Comparative life cycle assessment of LED lamps based on cadmium containing quantum dots and conventional phosphors prepared for Lumileds

Juliette Herin
Philips Environment & Safety
January 6, 2016

innovation + you

PHILIPS

Content

- Study goal and scope
- Approach
- Data collection
- Life cycle assessment: results
- Interpretation & conclusions

Goal and Scope definition

Goal

To compare the environmental impacts of cadmium-containing quantum dot LED lamps with current conventional phosphors LED lamps in general illumination applications.

Scope

"Cradle-to-grave" assessment: from the production of the raw materials, through the manufacturing, the use and end of life of the product.

Calculation method

ReCiPe H/A method, based on ISO 14040/44 (LCA) (http://www.lcia-recipe.net/)
ILCD 2011 Midpoint+ methodology for LCA (http://eplca.jrc.ec.europa.eu/uploads/LCIA-characterization-factors-ofthe-ILCD.pdf)

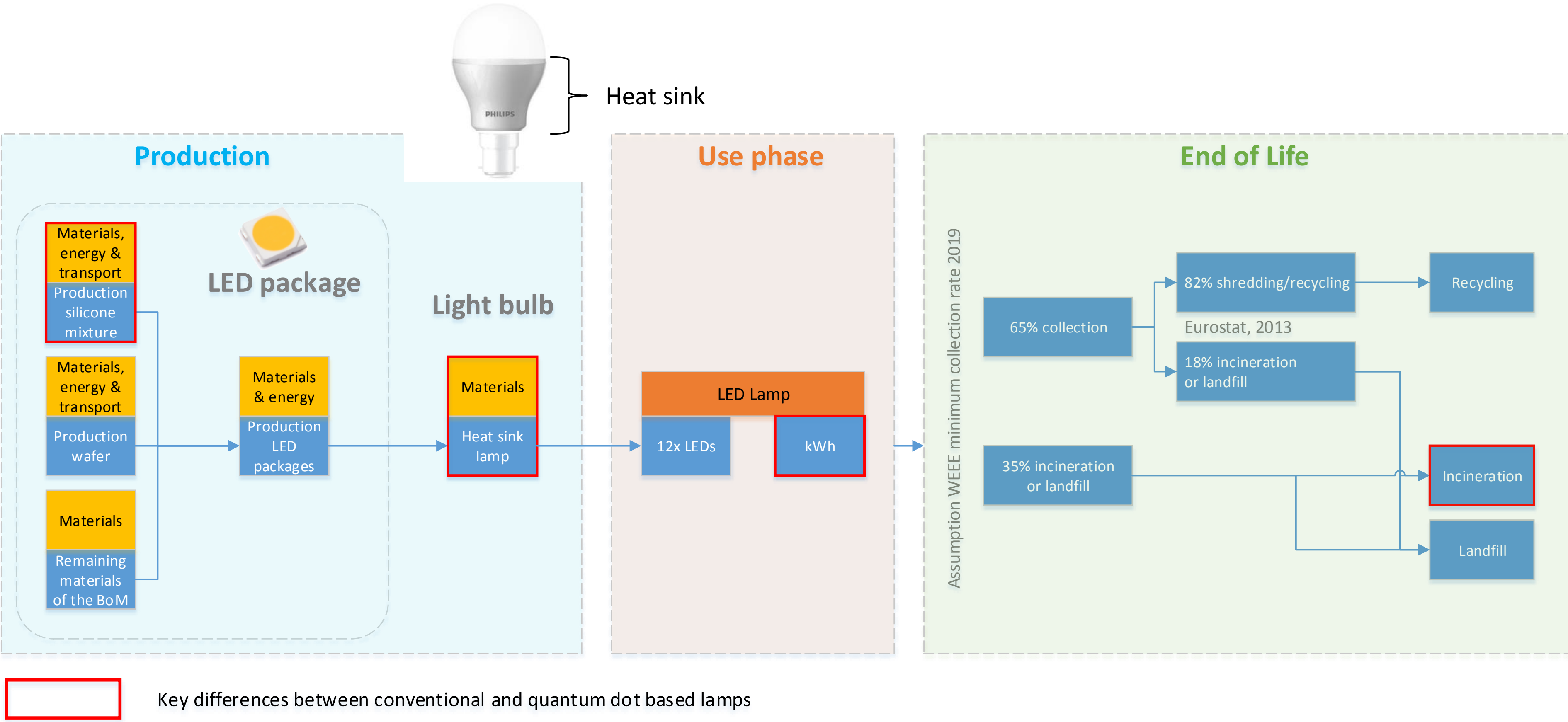
Functional unit*

Configurations of the lamp under study: LED replacement for 60W incandescent lamp (12 LED packages for 843 lm, 2700K, CRI 90) with a lifetime of 20,000hr. Three different configurations are being compared**:

- LED lamp with LED packages using current conventional phosphors (as baseline),
- LED lamp with LED packages using green phosphor and red quantum dots (first generation) with 12% increase in efficacy,
- LED lamp with LED packages using green phosphor and red quantum dots (second generation) with 25% increase in efficacy.

*The LED light bulb is used as a functional unit in this study for comparison purposes. LED packages are integrated into different types of lamps and luminaires in different configurations. Efficacy improvements in LED packages and heat sink reduction will result in similar overall improvements for other luminaires.
** The given efficacy improvements are estimates based on internal data and roadmaps for the given CCT/CRI combination relative to current conventional phosphors. The second generation is expected to replace the first generation of quantum dot LEDs within a year.

Goal and Scope definition



PHILIPS

Approach/source of data

Overall
Data modelled as provided by Lumileds in Life Cycle Inventory datasheets

LED package composition
The data for the sapphire wafer and the epi process have been taken from the DOE report*. The Epi process is representative of a high-power LED whereas the objects of this study are mid-power LEDs.
Data on production of QD solids have been collected directly from the QD suppliers. Phosphors' production data were estimated by experts based on in-house data for similar materials. Transport of QD materials and phosphors from the supplier to the factory have been included.
The data for the material content of the rest of the LED package is coming from the bill of material. Data on heat sink weight have been modelled by experts in thermal management of the lamp
Use of Ecoinvent database v.3.0 for background data and use of proxies when no data was available.

LED package manufacturing
Data from the Penang factory for year 2015 for LED package production.
Only electricity for production steps have been modelled, due to the lack of data on emissions of substances. Production phase was shown to be insignificant overall.
Use of Ecoinvent database v.3.0 for background data.

Use phase
ENTSO electricity mix as provided by Ecoinvent.
The LED packages with quantum dots have a higher efficacy and can be operated at a lower current. The light output per LED package does not change. The number of LED packages is the same for all configurations.
Transport of the product to the customer and to the disposal facility at end of life are not considered for this assessment. There would actually be a small difference due to the reduced weight of the heat sink, but this is negligible.

Lamp composition and manufacturing
The size of the heat sink in the lamp can be reduced when the efficacy increases.
Other parts of the lamp, such as optics, screw cap and electronics will remain unchanged. They are not considered for this assessment.

End-of-Life
Ecoinvent data for final disposal of product (WEEE). Aluminum is considered collected for recycling before incineration.
Cut-off approach for wastes going to recycling facilities.

*U.S Department of Energy. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 2: LED Manufacturing and Performance (June 2012).*

PHILIPS

Data collection

LED package

One LED package

Part of the LUXEON 3535 L LED package	Material	Percentage weight
LED die	InGaN	0.8%
	AuWTiAg	
	Ceramics	
Gold Wire	Refined Gold (99.995)	0.3%
Glue	Glue	<0.1%
Copper Frame	B-Cu87Ag(Ni)-645/725	64.7%
Silicone mixture	Phosphors (red and green) / Quantum dot solids Silicones	10.8%
Housing	PCT	23.4%

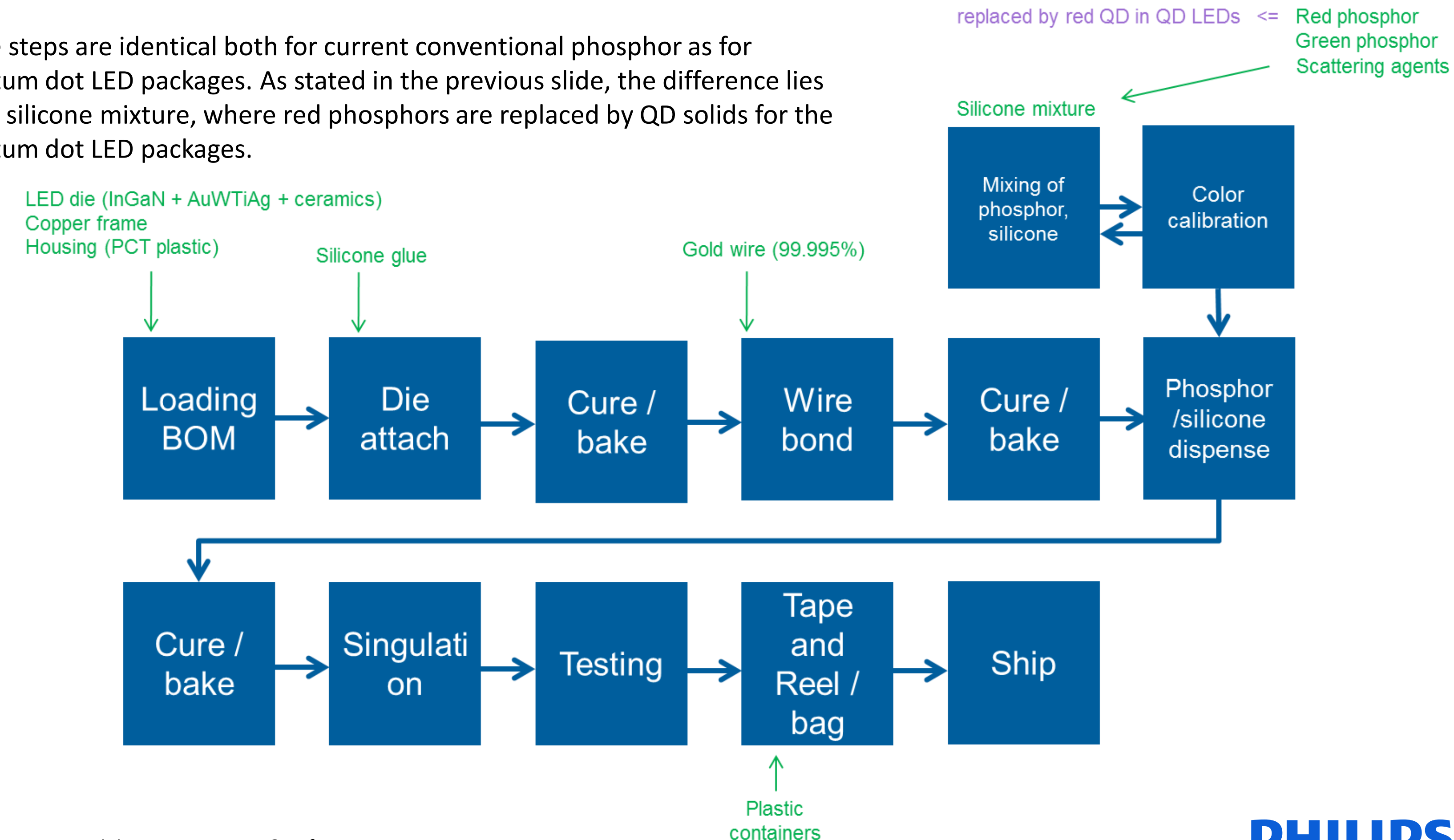
The table has been extracted from the bill of material of the product.
The materials used to produce a LED package are almost identical whether it is for a current phosphor LED package or a quantum dot LED package.
The difference lies in the silicone mixture, where red phosphors are replaced by quantum dot solids for the quantum dot LED packages. Data have been collected at suppliers for the quantum dot solids and estimated by experts for conventional phosphors.

Data collection

LED package process (identical for both products)

Flowchart of the process steps to manufacture a LUXEON 3535L LED package, tacking place in Penang, Malaysia. Data have been collected on year 2015.

These steps are identical both for current conventional phosphor as for quantum dot LED packages. As stated in the previous slide, the difference lies in the silicone mixture, where red phosphors are replaced by QD solids for the quantum dot LED packages.



PHILIPS

Data collection

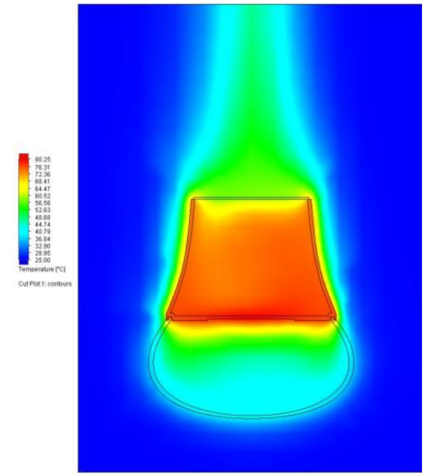
Heat sink

As quantum dots LEDs show an increase in efficacy compared to current conventional phosphor LEDs, more of the input wattage is converted to useful lumens of light (instead of waste heat), resulting in a decrease in the heat sink size. The thermal management of current conventional phosphor and quantum dots LED lamps have been modelled to estimate the volume, thus the weight of the heat sink needed to dissipate the heat.

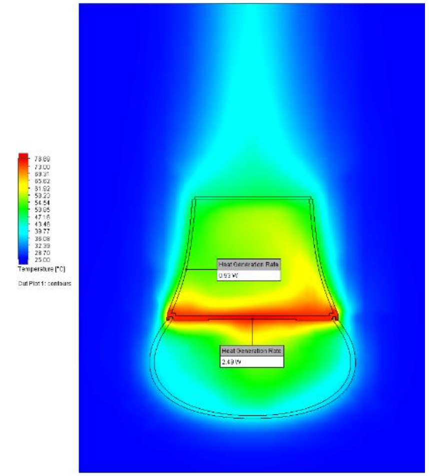
The diagrams on the right come from an analysis performed by Lumileds: models and simulations were done with Solidworks flow application and were tuned to achieve the same heatsink temperature on all models. The amount of aluminum was changed to achieve this goal.

In the table below are the weights of the heat sink used in the LCA.

	Weight heatsink (g)
Current conventional phosphor LED lamp	17.4
First generation of quantum dot LED lamp	12.6
Second generation of quantum dot LED lamp	7.3



Current conventional phosphor LED lamp



Second generation of quantum dot LED lamp

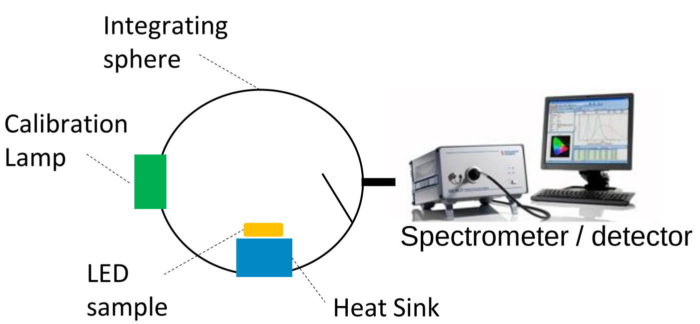
PHILIPS

Data collection

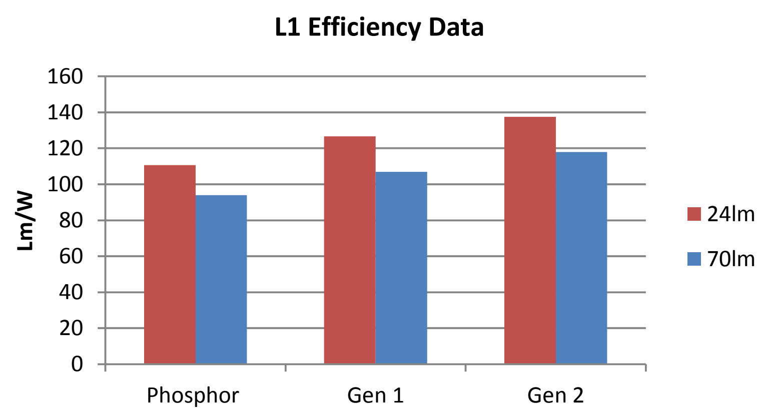
Use phase

- As the QD substance is encapsulated within a solid matrix only destructible at high temperature (> 1000 °C) no exposure to cadmium is likely to occur during the use phase of the product.

- Regarding the energy use, tests have been performed to measure and predict the increase in efficacy between current conventional phosphors and quantum dot LED packages and lamps.



*Test system following CIE127 design protocols



Data collection

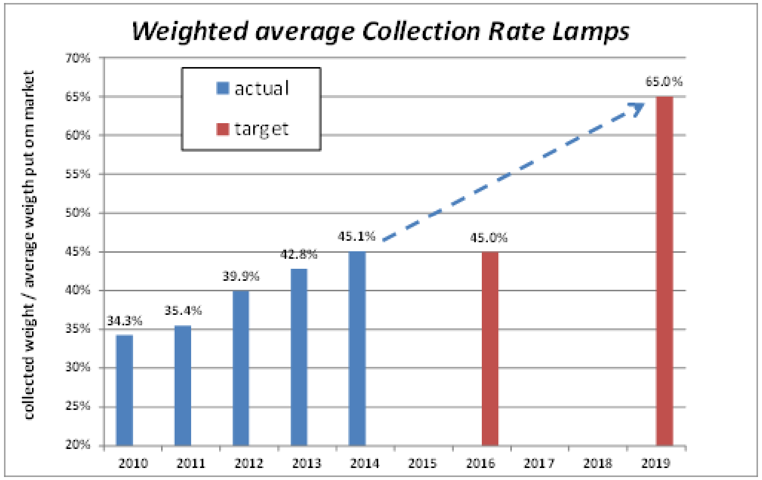
End of Life scenario

The reporting from the various collective schemes for Collection & Recycling of Lamps in which Philips participates in the various EU member states shows over 2014 a weighted average collection rate of 45.1% for Lamps

The graph shows an overview with the trend from the previous years.

The calculation method is based upon the EU directive for WEEE that defines as collection rate;
The collected weight in year "n" divided by the average weight put on market in the previous 3 years (year n-1, year n-2, year n-3)

The targets refer to the overall targets per EU member state for the total WEEE scope (all product categories) as defined in the EU directive for WEEE. There are no EU targets for Lamps specific. Only in a small number of countries there are specific targets for Lamps defined in the local legislation based upon different methodologies.



According to the European averaged recycling rates for lighting equipment of the European agency of statistics *Eurostat*, it is assumed that 82 % of collected materials are recycled. The remaining WEEE percentage that is neither reused nor recycled is incinerated in a solid waste incineration plant or landfilled.

A TCLP* test has been performed as input for this LCA on quantum dot LEDs, resulting in no Cadmium released in the environment. Recycling or landfilling impacts do not differ between conventional phosphor LEDs and quantum dot LEDs.

Of the three disposal scenario, only incineration could therefore possibly increase the environmental impacts of the quantum dot LED lamp, as the cadmium contained in the product could escape the incineration plant control and be released during incineration (assumed 10%**).

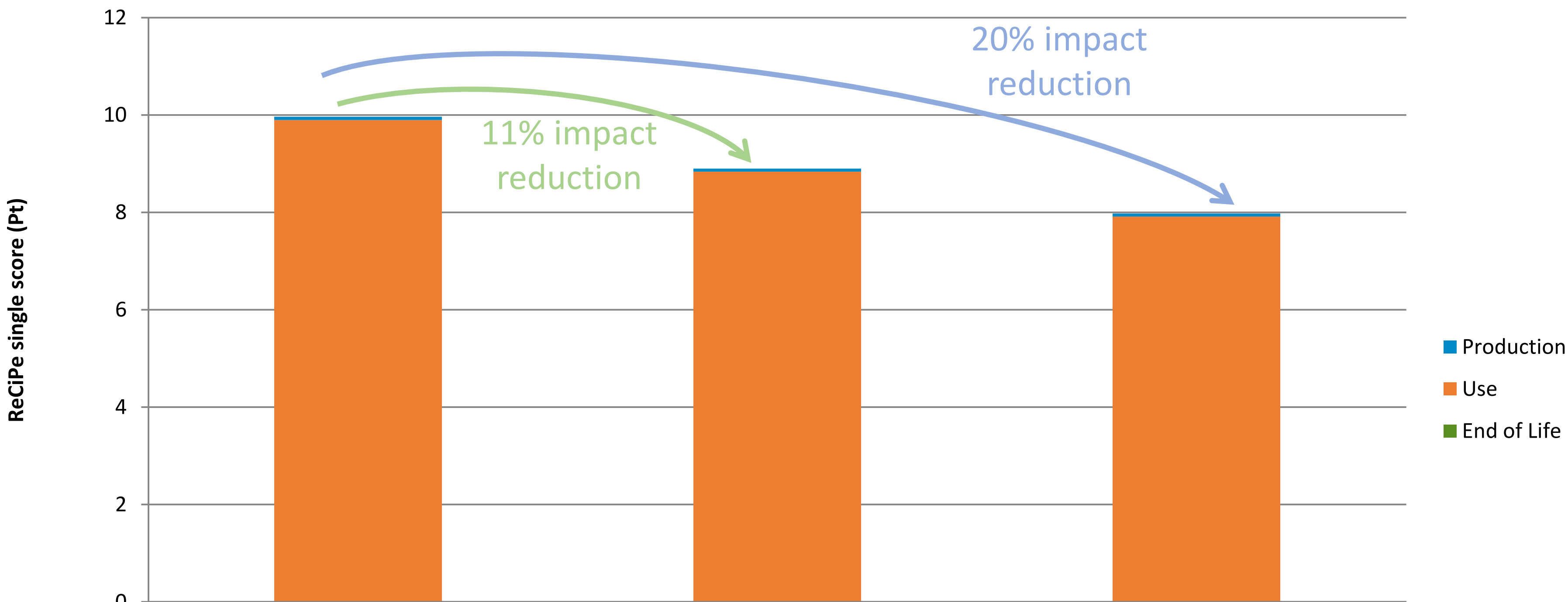
* TCLP: Toxicity Characteristic Leaching Procedure. The testing procedure mimics the environment found in a landfill.
** The Acta Group. *Supplemental Statement on Life Cycle Analysis and Comparison of Cadmium (CASRN 7440-43-9, EC 231-152-8), Cadmium Selenide (CASRN 1306-24-7, EC 215-148-3) vs. Indium Phosphide (CASRN 22398-80-7, EC 244-959-5) for Color Conversion in Displays.* (October 2015).

PHILIPS

Life cycle assessment: results

PHILIPS

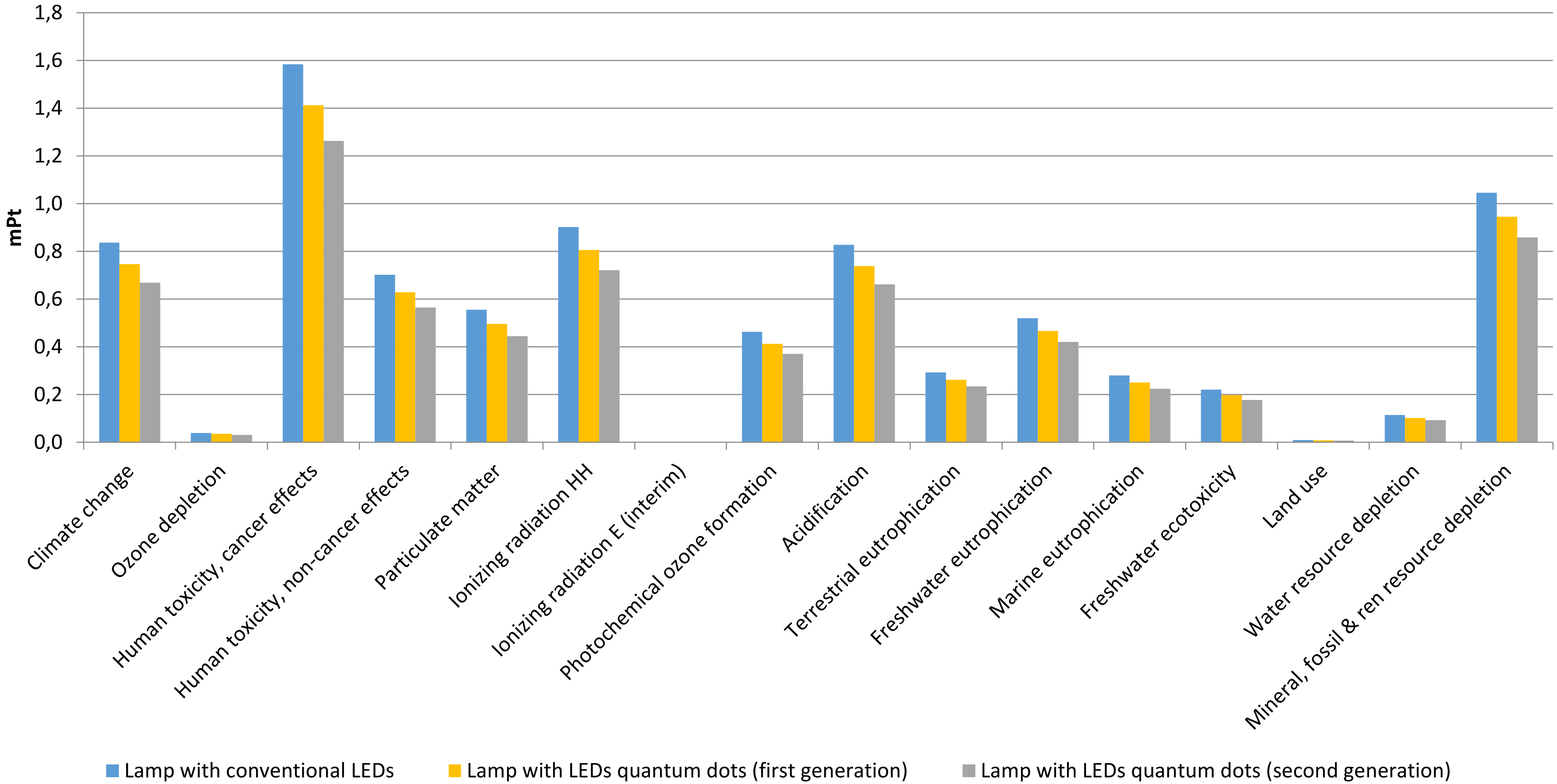
Impact reduction over complete life cycle with the ReCiPe methodology for LCA



	Lamp with conventional LEDs	Lamp with LEDs quantum dots (first generation)	Lamp with LEDs quantum dots (second generation)
Production	0,0674	0,0640	0,0595
Use	9,8984	8,8362	7,9160
End of Life*	1,41E-05	1,45E-05	1,45E-05

* End of Life single scores differ from the preliminary report due to the change in the end of life scenario modelling

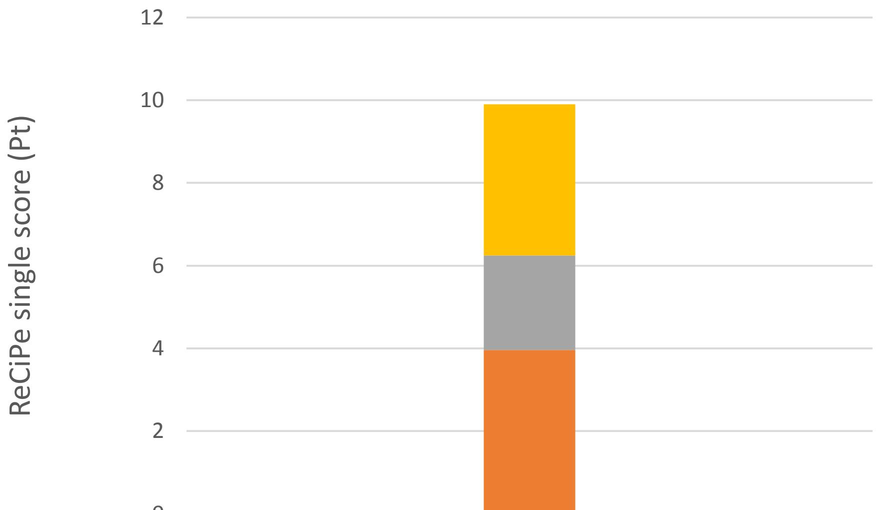
Impact reduction over complete life cycle with the ILCD methodology for LCA



PHILIPS

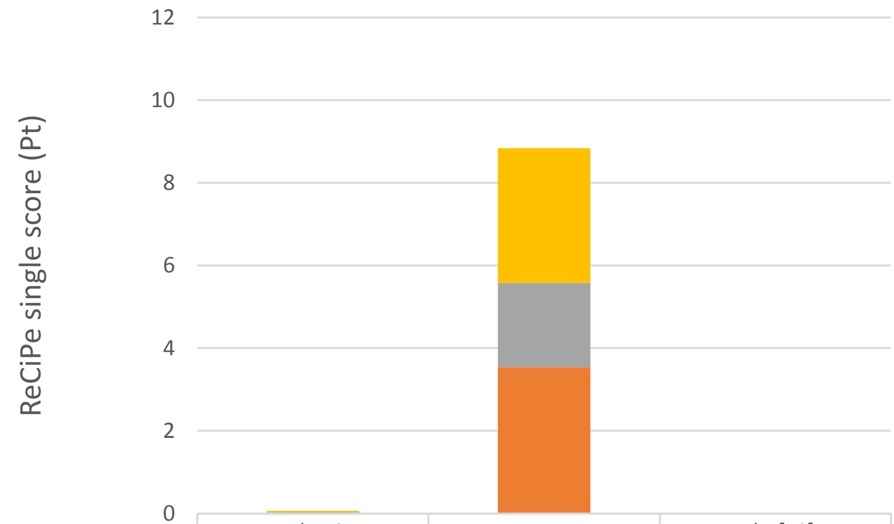
LCA results per life cycle step

LED lamp using conventional phosphors



	Production	Use	End of Life
Resources	0,0288	3,6507	2,72E-06
Ecosystems	0,0136	2,2851	4,34E-06
Human Health	0,0250	3,9627	7,06E-06

LED lamp using quantum dots (first generation)



	Production	Use	End of Life
Resources	0,0278	3,2589	2,72E-06
Ecosystems	0,0128	2,0399	4,34E-06
Human Health	0,0234	3,5374	7,42E-06

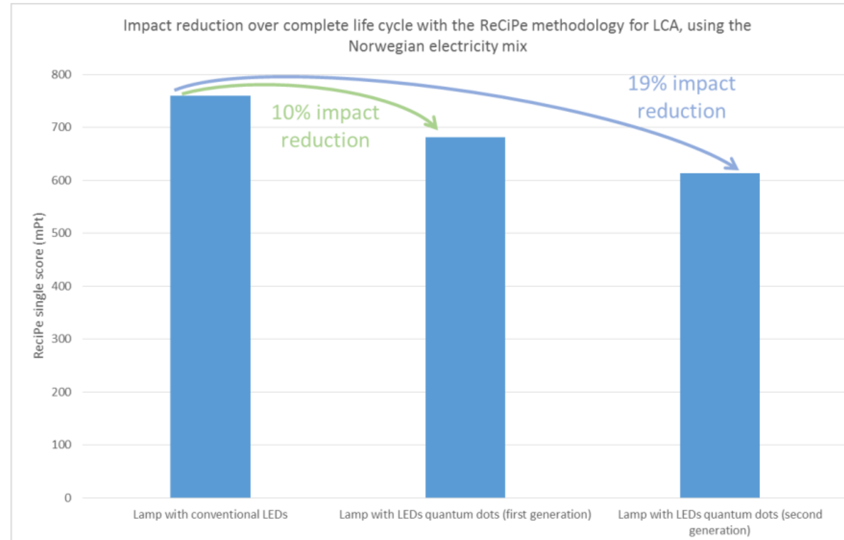
PHILIPS

Results

Sensitivity analysis

Use phase
The use phase impact is determined by the electricity grid and energy mix in the country of the user, following country specific shares of energy sources.

For example taking the Norwegian mix has proven to be much less impacting than the average European mix. Nevertheless, it only influences absolute values of impacts. It slightly reduces the gap of impacts between the three configurations (as shown on the graph), but the conclusions remain unchanged.



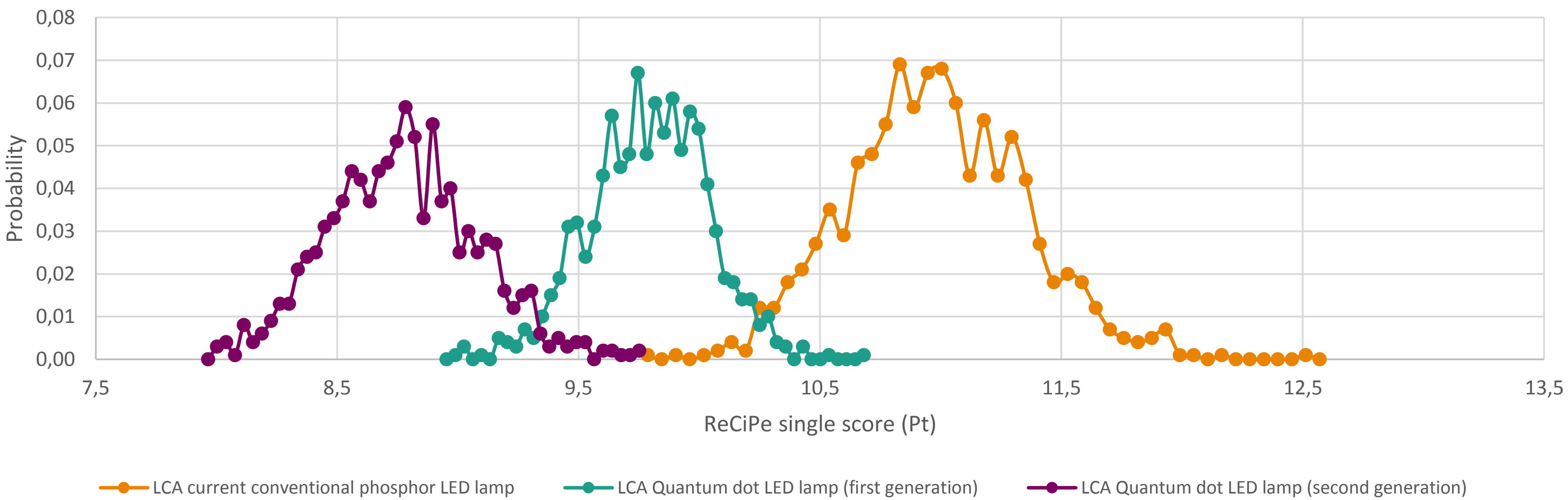
End of Life
When the worst-case end of life scenario is used, i.e. the product is incinerated and all cadmium is released into the air during incineration, only the human toxicity indicator (for ReCiPe and ILCD2011) and the terrestrial and marine ecotoxicity indicators (for ReCiPe) are slightly increasing. For both methods, this has no significant influence on the results.

PHILIPS

Results

Uncertainty analysis

Because the uncertainties in the Ecoinvent database are the same for parts that don't change between the lamps under study, they have not been taken into consideration. Uncertainties have been added only to the data that are differing from one system to another (silicone mixture, heat sink and electricity used) according to the quality of the data collected.
Below is a graph representing the results of the Monte Carlo analysis for the ReCiPe single score for the three products (number of runs: 1000).



There is a slight increase in the single scores showing the highest probability for all configurations compared to the initial results. This comes from the lognormal distributions of the uncertainties and is not abnormal. The uncertainty analysis indicated no variation of the end results.

Conclusions

The LCA results are in favor of the cadmium containing quantum dot LED lamps when compared to current conventional phosphor LED lamps. The environmental impact of cadmium in the LED packages is negligible when looking to the total life cycle impacts.

Increases in the environmental impact of quantum dot LED lamps, compared to current conventional phosphor LED lamps, come from two phases:

In the production phase the impact increases for the quantum dot LEDs due to the higher energy needed to produce the quantum dots (compared to conventional phosphors)

In the end of life phase, when incinerated, the cadmium released into air increases the impacts of the quantum dot LEDs

The increase of impacts in these two phases is outweighed by the reduction of impacts in other phases of the life cycle, namely:

In the use phase, thanks to the increase in energy efficiency of the quantum dot LED lamp, less electricity is needed over the lamp lifetime compared to the conventional LED lamp.

In the production phase, the weight reduction of the aluminum heat sink for the quantum dot LED lamp reduces the environmental impacts compared to a current conventional phosphor LED lamp.

Impact reduction or increase per phase compared to a current conventional phosphor LED lamp	**First generation of quantum dot LED lamp**	**Second generation of quantum dot LED lamp**
Production	-5%	-12%
Use (European electricity mix)	-11%	-20%
End of Life	+2%	+2%
Total*	-11%	-20%

* The total impact is determined primarily by energy consumption during the use phase

PHILIPS

External review

Review of LCA for comparison of 2 LED technologies

Performed by J. Coustillas, Pré Consultants bv

Review summary

- Review performed as an on-going process at each stage of the study
- Performed on the following aspects
  - Goal and Scope
  - Bill of material & Production data
  - Electricity use
  - End of life assumptions and test results
  - LCA calculations and results
- Given the level of involvement from the reviewer, this is NOT an ISO-compliant review.

Review summary – Comments

Comments made have been listed in the Excel file attached to the report (extract provided next page). They provide an opportunity for the practitioner to improve its analysis and give feedback to the reviewer. The main points covered were:

- An alternative assessment with the ILCD method should be presented.
- Missing data shall be estimated using closest as possible proxies, and assumptions taken should follow a sensitivity test if their contribution is important
- Uncertainty data, or estimates, should be gathered for the most important contributors and assessed in the final report

Other small remarks were made but prove to have little influence on the results

Review summary – Comments

G = general
T = technical
E = editorial

Document reviewed	Location in document	Information reviewed	Type of comment	Re	Reviewer recommendation	Practitioner response
LCA study Lumileds_draft.pptx (04/01/2016)	Slide 5 LED package composition	Transport of QD materials and phosphors from the supplier to the factory have been included	T	Is that real data (i.e. details on actual trucks & boats, transported loads and distance) or estimated (you know the locations, and estimate the transport means and distances)?	Even if this is overall completely negligible, data should be provided to clarify that (in supporting report)	Data were estimated (locations are know and transport means and distances are esimated) Will be provided in reviewed version of the supporting report
LCA study Lumileds_draft.pptx (04/01/2016)	Slide 5 USE phase	ENTSO electricity mix as provided by Ecoinvent	T	ENTSO data are for HV production only. LED lamps will be used on LV network. How did you take in account the losses due to distribution of electricity	Since the losses data are difficult to gather (you would need an average for Europe that deosn't exist in the databases), you could waive it out by finding a rough value for EU. If not available, discuss the fact that you are lowering the impact for both cases, BUT lowering it more for Ph lamps (since consumption higher) In supporting report for the detailed reasoning, with a quick summary in the slides	ENTSO for LV as found in the document made accessible by Ecoinvent which can be found throught this link
LCA study Lumileds_draft.pptx (04/01/2016)	Slide 5 EoL	Ecoinvent data for final disposal of product (WEEE	E	The exact dataset used should be described in report	In supporting report	Added to report
LCA study Lumileds_draft.pptx (04/01/2016)	Slide 5 EoL	Aluminum is considered collected for recycling before incineration.	T	Do you have any data to back-up that assumption?	In supporting report. Could be waived out with a quick discussion: Heatsink being heavier on Ph lamps, not conidering recycling is even more beneficial for QD lamps	Incineration plants try to separate aluminum before incineration. If aluminum is nonetheless being incinerated, the results would even be more beneficial to QD lamps as less aluminum would be incinerated
LCA study Lumileds_draft.pptx (04/01/2016)	Slides 6, 7 & 8		G	More references, data listings,… needed as supporting evidences	In supporting report	provided in excel file and supporting report