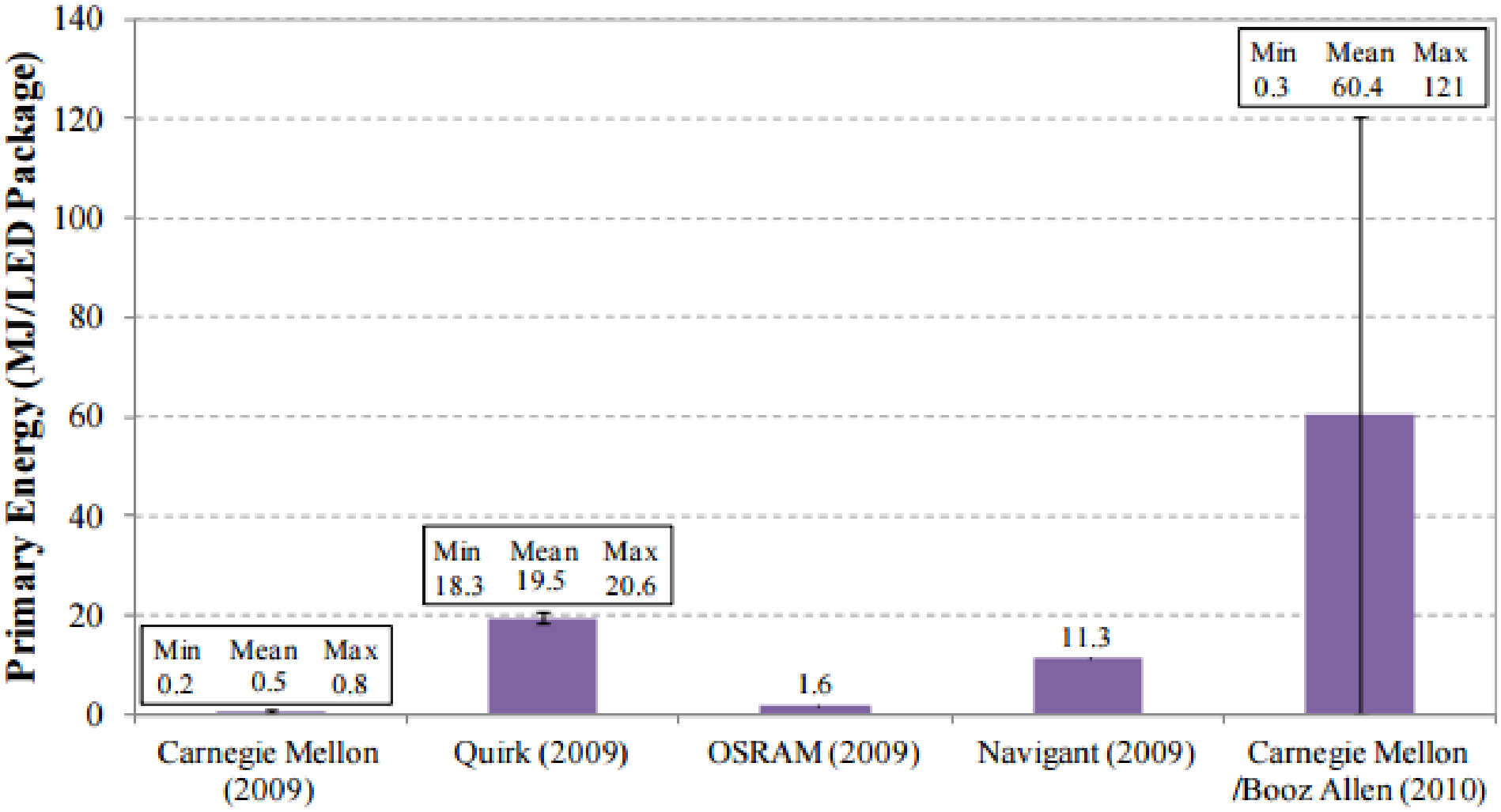
Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products

Part 2: LED Manufacturing and Performance

Study	Product(s)	Component(s) Analyzed	Data provided
Carnegie Mellon (2009)	LED package	LED package	Secondary electricity
Quirk (2009)	EarthLed A19 lamp	LED package[1], Bulk lamp material	Primary energy
OSRAM (2009)	Osram Golden Dragon Plus (LED package); Parathom LED lamp	LED package, Bulk lamp material	Primary energy
Navigant (2009)	A19 LED lamp	LED package[2], Bulk lamp material	Global warming potential (GWP), lamp component masses
Carnegie Mellon (2010)	LED Spotlight; LED Floodlight; A19 LED lamp	Bulk lamp material	Lamp component masses
Carnegie Mellon/ Booz Allen (2010)	LED package	LED package	Primary energy

1. Uses data from the Carnegie Mellon (2009) publication to develop energy estimates for the LED package.
2. Uses the manufacturing of an LED indicator light as a proxy for an LED package.

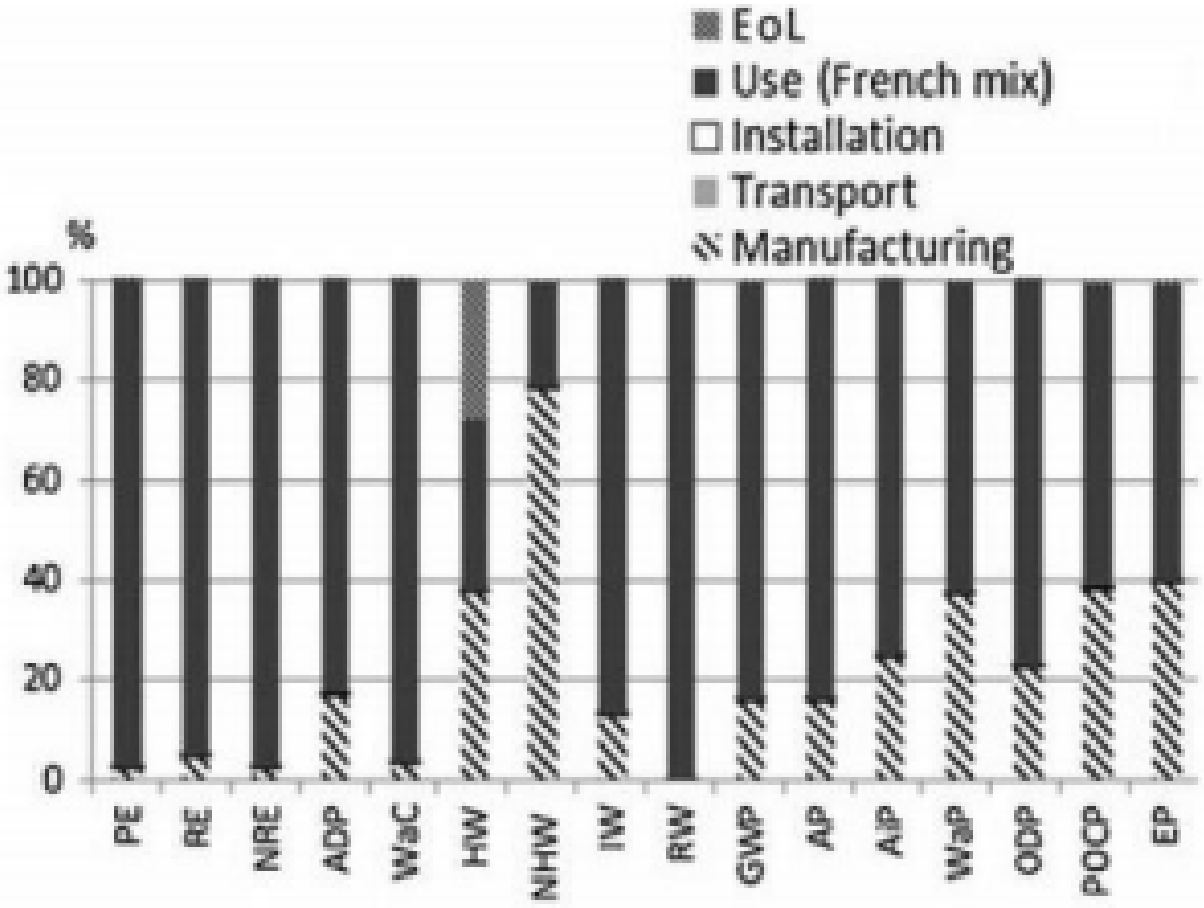
Uncertainty over energy use for manufacturing 1 LED Package

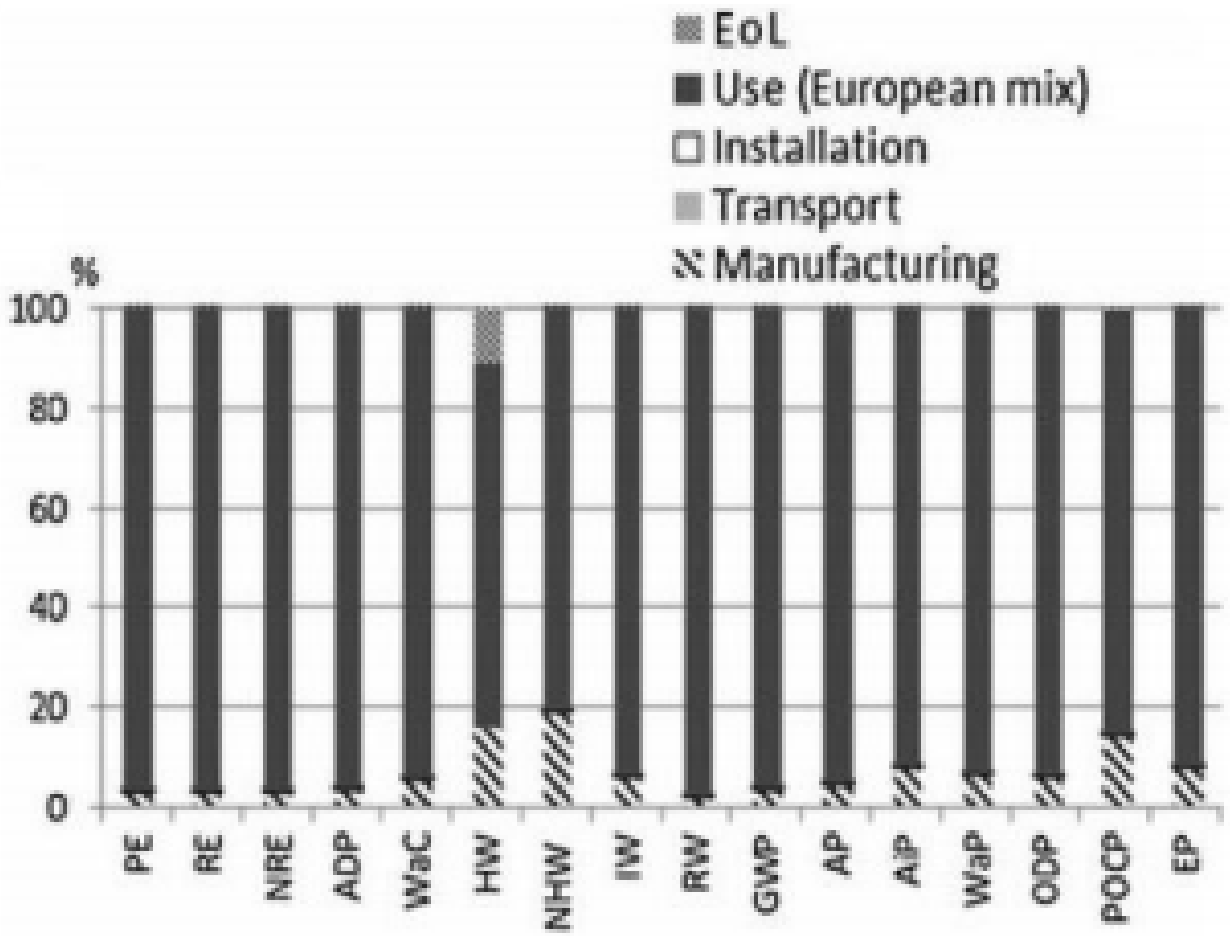


Life-Cycle Manufacturing Primary Energy

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 LED Package	Carneige Mellon/Booz Allen (2010)	0.3	60.4	121

Environmental contribution depending upon the electricity mix





Source: Tähkämö et al. 2013a

Environmental impact category	French electricity mix (%)	European electricity mix (%)
Non-hazardous waste (NHW)	~78	~20
Inert Waste (IW)	~16	~4
Global Warming Potential (GWP)	~17	~2
Acidification Potential (AP)	~17	~3
Air Pollution (AiP)	~23	~4
Ozone Depletion Potential (ODP)	~22	~3

Cleanroom requirements for production


http://www.onboardsolutions.com.au/wp-content/uploads/2012/05/cleanroom-homepage.jpg

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

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

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

Increasing energy costs of high maintenance

Manufacturing practices - Quality check at sites

IKEA recalls PATRULL nightlight for risk of electric shock hazard

08/18/2015 10:00 AM |

[National]

PATRULL Nightlight
Orange 302.411.40

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

Social initiatives…

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

IKEA IWAY Standard
Minimum Requirements for Environment and Social & Working Conditions when Purchasing Products, Materials and Services.

IKEA's Code of Conduct

- Working conditions
- Prevention of Child labour
- Environment

Based on International conventions

Aura Light

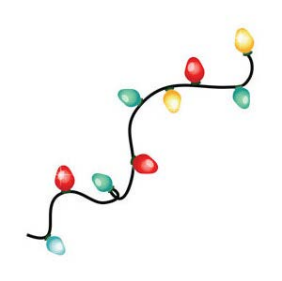
Code Of Conduct:

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

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

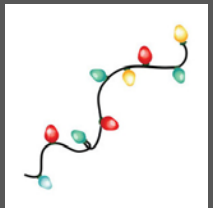
LED powered shoes

Bed by French furniture designer Philippe Boulet

hwww.archiproducts.com/en/products/111095/modular-led-light-bar-philips-luminous-textile-philips-large-luminous-surfaces.html

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

Sources



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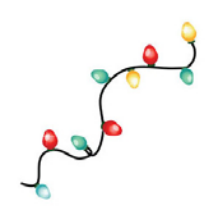

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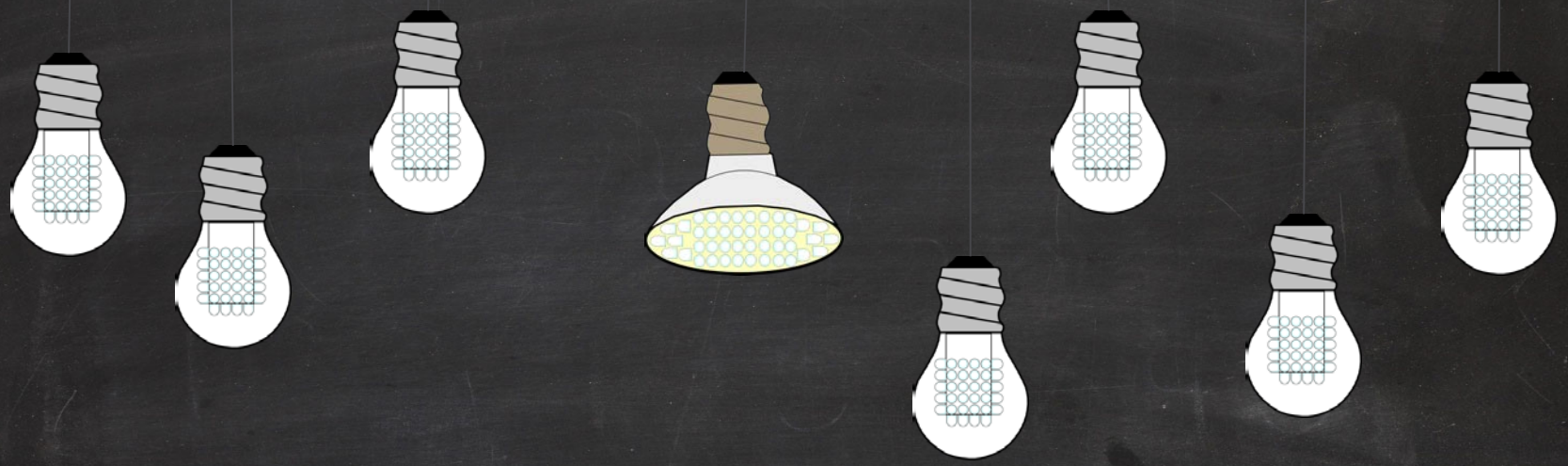


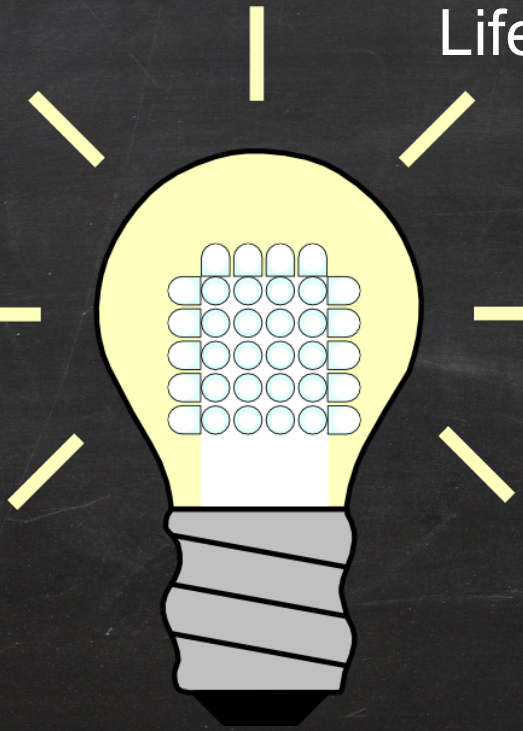
DISTRIBUTION & USE PHASE OF LED LIGHTS

Marula Tsagkari & Brayton Noll

OUTLINE

Electricity mix

Life-time



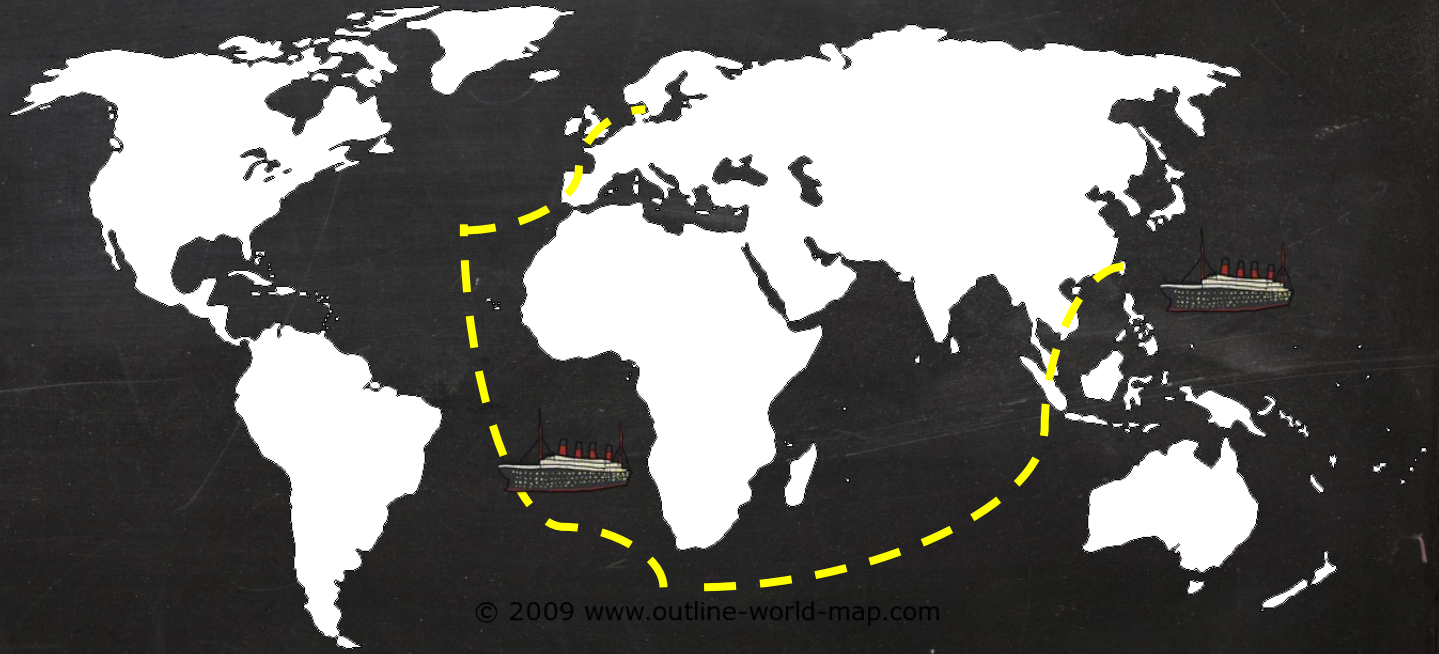
Distribution

Rebound effect & Energy savings possibilities

DISTRIBUTION OF LEDs

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

Case (Region)	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%

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%

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Take Away

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

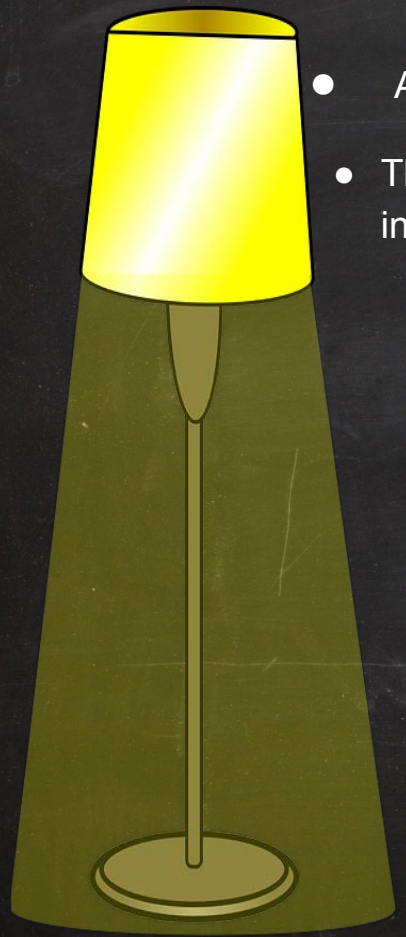
- WHAT IS IT?

"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

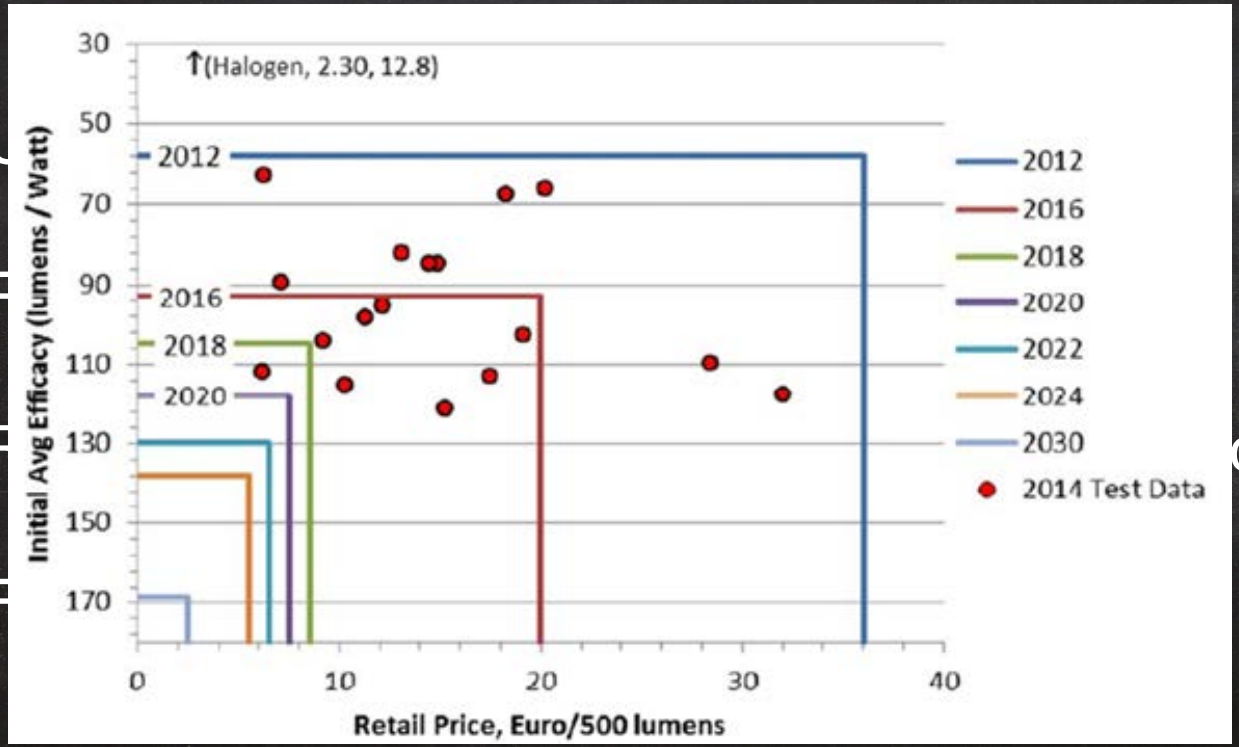


- A high quality LED will normally last 70,000 hours -or longer (US Department of Energy, 2016).
- The crucial time of an LED, is the point after which the LED light puts out only 70% of its initial light, although this does not mean total failure- L_{70} = minimum 50,000 hours

Operation hours per day/lifetime hours	50.000h	100.000h
24h	5.7 years	11.4 years
15h	9.1 years	18.3 years
10h	13.7 years	27.4 years
8h	17 years	34.2 years
4h	34.2 years	685 years

OTHER PARAMETERS THAT CAN AFFECT THE LIFETIME OF LEDs

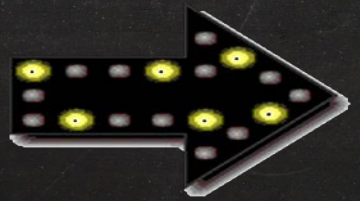
- U
- R
- R cement
- R



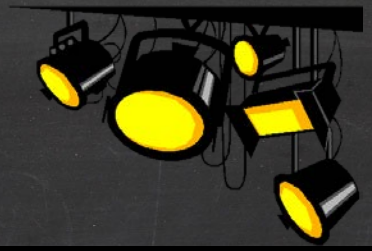
(Bennich et al. 2015)

OTHER PARAMETERS THAT CAN AFFECT THE LIFETIME OF LEDs

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

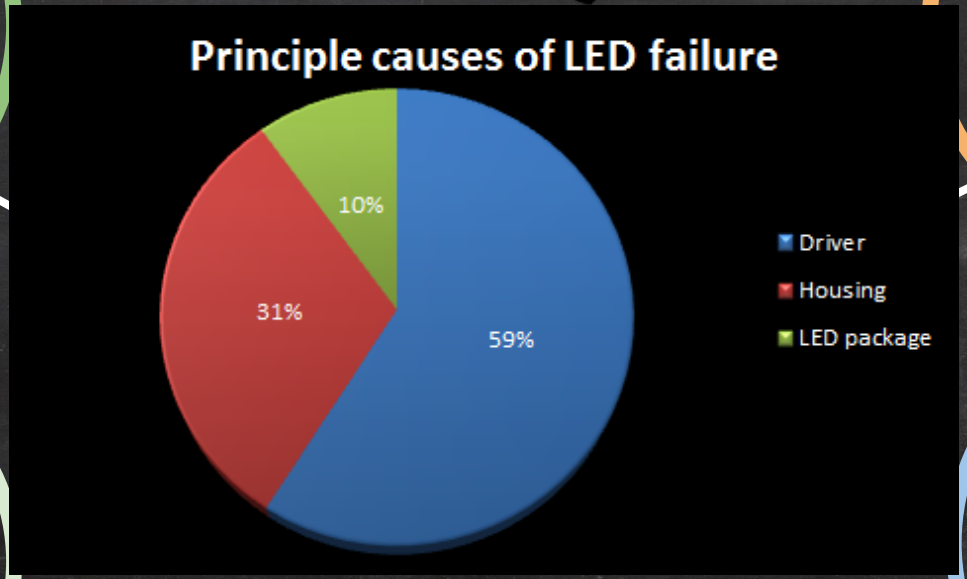


A “failure” is an event which ends the life of a specific product or component” (Next Generation Lighting Industry ALliance and US. Department of Energy, 2011)



DESIGN
- Electrical parameters
- Heat transport
- Electrostatic discharge layout

ENVIRONMENT
- Temperature
- Moisture
- Pollution



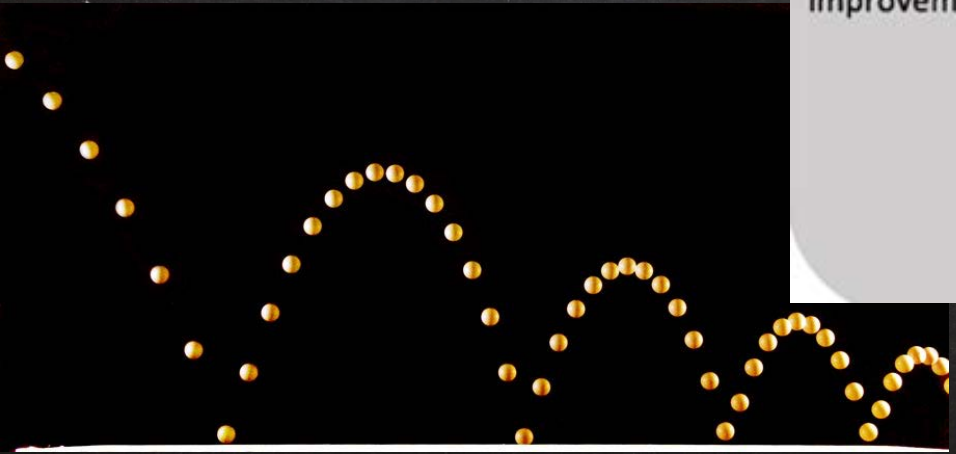
Most common failures appeared in a family of outdoor LEDs, from one manufacturer. The lights were operating for 34 million hours

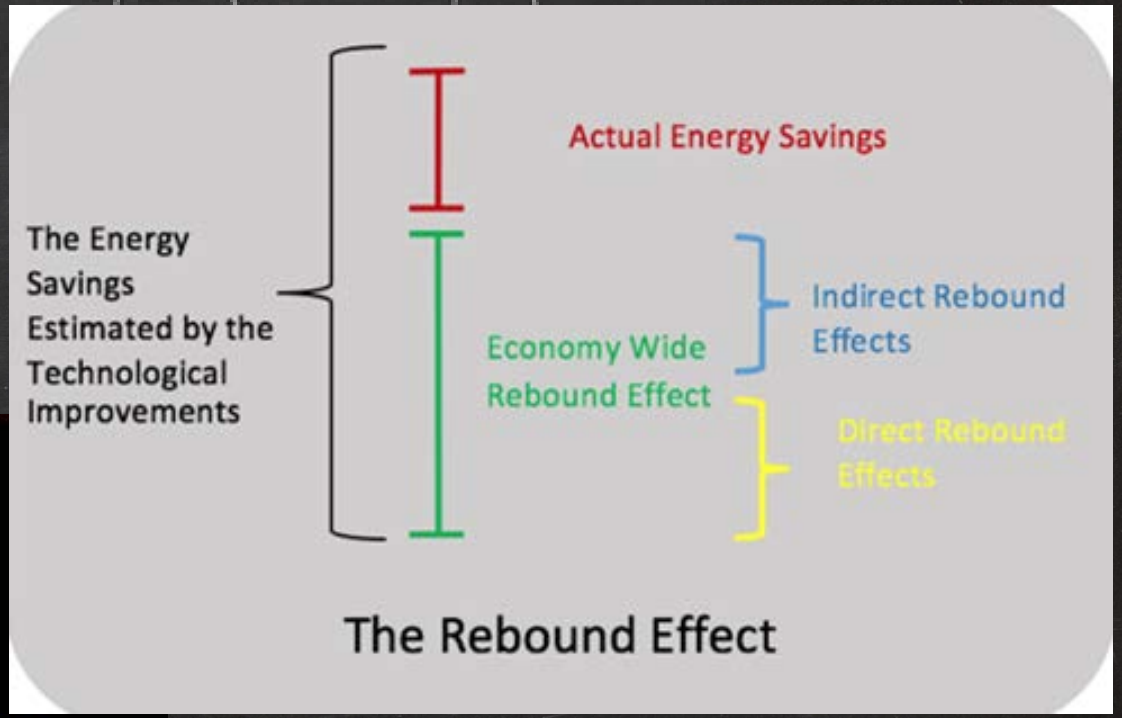
APPLICATION
- Storage
- Soldering
- Handling

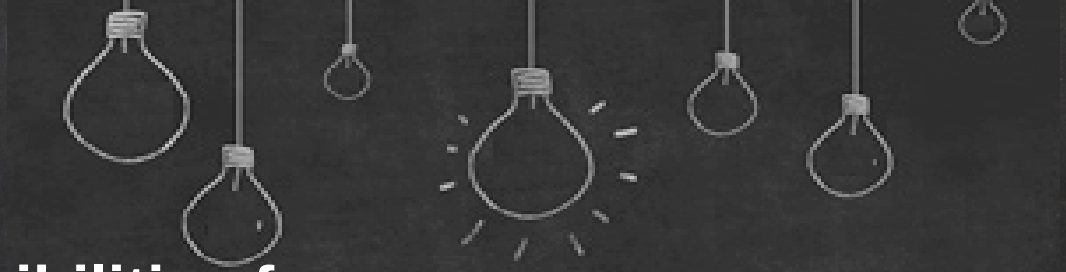
MECHANICAL
- Heat Transport
- Electrical circuit
- Assembly

Data from Chang et al. 2012 and OSRAM 2013

The Rebound Effect

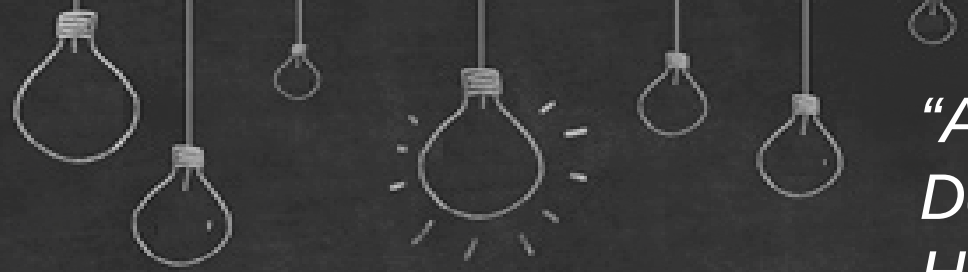






Policy Possibilities for Electricity Providers

- 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”


Thank You

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After-Light:

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

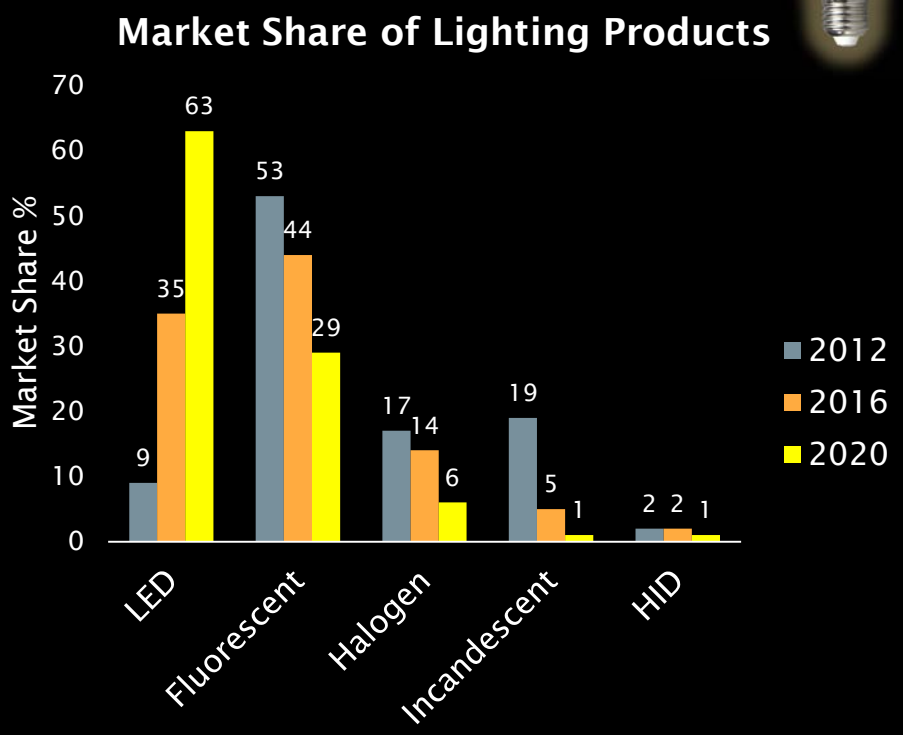
Savannah Carr-Wilson
Gabrielle Freeman
Sandeep

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 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 = .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

- <u>CycLED Project</u>
- 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

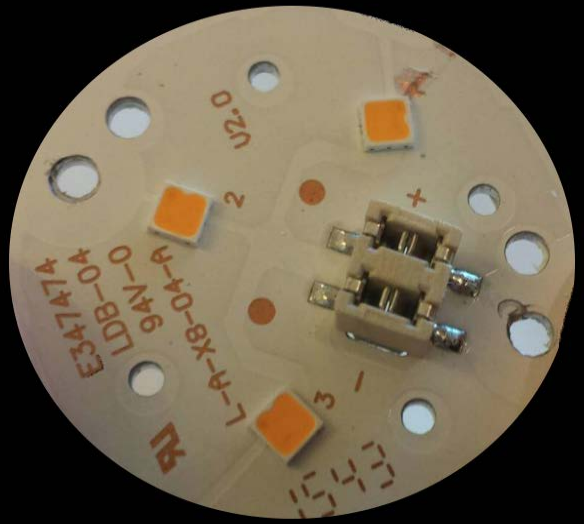


Photo credit: authors

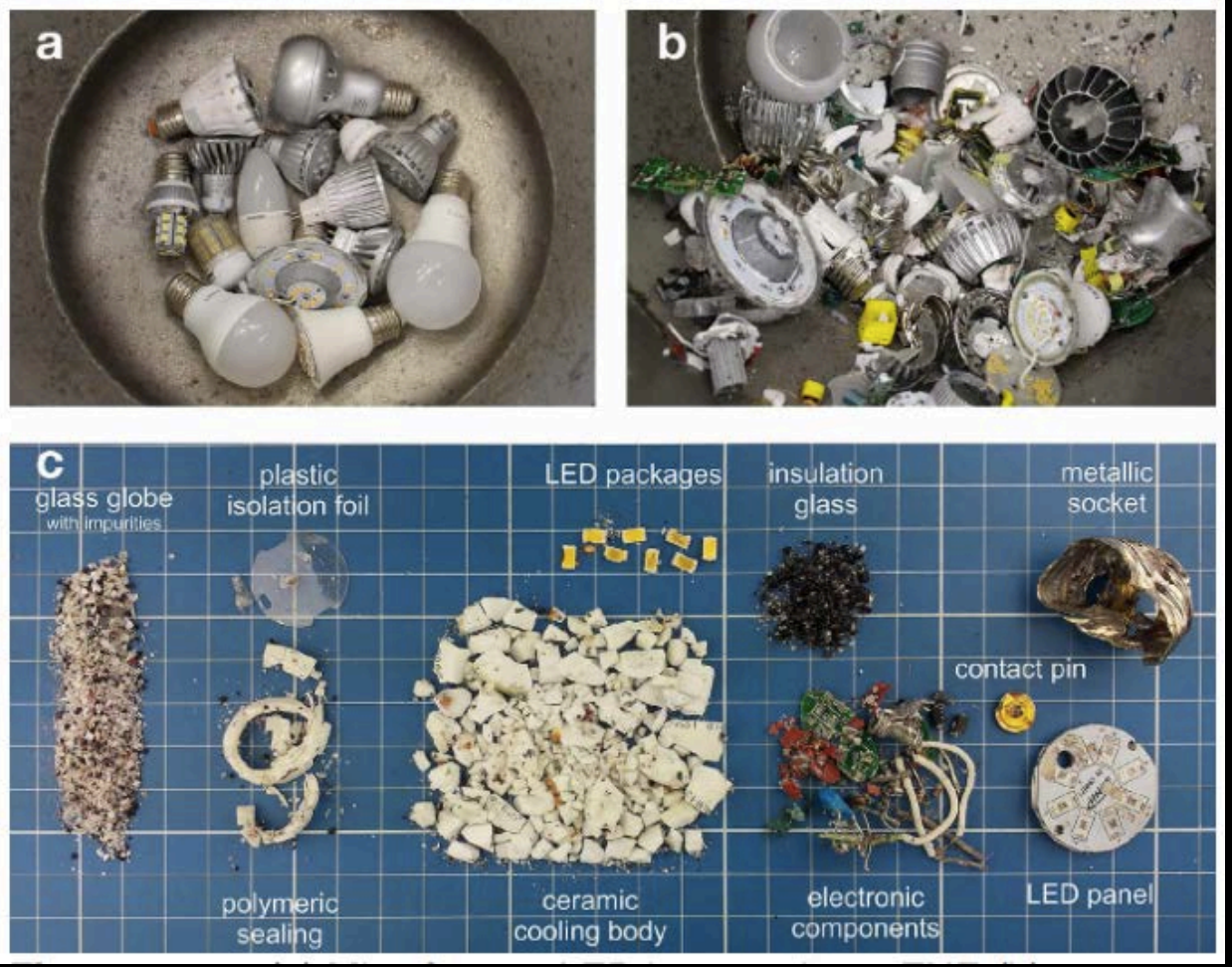


Illustration of the electrohydraulic fragmentation (EHF) method
Photo credit: ©Fraunhofer Project-Group IWKS

Improving LED Design

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

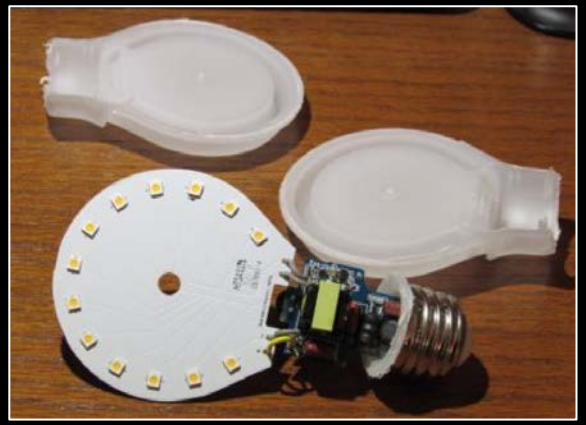


Photo credit: Net of Everything http://netofeverything.blogspot.se/2014_02_11_archive.html

Lighting as a Service

- Aka "pay per lux"
- Philips
  - Amsterdam’s Schiphol Airport
  - National Union of Students office in the UK
  - Amsterdam based RAUArchitects 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!

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