

**Life Cycle Assessment of Illuminants
A Comparison of Light Bulbs, Compact Fluorescent
Lamps and LED Lamps**

Executive Summary

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OSRAM Opto Semiconductors GmbH
Innovations Management
Regensburg
Germany

Siemens Corporate Technology
Center for Eco Innovations
Berlin
Germany

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Summary

OSRAM Opto Semiconductors' study on the life cycle assessment (LCA) compared the environmental performance of three different types of lamps: a conventional light bulb (GLS), a compact fluorescent lamp (CFL) and a light-emitting diode lamp (LED lamp). In order to evaluate lamps and how they actually deal with energy and resources, it is not enough just to consider energy consumption while they are in use. The aim of this LCA is therefore to analyze the environmental impact of an LED lamp over its entire life and to compare it to a CFL and a GLS. The relevant material and energy supplies, including all input and outputs, were determined in detail for all the LED lamp's components and production processes. Apart from a detailed analysis of each individual production stage, for LED chips and lamp housings, for example, these also include all necessary transports. Apart from the primary energy and resource consumption, the impact on the environment corresponding to selected environmental impact categories, i.e. acidification, eutrophication, photochemical ozone depletion and human toxicity was evaluated.

A comparison of the life cycle of three lamp types was accomplished: a 40 W GLS, an 8 W CFL Dulux Superstar and an 8 W Parathom LED lamp.

Main findings:

- **Less than 2% of the total energy demand is needed for production of the LED lamp**

The manufacturing phase is insignificant in comparison to the use phase for all three lamps as it uses less than 2% of the total energy demand. This study has dismissed any concern that production of LEDs particularly might be very energy-intensive. Merely about 0.4 kWh are needed for production of an LED (OSRAM Golden Dragon Plus), about 9.9 kWh for the production of the Parathom LED lamp including 6 LEDs.

- **LED lamps are competitive to CFL today**

In contrast to the primary energy consumption of incandescent lamps of around 3,302 kWh, CFL and LED lamps use less than 670 kWh of primary energy during their entire life. Thus 80% of energy can be saved by using CFL or LED lamps. The bottom line is that LED lamps are more efficient than conventional incandescent lamps and also ahead in terms of environmental friendliness. Even today, LED lamps show nearly identical impact on the environment compared to CFL.

- **Future improvements of LED lamps will further cut down energy demand**

As the efficiency of LEDs continues to increase, LED lamps will be capable of saving more energy and achieving even better LCA results in future.

This life cycle assessment proves that LED lamps are amongst the most environmentally friendly lighting products.

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Introduction - Energy Saving with Solid State Lighting

In March 2007, the European Council agreed to save 20% of green house gas emissions by 2020. Worldwide, almost 20% of the electricity consumption is used by lighting applications, which corresponds to 2651 TWh/year¹. 70% of this energy is consumed by inefficient lamps. Thus, starting on September 1, 2009 and ending in 2016, the European legislation has planned to phase-out less efficient light sources. During this time Europeans will have to part with their conventional light bulbs, and other heavy users of electricity. Energy-efficient alternatives are urgently needed.

Solid state light sources, **e.g. light-emitting diodes (LED)**, are based on inorganic semiconductors that emit light by electroluminescence. LEDs will revolutionize modern lighting due to their unique properties such as long lifetime, colour tuneability, and instantaneous switching. Moreover, they are mercury-free. But most important: LEDs will be amongst the most efficient light sources in the near future. Today, LEDs are already five times more efficient than incandescent lamps. In the future, however, it is expected that LEDs will become more than ten times more efficient compared to incandescent bulbs. No doubt, tremendous amounts of energy could be saved which will not only reduce CO₂ emissions but also lower the energy bill of consumers. The Ad-hoc Advisory Group "ICT for Energy Efficiency"² stated that theoretically > 50% of the electrical energy could be saved per year in the near future by switching to LED lighting.

In order to label a new lamp technology as "green" though, it is not enough to just consider energy consumption in use. Instead, the complete life cycle covering resources, energy needed during manufacturing, transport and use as well as the end-of-life needs to be analyzed.



Goal and Scope – Overview

The aim of this life cycle assessment (LCA) carried out by Siemens Corporate Technology, Center for Eco Innovations, OSRAM and OSRAM Opto Semiconductors is to analyze the environmental impact of an LED lamp over its entire life and to compare it with a compact fluorescent and an incandescent lamp. An independent critical review panel was established in order to ensure compliance with ISO 14040 and ISO 14044.

¹ Light's Labour's Lost – Policies for Energy-efficient Lighting, International Energy Agency (2006)

² Report of the Ad-hoc Advisory Group on "ICT for Energy Efficiency" by European Commission; 2008

The complete life cycle of all three light sources was carefully modeled and analyzed from start to finish. The relevant material and energy supplies were determined in detail for all components and production processes of the lamps. The impact inventories are broken down into the five life cycle stages, which are (1) raw material production, (2) manufacturing & assembly, (3) transport, (4) use and (5) end of life, shown in figure 1. The results allow for conclusions not only on resource consumption and primary energy input but also on environmental categories such as acidification, eutrophication, the greenhouse effect, photochemical ozone depletion and toxicity. The goal was to find out what environmental impact the lamps have each step of the way, and how they rank in comparison to each other.

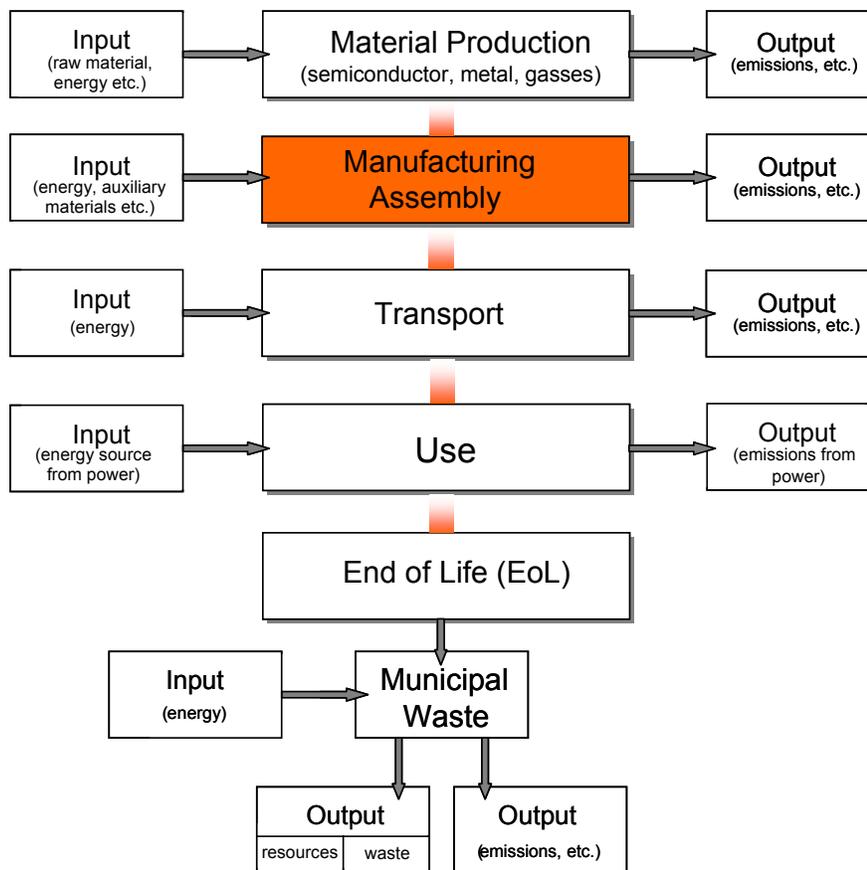


Figure 1: Stages investigated in the LCA of lamps

Three types of lamps were analyzed: a 40W incandescent lamp (GLS), an 8 W DULUX Superstar compact fluorescent lamp (CFL) and an 8 W Parathom LED lamp with 6 Golden Dragon LEDs (figure 2). Common basis for the comparison was a luminous flux of

all lamps in a range between 345 and 420 lumen (a 40 W equivalent requires 345 lumen minimum according to IEC Norm 60064), a correlated color temperature between 2700 – 3000 K (warm white), a colour rendering index of ≥ 80 and a Classic A shape with E27 socket. All lamps provide comparable luminous flux and all are warm white lamps but the fact of a “cold” perception of the light from different emission spectra of the lamp types is not considered.



Figure 2: Type of lamps compared in the Life Cycle Assessment: a 40 W incandescent lamp, a compact fluorescent DULUX Superstar and a Parathom LED lamp

To ensure comparability of the three lamp types a lifetime of 25,000 hours was taken a reference parameter which was evened out by the number of lamps used. This way, the lifetime of 25 incandescent bulbs (25,000 hours) equals the lifetime of 2.5 compact fluorescent lamps, which equals the lifetime of one Parathom LED lamp. For comparability reasons in the study, it was assumed that all three lamps would have a light output between 345 to 420 lm during their whole lifetime, and then burn out. An extra analysis was done that took the gradual reduction of brightness into account. The difference was too small to impact results, though. Turn-on and –off cycles were excluded from the study.

The production of the GLS and CFL takes place in Europe. For the Parathom LED lamp, production of the Golden Dragon LEDs is located in Germany (frontend) and Malaysia (backend) and the production of the LED lamp in China. The location of the use phase, end of life, and any other processes was Europe.

Life Cycle Impact Assessment Method

The method for this analysis is the life cycle assessment as outlined in ISO 14040 and 14044. In order to obtain the environmental performance of the studied processes, a combination of a Life Cycle Impact Assessment (LCIA) method developed at the University Leiden, the so called CML (Centrum voor Milieuwetenschappen (Institute of Environmental Sciences)) method and key performance indicators were used. The CML method defines several impact categories for emissions and for resource consumption. This method groups by-products, emissions and resource consumption caused by these processes, into specific environmental impacts.

The primary energy demand was taken as key performance indicator. Six environmental impact categories have been chosen in this study that address impacts on air, soil and resources.

Choice and usage of the electricity mix have a high impact on LCA results. The electricity mix specifies the percentage composition of the energy carrier for a specific region. The location of production used in the study was the actual location where production normally takes place and consequently the corresponding electricity mixes (Europe, Germany, Malaysia and China) were taken into account. German and European electricity mixes consists mainly of power generation by nuclear and coal plants and of renewables, power supply in China is mainly generated by coal plants in contrast to Malaysia where it is generated mainly by natural gas. Due to this fact different electricity mixes causes different environmental burden. Usage and End of Life of all lamps are based on the European electricity mix.

Primary Energy Demand (CED)

The primary energy demand or the cumulated energy demand (CED) summarizes the energy needed for the different stages of the life cycle. Primary energy is the energy embodied in natural resources, like coal, oil, sunlight, uranium etc. that has not (yet) undergone any anthropogenic transformation. Primary energy use can be measured in MJ or kWh. For lamps mainly the use of kWh is of interest. Taken the European average electricity mix into consideration, to produce 1 kWh of electricity approximately 3.3 kWh primary energy are needed.

Consequently, primary energy use can be seen as an environmental impact category, even though it is in principle an environmental inventory value (no characterization factor).

Environmental Categories

The six environmental categories chosen in this study are depicted in figure 3 and explained in the following.

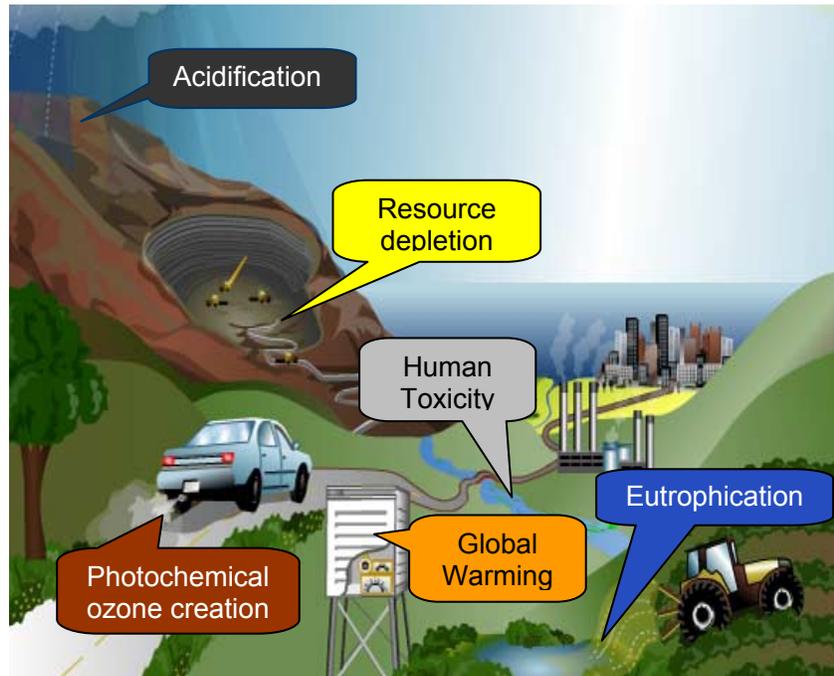


Figure 3: Environmental impact categories³

1. Global Warming Potential (GWP)

The Global Warming Potential (GWP) is an index to measure the contribution to global warming of a substance that is released into the atmosphere. The GWP is impacted mainly by the emission of greenhouse gases, i.e. carbon dioxide (CO₂) and methane (CH₄). It was calculated for a time frame of 100 years. The GWP is measured in CO₂ equivalents.

2. Acidification Potential (AP)

The AP calculates the loss of the nutrient base (calcium, magnesium, potassium) in an ecosystem, and its replacement by acidic elements caused by atmospheric pollution. Acidification originates from the emissions of sulfur dioxide and oxides of nitrogen. Here the AP is dominated by nitrogen (NO₂) and sulfur dioxide (SO₂) emissions. In the atmosphere, these oxides react with water vapor and form acids which fall down to the earth in the form of rain or snow, or as dry depositions. This affects soils, waters, flora and

³ Source: IISI Sustainability Assessment in Internet <http://www.steeluniversity.org>

fauna, and can even damage building materials. The resultant 'acid rain' is best known for the damage it causes to forests and lakes. AP is measured in SO₂ equivalents.

3. Eutrophication Potential (EP)

Eutrophication originates mainly from nitrogen and phosphorus in sewage outlets and fertilizers. Thus the EP is caused mainly by nitrogen oxide (NO_x) emissions, followed by chemical oxygen demand and ammonia. Basically, EP is the build-up of a concentration of chemical nutrients in an ecosystem which leads to abnormal productivity. For example, this causes excessive plant growth like algae in rivers, which chokes aquatic vegetation and causes severe reductions in water quality and animal populations. EP is measured in phosphate (PO₄³⁻) equivalents.

4. Photochemical Ozone Creation Potential (POCP)

Ozone is protective in the stratosphere, but on the ground-level it is toxic to humans in high concentration. Photochemical ozone, also called "ground level ozone", is formed by the reaction of a volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The POCP depends largely on the amounts of carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen oxide (NO), ammonium and NMVOC (non-methane volatile organic compounds). POCP also known as summer smog is measured in ethene equivalents.

5. Human Toxicity Potential (HTP)

The human toxicity potential (HTP), a calculated index that reflects the potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of a compound and its potential dose. These by-products, mainly Arsenic, Sodium Dichromate, and hydrogen fluoride, are caused, for the most part, by power consumption. These are potentially dangerous chemicals to humans through inhalation, ingestion, and even contact. Cancer potency, for example, is an issue here. The human toxicity potential (HTP) is measured in 1,4-Dichlorobenzene equivalents.

6. Abiotic Depletion Potential (ADP)

The impact category abiotic resource depletion (ADP) records the abiotic resource consumption. The value of the abiotic resource consumption of a substance (e.g., lignite,

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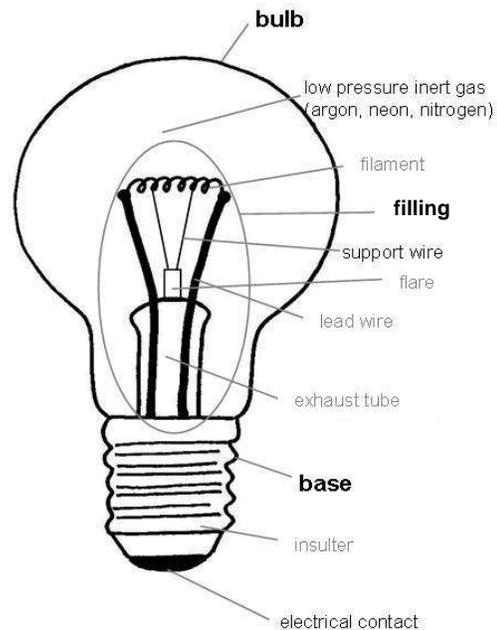
coal) is a measure of the scarcity of a substance, i.e. it depends on the amount of resources and the extraction rate. ADP is represented by natural gas, hard coal, lignite, and crude oil. It is formed by the amount of resources that is depleted. Abiotic Depletion Potential is measured in Antimony equivalents.

Life Cycle Assessment of the three lamp types

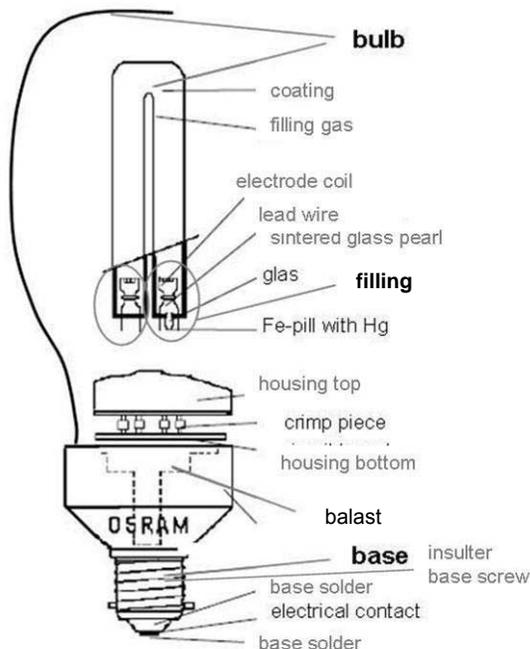
Lamp types

1. The Incandescent Bulb Classic A

A classical incandescent bulb in use ever since Thomas Edison turned it into a product for the masses in the early 1900s was used for the comparison. The model was an OSRAM Classic A 40 W incandescent bulb.



2. The Compact Fluorescent Lamp Dulux Superstar



A compact fluorescent lamp (CFL) also known as the energy saving lamp used for the comparison was the Dulux Superstar Classic A.

To ensure comparability in terms of light output a virtual 8 W model was chosen instead of 7 W usually available. A CFL (DULUXSTAR) with tube form and 8 W is part of the OSRAM portfolio.

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3. The LED Lamp: Parathom Classic A

An LED lamp, the 8 W Parathom Classic A55, with six Golden Dragon Plus LEDs from OSRAM, launched in August 2009, was used in the study to for comparison to the other two lamps.

For the LEDs all data for all processes, materials and common consumption or wastages were collected at OSRAM Opto Semiconductors; for the LED lamp data were provided by OSRAM. For the GLS and CFL all data were taken from two existing studies on behalf of OSRAM. The data for core processes were taken from that two studies combined with actual data sheets provided by OSRAM.

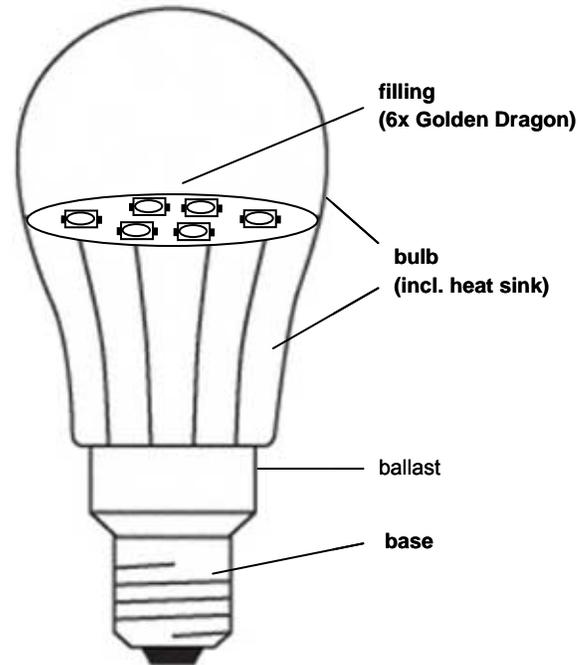
Other process and raw materials data were taken from the GaBi database⁴ whenever possible. In cases where no information was available in GaBi, data were taken from literature^{5,6} or from the database Ecoinvent⁷.

The whole lifecycle includes: Manufacturing, Use and End of Life. The phases are explained in the following.

Manufacturing Phase

All lamps are divided into parts for the base, bulb, filling, including packaging and transportation.

The packaging consists of a cardboard box, and transportation includes all transportation processes within the manufacturing phase, including transport of the final product to the customer in Europe.



⁴ GaBi: Data Set PE International

⁵ Study „Umweltbewertung PC-Reuse“, TU Berlin, Schichke K., Kohlmeier R.

⁶ Winnacker, K. & Küchler, L. (Hrsg.) (1983): Grundzüge der chemischen Technik, Anorganische Chemie 1+2, Organische Chemie 2+3, Metalle. - Carl Hanser Verlag, München - Wien.

⁷ Ecoinvent life cycle impact assessment database, from the Swiss Centre for Life Cycle Inventories (<http://www.ecoinvent.org>), 2006, Switzerland

	GLS	CFL	LED Lamp
Base	<ul style="list-style-type: none"> - Solder - Screw Shell - Insulter - Basing Cement - Electrical Contact 	<ul style="list-style-type: none"> - Basing Cement - Housing (top + bottom) - Glue - Screw Shell - Insulator - Solder - Electronic Ballast 	<ul style="list-style-type: none"> - Insulator - Contact Plate - Plastic Sleeve - Aluminum Board - Electronic Ballast
Bulb	<ul style="list-style-type: none"> - Glass 	<ul style="list-style-type: none"> - Glass 	<ul style="list-style-type: none"> - Bulb material - Heat Sink
Filling	<ul style="list-style-type: none"> - Getter - Filament - Wire (Support + Lead) - Exhaust Tube - Flare 	<ul style="list-style-type: none"> - Filling Gas - Coating - Frame (Electrode Coil, Emission Material, Sintered Glass Pearl, Wire, Tube (Stem +Exhaust) Fe-pellet with Hg) 	<ul style="list-style-type: none"> - 6 x Golden Dragon Plus

In this study, special emphasis was given to the investigation of the manufacturing of the LED itself, here the white Golden Dragon Plus. The production of the Golden Dragon (figure 4) is split up into two main process stages: frontend, where the 1 mm² semiconductor chip is fabricated, and backend, where the chip is contacted and packaged. It is essential to have a closer look at the complete manufacturing process of the LEDs as no other study did this in detail before. At OSRAM Opto Semiconductors access to the most advanced fabrication of LEDs is guaranteed. Thus these data were actually measured in the facilities in Regensburg and in Malaysia and not just assumed.

The main frontend and backend processes are shown in figure 5 and have been analyzed in detail. All processes take place in clean rooms with clean room classes from 100 up to 10,000. In a clean room class 100 a maximum of 100 particles ≥ 5 µm are permitted per cubic foot of air. To give perspective, the ambient air outside in a typical urban environment contains more than 1,000,000 particles per cubic foot.

The frontend processes in Regensburg include epitaxial growth of the LED structures on a sapphire substrate via metal organic vapour phase epitaxy (MOVPE). Various metallization and lithography steps are necessary for depositing structured barriers, the mirror and the solder. In the thin film process invented by OSRAM Opto Semiconductors the initial substrate is replaced by a carrier substrate before chip separation.

In Malaysia the backend processes are carried out that include the deposition of the LED chip into a leadframe, wire-bonding as well as phosphor and lens deposition. All processes are accompanied by optical and electrical inspection.

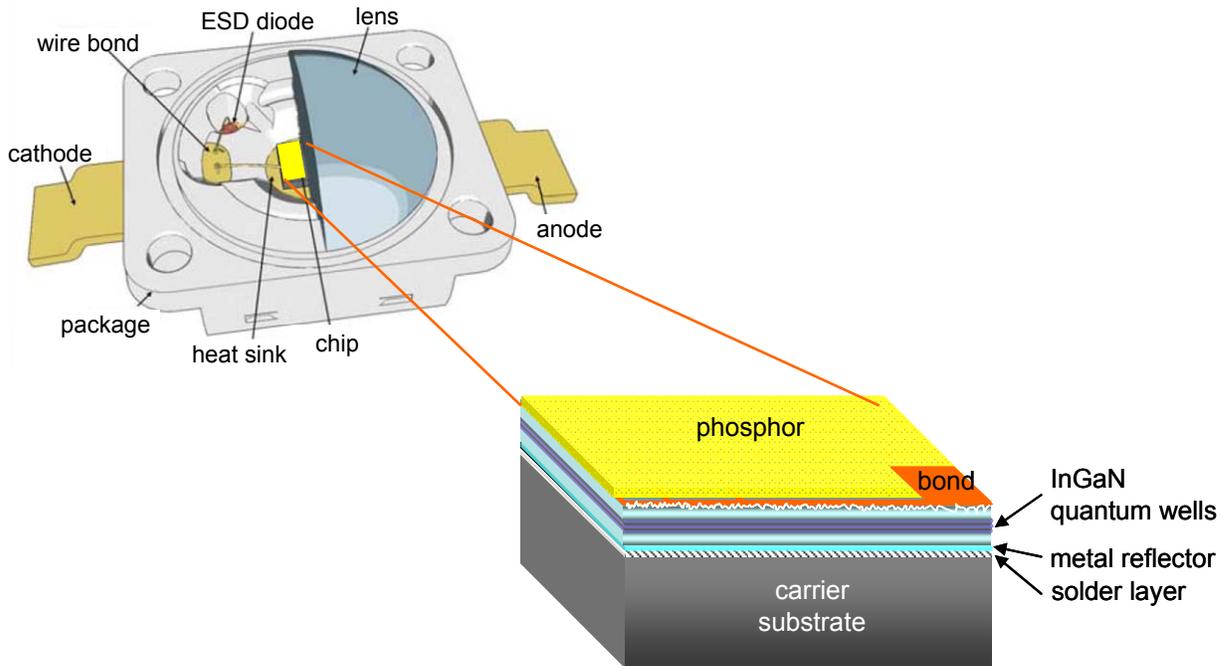


Fig. 4 Schematic drawing of a white Golden Dragon Plus LED and the cross section of an LED chip

All other components needed to manufacture the Parathom LED lamp, such as the bulb and ballast, are produced in China.

Use Phase

The use phase was modeled by average processes without heating value or direct emissions. The emissions, as outcome from the use phase, are resulting only from power supply. For the use phase in Europe the power mix of the European Union was taken into consideration⁴. For the European average power mix, 1 kWh electricity has a CO₂ output of 0.55 kg.

End of Life Phase

For all systems as end of life scenario incineration of household waste is modeled. Although CFL and LED lamps are obliged to be recycled professionally according to the EU Directive 2002/96/EC-WEEE, many lamps are cast away by the consumer, which is the reason why disposal in domestic waste was assumed. For the CFL and LED lamp this is not the required method of disposal as valuable raw materials can be recycled, but all

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lamps were treated in the same way for comparative reasons. A professional disposal is handled in the sensitivity analyses.

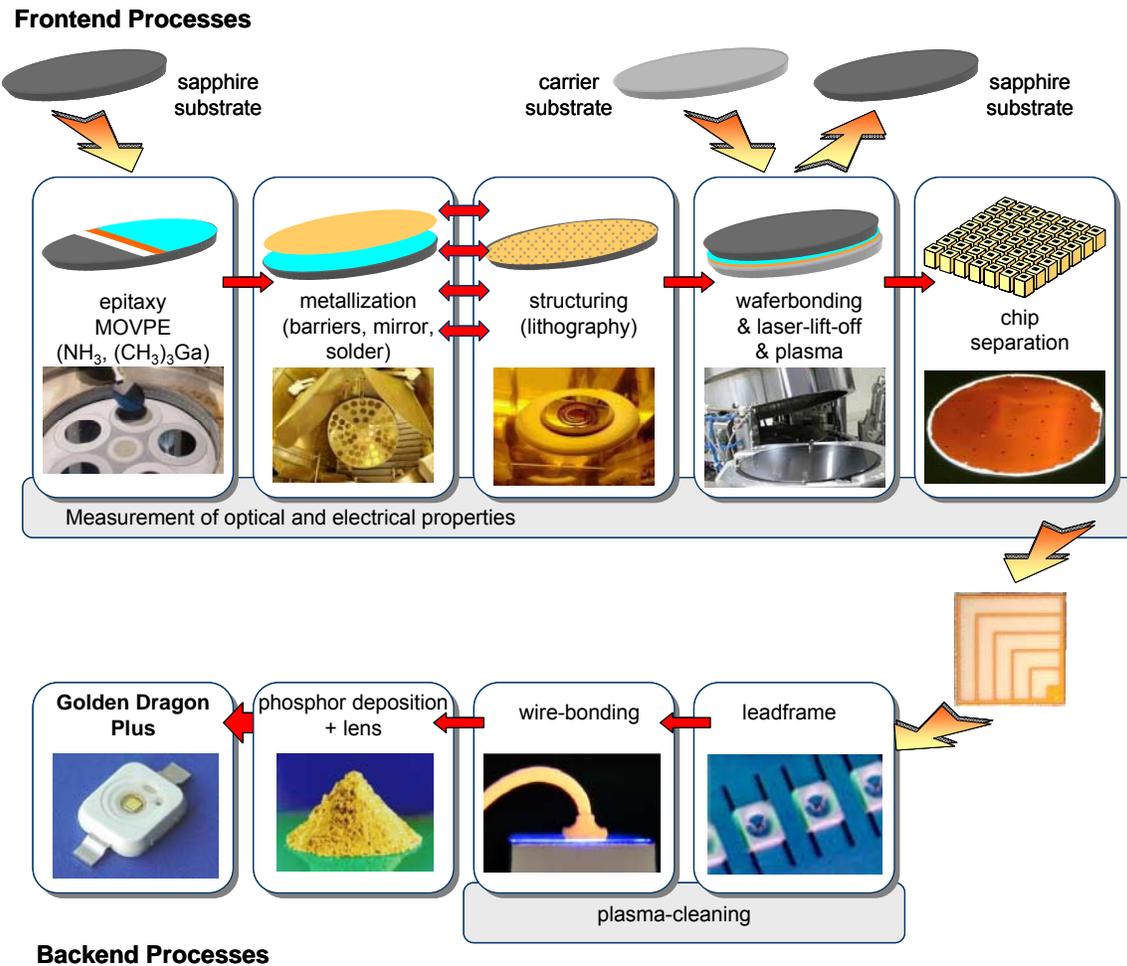


Fig. 5 Basic front- and backend processes in the manufacturing chain of a white Golden Dragon Plus

Results of the Life Cycle Assessment

Primary Energy Demand

The frontend processes, their energy demand and materials utilized in that processes were analyzed in detail while for the backend the materials were analyzed separately and an allocated value for common consumption was taken into account. Thus

the columns for frontend and backend show different categories (figure 6). About 0.41 kWh of primary energy is needed for the production of one Golden Dragon Plus. Frontend and backend consume almost the same amount of energy. It was assumed that the production of LEDs results in 100% yield, which is not realistic. In the sensitivity analyses a worst case scenario with reduced frond- and backend yields was modeled. It did not make a discernable difference in the final outcome.

The total primary energy demand for the LED lamp is 9.9 kWh. The LEDs themselves have a share of 30% of the primary energy demand of the LED lamp out of which the metals included have a dominant share. The CED of the lamp is dominated by the common power consumption for production, the large amount of aluminum required for the heat sink and the ballast.

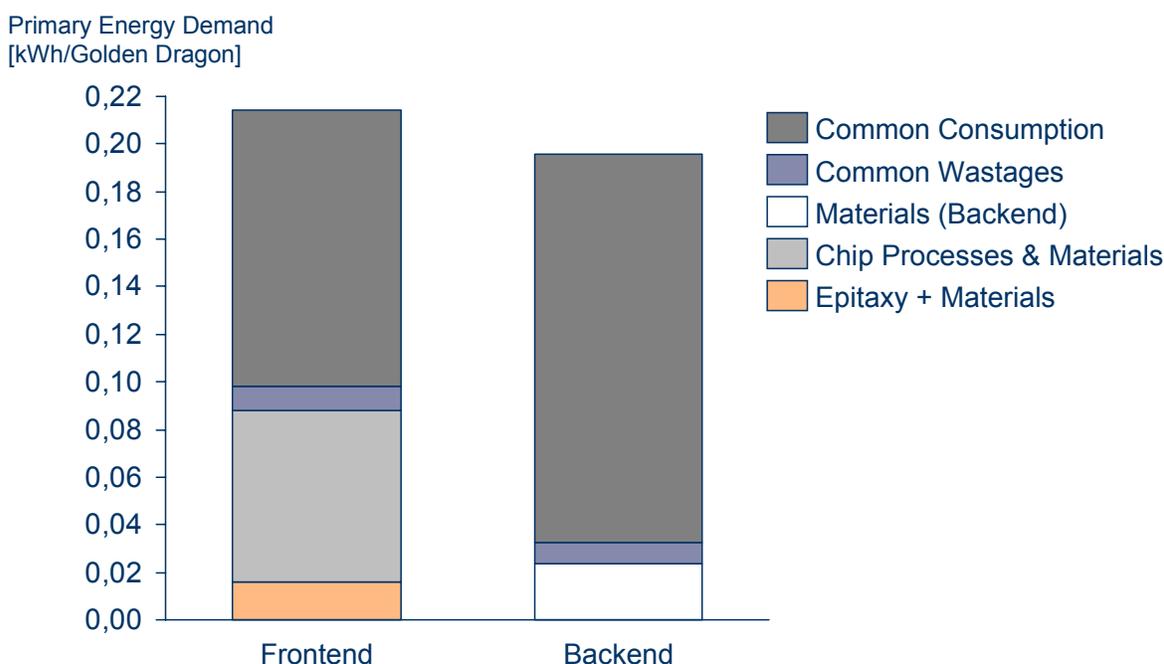


Fig. 6 Primary Energy Demand of front- and backend manufacturing for the Golden Dragon Plus

In figure 8 the primary energy demand of all three lamp types is depicted, multiplied by the number of lamps needed for a lifetime of 25,000 hours. With about 0.61 kWh the GLS consumes the lowest amount of energy during manufacturing. However, 25 bulbs are needed to compensate a lifetime of 25,000 hours and thus the GLS solution has the highest CED. CFL and LED are consuming about the same amount of primary energy over 25,000 hours.

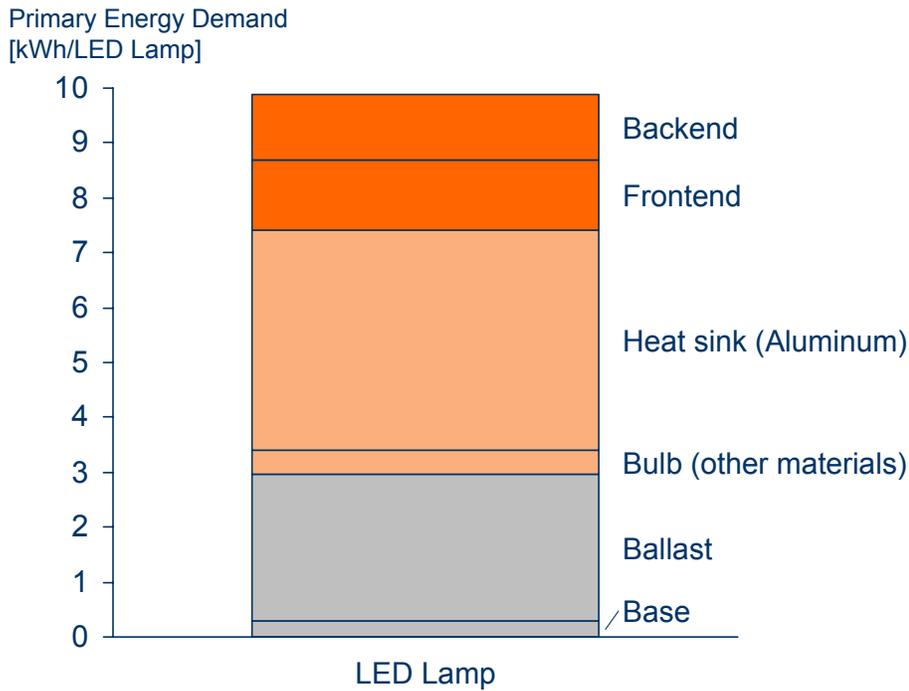


Fig. 7 Primary Energy Demand for manufacturing of the Parathom LED lamp (Transportation included)

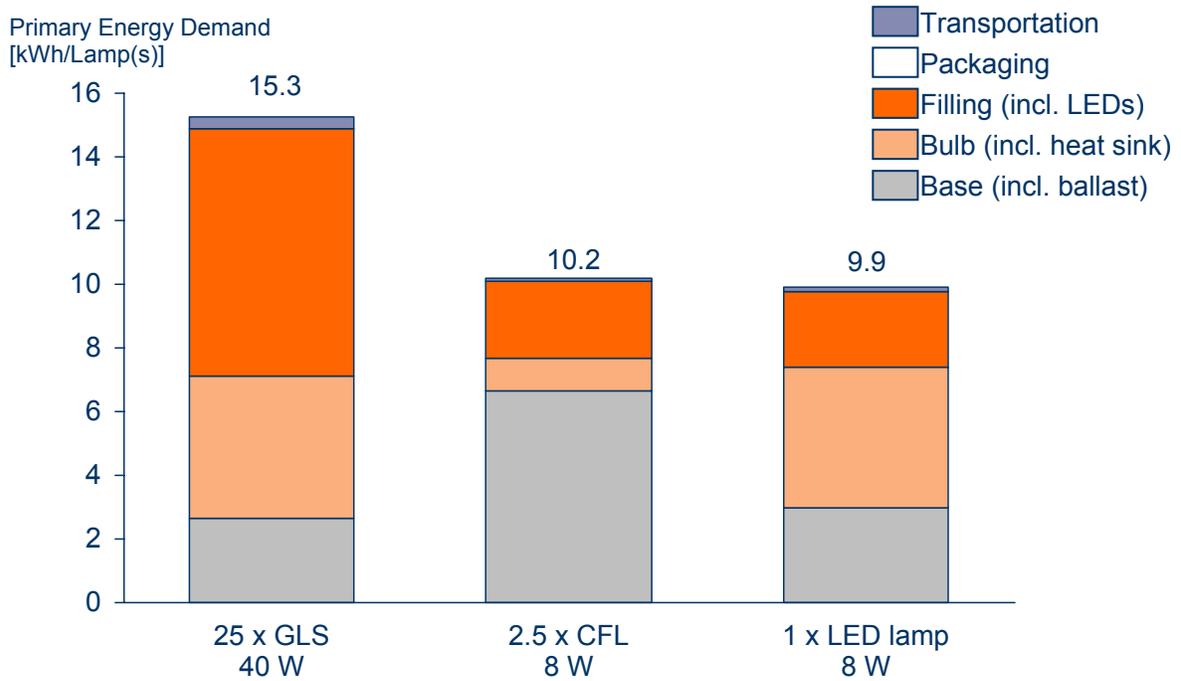


Fig. 8 Primary Energy Demand for manufacturing of all three lamps (Transportation displayed separately)

Over the entire life cycle of the lamps, including manufacturing, use and end of life, it was found that the use phase dominates the manufacturing phase in terms of energy consumption by far. The primary energy consumption over the entire life cycle of the LED lamp and CFL is about 667 kWh, while that of the GLS is about 3302 kWh – almost 5 times more. Since the use phase of the CFL and LED lamp is dominant and they run on equal wattage, they had the same total primary energy consumption as well as electricity consumption. For electricity consumption that means: over their life of 25,000 hours the GLS consume 1000 kWh, while the CFL and the LED lamp merely consume 200 kWh of electricity, thus provide 80% saving potential.

The energy demand of the manufacturing has been zoomed out by a factor of 10 as otherwise it cannot be seen (figure 9). Less than 2% of the primary energy demand over the complete life cycle is required for manufacturing. End of Life is not depicted in the diagram, as it is not visible due to the extremely small role it plays with about 0.1% of the primary energy demand over the entire life cycle. For the GLS a credit of 3 kWh is obtained, for the CFL and LED lamp less than 1 kWh is gained. Thus the above values for the entire life cycle are achieved.

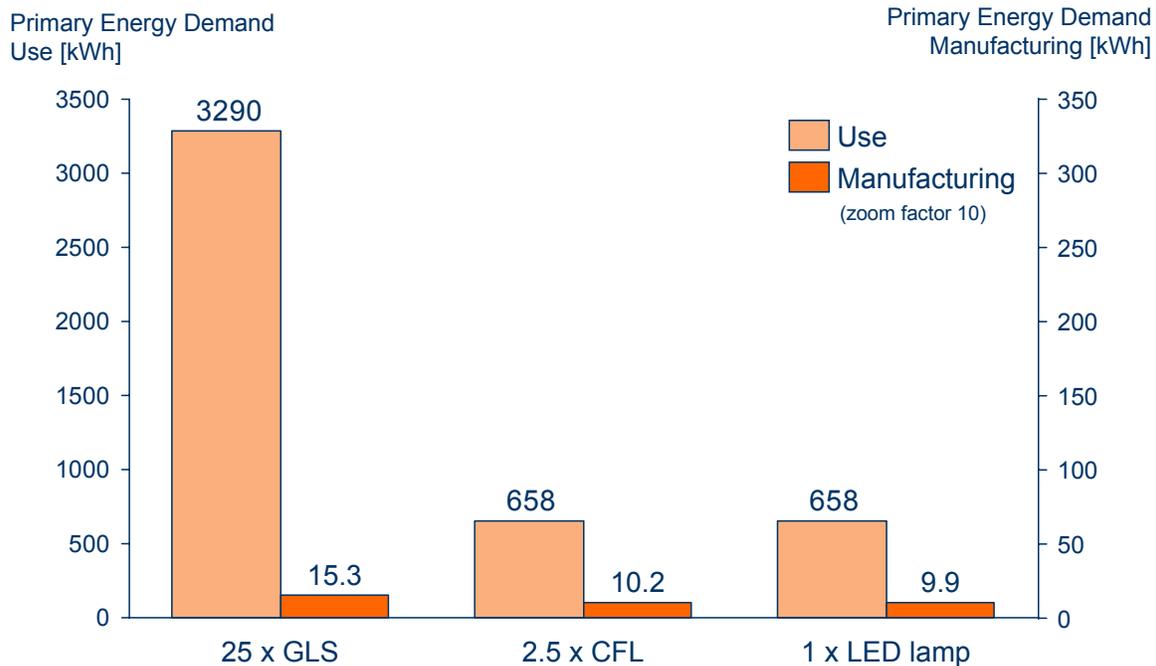


Fig. 9 Primary Energy Demand for manufacturing and use of all three lamps

Environmental Impact Categories

The domination of the use phase over the manufacturing phase observed for the CED was found for all environmental impact categories. Extremely high results for the GLS are caused by the high number needed for 25,000 hours, and the comparatively high wattage needed to run them. The required energy dominates the environmental impact categories. Thus the diagrams for all other CML categories (AP, EP, POCP, etc.) show the same tendency: The GLS always have very high values, while the CFL and LED have equally low results. Thus only the manufacturing phase is interpreted in the following. End of life, again, has such a minor impact that it is not depicted here.

1. Global Warming Potential (GWP)

The high impact of the 25 GLS on GWP (figure 10) during manufacturing is mainly caused by aluminum in the base and power consumed in all processes. The most relevant processes for the CFL are the ballasts, most influenced by the printed circuit board and all power-consuming processes. The results for the LED lamp are influenced by aluminum as a heat sink that consumes much power during its production, and by the ballast, as well as by power-consuming processes.

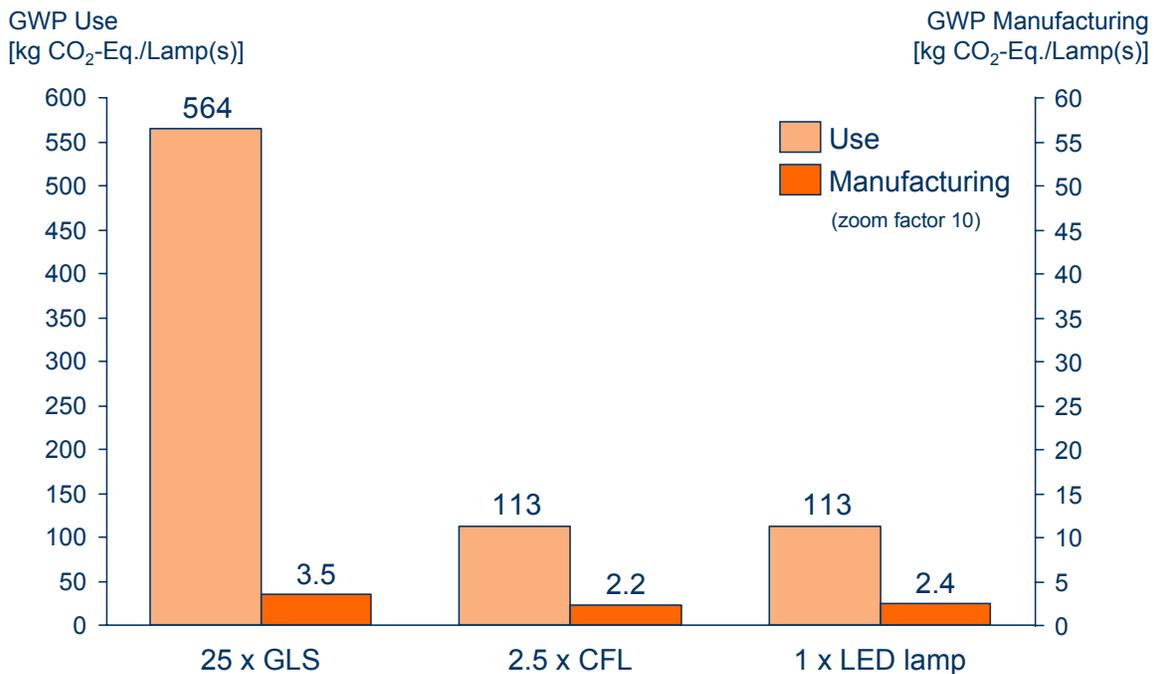


Fig. 10 Global Warming Potential for manufacturing and use of all three lamps

2. Acidification Potential (AP)

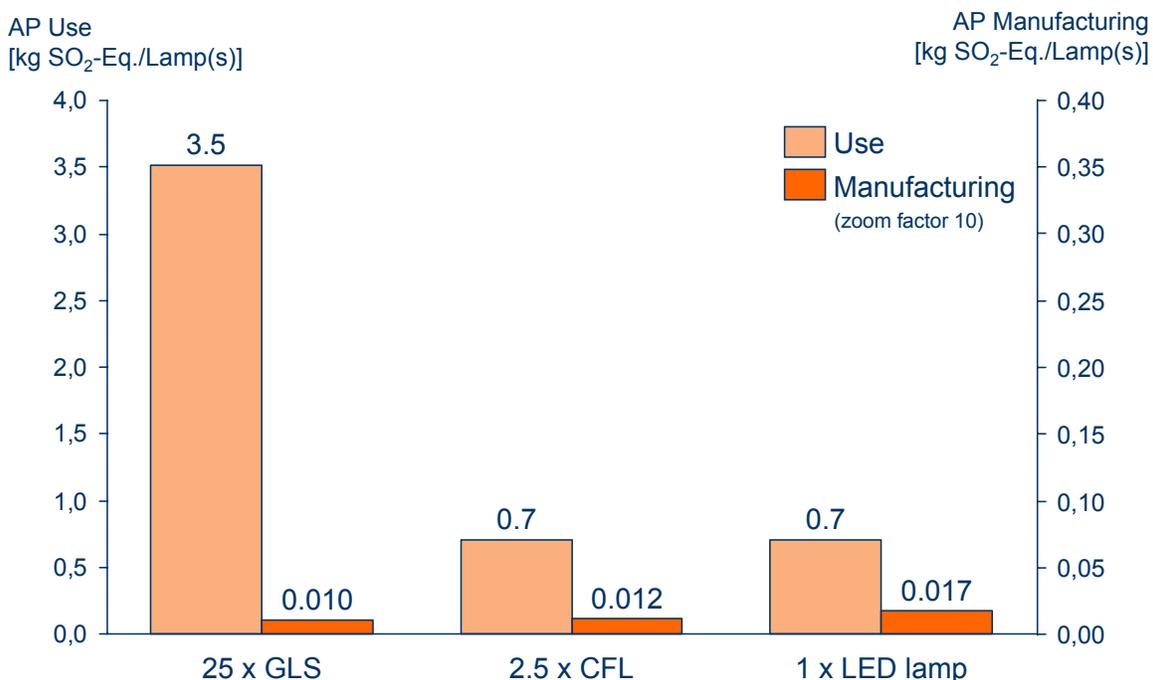


Fig. 11 Acidification Potential for manufacturing and use of all three lamps

The AP for the LED lamp during manufacturing is higher than for the other two lamps. The power consumed for the production of the aluminum heat sink, ballast, metals such as gold or copper, and the bulk carrier, as well as the common power consumption were the main contributors of the LED lamp to acidification. Just like the GWP, CFL and GLS were dominated by power consumption, caused by the ballast for the CFL and aluminum for the GLS. Nevertheless, the AP during the manufacturing phase is less than 2.5% for all lamps of the overall AP over the life cycle.

3. Eutrophication Potential (EP)

Concerning the manufacturing phase, the EP of the GLS is worse (figure 12). Relevant contributors to the eutrophication on the LED manufacturing side are chemicals in common waste of the LED frontend process. Transportation included in the manufacturing is also a big contributor to EP.

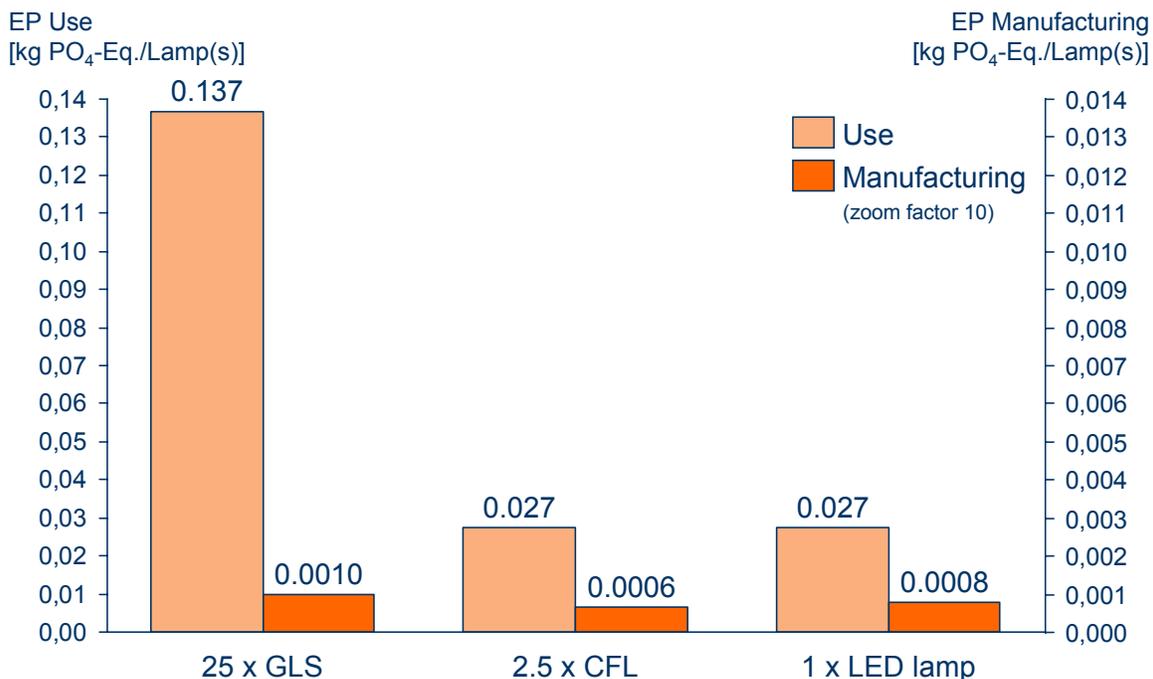


Fig. 12 Eutrophication Potential for manufacturing and use of all three lamps

4. Photochemical Ozone Creation Potential (POCP)

The LED lamp shows higher values for the POCP of the manufacturing phase than the other two lamps due to chemicals in common waste of the LED frontend process. However, that minor difference is negligible with respect to the use phase. Less than 2.5% accounts for the manufacturing phase compared to the POCP of the entire life cycle (figure 13).

5. Human Toxicity Potential (HTP)

It must be noted that in general the HTP for the manufacturing phase of all lamps is higher compared to the other environmental impact categories (figure 14). For the CFL and LED lamp the HTP of the manufacturing phase is almost 10% of the HTP over the life cycle. The hot spots for HTP are impacted by the heat sink, gold (LED lamp), ballast and power (CFL), and insulter. The toxicity emissions are mainly caused by power consumption.

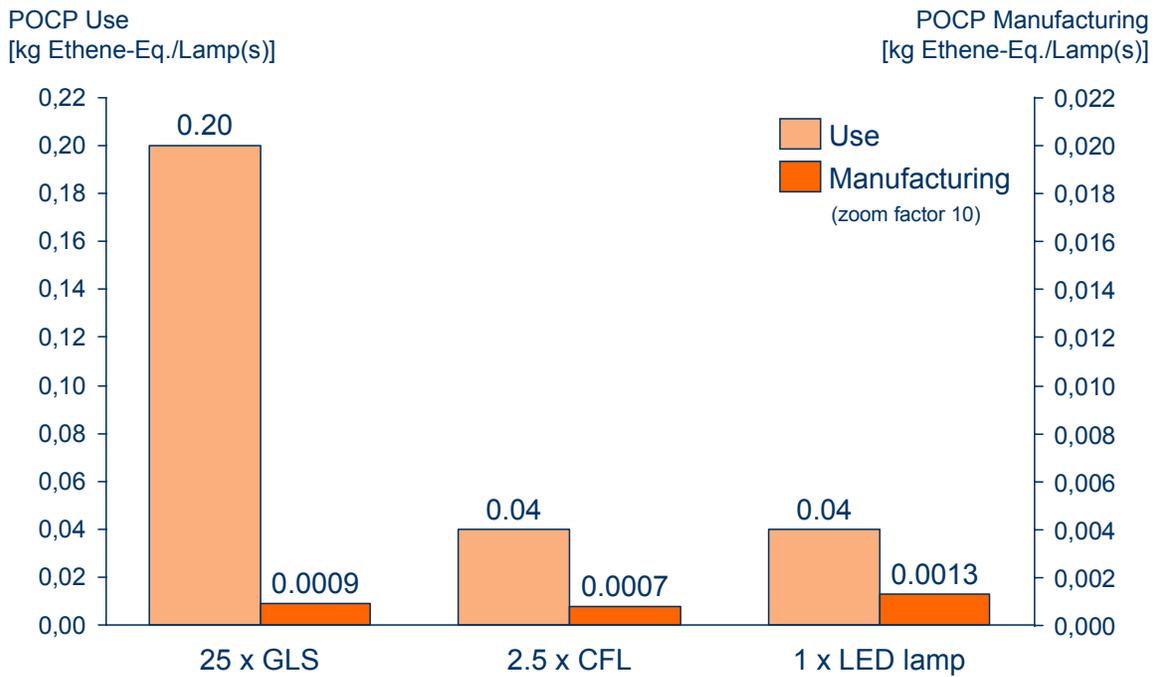


Fig. 13 Photochemical Ozone Creation Potential for manufacturing and use of all three lamps

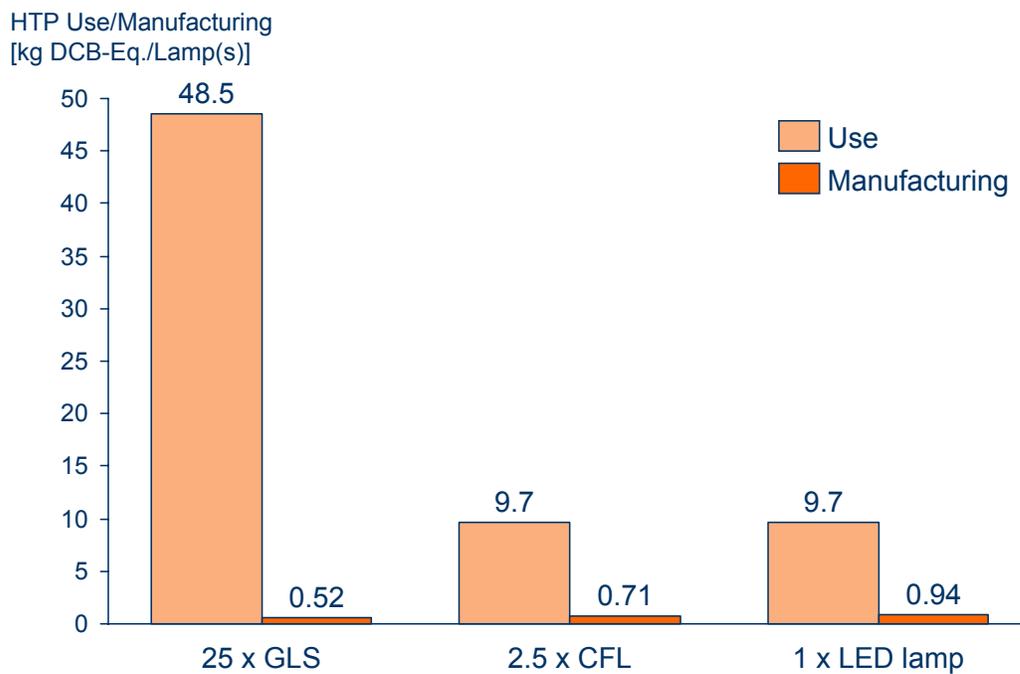


Fig. 14 Human Toxicity Potential for manufacturing and use of all three lamps

6. Abiotic Depletion Potential (ADP)

The GLS have the largest ADP values in manufacturing since the processes that consume the most power are relevant (figure 15). Consumption of coal or gas is dominant for the abiotic depletion rather than the raw materials used in the lamps.

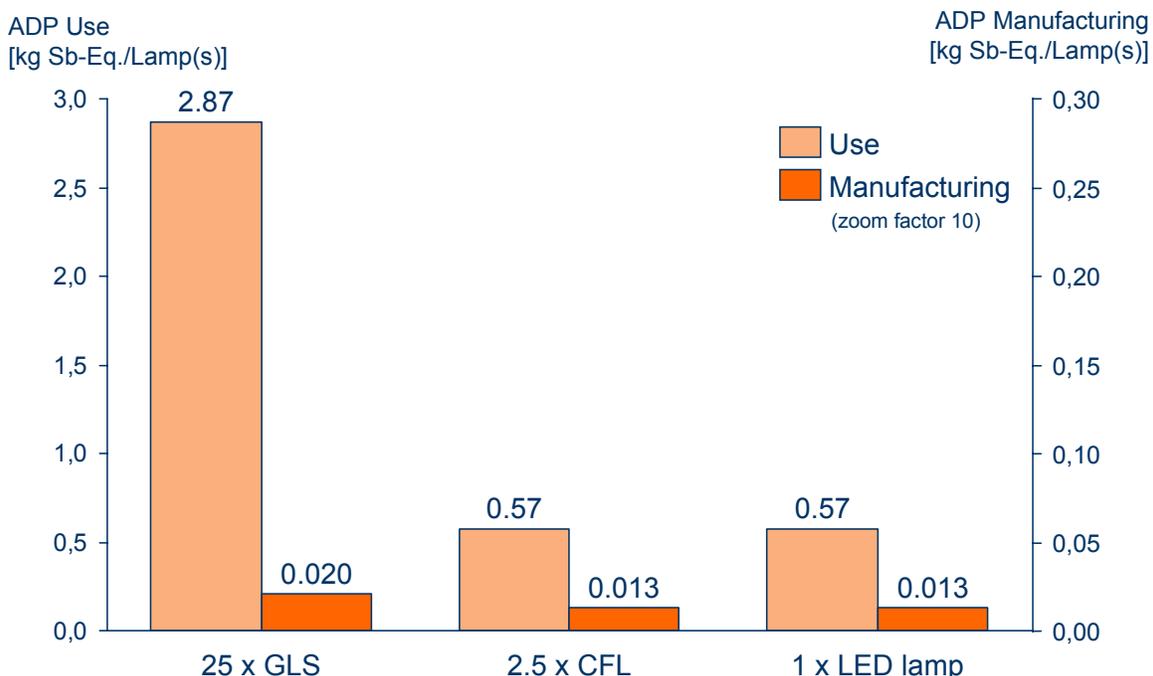


Fig. 15 Abiotic Depletion Potential for manufacturing and use of all three lamps

End of Life

End of Life, as before mentioned, is incineration for all three lamps. When a lamp is burned, residues and emissions occur but in turn electricity is won. In the study, that was taken into account by giving the electricity a credit, so that it is subtracted from the impact during use. For some categories the whole End of Life process results in a credit. This happens when the amount of electricity is larger than the residues and emissions that have potential to harm the environment. Thus a positive return of e.g. energy is achieved which results in a credit for the overall life cycle. All lamps are treated in the same way, and the quantity of impacts and credits are based on incinerated masses (25 GLS, 2.5 CFL and 1 LED incinerated). All three lamps have credits as a result of the burning process, including credits for electricity and steam. But in relation to the whole life cycle, the EoL is negligible for all lamps as less than 0.1% credit is achieved for each lamp over their life cycle. Professional recycling is treated in the sensitivity analyses.

Sensitivity analyses

A number of sensitivity analyses were performed in order to investigate the stability of the result. These include professional lamp disposals or yield corrections for front- end backend processing. Also heating benefits and energy mix were discussed.

In the base case of this study incineration by household waste is used for all lamps. But an LED lamp is an electronic product and must be recycled according to the EU Directive 2002/96/EC-WEEE to recycle valuable raw materials. The CFL also has to be disposed of in a professional manner, because it is an electronic device and because of the mercury inside the lamp. Although compact fluorescent lamps and LED lamps are obliged to be recycled professionally, many lamps are cast away by the consumer, which is the reason why this was analyzed in the basis scenario. Furthermore, we wanted to walk away from criticism that we were modeling an advantage for the CFL and LED. For GLS there is no professional treatment process existent.

But once again, CFLs and LED lamps have to be collected separately from household waste. Both lamps have to be treated in a professional manner.

Waste treatment is handled according to above mentioned EU Directive. The following model uses recycling of metals, and incineration of remaining mass and cardboard. That means that this modeling includes credits for the main raw materials like copper, brass, aluminum and glass, while the rest of the lamp is incinerated.

Treatment in a professional manner results in credits for the environmental categories, but over the life cycle it is still negligible. High credits are achieved for HTP and ADP because of credits for noble metals.

It was assumed that the production of LEDs results in 100% yield, which is not realistic. An analysis assuming a worst case scenario of only 40% yield in the frontend and 80% yield in the backend was done. That would result in an additional primary energy demand of the LED lamp of about 2.7 kWh. The total primary energy demand for an LED lamp is 9.9 kWh and thus increases to 12.6 kWh with this worst case yield correction. Overall even if the worst case is assumed no discernible difference in the final outcome over the life cycle is resulting.

The heating benefit of a GLS always leads to a discussion. This chapter estimates the actual benefit of heating losses during usage. By assuming 250 heating days, 1000 hours of GLS burning time per year, 75% GLS lighting during heating days, and heating with natural gas, it would lead to a reduction of 17 kg CO₂ over 25.000 hours. This saved amount is negligible in comparison to the whole life cycle, and there is no reason to hold on that argument. Furthermore, the heating benefit could also serve as a disadvantage when cooling is necessary.

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The overall result over the life cycle is dominated by the electricity mix. Taking different energy mixes into account (Energy mix China or by nuclear power) has significant impact on the results. However, as all lamps are referring to the same electricity mix and the use phase is dominant for all lamps, the ranking between the technologies was unchanged.

Future Outlook

Since the LED has incredible development potential in comparison to the relatively mature CFL and GLS technologies, a future scenario was calculated. In the future, LEDs are predicted to achieve 150 lm/W for warm white and even 180 lm/W for cold white light emission. Taking into account losses in the electronic ballast and optics as well as thermal losses, an LED lamp could reach an efficacy of 100 lm/W. And that is even a more conservative assumption.

In that case a light output of 400 lm can be achieved with just 4 W of power consumption. That would cut down all values for the use phase by half. In the use phase the LED lamp would only need about 335 kWh of primary energy over its lifetime of 25,000 hours, or 100 kWh of electricity.

In the manufacturing phase, improvements are also expected: less aluminum will be needed in the heat sink in the future. Thus the LED lamp will also be the favored solution with respect to all environmental impact categories.

Conclusions

The main findings of this study are:

- **Less than 2% of the total energy demand is needed for production of the LED lamp**
The manufacturing phase is insignificant in comparison to the use phase for all three lamps as it uses less than 2% of the total energy demand. This study has dismissed any concern that production of LEDs particularly might be very energy-intensive. Merely about 0.4 kWh are needed for production of an LED (OSRAM Golden Dragon Plus), about 9.9 kWh for the production of the Parathom LED lamp including 6 LEDs.

- **LED lamps are competitive to CFL today**

In contrast to the primary energy consumption of incandescent lamps of around 3,302 kWh, CFL and LED lamps use less than 670 kWh of primary energy during their entire life. Thus 80% of energy can be saved by using CFL or LED lamps. The bottom line is that LED lamps are more efficient than conventional incandescent lamps and also ahead in

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terms of environmental friendliness. Even today, LED lamps show nearly identical impact on the environment compared to CFL.

- **Future improvements of LED lamps will further cut down energy demand**

As the efficiency of LEDs continues to increase, LED lamps will be capable of saving more energy and achieving even better LCA results in future.

This life cycle assessment proves that LED lamps are amongst the most environmentally friendly lighting products.

Annex: Critical Review

This executive summary is based on a comprehensive LCA report which was critically reviewed against ISO 14040/44 from Prof. Matthias Finkbeiner, TU Berlin, Germany (chair) Associate Professor Stig Olsen, Danmarks Tekniske Universitet Copenhagen (LCA methodology), Prof. Jens Hesselbach, Limón GmbH (energy expertise, LCA methodology). This executive summary and its interpretations were not part of the critical review process, but all quantitative results are taken from the reviewed LCA report.

