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BUILDING TECHNOLOGIES PROGRAM

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

Part 2: LED Manufacturing and Performance

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Prepared by:
Pacific Northwest National Laboratory
N14 Energy Limited

DISCLAIMER

AUTHORS

Michael J. Scholand, LC
N14 Energy Limited

Heather E. Dillon, Ph.D.
Pacific Northwest National Laboratory

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Lesley Snowden-Swan	Pacific Northwest National Laboratory
Jason Tuenge	Pacific Northwest National Laboratory
Mary Ashe	Navigant, Inc.

COMMENTS

Pacific Northwest National Laboratory and the U.S. Department of Energy are interested in receiving comments on the material presented in this report. If you have any comments, please submit them to Marc Ledbetter at the following address:

Marc Ledbetter
Pacific Northwest National Laboratory
PO Box 999
Richland, WA 99352
marc.ledbetter(at)pnnl.gov

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Acronyms and Abbreviations

Ag	silver
Al	aluminum
AlN	aluminum nitride
Al_2O_3	aluminum oxide (alumina)
Au	gold
CCT	correlated color temperature
Ce	cerium
CH_4	methane
CO_2	carbon dioxide
CVD	chemical vapor deposition
DOE	Department of Energy
ECD	electrochemical deposition
ESD	electrostatic discharge
GaN	gallium nitride
g	grams
H_2	hydrogen
H_2O_2	hydrogen peroxide
HCl	hydrochloric acid
HF	hydrofluoric acid
ISO	International Standards Organisation
kWh	kilowatt-hour
LCA	life cycle assessment
LCD	liquid crystal display
LCI	life cycle inventory
LCIA	life cycle impact assessment
LED	light emitting diode
LLO	laser lift off
lm	lumen
mA	milliampere
mm	millimeter (m^{-3})
MOCVD	metalorganic chemical vapor deposition
N_2	nitrogen
nm	nanometers (m^{-9})
NH_3	ammonia
NH_4OH	ammonium hydroxide
Ni	nickel
NO_x	oxide of nitrogen
O_2	oxygen
pcLED	phosphor converting LED
PNNL	Pacific Northwest National Laboratory
PVD	physical vapor deposition
R&D	research and development
SF_6	sulfur hexafluoride
SiC	silicon carbide
SiH_4	silicon tetrahydride (silane)
Sn	tin
SO_2	sulfur dioxide
SSL	solid state lighting
Ti	titanium
TMAl	trimethylaluminum
TMGa	trimethylgallium
TMIn	trimethylindium
UK	United Kingdom
µm	micrometer (m^{-6})
UPW	ultra-pure water
U.S.	United States
UV	ultraviolet
V	volts
W	watts
W	tungsten
YAG	yttrium aluminum garnet
ZnSe	zinc selenide

1 Executive Summary

The report *LED Manufacturing and Performance* covers the second part of a larger U.S. Department of Energy (DOE) project to assess the life-cycle environmental and resource costs in the manufacturing, transport, use, and disposal of light-emitting diode (LED) lighting products in relation to comparable traditional lighting technologies. The assessment comprises three parts:

- *Part 1: Review of the Lifecycle Energy Consumption of Incandescent, Compact Fluorescent and LED Lamps*. Comparison of the total life-cycle energy consumed by LED and other lamp types based on existing life-cycle assessment (LCA) literature. This report was published in February 2012 and is available on U.S. DOE website:
  http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf
- *Part 2: LED Manufacturing and Performance*. This study develops a conservative LCA method for considering both the direct and indirect material and process inputs to fabricate, ship, operate and dispose of LED products in 2012 and estimated for 2017. An LCA comparison to an incandescent lamp and a compact fluorescent lamp (CFL) is provided.
- *Part 3: LED Environmental Testing*. The purchase, disassembly and chemical testing of LED and conventional lighting products to study whether potentially hazardous materials are present in concentrations that exceed hazardous waste regulatory thresholds.

Part 1 of the overall effort reviewed existing LCA literature to determine the range of energy consumption and downstream energy savings. The report compared existing life-cycle energy consumption of an LED lamp product to incandescent lamp and CFL technologies based on 10 literature studies. Part 1 of the work provided the following results:

1. A detailed literature review of more than 25 existing LCA studies in this field.
2. A summary of the LCA process and methodology.
3. A meta-analysis based on a functional unit of 20 million lumen-hours for incandescent, halogen, CFL and LED lamps.

The Part 1 report concluded that the life cycle energy consumption of LED lamps and CFLs are similar at approximately 3,900 MJ per 20 million lumen-hours. Incandescent lamps consume significantly more energy (approximately 15,100 MJ per 20 million lumen-hours). The authors also concluded that the use phase is the most important contributor to the energy consumption, followed by manufacturing of the lamps and finally transportation (less than 1% of energy consumption). One key issue identified in the report is the high uncertainty in energy consumption associated with the manufacturing process estimates in surveyed literature range from 0.1% to 27% of the total life-cycle energy consumption.

Part 2 of the project (this report) uses the conclusions from Part 1 as a point of departure to focus on two objectives: producing a more detailed and conservative assessment of the manufacturing process and providing a comparative LCA with other lighting products based on the improved manufacturing analysis and taking into consideration a wider range of environmental impacts. In this study, we first analyzed the manufacturing process for a white-light LED lamp (based on a sapphire-substrate, blue-light, gallium-nitride LED package pumping a yellow phosphor applied to the lamp envelope), to understand the impacts of the manufacturing process. We then conducted a comparative LCA, looking at the impacts associated with the Philips EnduraLED and comparing those to a CFL and an incandescent lamp. The comparison took into account the Philips EnduraLED as it is now in 2012 and then projected forward what it might be in 2017, accounting for some of the anticipated improvements in LED manufacturing, performance and driver electronics.

Overall, this study confirmed that energy-in-use is the dominant environmental impact, with the 15-watt CFL and 12.5-watt LED lamps performing better than the 60-watt incandescent lamp. These three lamps all produce approximately the same light output (~850 lumens), but the environmental impacts associated with the incandescent are markedly more significant than the CFL and LED lamps because of the energy-in-use phase of the life-cycle.

In order to evaluate the fifteen impact measures of interest across the four lamp types considered, "spider" graphs were prepared. Each of the fifteen impacts is represented (and labeled) by a spoke in the web, and the relative impacts of each lamp type are plotted on the graph. The lamp type having the greatest impact of the set analyzed (incandescent, in this case) defines the scale represented by the outer circle at the greatest distance from the center of the web. The other products are then normalized to that impact, so the distance from the center denotes the severity of the impact relative to the incandescent lamp. In other words, those sources with the least impact will have their circle close to the center and those with the greatest impact would be on the outer perimeter of the web. The data plotted in this graph are normalized for the quantity of lighting service, measured in lumen-hours.

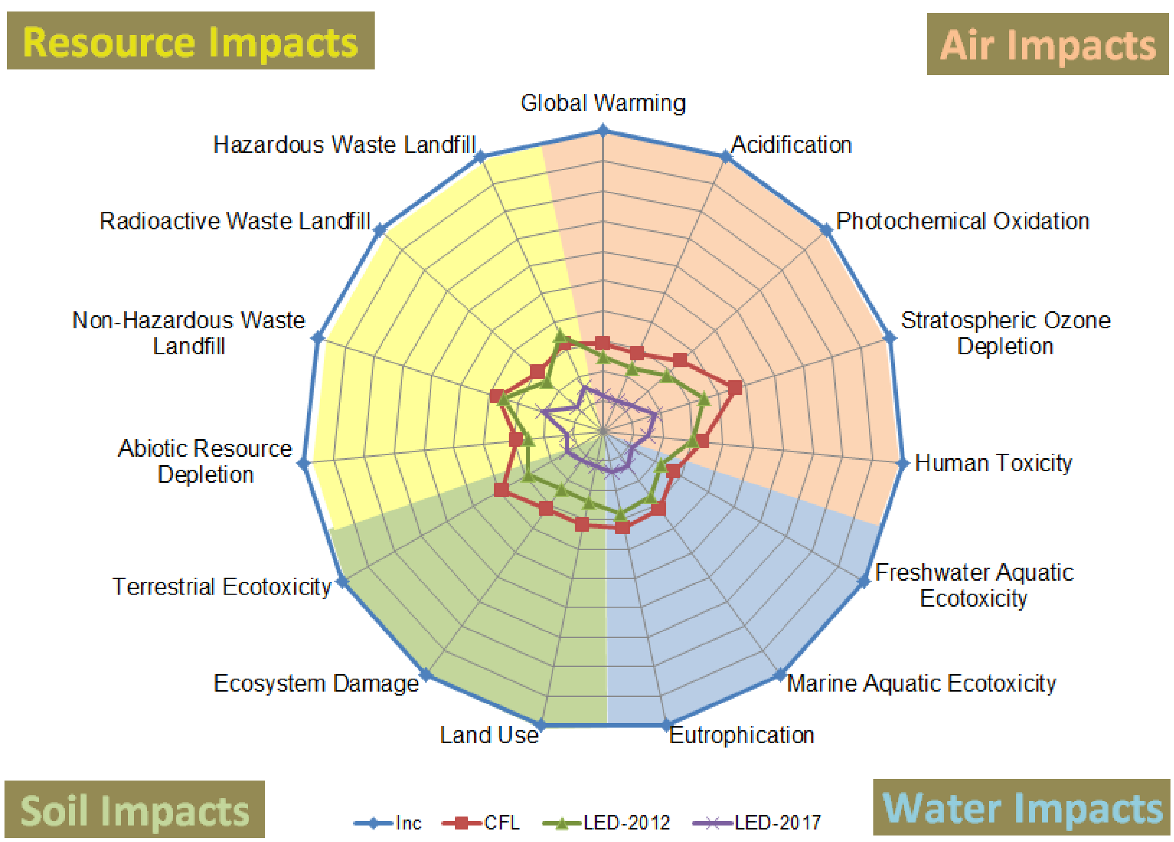


Figure 1-1. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to Incandescent

As shown in Figure 1-1, the plots representing LED and CFL technology fall well within the outer circle, illustrating clearly that the incandescent lamp has the highest impact per unit lighting service of all the lamps considered. This finding is not a function of the material content of a single lamp, as the incandescent lamp has the lowest mass and is least complex lighting system. Rather, it represents the low efficacy of this light source, and the resulting large quantities of energy required to produce light and many replacements are required to span the (longer) rated life of an LED lamp or CFL. Generating the higher amount of electric energy consumed per unit of light output causes substantial environmental impacts and results in the incandescent lamp being the most environmentally harmful across all fifteen impact measures.

While it has substantially lower impacts than incandescent, the compact fluorescent lamp is slightly more harmful than the 2012 integrally ballasted LED lamp against all but one criterion – hazardous waste landfill – where the large aluminum heat sink causes the impacts to be slightly greater for the LED lamp than for the CFL. The best performing light source is the projected LED lamp in 2017, which takes into account several prospective improvements in LED manufacturing, performance, and driver electronics.

Figure 1-2 presents the same findings shown in Figure 1-1, but the graph has been adjusted to remove the incandescent lamp and provide the impacts relative (primarily) to the CFL.

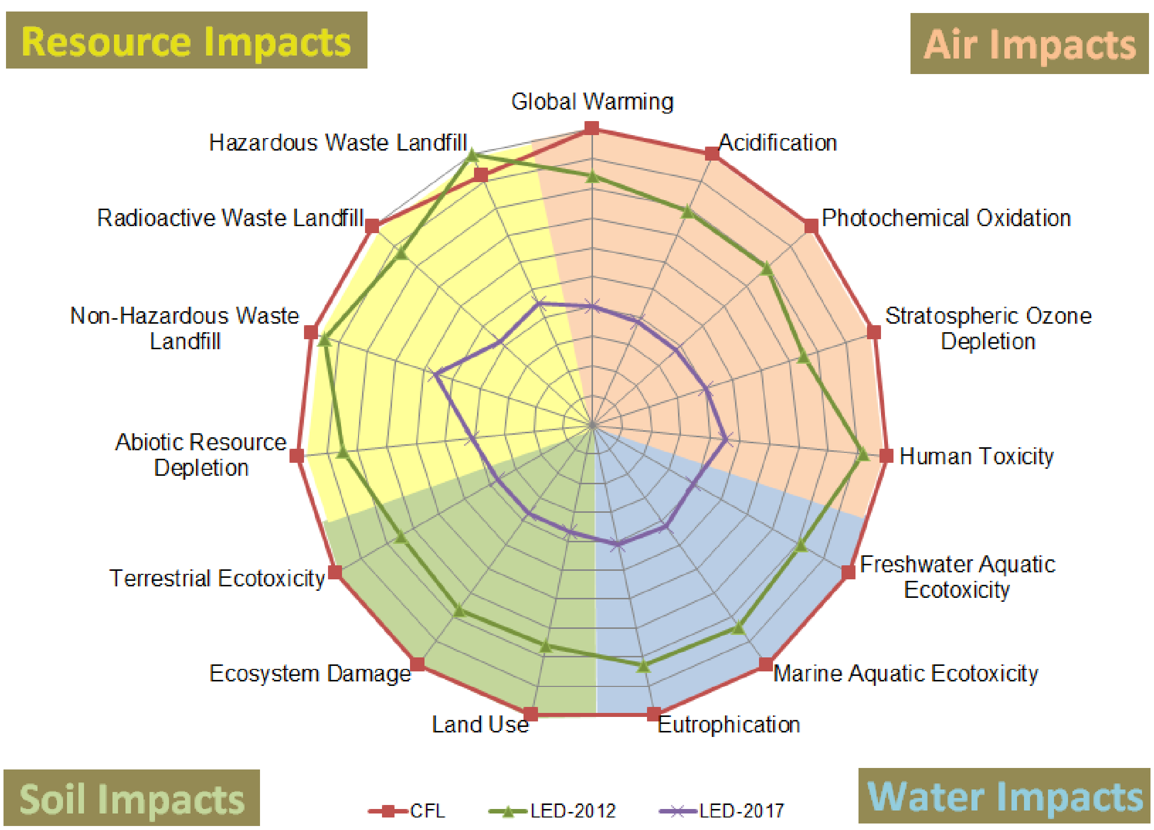


Figure 1-2. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to CFL

Overall, the prospective impacts of the improved LED lamp in 2017 are, like the others, significantly less than the incandescent, and about 70% lower than the CFL and approximately 50% lower than the 2012 LED lamp, which reflects the best available technology today. The important finding from these graphs is not necessarily the minor relative differences between the LED lamp and the CFL, but instead the very significant reduction in environmental impacts that will result from replacing an incandescent lamp with a more efficient product. Environmental impact reductions on the order of 3 to 10 times are possible across the indicators through transitioning the market to these new, more efficacious light sources. Because of the dominant role of energy consumption in driving the impacts, continued focus on efficacy targets, cost reduction and market acceptance is appropriate. Furthermore, the greatest environmental impact after energy in-use for the LED sources is the aluminum heat sink, which would be reduced in size as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat). The heat sink is the main reason that the LED currently exceeds the CFL in the category of hazardous waste to landfill, which is driven by the upstream energy and environment impacts from the manufacturing of the aluminum from raw materials. Although end-of-life was evaluated in a conservative way for this report, recycling efforts could also reduce the adverse impact of manufacturing the aluminum heat sink. The potential to alleviate impacts through good design and end of life recovery was evaluated in a letter published by Carnegie Mellon University (Hendrickson, 2010).

Underlying LED Technology Assumptions

In the literature reviewed for Part 1 of this study, one of the researchers had used the Ecoinvent database entry for the LED when characterizing the packaged LEDs from a general illumination lamp. This entry is for an indicator LED, and it is based on LED manufacturing technology from 2007, rather than the equipment being used today. For the purposes of understanding how much LED technology has improved or otherwise differs from the LED characterization in the present Ecoinvent database version 2.2, the authors prepared a comparison of the environmental impacts associated with two representative LEDs, one assumed by Ecoinvent, and the other reflecting newer technology. Due to the fact that the former LED is a 5 millimeter indicator lamp and the latter a high-brightness LED used in general illumination applications, the impacts need to be normalized for lighting service (i.e., lumen-hours) from each device. The indicator lamp was found to have a light output of 4 lumens, while the high-brightness LED was found to have a light output of 100 lumens (Radio-Electronics, 2012; Philips, 2012). The results show a significant reduction in the environmental impacts on a per-lumen basis that have been achieved between the 2007 Ecoinvent assessment and the 2011 technology that was assumed in this study. Overall, the average reduction in impact is 94.5%. Thus, on a lumen output basis, it would appear that high-brightness LEDs manufactured in 2011 are significantly less harmful for the environment than the 5mm indicator LEDs that were produced in 2007.

This report represents the first publicly available LCA that includes a unit process for the LED manufacturing specific to illumination applications. This process can be used for future investigations of other lighting products based on LEDs and can be refined by the lighting community to represent new processes as they become available. As one of the first public assessments of this type, the authors have made several conservative assumptions:

- Recovery and recycling of materials – there is a lack of information in the public domain about the extent to which materials used in the manufacturing of LEDs are reused and recycled. If these materials are recovered, processed and then reused, this would reduce the per unit production environmental impacts. However, this version of the study assumes new materials are used at all stages of the LCA process, thus providing a conservative estimate of the impacts. In other words, to the extent that materials are recovered and recycled, the environmental impacts will be less than those reported in this study.

- Transport and end-of-life – Information was limited on the transport and end-of-life phases of LED, CFL and incandescent lamps. Working estimates were developed based on available data and supplemented with stakeholder input to try and address all aspects of the life cycle.

- Wafer size – This report assumes a three-inch sapphire wafer substrate, although industry sources indicate that larger wafers are rapidly being adopted. This assumption is also conservative to the extent that improvements in this area also reduce the impact of LEDs in the next 5 years.

2 Introduction

The U.S. Department of Energy (DOE) supports the market introduction of new energy efficient products through several programs. The research described in this report falls within DOE's Solid-State Lighting (SSL) program and seeks to apply the internationally-recognized environmental assessment method called Life Cycle Assessment (LCA) to the environmental impact of light emitting diodes (LEDs). LED-based general illumination products have the potential to surpass many conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality. According to a recent forecast, LED lighting will represent 74 percent of U.S. general illumination lumen-hour sales by 2030, resulting in an annual primary energy savings of 3.4 quads (DOE, 2012d).

An LCA is a scientific methodology that enables researchers to quantify the environmental and sustainability impacts of a product across a range of categories for a product over its entire life cycle. An LCA study can take on many forms, including, for example, analysis of different products to determine their comparative impacts. LCA studies are publicly available on a wide range of products, including supermarket shopping bags (EAUK, 2011), automobile tires (Continental, 1999), lithium-ion batteries (Gaines, 2010) and lamps and luminaires (OSRAM, 2009).

Published earlier in 2012, Part 1 of this study identified gaps in the public literature associated with LED manufacturing and use (DOE, 2012a). The authors reviewed existing LCA literature, focusing on the energy consumed in manufacturing and use of the lamps studied. The report compares the life-cycle energy consumption of an LED lamp to those of an incandescent lamp and a CFL based on the findings of ten independent studies. The Part 1 report provides the following results:

1. A literature review of more than 25 LCA studies in this field.
2. A summary of the LCA process and methodology.
3. A meta-analysis based on findings of the ten most relevant studies and a functional unit of 20 million lumen-hours for incandescent, halogen, CFL and LED lamps.

Table 2-1 shows the ten studies that were used for the Part 1 analysis.

Table 2-1. Key Publications Reviewed in DOE's Part 1 Report (DOE, 2012a)

Publication Title	Author	Year	Lamp Types		
			GLS	CFL	LED
1. Life-cycle Analyses of Integral Compact Fluorescent Lamps Versus Incandescent Lamps	Technical University of Denmark	1991	X	X	
2. Comparison Between Filament Lamps and Compact Fluorescent Lamps	Rolf P. Pfeifer	1996	X	X	
3. The Environmental Impact of Compact Fluorescent Lamps and Incandescent Lamps for Australian Conditions	University of Southern Queensland	2006	X	X	
4. Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp	Rocky Mountain Institute	2008	X	X	
5. Energy Consumption in the Production of High-Brightness Light-Emitting Diodes	Carnegie Mellon University	2009			X[1]
6. Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies	Ian Quirk	2009	X	X	X
7. Life-cycle Assessment of Illuminants - A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps	OSRAM, Siemens Corporate Technology	2009	X	X	X
8. Life-cycle Assessment of Ultra-Efficient Lamps	Navigant Consulting Europe, Ltd.	2009	X	X	X
9. Reducing Environmental Burdens of Solid-State Lighting through End-of-Life Design	Carnegie Mellon University	2010			X[2]
10. Life-cycle Energy Consumption of Solid-State Lighting	Carnegie Mellon University, Booz Allen Hamilton	2010			X[3]

1. The Carnegie Mellon (2009) study only provides energy estimates for an LED package.
2. The Carnegie Mellon (2010) study only provides data on the bulk lamp materials of an LED lamp.
3. Data from this publication was provided from a poster presentation at the 2011 DOE SSL R&D Workshop.

The Part 1 report concluded that the life cycle energy consumption of LED lamps and CFLs are similar at approximately 3,900 MJ per 20 million lumen-hours of lighting service as shown in Figure 2-1. Incandescent lamps consume approximately four times more energy (approximately 15,100 MJ per 20 million lumen-hours). The authors also conclude that the use phase is the largest contributor to the energy consumption, followed by manufacturing of the lamps and finally transportation (the last representing less than 1% of total energy consumption). One key issue identified in the report is the high uncertainty associated with the manufacturing process reflecting differences among studies in literature, which span a range of 0.1% to 27% of the total energy consumption from manufacturing.

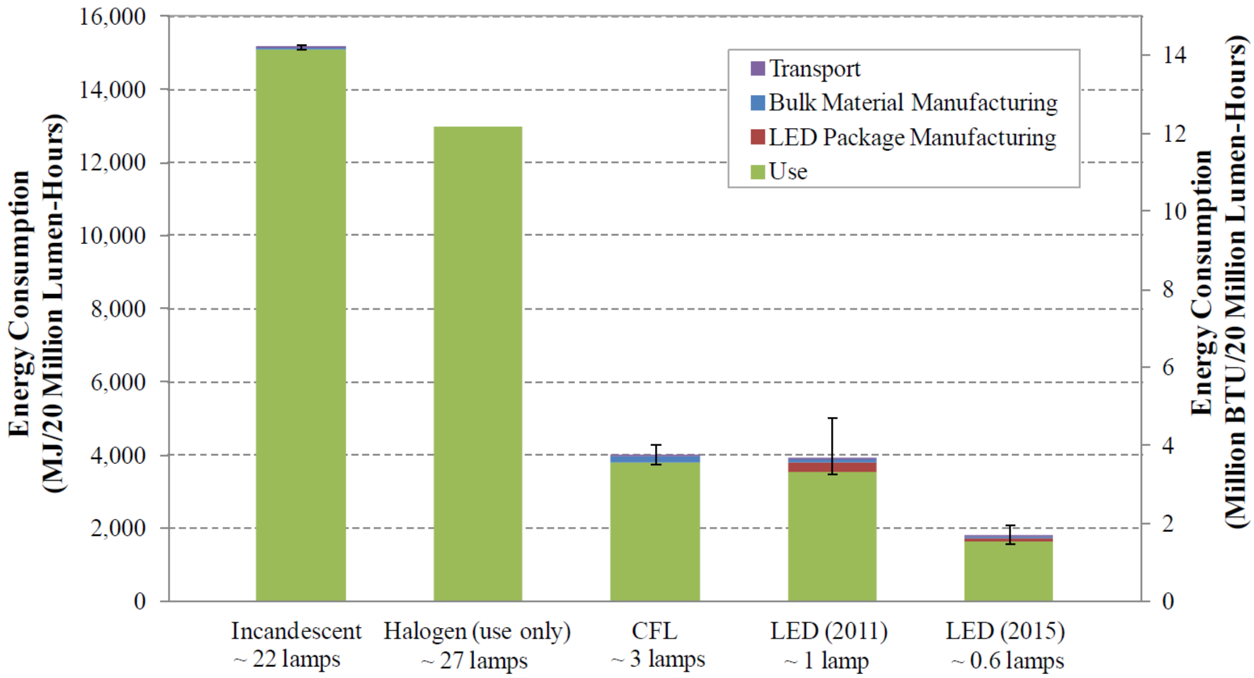


Figure 2-1. Life-Cycle Energy of Incandescent Lamps, CFLs, and LED Lamps (DOE, 2012a)

The manufacturing process for packaged LEDs has only been analyzed in two sources of literature. The first involves a simple unit process for LED's used by the electronic industry for indicator lights developed in 2007 (Ecoinvent 2012) and the second is an independent LCA performed by a manufacturer, OSRAM (OSRAM 2009). Since each of these studies has its respective limitations, the focus of Part 2 is exploring the LED manufacturing process in an attempt to address the high uncertainty in the literature.

This Part 2 report seeks also to evaluate the materials and processes that are hazardous to human health and the environment involved in the manufacturing of LED based products. The results of this analysis were then incorporated into a study of the wider life-cycle impacts of LED lamps and luminaires (addressing residential and commercial products), relative to conventional light sources.

3 Life-Cycle Assessment Methodology

An LCA is a scientific methodology that enables researchers to quantify the environmental and sustainability impacts across a range of categories for a product over its entire life cycle. An LCA characterizes and quantifies the inputs, outputs, and environmental impacts of a specific product or system at each life-cycle stage (ISO, 2006). The general procedure for conducting a life-cycle analysis is defined by the International Organization for Standards (ISO) 14000 series. The main phases of an LCA according to ISO guidelines are goal, scope, and boundary definition; life-cycle inventory (LCI) analysis; life-cycle impact assessment; and interpretation. The LCA is discussed in more detail in the Part 1 report (DOE, 2012a).

3.1 International LCA Standards

LCA methods are scientifically grounded in a series of standards and technical specifications issued by the ISO. A list of the current standards and reports included in this series is provided below, along with the ISO's brief descriptions of each document (note: some of the ISO descriptions make reference to ISO standards that have subsequently been superseded by other standards). The DOE research project conducting an LCA of LED lamps and luminaires compared to traditional light sources conforms to the methodology and requirements of the current ISO standards and technical specifications.

- **ISO 14040:2006**. Environmental management – Life cycle assessment – Principles and framework. ISO 14040:2006 describes the principles and framework for a LCA including: definition of the goal and scope of the LCA, the LCI phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14040:2006 covers LCA studies and LCI studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.

- **ISO 14044:2006**. Environmental management – Life cycle assessment – Requirements and Guidelines. ISO 14044:2006 specifies requirements and provides guidelines for LCA including: definition of the goal and scope of the LCA, the LCI phase, the LCIA phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14044:2006 covers both LCA and LCI studies. This standard supersedes and replaces ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000.

3.2 Brief Overview of an LCA

The four primary phases of an LCA process involve iterations of interpretation and revision. The diagram below illustrates these key aspects of the process, and a brief description on each is presented below the diagram. Each aspect of the process is discussed in more detail in the Part 1 report (DOE, 2012a).

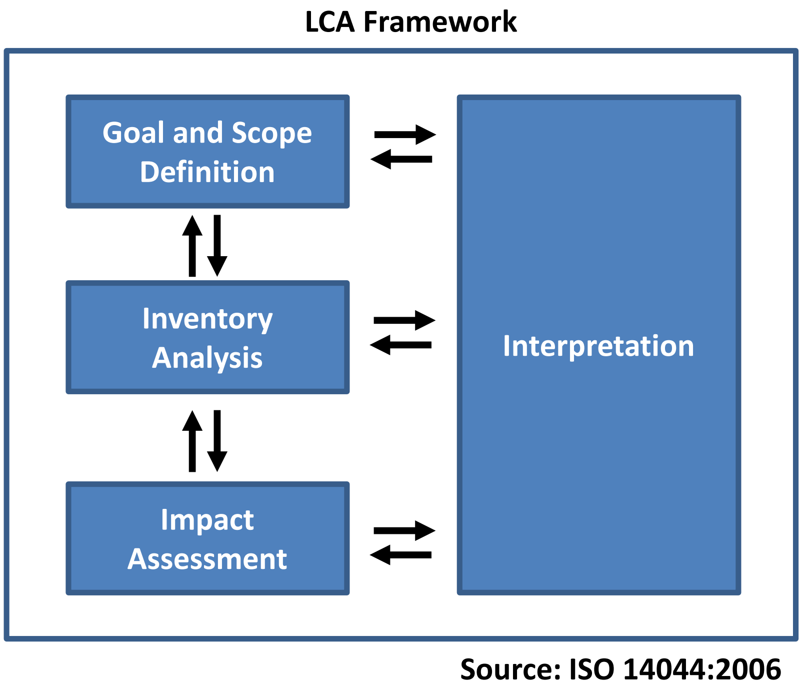


Figure 3-1. Key Aspects of an LCA Study (ISO 2006)

1. ***Goal & Scope Definition: section 4.2 ISO 14044:2006.*** The first phase of an LCA is to specify the goal and scope of the study. The goal has four key aspects, including: (1) the intended application of the study (e.g., marketing, product development, strategic planning); (2) the purpose of the study (e.g., to be published or used internally); (3) the intended audience, including shareholders, executives, consumers; and (4) use as a comparative analysis, whereby the LCA results are used to compare with other products or materials.

2. ***Inventory Analysis: section 4.3 ISO 14044:2006.*** The second phase is characterized by the compilation and quantification of inputs and outputs for a given product system through its life cycle. The data collected and used in this phase includes all environmental and technical quantities for all relevant unit processes within the system boundaries.

   The final part of this phase is a data quality and processing stage, which requires the following three actions to be completed: (1) data validation (an on-going process); (2) relating data to unit processes and (3) relating data to the functional unit. This stage is necessary in order to complete the next phase, calculating the impact for each unit process and the overall system.

3. ***Impact Assessment: section 4.4 ISO 14044:2006***. This third phase identifies and evaluates the magnitudes and relative importance of the environmental impacts arising from the inventory analysis. The inputs and outputs are assigned to impact categories and their potential impacts are quantified according to the characterization factors. Examples of the impact categories include: resource depletion (energy, water, fossil fuels, chemicals, etc.), land use, greenhouse gas emissions, and water pollution. According to ISO 14044, certain mandatory elements must be included when conducting an LCA – such as the selection of relevant impact categories,

classification and characterization. Other elements are optional, such as normalizing the findings, grouping them and/or applying a weighting of any sort.

Impact categories are chosen as the outputs from the study, for which environmental effects of the analyzed system will be quantified. This selection of categories is driven at least in part by the goal of the study, ensuring that the metrics for comparison are relevant to the objective.

4. ***Interpretation:*** In this final phase, the results are checked and evaluated to confirm that they are consistent with the goal of the study. As shown in the diagram, the three other phases are all connected to Interpretation, illustrating the point that this phase is a pivotal part of the process and can lead to revisions in any point of the process.

   The evaluation step is focused on enhancing the reliability of the study. This includes for example a sensitivity check on the uncertainties around the data, assumptions, allocation methods and calculations. It also includes a gap analysis or completeness check, to ensure there aren't any missing or incomplete areas that need to be analyzed in order to meet the goal and the scope of the study. If no missing information is identified, then this should be noted in the report. Finally, the evaluation step includes a consistency check to ensure that the methods and the goal are met, including for example, data quality, system boundaries, data symmetry or time period, and so on.

4 Goal and Scope

During the scope phase, the product or process under study is fully described, all assumptions are defined and the methodology that will be used to assess the product system is presented. There are many factors that must be taken into consideration in the scope phase, including the function of the product, the functional unit, the system boundaries, the impact categories and assessment method, the data requirements and assumptions, and the limitations of the analysis.

4.1 Goal Statement

The DOE is conducting a broad study to assess and compare the environmental impacts of general illumination LED lamps and luminaires with conventional lamps and luminaires. Table 1 provides an overview of the goal of the study consistent with the ISO standard (ISO, 2006).

Table 4-1. Summary of the Life-Cycle Assessment Goal for this Report

LCA Element	Summary for this Work
Intended Application	To compare the energy and environmental impact of LED lamps used in general illumination applications with traditional lighting products.
Reasons for the Study	• To quantify the energy and environment impacts of LEDs. • To address uncertainty in the existing body of literature and LCA reports concerning LED manufacturing methods and assumptions.
Audience	Lighting designers, policy makers, researchers and technical experts considering LED technology in general illumination applications.
Public Results	Results of this study will be freely available, published on the U.S. DOE Solid State Lighting website: http://www1.eere.energy.gov/buildings/ssl/

4.2 Scope

The scope of this study is a comparison between the energy and environmental impacts of LED technology used in general illumination applications and traditional light sources, namely incandescent lamps and CFLs. For consistency with Part 1 of the work the functional unit has been established as 20 million lumen-hours of lighting service, which is approximately representative of total light output of a Philips EnduraLED 12.5W lamp over its lifetime.

The diagram in Figure 4-1 depicts the system boundary and the five stages (Inputs, Manufacturing, Transport, Use and End of Life) of the LCA analysis. All of these stages will be discussed and analyzed for an integrated LED lamp in the context of this (Part 2) study. The red box highlights three unit processes for the LCA that focus specifically on the manufacturing of LEDs. In general, the authors found that this has not been reported in adequate detail in prior literature and thus represents an important area for study and analysis.

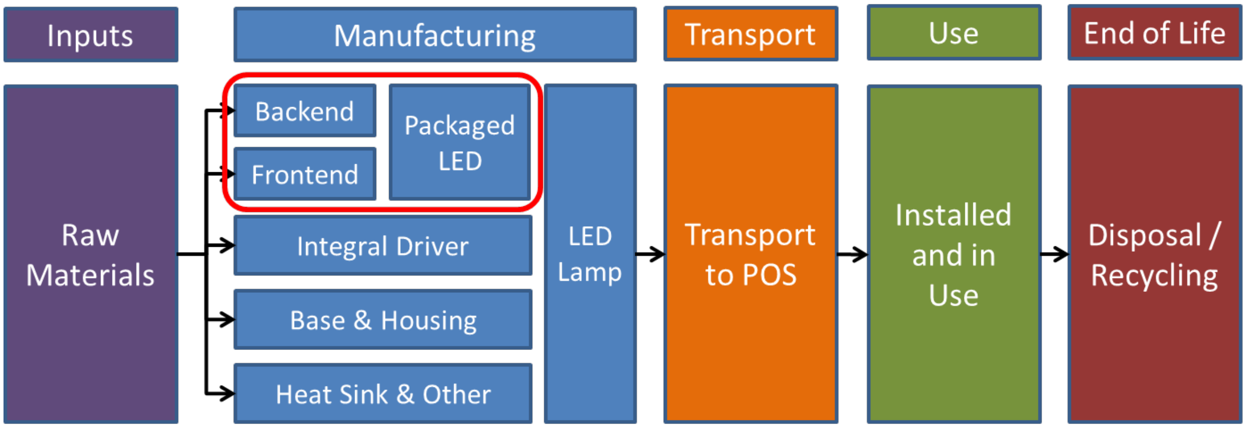


Figure 4-1. System boundary of the Life Cycle Assessment of this Study (Part 2)

As shown in the figure above, the impact inventories are broken down into the five life cycle stages, which include (1) inputs / raw materials, (2) manufacturing, (3) transportation to point of sale, (4) use of the product and (5) end-of-life disposal / recycling. These five stages of an LCA are briefly described below.

1. Raw Material Production - many products are made up of multiple components, and lamps are no exception. This first stage of the life cycle accounts for the emissions and resource usage associated with the production and transport of the various raw materials and intermediate products that are inputs to the final product. Estimating impacts of producing and transporting material inputs prior to their reaching the final manufacturer relies on Ecoinvent (version 2.2), an extensive database developed and maintained by the Swiss Center for Life Cycle Inventories.[1]

2. Manufacturing - the manufacturing phase takes all of the raw materials defined above, as delivered to the point of production, and accounts for the energies used and emissions associated with fabricating the lamp. In this analysis all of the major component parts are depicted in the figure to highlight these component parts.

3. Distribution - the distribution phase covers the transportation of the product from its point of manufacture to its point of installation and use. There might be a tendency when thinking about an LCA to believe that a detailed transport model will be required. However, for many products, transport and distribution form a small part of the overall environmental footprint. Impacts from distribution tend to be much more significant if the product needs to be refrigerated during the distribution stage of the process, which isn't the case for lighting products.

4. Use/Consumption - the use/consumption phase of a product is usually straightforward to describe, though it is important that a consistent basis is chosen to enable fair comparisons between different products. In order to be consistent with the Part 1 study, the use phase is based around the lighting service associated with each lamp type.

[1] Swiss Center for Life Cycle Inventories, http://www.ecoinvent.org/

5. End-of-Life - the final stage of a life cycle is the end-of-life stage which reflects what happens to the lighting products when they have stopped working and are no longer required. The end-of-life phase takes into account any other integral parts of a product's life-cycle, most notably the box and packaging. There is also the question of whether to give a process credit for any end-of-life recycling which could, for example, reduce reliance on raw materials. However, if a particular process assumes a reduced impact due to the incorporation of recycled materials, this might constitute double-counting. For this study therefore, any benefits associated with recycling packaging have been excluded from the system boundary.

4.3 Bounding the Scope of the Study

Due to the fact that there are many different materials, methods and technologies available for producing packaged white light LEDs, some analytical decisions were made to ensure the scope of this LCA is manageable and representative of LEDs used for general illumination. These decisions were taken with the objective of ensuring that the material and/or the process selected is common practice in the market or is representative of the methods that will be adopted in the future. In this way, the findings from this LCA study are intended to be representative of the LEDs commonly used in general illumination. Future innovations such as improved yield rates and larger wafer sizes will reduce the waste and environmental impact associated with manufacturing each packaged LED. In this way, the conclusions from this analysis represent a conservative estimate of the impacts.

Given the many different approaches and technologies for creating white-light LEDs, several decisions are needed in order to create a manageable scope for this LCA study. These decisions relate to (1) the substrate used in manufacturing, (2) the type of LED produced and (3) the methodology used to create white light.

4.3.1 Substrate

Gallium nitride (GaN) LEDs, which are commonly used as the light source for white light LEDs, can be grown on a range of different substrates, including sapphire, silicon carbide (SiC), bulk GaN, silicon, germanium, borosilicate glass, poly-crystal aluminum nitride (AlN), zinc oxide and diamond.[2] Of these, the one most commonly used for growing GaN LEDs is sapphire. In fact, it is estimated that more than 80 percent of LEDs are built on a sapphire substrate (Compound Semiconductor, 2011). Indicative of this majority share in the market, the recent surge in demand for LEDs as the television industry converted liquid crystal display (LCD) flat-screen back-lighting technology from cold-cathode fluorescent to white-light LED, the market experienced an acute shortage in sapphire wafers (Yole, 2011).

Within the substrate technologies, the general trend is toward larger wafer size in LED manufacturing. It is understood, from years of experience working with semiconductors that moving to larger wafer sizes will not only reduce manufacturing costs but will also improve yield. In moving to the larger substrate wafers, manufacturers get better results through more efficient use of the epitaxy reactor and fewer edge-related defects. However, due to deposition stresses experienced by the wafers, larger diameter wafers have to be thicker than smaller diameter wafers. The typical thickness of a 2" (51 mm) wafer is 425 µm compared to a 6" (150 mm) wafer which is typically 625 µm thick (Dadgar, 2006) – an increase of 47%.

[2] Yole Développement, personal communication, November 2011.

However, the process improvements in the reactor more than off-set the higher substrate cost, so the overall effect is a net reduction in per unit cost (LED Magazine, 2010).

The manufacturing shift to larger wafers will reduce the unusable edge area on each wafer that has to be excluded from further processing, and it enables more effective (and less wasteful) use of metal organics and hydrides in the metalorganic chemical vapor deposition (MOCVD) process. Consider the output data from the Aixtron 2800G4 HT, one of the popular MOCVD reactors used by the LED industry. The comparison is illustrated in the figure below, which shows one of the wafer trays, loaded with 42 two inch wafers on the left and 6 six inch wafers on the right.

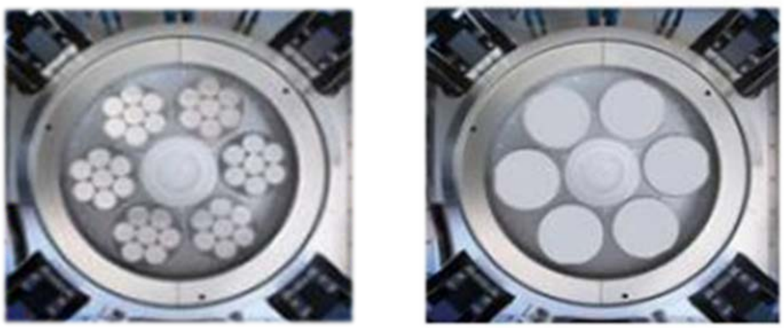


Figure 4-2. Comparison of MOCVD Reactor Tray, 2" versus 6" wafers

The table below provides the data behind the rationale for this gradual shift toward larger wafer sizes. In this table, the total wafer area that can be loaded into the machine is calculated, and then in a second calculation, the un-usable rim area is deducted from the usable area, giving the anticipated number of LED chips that would result from using the larger wafer size. For example, the surface area of a six inch wafer is nine times that of a two inch wafer, but it can yield between ten and twelve times as many chips as a two inch. Thus, industry experience with wafers for LED production has shown the yield multiplier is greater than the surface area multiplier.

Table 4-2. Wafer Sizes and the Corresponding Surface Area and Yield of LED Chips

Wafer Size	Surface Area Multiplier	Yield Multiplier (i.e., Number of LED Chips)
2 inch (51 mm)	S	N
4 inch (100 mm)	4·S	4.5·N to 5·N
6 inch (150 mm)	9·S	10·N to 12·N
8 inch (200 mm)	16·S	20·N to 22·N
12 inch (300mm)	36·S	45·N to 50·N

Source: Compound Semiconductor, 5 December 2011.

According to a study by Aixtron, a German manufacturer who produces MOCVD reactors, the overall result is a 52% increase in the usable wafer area that can be gained simply by moving from two inch diameter to the larger six inch wafers. These significant gains in LED manufacturing reflect the same savings that the silicon industry experienced as it scaled microchip production to larger and larger wafer diameters. In addition, the cost associated with retooling the MOCVD reactors to move from two inch to four or six inch, as shown by the illustration above, is not a high – the equipment has been designed to be flexible and thereby accommodate the anticipated transition to larger substrate diameters.

The following diagram prepared by Yole Développement depicts the forecasted trend in sapphire substrate diameters for the coming years (Compound Semiconductor, 2011). Small two inch (51 mm) diameter wafers are expected to be 1% by 2015, while six inch wafers (150 mm) are projected to be more than half the market in that year.

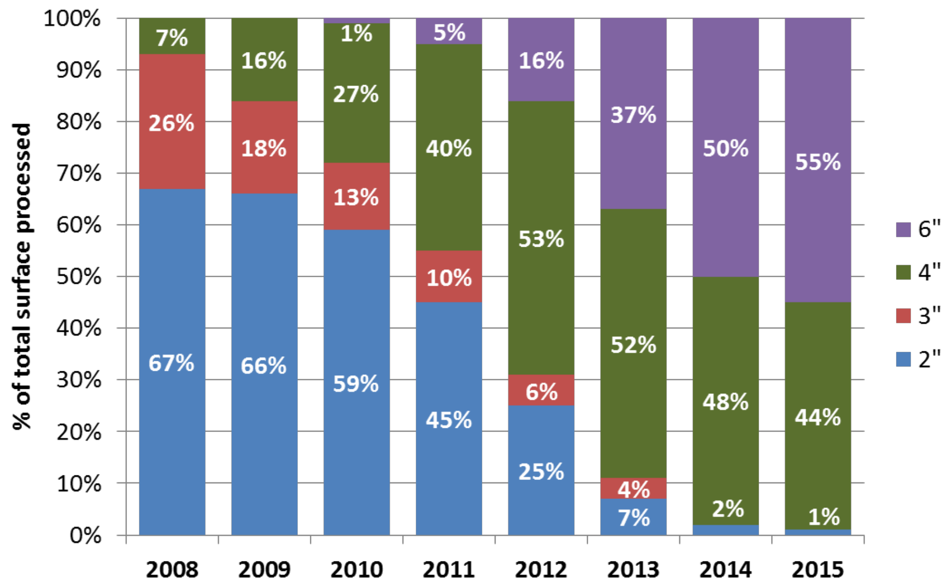


Figure 4-3. Trends in Diameter of Sapphire Substrates for LED Manufacturing
Source: Yole Développement, 2011 as published in Compound Semiconductor, December 2011.

Although Yole Développement projects a trend in the market toward larger wafer sizes, for the purposes of this study, we focused on three inch sapphire wafers for two main reasons. First, LED manufacturing with smaller diameter wafers is better known and more widespread in 2012, thus it is easier to gather data and input from experts familiar with the common practice. Second, the environmental impact per unit of LED produced (i.e., LED yield) at a smaller diameter will be greater than the impact experienced at the larger wafer sizes, which will be more prevalent in the future. Thus, by quantifying the LCA impacts of a three inch wafer in 2012, we know that these impacts represent an upper limit of environmental impacts now, and future impacts will be less than those in 2012 as the industry migrates to larger wafer sizes.

4.3.2 LED Type

Numerous chemistries have been developed for commercially available LEDs based around phosphides and nitrides. The light emission from an LED depends on the p-n junction and the chemicals (e.g., gallium, arsenic) that are doped into the layers of the LED and used to construct the active layer. These different materials emit light at discrete wavelengths in the electromagnetic spectrum, spanning from the infrared through to the ultraviolet, and including visible light. The exact choice of the semiconductor material used in the LED helps to determine the color of the light emission.

The following table presents some of the common chemistries used today in producing the colored LEDs listed in the first column.

Table 4-3. Summary of LED Colors and Common Chemistries

Color	Wavelength	Materials
Infra-Red	850-940 nm	Gallium arsenide, Aluminum gallium arsenide
Red	630-660 nm	Aluminum gallium arsenide, Gallium arsenide phosphide, Gallium phosphide
Amber	605-620 nm	Gallium arsenide phosphide, Aluminum gallium indium phosphide
Yellow	585-595 nm	Aluminum gallium phosphide, Gallium arsenide phosphide, Gallium phosphide
Green	550-570 nm	Aluminum gallium phosphide, Gallium nitride
Blue	430-505 nm	Indium gallium nitride, Gallium nitride, Silicon carbide, Sapphire, Zinc selenide
Ultraviolet	370-400 nm	Indium gallium nitride, Aluminum gallium nitride

LEDs are discrete wavelength emitters, meaning they produce light in a narrow bandwidth based on the chemistry of their underlying p-n junction. White light, on the other hand, consists of many different wavelengths (colors) of light which, when blended together, are perceived by the human eye as being "white". As discussed in the next section of this report, there are several different methods for producing white light from LEDs, however it is recognized that the vast majority of white light LEDs manufactured today are based on the combination of a blue-emitting gallium nitride (GaN) or indium gallium nitride (InGaN) LED source used in combination with a yellow-emitting cerium-doped yttrium aluminum garnet (Ce3+ YAG) phosphor (LFW, 2011).

For general illumination applications, lamp and luminaire manufacturers have some flexibility when designing the light producing portion of their equipment. This can include, for example, a cluster of many low-power LEDs which have a low light output individually, but when grouped together produce light levels sufficient for general illumination applications. This may also include devices that incorporate a small number of jumbo LEDs or multi-chip arrays, each emitting thousands of lumens. Although there is potential to use any of these approaches in general illumination applications, it is expected that the high power and jumbo LEDs will ultimately dominate the lighting market as these configurations can benefit from better optics, optimized thermal control and fewer components. The following table presents some of the electrical characteristics and applications for the different classes of white light LEDs.

Table 4-4. White Light LED Package Segmentation

Item	Low Power LED	Mid Power LED	High Power LED	Jumbo LEDs & Multichip Arrays
Driving current	5 to 20 mA	50 to 150 mA	≥ 350 mA	≥ 350 mA (up to 6.5)
Bias voltage	2.9 to 3.5 V	2.9 to 3.5 V	2.9 to 3.5 V	3 to 3.5 V
Power	<100 mW	<500 mW	1 to 3 W	1 to 3 W
Die size	200 to 360 µm	380 to 600 µm	500 to 1500 µm	>4 mm^2 (up to 36 mm^2)
Package flux	4 to 15 lm	12 to 65 lm	70 to 120 lm	up to 6000 lm
Packaging	Encapsulated LED, SMD top & side	SMD top & side	Power package	Power package; arrays
Typical Applications	Mobile phones – keypad and display Small LCD backlight Signs, large displays	TV backlighting Automobile headlights Large displays General lighting	Automobile headlights Projection General lighting	General lighting Projection Automobile headlights

Although it is possible to have general illumination devices developed from low power LEDs, devices in 2012 are more commonly designed around mid-power, high-power and jumbo-LEDs. For the purposes of this study, we will therefore focus our LCA assessment on the 1-watt LED devices which can be commonly found in multiple-LED configurations in lamps and luminaires for general illumination applications.

4.3.3 White Light

As discussed, LEDs are discrete semiconductors that produce a narrow-band emission which, depending on the chemistry, can emit energy in the ultraviolet (UV), visible, or infrared regions of the electromagnetic wavelength spectrum. To produce white light for general illumination applications, either the narrow spectral emission from LEDs must be converted into white light or two (or more) discrete LED light outputs must be mixed together.

White light LED devices are generally based on one of three approaches for producing a distribution of visible wavelengths that are perceived as “white light”. These are: (a) phosphor-conversion LEDs (pc-LEDs); (b) discrete color-mixing; or (c) a hybrid method, as shown in the figure below (DOE, 2012b). Phosphor-conversion LEDs create white light by blending a portion of the blue light emitted directly from the chip with light emission down-converted by a phosphor from the blue part of the spectrum to other colors. Discrete color-mixing, on the other hand, starts with discrete colored sources and uses color mixing optics to blend together the light output to create white light emission. The hybrid method uses a combination of pcLEDs and discrete-colored LEDs to create the desired light output. Two other methods of producing white light emission that are not discussed here include (1) an approach based on homoepitaxially grown zinc selenide (ZnSe) on a ZnSe substrate that emits blue light from the active region and yellow light from the substrate (Chang, 2007) and (2) quantum dots that achieve the light wavelength down shift within the visible spectrum (Salisbury, 2005).

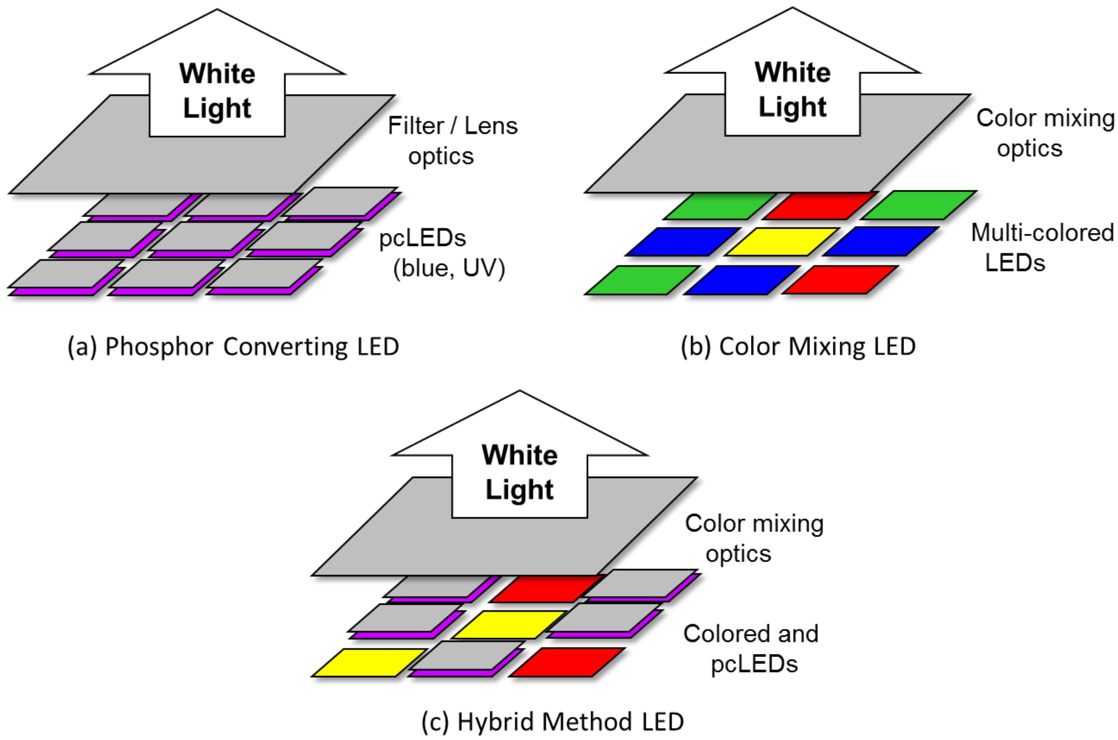


Figure 4-4. General Types of White Light Emitting Diode (LED) Devices
Source: DOE, 2012b. Solid-State Lighting Research and Development: Multi-Year Program Plan.

The majority of white light LEDs in production today are phosphor converting LEDs based on gallium-nitride, emitting blue light between 450-470 nm (DOE, 2011). This blue light excites a yellow phosphor, usually made of Ce3+:YAG crystals that have been converted into a powder. As the LED chip emits blue light, some is emitted directly through the phosphor and some is converted by the phosphor to a broad spectrum centered around 580 nm (yellow) by the Ce3+:YAG. This yellow light stimulates the red and green receptors in the human eye, resulting in a mix that gives the appearance of white light.

The pcLED approach, developed by Nichia, was first marketed by them in 1996 as a white-light LED. This approach has since been adopted by numerous other manufacturers as a method for producing white light, and constitutes the most common approach today. Depending on the phosphors used, and whether those phosphors are mounted in the LED package or located remotely (e.g., such as you find with the Philips EnduraLED lamp), there can be improvements made in the light quality and efficiency of the phosphor. While improvements in phosphor technology will yield benefits to the performance overall, the losses associated with absorbing blue light and down-converting it to other wavelengths such as green, yellow and red, establish a limit to the ultimate efficiency of the LED system. These losses are called “Stoke’s loss” and are associated with any phosphor-based down-conversion of light, including the process by which fluorescent tubes emit white light.

Discrete color-mixing of LED light emissions avoids the need for phosphors, and therefore promises to offer the highest efficacy LED device. In color-mixing, LED devices mix discrete light emissions from two or more LED chips which are blended together to produce white light. The principal advantage of the color-mixing method is that it does not involve phosphors, thereby eliminating phosphor conversion losses in the production of white light. This approach is not without its challenges however, such as multichip mounting and potentially sophisticated optics and electronics for blending and maintaining the balance of colored light emissions.

The third method shown in the figure is a hybrid approach that combines pc-LEDs and colored-light emission LEDs into the same luminaire, producing the desired white light output. For example, some manufacturers are combining pc-LEDs with high (cool-white) correlated color temperature[3] (CCT) emission with several yellow and red-light emitting LEDs to create a lower (warm-white) CCT. In this example, the discrete color-emitting LEDs are used to change cool-white CCT to a warm-white CCT. The efficacy of this hybrid system will be higher than a pc-LED system, but lower than a color-mixing system, and will be proportional to the relative share of light output of the LEDs used in the hybrid system.

The most common approach used in white light LEDs today for general illumination applications are the blue-light emitting phosphor converting LEDs. These LEDs can have a range of resultant CCT values, depending on the types and amounts of phosphor used. For lamps that use remote phosphors, the LEDs will emit a deep blue light which is then converted by the remote phosphor into white light. For the purposes of this study, we are focusing on this system – namely blue light LEDs that are pumping a remote phosphor and creating a warm white light emission.

4.3.4 The Representative LED for the Manufacturing Unit Processes

Taking into account the discussion in this chapter, the conclusion reached is that this LCA study will focus on the following archetype general illumination LED lamp system:

- Three-inch sapphire wafer substrate
- Indium-Gallium Nitride grown on sapphire substrate
- High brightness LED packages (i.e., greater than 0.5 watt / package)
- Deep-blue LEDs (which are pumping a remote phosphor)

Overall, the type of LED which is meant to be characterized by this study then would be something akin to the following commercially available high brightness products such as: Cree's XLamp; Osram's Dragon; Philips' Luxeon Rebel or Seoul Semiconductor's P4. The decision to use a three-inch wafer is intended to make the LCA conservative in assessing the technology, although it is known that the larger wafers are being adopted quickly as shown in Figure 4-3.

4.4 Limitations of the Study

The content of the literature and technical information assessed for this study was focused as much as possible on LED manufacturing and lamp parts / assembly. As discussed in the next section, matches between the material and the process in the Ecoinvent database were imperfect in some instances. The

[3] The CCT is the temperature of a blackbody that best matches the color of a given light source. It describes the color appearance of the source, measured on the Kelvin (K) scale. Lamps with a CCT below 3500 K appear more yellowish-white (i.e., warm) in color. Lamps at or above 4000 K appear bluish-white (i.e., cool) in color. For additional information, see the DOE fact sheet "LED Color Characteristics" (www.ssl.energy.gov/factsheets.html).

study investigators chose the best appropriate match, and in one instance adjusted one of the key impact parameters to account for a more energy intensive version of a similar material.

There are some gaps in relation to the life cycle assessment which have been identified:

- Emissions during LED manufacturing stage - it should be noted that direct emissions from the manufacturing process were not included in this analysis, due to lack of available data. The facilities where LEDs are manufactured operate in ‘clean room’ environments and use reactors to create the LED die. These reactors have some recovery systems that are able to reuse materials and others that allow harmless gases like nitrogen to vent into the atmosphere.

- Recovery and recycling of materials – there is a lack of information in the public domain about the extent to which materials used in the manufacturing of LEDs are reused and recycled. If these materials are recovered, processed and then reused, this would reduce the per unit production environmental impacts. However, in this version of the study, we are assuming new materials are used at all stages of the LCA process, thus providing a conservative estimate of the impacts. In other words, to the extent that materials are recovered and recycled, the environmental impacts will be less than those reported in this study.

- Transport and end of life – information on the transport and end of life phases of LED, CFL and incandescent lamps was limited. Working estimates were developed based on available data and supplemented with stakeholder input in an attempt to address all aspects of the life cycle.

4.5 Critical Review

In order to ensure the results of this work are accurate, a formal review process for the manufacturing unit process was initiated early in the study. In the expert interviews stage, manufacturers and researchers were invited to review the draft flow diagram for the manufacture of LEDs, and to comment on the various inputs and steps in that process. These comments provided corrections as well as new data to improve the accuracy of the process description. The final study has been reviewed in a similar way by a group of reviewers broader than the initial review team, but inclusive of the same group of manufacturers and researchers.

The diagram in Figure 4-5 depicts the analytical process that was followed for the manufacturing unit process part of the study, and identifies the two steps in the process where external expertise was requested. These occurred at the “Expert Interviews” stage where the draft process flow diagram was circulated with experts for review and at the “Expert Review” stage where the findings of this study compiled in a report form were again circulated for review and comment.

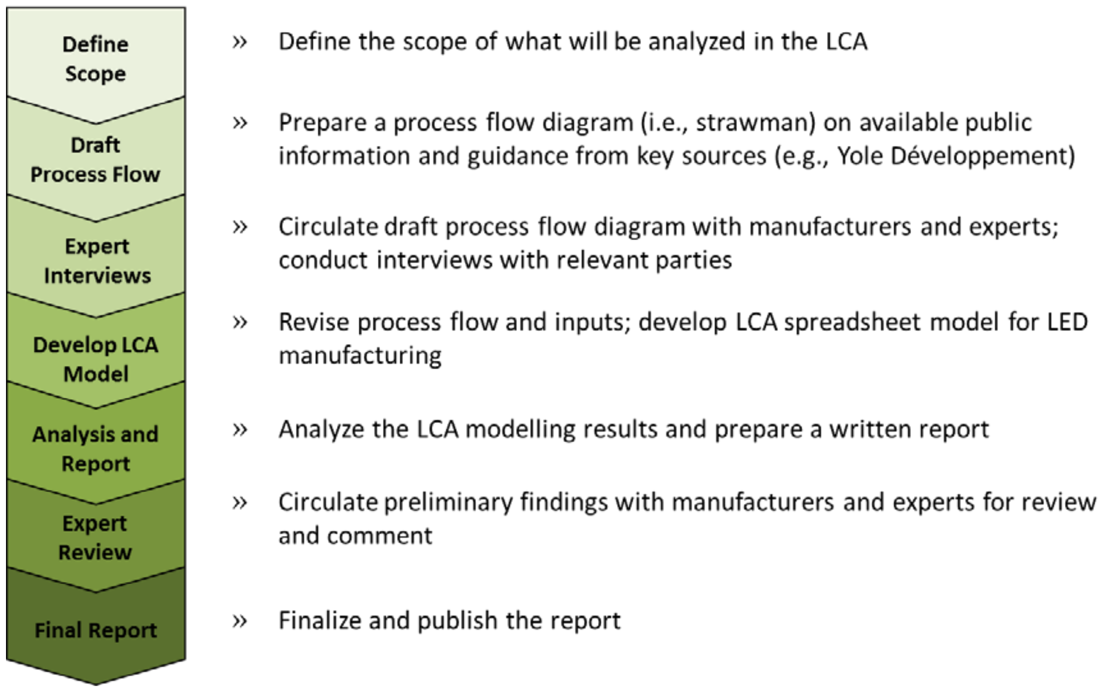


Figure 4-5. Flow of Data Gathering and Analysis for this Research Project

5 Life Cycle Inventory Analysis

This inventory of materials and processes developed for LED, CFL and incandescent lamps is drawn from the work shared by Yole Développement and System Plus Consulting, Navigant Consulting Europe's report on a life-cycle assessment of ultra-efficient lamps, summary data from Osram Optoelectronic's 2009 life-cycle assessment of an LED lamp, and various industry experts and researchers who provided comment and input on the draft analysis. The quantification of the life-cycle impacts is based on the Ecoinvent database (version 2.2). To address the large error bars associated with LED manufacturing which was identified in DOE's literature summary (DOE, 2012a), the focus of this life cycle inventory will include this specific area.

5.1 Inputs

To quantify the environmental impacts of the incandescent, CFL and LED lamps, the authors used the Ecoinvent life cycle impact assessment database version 2.2, from the Swiss Centre for Life Cycle Inventories (http://www.ecoinvent.org). This database contains environmental impact data on over 4000 manufacturing or related processes, such as the impacts associated with the production of a kilogram of cast aluminum from bauxite or the transportation by truck of one ton of material for one kilometer. For each material and process in the database, there are estimates of the environmental impact for over 250 standard environmental indicators. For example, the database estimates that the global warming potential impact associated with one kilogram of cast aluminum is 3.0614 kilograms of carbon dioxide equivalents.

In this chapter, there are a series of tables presented which provide detail on the inventories of materials and processes associated with LED manufacturing and then with each of the mains-voltage general illumination lamps studied. These tables give detail on the materials and processes that were selected from Ecoinvent and used to model those materials and processes. Some of the Ecoinvent materials and processes are very close matches to the ones used in the lamps while others are approximations. The relative significance of these approximations becomes clear when the results are reviewed in Chapter 6, and the more critical materials and processes are investigated in the sensitivity analysis presented in Appendix A of this report.

Each of the three finished lamps analyzed in this study is different, having different levels of power consumption and operating life. In order to make a fair comparison between the lamp technologies, it becomes necessary to compare their relative performance over a comparable time period and using a common metric. To achieve this, all of the impacts calculated for the three lamps are compared on a normalized basis of lighting service delivered during the analytical time period. The quantity of light produced over that time period is reported in lumen-hours of lighting service and then used to normalize the estimated impacts.

Although the three lamps were chosen because they have approximately equal instantaneous light output, it should be noted that over the lifetime of each lamp, the total lighting service is different. For instance, due to the large disparity between the incandescent lamp and the LED lamp, the incandescent lamp must take into account multiple lamp changes (and thus multiples of lamp-related impacts are compounded in the analysis). Ultimately, all of the analysis culminates in a measurement of impacts in megalumen-hours (Mlm-hr) over the full "use" stage of the LCA. For example, the final results for global warming potential will be presented in units of kilograms of CO_2-equivalent per Mlm-hr.

In addition to considering the impacts associated with an LED lamp in 2012, this study also projects the impacts of the LED lamp in 2017. The impacts of the future LED lamp are expected to be lower due to the fact that LED performance and drivers will continue to improve and materials and components used in the lamp can be reduced over time. Details relating to the assumptions behind the LED lamp in 2017 are provided in this chapter.

The following table provides the performance parameters used as inputs to the three lamps analyzed and the projected performance of an LED lamp in 2017. The second row from the bottom of the table calculates the “total lifetime light output”. This parameter represents the cumulative light output measured over the entire service life of the lamp, and is measured in megalumen-hours of light. The total light output for the 2012 LED lamp, 20.3 Mlm-hr represents the functional unit from DOE’s Part 1 study and is used in this analysis as a normalizing factor to adjust the impacts for equivalency. The scalar shown in the bottom row of the table is calculated from the ratios of the lighting service output relative to the 2012 LED lamp.

Table 5-1. Performance Parameters for Lamps Considered in this Analysis

Characteristics	Incandescent	CFL	LED lamp – 2012	LED lamp – 2017
Power Consumption	60 watts	15 watts	12.5 watts	6.1 watts
Lumen Output	900 lumens	825 lumens	812 lumens	824 lumens
Efficacy	15 lm/W	55 lm/W	65 lm/W	134 lm/W
Lamp Lifetime	1500 hours	8000 hours	25,000 hours	40,000 hours
Total Lifetime Light Output	1.35 Mlm-hr	6.6 Mlm-hr	20.3 Mlm-hr*	33.0 Mlm-hr
Impacts Scalar	15.04	3.08	1.00	0.61

* In Part 1 of DOE’s study (*Review of the Lifecycle Energy Consumption of Incandescent, Compact Fluorescent and LED Lamps*), 20 megalumen-hours was selected as the functional unit for comparison of the energy use. In this study (Part 2), we use the same functional unit as a normalizing scalar to ensure the impacts are comparable.

5.2 LED Manufacturing

LED manufacturing is a very complex and highly technical process and very few companies in the world operate across all segments of the value chain. In an effort to simplify the process for producing a packaged LED and to better align with the areas of specialization and expertise that exist in the industry, we have broken down the value chain for LED manufacturing into three large segments – (1) substrate production, (2) LED die fabrication and (3) packaged LED assembly. The flow diagram in Figure 5-1 summarizes these stages and the major steps contained within each stage. It should be noted that direct emissions from the manufacturing process were not included in this analysis, due to lack of available data.

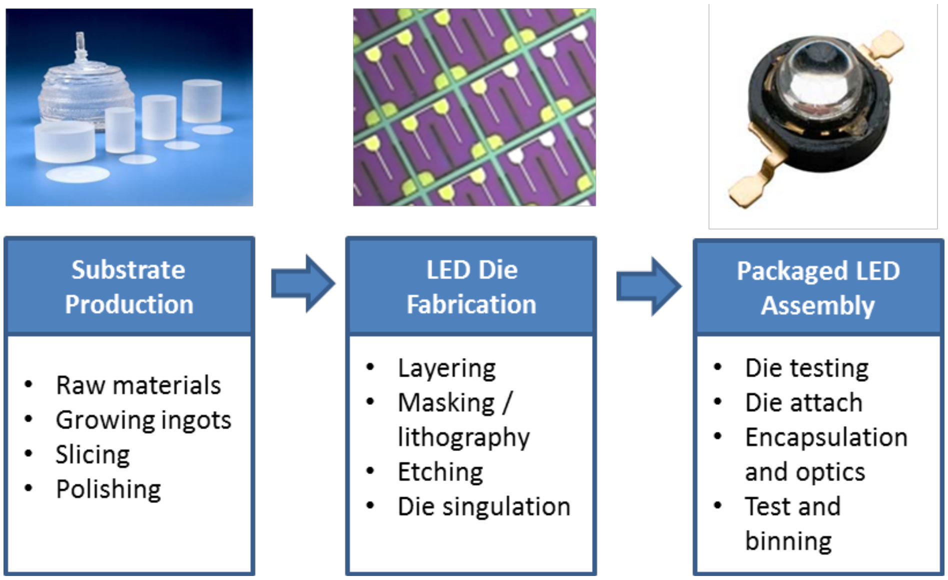


Figure 5-1. Three Major Stages of Packaged LED Manufacturing

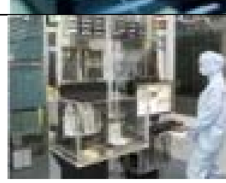
Following this structure, this chapter is divided into three sections, each discussing and describing these stages of LED manufacturing.

5.2.1 Substrate Production

This stage is focused on preparing polished, cleaned sapphire wafers to use in an MOCVD reactor for LED die fabrication. Wafer manufacturing starts with the growth of large sapphire crystal boules. To produce these boules, a large amount of aluminum oxide is melted down and a seed crystal is introduced to the molten solution. This seed crystal is then pulled slowly out of the solution, and because crystal growth occurs uniformly in all directions, the cross section of the resulting crystal is circular. The diameter of the crystal is a function of the melt temperature, the speed of rotation and the speed at which the seed holder is pulled from the melt. The resulting boule must then be ground down to obtain the desired diameter before it is sliced into wafers, polished and cleaned for LED fabrication.

The table on the following page provides the main processing steps involved in the production of sapphire wafers, starting with the growth of sapphire boules and ending with finished, cleaned wafers. A brief description of each step is provided in the table, along with an indication of the resources consumed in the process, including both energy and material. The estimates provided in this table were kindly provided by Yole Développement and System Plus Consulting for the purposes of assisting with this LCA study.

Table 5-2. Steps Associated with Sapphire Wafer Substrate Manufacture

Processing Step	Picture	Description	Inputs
Boule growth in reactor		Using the Czochralski method to melt aluminum oxide (Al_2O_3) and grow a large sapphire crystal boule	Energy: 15.51 kWh/wafer Alumina: 16.61 gm/wafer Water: 100 liters/wafer
Core fabrication		Using diamond tooling, drill the sapphire boule to create the sapphire cores in the appropriate diameters	Energy: 1.35 kWh/wafer
Wafer slicing		Slicing the cores into thin wafers using a diamond internal diameter saw with deionized cooling water	Energy: 1.24 kWh/wafer Water: 2 liters/wafer
Lapping and beveling		Rough-cut wafers are treated to remove saw marks and other defects on both sides; also thins the wafer and relieves stresses accumulated from slicing; uses a diamond slurry, 6μm	Energy: 0.09 kWh/wafer Slurry: 430 gm/wafer Water: 0.67 liters/wafer
Polishing and Chemical-mechanical planarization		Wafers are subjected to 2-3 polishing treatments using progressively finer slurry of polycrystaline diamond (3μm - 1μm); removes irregularities making wafer flat (i.e., planar)	Energy: 0.06 kWh/wafer Slurry: 400 gm/wafer Water: 0.67 liters/wafer
Geometry and optical inspection		Inspection to identify geometric or optical defects that may limit yield (e.g., surface pits or micro-cracks)	N/A
Final cleaning		Cleaning to remove trace metals, residues and particles. Uses NH_4OH, followed by dilute HF acid, followed by a deionized water rinse. The second clean consists of HCl and H_2O_2 followed by a deionized water rinse.	Energy: 0.001 kWh/wafer Cleaner: 3.50 liters/wafer Water: 2 liters/wafer

Source: Yole Développement and System Plus Consulting for quantities of process inputs.

As a quality assurance check on the mass of Alumina consumed to produce one wafer, a simple mass calculation can be performed that takes into account the finished product and quantities of material lost through processing from the raw crystal. Given that a three inch wafer diameter is 7.62 cm (radius [r] = diameter/2 = 3.81 cm), the thickness (t) of the wafer is 0.033 cm and the density (ρ) of sapphire is

3.98 g/cm^3, the mass of the finished three inch wafer is $m=r^2 \cdot \pi \cdot t \cdot \rho$ = 6.0 grams. Taking into account sawing and polishing losses per wafer which are approximately 85% of the finished wafer, the mass of sapphire core necessary to produce one finished 6.0 gram wafer would be 11.1 grams. A further 40% of the original boule is lost when the sapphire cores are cut and approximately 5% of the Alumina remains in the crystal-growing chamber. Taking these further adjustments into account, the 11.1 grams of sapphire core scales to a raw material consumption to 16.3 grams per finished 6.0 gram wafer. The estimated consumption of Alumina (Al_2O_3) per finished three-inch wafer was given in Yole Développement's data as 16.6 grams, therefore this estimate seems accurate.

Combining all of the materials and impacts quantified in the table above, the quantity of materials used in producing cleaned, polished sapphire wafers for GaN LED fabrication are shown in the table below. This table provides both the quantity consumed per wafer both in terms of volume and in terms of mass. The right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

Table 5-3. Energy and Material Consumption for Three-Inch Sapphire Wafer Manufacturing

Stage	Material Used	Amount		Eco-ID	Ecoinvent Description
		Volume per wafer	Mass per wafer		
Material	Alumina (Al2O3)	16.6 g/wafer	16.6 g/wafer	244	aluminum oxide, at plant
Material	Cleaning Chemical (alkali detergent)	3.5 liters/wafer	3.5 kg/wafer	5902	ethoxylated alcohols (AE7), petrochemical, at plant
Production	Energy Consumption	18.3 kWh/wafer	18.3 kWh/wafer	6693	electricity mix in China
Material	Diamond Slurry	830.0 g/wafer	0.83 kg/wafer	1997	zeolite, slurry, 50% in H2O, at plant (adjusted)
Material	Water	105.3 liters/wafer	105.3 kg/wafer	7237	water, ultrapure, at plant

To represent the diamond slurry used in manufacturing, the closest match in the Ecoinvent database is zeolite slurry, however there are two important differences. First, the embodied energy in diamonds is greater than that of zeolite, and second the concentration of diamond abrasive in the slurry is lower than the 50% level associated with the zeolite slurry. Due to these differences, and to make sure that this stage of the LCA did not underestimate impacts, the authors increased the zeolite slurry energy impacts by a factor of ten to represent the higher energy consumed manufacturing the diamonds. Overall, this adjustment resulted in a 15% increase in the GHG emissions associated with the manufacturing of a packaged LED, but constituted less than one-tenth of one percent of GHG emissions over the life cycle of the 2012 LED lamp (i.e., including the balance of system (i.e., driver, housing, heat sink) as well as other stages of the LCA including energy in use, transport and disposal).

5.2.2 LED Die Fabrication

In this section, the steps associated with fabricating LED die are described, with estimates of the associated energy and materials consumed in these manufacturing steps. The LED die fabrication process is subdivided into epitaxial growth and other front-end processes.

In the epitaxial growth phase, the substrate is mounted in an metal organic chemical vapor deposition (MOCVD) reactor and experiences a heating stage, followed by the deposition of the nucleation layer, the n-type layer, the active layers (multi-quantum well) and finally the p-type layer. At the end of this phase, the wafer is referred to as an LED epitaxial wafer.

The nucleation layer is critical because crystalline or contaminate defects will have a detrimental effect on the yield from the wafer, so it is imperative that the sapphire layer is ultra-pure. This is a layer of sapphire that is grown on the raw sapphire wafer through an epitaxial growth process. The layer is very thin, just 3% or less of the wafer thickness, but it is a critical step in the fabrication process.

Table 5-4. Steps Associated with Gallium Nitride Epitaxy

Processing Step	Description	Inputs
Bake out	Nitridation of the sapphire substrate at high temperature in a hydrogen and ammonia atmosphere.	8.75 kWh/wafer 0.06 m^3 H_2 / wafer 0.02 kg NH_3 / wafer
Nucleation layer	The wafer is then lowered in temperature to 550°C to grow the nucleation layer.	4.74 kWh/wafer
Temperature ramp	The reactor chamber is heated to a very high temperature (1200°C) under reduced ammonia pressure to stabilize the nucleation layer.	1.46 kWh/wafer 0.02 kg NH_3 / wafer
Buffer + N layer (3.84µm)	The temperature is dropped to approximately 550°C to grow the buffer layer. This is a thin amorphous film of gallium, just 50 to 100 atoms thick grown directly on the wafer. The wafer is then heated up until the gallium forms a smooth, mirror-like layer of gallium nitride. Next, a layer of negatively doped gallium nitride is deposited, with silane (i.e., silicon tetrahydride, SiH_4) as the electron-donating dopant.	9.77 kWh/wafer 1.38 grams TMGa[4] / wafer 0.42 kg NH_3 / wafer 1.54 m^3 H_2 / wafer 1.54 m^3 N_2 / wafer 0.06 g SiH_4 / wafer
Active layer MQW (60nm)	The temperature is dropped from 1,200°C to 750-850°C to grow an indium gallium nitride quantum well. This will include approximately 20 angstroms of InGaN and 100 angstroms of GaN. This process is repeated to grow several wells.	4.74 kWh/wafer 0.03 grams TMGa / wafer 0.01 kg NH_3 / wafer 0.01 m^3 H_2 / wafer 0.01 m^3 N_2 / wafer 0.01 g TMIn[5] / wafer

[4] TMGa = trimethylgallium
[5] TMIn = trimethylindium

Processing Step	Description	Inputs
P layer (170nm)	After growing the last combination of InGaN+GaN, the wafer is heated back up and a confining layer of positively doped aluminum gallium nitride (AlGaN) is deposited. The positively doped layer confines the charge carriers in the active layer.	3.28 kWh/wafer 0.06 grams TMGa / wafer 0.02 kg NH_3 / wafer 0.06 m^3 H_2 / wafer 0.06 m^3 N_2 / wafer 0.00 g TMAl[6] / wafer

Source: Yole Développement and System Plus Consulting for quantities of process inputs.

Taking the LED epitaxial wafer, a series of steps are followed which are working toward making the device and preparing it for packaging. Following inspection, the wafer is subjected to masking / lithography, followed by etching and then establishing metallization / contacts on the LED. These process steps create the LED mesa-structure, and results in visible LED dies on the wafer. Once these are developed, the substrate is separated from the LED dies, and they are then cut (i.e., die singulation) and tested/ binned according to their performance. At the end of this stage, the LED dies are ready to be packaged.

[6] TMAl = trimethylaluminum

Table 5-5. Post-Epitaxy Steps Associated with LED Die Fabrication

Processing Step	Process Sub-Steps	Inputs
Wafer Inspection	Detailed inspection of the wafer to determine if there are any cracks or defects that might otherwise make the wafer unsuitable.	Energy: 0.03 kWh/wafer
P contact	• Cleaning • Silver (Ag) Deposition (PVD - 0.097µm) • Ti Deposition (PVD : 0.103µm) • W Deposition (PVD : 0.681µm) • Measurement • Cleaning	Target Ag 0.44 mm^3/wafer Target Ti 0.47 mm^3/wafer Target W 3.09 mm^3/wafer UPW[7] 60.00 l/wafer N_2 0.70 m^3/wafer Energy: 1.19 kWh/wafer
N contact Opening	• Litho 1 - Coatings • Litho 1 - Baking • Litho 1 - Stepper • Litho 1 - Development • Measurement • Wet Etching Ti + W • Wet Etching Ag • Photoresist Removal • Measurement • Cleaning • Litho 2 - Coating • Litho 2 - Baking • Litho 2 - Stepper • Litho 2 - Development • Measurement • GaN Etching (1.5µm) • Photoresist Removal • Measurement • Cleaning	Acetone 0.20 l/wafer Developer 50.00 ml/wafer Etchant Ag 30.00 ml/wafer Etchant Metal 60.00 ml/wafer GaN Etchant 0.19 l/wafer Photoresist 8.00 ml/wafer UPW 60.00 l/wafer N_2 0.70 m^3/wafer Energy: 2.30 kWh/wafer

[7] UPW is an abbreviation for Ultra Pure Water

Processing Step	Process Sub-Steps	Inputs
GaN Pattern	• Dielectric (CVD : 400nm) • Measurement • Cleaning • Litho 3 - Coating • Litho 3 - Baking • Litho 3 - Stepper • Litho 3 - Development • Measurement • Dielectric Etching • Photoresist Removal • Measurement • Cleaning	Acetone 0.10 l/wafer Developer 25.00 ml/wafer Photoresist 4.00 ml/wafer SF_6 0.10 l/wafer SiH_4 0.18 g/wafer UPW 60.00 l/wafer N_2 0.70 m^3/wafer O_2 2.00 m^3/wafer Energy 2.71 kWh/wafer
N Contact	• Litho 4 - 2 Coating • Litho 4 - Baking • Litho 4 - Stepper • Litho 4 - Development • Measurement • Cleaning • Al Deposition (PVD : 0.284µm) • Ni Deposition (PVD : 0.069µm) • Gold-Tin (ECD : 3.256µm) • N Contact- PR Removal • Measurement • Cleaning	Acetone 0.10 l/wafer AuSn 14.77 mm^3/wafer Developer 40.00 ml/wafer Photoresist 7.00 ml/wafer Target Al 1.27 mm^3/wafer Target Ni 0.42 mm^3/wafer UPW 60.00 l/wafer N_2 0.70 m^3/wafer Energy 1.13 kWh/wafer
Other	• Back Grinding Sapphire • Fine grinding Sapphire - 75µm • Scribe laser • Break substrate	Energy 2.47 kWh/wafer

Source: Yole Développement and System Plus Consulting.

The following table summarizes all the materials and energy consumed in this second stage of LED manufacturing, the LED die fabrication stage. This table combines the material and energy consumption of both the epitaxy and P-N junction deposition stage and post-epitaxy steps associated with contacts, patterning, substrate removal and preparing finished LED die. The second and third columns of the table specify the quantity of material used (presented with the units), and the right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

Table 5-6. Energy and Material Consumption for LED Die Fabrication

Material	Quantity Consumed		Eco-ID	Ecoinvent Description
	Volume / Wafer	Mass / Wafer		
Acetone	0.59 l/wafer	467 g/wafer	363	acetone, liquid, at plant
AuSn solder	14.8 mm^3/wafer	0.29 g/wafer	10107	gold, from combined metal production, at refinery
Developer	115 ml/wafer	115 g/wafer	264	chemicals inorganic, at plant
Etchant Ag	30 ml/wafer	30 g/wafer	283	hydrogen fluoride, at plant
Etchant Metal	60 ml/wafer	60 g/wafer	283	hydrogen fluoride, at plant
GaN Etchant	0.192 l/wafer	192 g/wafer	283	hydrogen fluoride, at plant
H_2	1.62 m^3/wafer	136 g/wafer	286	hydrogen, liquid, at plant
N_2	4.42 m^3/wafer	5527 g/wafer	300	nitrogen, liquid, at plant
NH_3	0.447 kg/wafer	447 g/wafer	246	ammonia, liquid, at regional storehouse
O_2	2 l/wafer	2.3 kg/wafer	301	oxygen, liquid, at plant
Photoresist	19 ml/wafer	19 g/wafer	382	chemicals organic, at plant
Energy	42.57 kWh/wafer	42.57 kWh/wafer	6694	electricity mix
SF_6	0.1 l/wafer	13 g/wafer	348	sulfur hexafluoride, liquid, at plant
SiH_4	0.242 g/wafer	0.242 g/wafer	321	silicon carbide, at plant
Slurry	2.3 l/wafer	2.3 kg/wafer	1997	zeolite, slurry, 50% in H2O, at plant
Target Ag	0.44 mm^3/wafer	0.005 g/wafer	10122	silver, from combined gold-silver production, at refinery
Target Al	1.27 mm^3/wafer	0.003 g/wafer	1056	aluminum, production mix, at plant
Target Ni	0.417 mm^3/wafer	0.004 g/wafer	1121	nickel, 99.5%, at plant
Target Ti	0.467 mm^3/wafer	0.002 g/wafer	355	titanium dioxide, production mix, at plant
Target W	3.089 mm^3/wafer	0.06 g/wafer	8143	palladium, secondary, at precious metal refinery
TMAl	0.003 g/wafer	0.003 g/wafer	1056	aluminum, production mix, at plant
TMGa	1.47 g/wafer	1.47 g/wafer	6908	gallium, semiconductor-grade, at plant
TMIn	0.01 g/wafer	0.01 g/wafer	7164	indium, at regional storage
UPW	240 l/wafer	240 kg/wafer	7237	water, ultrapure, at plant

5.2.3 Packaged LED Assembly

This third phase of LED manufacturing is referred to as the "packaging" of the device. It involves taking the LED die, mounting it in housing, making electrical connections, applying phosphor, encapsulant and optics. It also involves testing and binning the LED into the correctly classified product.

Table 5-7. Steps Associated with LED Packaging and Assembly

Processing Step	Description	Inputs
Package Element Building	The ceramic substrate (2-layers of alumina) are prepared for mounting the LED chip.	0.01 kWh / LED 13.5 mm^2 Alumina / LED
Stud Bumping	Wire bonding process, where gold is bonded to the die pad.	0.001 kWh / LED 0.004 mm^3 gold / LED
Reflow	The LED is heated to a temperature above the melting point of the solder, but below the temperature that may damage other parts of the LED package.	0.003 kWh / LED
LED & Protective die attach	The LED is attached to the package element, incorporating protection against electrostatic discharge (ESD).	0.003 kWh / LED 0.220 mm^2 ESD diode (silicon) / LED
Reflow	The LED is heated again to the melting point of solder.	0.003 kWh / LED
Under filling	Underfill (i.e., an organic polymer and inorganic filler) is added to the package that provides support to the solder ball interconnect.	0.003 kWh / LED 0.05 mm^3 underfill / LED
Phosphor	Application of a Ce3+:YAG phosphor coating that will convert a portion of the blue light emission from the LED die to longer wavelengths which gives the packaged LED emission the appearance of white light.	0.000 kWh / LED 0.192 mm^3 phosphor / LED
Lens	An optical lens that gathers and directs the light in the appropriate beam angle for the desired application.	0.003 kWh / LED 8.400 mm^3 silicon / LED
Annealing	The package is heated to anneal together the polymer, phosphor and lens into one cohesive unit.	0.003 kWh / LED
Substrate Dicing	The substrate is cut into the individual packaged LEDs for use.	0.001 kWh / LED

Source: Yole Développement and System Plus Consulting for quantities of process inputs.

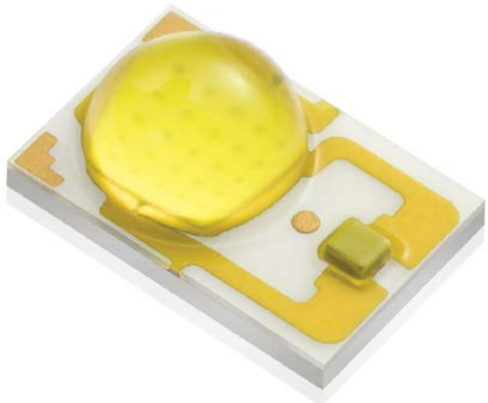


Figure 5-2. Example of the Finished Packaged LED, the Philips Luxeon Rebel

Taking into account all the inputs for LED packaging and assembly presented in Table 5-7, the following table presents the aggregate consumption per LED produced. The middle columns of the table specifies the quantity of material used (presented with the units), and the right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

Table 5-8. Energy and Material Consumption for LED Packaging Assembly

Stage	Material Used	Amount		Eco-ID	Ecoinvent Description
		Volume per LED	Mass per LED		
Material	Ceramic Substrate (2-layer Alumina)	13.5 mm^2/LED	0.0135 g/LED	244	aluminum oxide, at plant
Production	Energy (kWh)	0.03 kWh/LED	0.03 kWh/LED	6693	electricity mix for China
Material	ESD diode (Silicon)	0.22 mm^2/LED	0.055 g/LED	7111	diode, unspecified, at plant
Material	Gold	0.004 mm^3/LED	0.00006 g/LED	10107	gold, from combined metal production, at refinery
Material	Underfill	0.05 mm^3 / LED	0.0196 g/LED	324	silicone product, at plant
Material	Silicone	8.4 mm^3/LED	0.00006 g/LED	1802	epoxy resin, liquid, at plant

5.3 LED Lamp Analysis

After preparing an Ecoinvent inventory of the materials and processes that contribute to the production of a packaged LED, the next step in the analysis is to consider installing several of these packaged LEDs into a self-ballasted LED lamp that can be inserted into a mains voltage socket. For the purposes of this study (and not as an endorsement of the product) we selected the Philips EnduraLED lamp that was introduced in 2011 and was commonly available in the U.S. market in 2012. There is a picture of this lamp on the right.

The table below presents the materials used in manufacturing the LED lamp and accounts for the energy involved in the assembly and manufacturing steps. The finished LED lamp weighs 178 grams and the card-stock packaging was measured at 37 grams, taken together the lamp inside the box totals approximately 215 grams.

The table estimates the transport of the lamp from China to the U.S. by sea and then a further 1000 kilometers distribution within the U.S. The table presents the energy consumed by the lamp over its lifetime – specifically, 12.5 watts times 25000 hours, or 312.5 kilowatt-hours. Finally, in the end of life stage, the table presents some estimates of the rates of recycling, with the LED lamp being recycled 20% of the time and the packaging 30% of the time. The middle column of the table specifies the quantity of material used (presented with the units), and the right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

Table 5-9. LCA Inventory for the 12.5 Watt LED Lamp in 2012

Stage	Material Used	Amount	Eco-ID	Ecoinvent Description
Material	LEDs (blue light)	12 units		LED impacts taken from the above section
Material	Remote phosphor	1.0g	6954	rare earth concentrate, 70% rare earth oxide (REO), from bastnasite, at beneficiation
Material	Plastic phosphor host	11.1g	6954	rare earth concentrate, 70% REO, from bastnasite, at beneficiation
Material	Aluminum heat sink	68.2g	1057	aluminum, production mix, cast alloy, at plant
Material	Copper	5.0g	1084	copper, primary, at refinery
Material	Nickel	0.003g	1121	nickel, 99.5%, at plant
Material	Brass	1.65g	1066	brass, at plant
Material	Cast iron	4.0g	1069	cast iron, at plant
Material	Chromium	0.0002g	1072	chromium steel 18/8, at plant
Material	Inductor	5 pcs.	1074	copper, at regional storage
Material	IC chip	2.0g	7016	integrated circuit, IC, logic type, at plant
Material	Capacitor SMD	8 pcs.	7010	capacitor, SMD type, surface-mounting, at plant
Material	Electrolytic Capacitor	6 pcs.	7011	capacitor, electrolyte type, < 2cm height, at plant

Stage	Material Used	Amount	Eco-ID	Ecoinvent Description
Material	Diode	6 pcs.	7075	diode, glass-, SMD type, surface mounting, at plant
Material	Printed Wiring Board	15.0g	10995	printed wiring board, surface mount, lead-free surface, at plant
Material	Resistor SMD	35 pcs.	7068	resistor, SMD type, surface mounting, at plant
Material	Resistor	3 pcs.	7109	resistor, wirewound, through-hole mounting, at plant
Material	Transistor	6 pcs.	7113	transistor, wired, big size, through-hole mounting, at plant
Material	Resin Glue	4.5g	1802	epoxy resin, liquid, at plant
Material	Solder paste	0.3g	10800	flux, wave soldering, at plant
Production	Power	5.0 MJ	6693	electricity mix for China
Production	Manufacturing	178g	10169	assembly, LCD screen
Material	Packaging	37g	1698	packaging, corrugated board, mixed fiber, single wall, at plant
Transport	Sea - 215g	10000 km	1968	transport, transoceanic freight ship
Transport	Road - 215g	1000 km	1943	transport, truck >16t, fleet average
Use	Energy in use	312.5 kWh	6694	electricity mix for the U.S.
End of Life	Lamp, Recycling	20%	10977	disposal, treatment of CRT glass
End of Life	Lamp, Landfill	80%	2071	disposal, glass, 0% water, to inert material landfill
End of Life	Package, Recycling	30%	1693	corrugated board, recycling fiber, single wall, at plant
End of Life	Package, Landfill	70%	2077	disposal, packaging cardboard, 19.6% water, to inert material landfill

Compared with the LED fabrication step of the manufacturing process, this stage (i.e., lamp assembly, transport, use and disposal) of the LCA study had some very good matches between the material used in the lamp and the options in the Ecoinvent database. It should be noted that there are two different electricity values used in the analysis – a mix of electricity for China which is used at the manufacturing stage and a mix of electricity for the U.S. which is used for the energy in use stage. It is important that the energy in use stage reflect the mix where the lamp is being used because the magnitude of the impact associated with the electricity consumed during the use phase is later found to be very important. The recycling levels are meant to represent levels that would be commonly found in the U.S. for the different materials – the lamp and its packaging.

As discussed earlier, in addition to considering the LCA impacts of the incandescent, CFL and LED lamps in 2012, the authors also examined the impacts of the projected performance of LED lamps in 2017. This is of particular interest because LEDs are a rapidly evolving technology and expectations are that it will continue to achieve substantial improvements in its performance in the coming years (DOE, 2012b). In order to determine the performance of a 2017 lamp, the 2012 LED lamp analysis was modified as detailed in the list below:

- Efficacy improvement from 65 lm/W (Philips EnduraLED lamp) to 134 lm/W system output – this adjustment is based on the projected performance improvement of warm-white LEDs in Figure 5.5 and Table 5.6 of the U.S. DOE 2012 Multiyear Program Plan (DOE, 2012b).
- Reduce wattage for the lamp in order to hold lumen output at approximately the equivalent of a 60 watt incandescent lamp. Wattage is reduced from 12.5W to 6.1W while lumen output is adjusted from 812 to 824 lumens.
- Lamp lifetime will increase, benefitting from less heat generated in the lamp itself and improvements in the LEDs and the drive electronics. The lifetime is adjusted from 25,000 to 40,000 hours.
- LED manufacturing improvements in the MOCVD reactors and migration to larger wafer sizes will result in LED die yield improvements. Presently, the model is running on the assumption of a 69% yield on a 3-inch wafer, producing 2438 units. By 2017, the wafer sizes will have increased and yield will have increased such that the expect yield relative to a 3-inch wafer would be approximately 92% (3250 units). The model is therefore adjusted to reflect this yield rate, which is equivalent to a 52% yield on a 4-inch wafer, a very conservative estimate.
- Fewer LEDs in the lamp – given expected improvements in efficacy and package power handling capability, luminous flux output is projected to increase, and thus fewer LEDs will be needed in the finished product to achieve the equivalent light output. For the 2017 lamp, it is assumed that only 12 LEDs will be used (whereas the 2012 lamp uses 18).
- Smaller heat sink – given that the power consumption of the lamp will be decreasing (from 12.5 W to 6.1 W, the heat sink mass necessary to conduct and disperse the heat will be smaller. It is assumed that the mass of the heat sink will be reduced proportionally with power reduction (i.e., 6.1/12.5).
- Fewer input chemicals needed for epitaxy – it is assumed that manufacturing processes will continue to advance, and chemicals required in the epitaxy and growth of LED die will decrease by 20%. Thus the input chemicals necessary for the creating the LED die are reduced by 20%. This adjustment does not, however, apply to the wafer preparation stage or the packaging of the LED, these are both assumed to remain constant.
- Redesign of the LED driver – it is expected that the LED driver component count will decrease as more sophisticated drivers are developed that reduce size and increase reliability of the driver. For 2017, the model assumes that there will be a 50% increase in the Integrated Circuit (IC) chips used in the LED driver and a 33% reduction in the number of individual components such as resistor, capacitors and diodes.
- Improvement in waste management – the model also considers the end-of-life stage, and for 2017, it is assumed that there will be slightly higher proportions of lamp and packaging recycling. Thus, the model assumes an improvement from 20% recycling of the LED lamp in 2012 to 30% in 2017. The model also assumes the packaging recycling rate increases from 30% in 2012 to 50% in 2017.

To provide more detail on these changes to the underpinning LED technology and lamp design, the table below provides an entry for each of the input variables that was changed from the 2012 to the 2017 lamp. The Ecoinvent records to which each of the materials and processes were matched in 2012 remained the same in 2017.

Table 5-10. Changes to LCA Inputs for LED Lamp Manufacturing in 2017

Material for Manufacturing	Quantity in 2012	Quantity in 2017	Units	Percentage Reduction / Increase
Acetone	0.59	0.472	l/wafer	20%
AuSn solder	14.8	11.817	mm3/wafer	20%
Developer	115	92	ml/wafer	20%
Etchant Ag	30	24	ml/wafer	20%
Etchant Metal	60	48	ml/wafer	20%
GaN Etchant	0.192	0.154	l/wafer	20%
H_2 gas	1.62	1.296	m3/wafer	20%
N_2 gas	4.42	3.536	m3/wafer	20%
NH_3 gas	0.447	0.358	kg/wafer	20%
O_2 gas	2	1.6	l/wafer	20%
Photoresist	19	15.2	ml/wafer	20%
Power	42.57	34.06	kWh/wafer	20%
SF_6	0.1	0.08	l/wafer	20%
SiH_4	0.242	0.194	g/wafer	20%
Slurry	2.3	1.84	l/wafer	20%
Target Ag	0.44	0.352	mm3/wafer	20%
Target Al	1.27	1.016	mm3/wafer	20%
Target Ni	0.417	0.334	mm3/wafer	20%
Target Ti	0.467	0.374	mm3/wafer	20%
Target W	3.089	2.471	mm3/wafer	20%
TMAl	0.003	0.002	g/wafer	33%
TMGa	1.47	1.176	g/wafer	20%
TMIn	0.01	0.008	g/wafer	20%
UPW	240	192	l/wafer	20%
LEDs (blue light)	18	12	packaged LEDs	33%
Aluminum heat sink	0.0682	0.032736	kg	49%
IC chip	0.002	0.003	kg	-50% (increase)
Electrolytic Capacitor	6	4	pieces	33%
Diode	6	4	pieces	33%
Resistor SMD	35	23	pieces	34%
Resistor	3	2	pieces	33%
Transistor	6	4	pieces	33%
Lamp Weight	0.178	0.143	kg	20%
Total Lamp+Pack Weight	0.215	0.18	kg	16%
Manufacturing	0.178	0.143	kg	20%
Energy in Use	312	240	kWh	23%
End of Life - lamp	20%	30%	Recycling	-50% (increase)
End of Life - lamp	80%	70%	Landfill	13%
End of Life - packaging	30%	50%	Recycling	-67% (increase)

Material for Manufacturing	Quantity in 2012	Quantity in 2017	Units	Percentage Reduction / Increase
End of Life - packaging	70%	50%	Landfill	29%

Comparing our findings to those presented in the Part 1 report, there is very good alignment for the energy in use phase for the LED lamp where we estimate that this phase represents on average 81% of the impacts associated with this lamp. In Part 1, it was reported that the primary energy in use 3,540 MJ per 20 megalumen-hours of lighting service. In Part 2, we calculate 3,527 MJ for the same lighting service (converted using an average power plant heat rate of 10,633 BTU/kWh for 2011 (DOE, 2012c). This shows that for the most important stage of the LCA, there is very good alignment between the two studies.

5.4 Incandescent Lamp Analysis

In order to benchmark the environmental impact of the LED lamp against a familiar light source, an inventory of materials and processes was developed for a 60 watt A-19 general lighting service incandescent lamp. The table below presents the materials used in manufacturing the lamp, and accounts for the energy involved in the glasswork and other manufacturing steps. The lamp itself weighs 38.2 grams and the card-stock packaging was measured at 40 grams, taken together the lamp inside the box totals approximately 78.2 grams.

The table estimates the transport of the lamp from China to the U.S. by sea and then a further 1000 kilometers distribution within the U.S. The table presents the energy consumed by the lamp over its lifetime – specifically, 60 watts times 1500 hours, or 90 kilowatt-hours. Finally in the end of life stage, the table presents some estimates of the rates of recycling, with the lamp being recycled 10% of the time and the packaging 30% of the time. The middle column of the table specifies the quantity of material used (presented with the units), and finally, the material or process in the Ecoinvent database to which it was matched is provided. The table shows both the unique Ecoinvent ID for each matched material or process and the database description.

Table 5-11. LCA Inventory for the 60 Watt Incandescent Lamp

Stage	Material Used	Amount	Eco-ID	Ecoinvent Description
Material	Argon gas	0.137g	252	argon, liquid, at plant
Material	Nitrogen gas	0.845g	300	nitrogen, liquid, at plant
Material	Oxygen gas	7.290g	301	oxygen, liquid, at plant
Material	Hydrogen gas	0.001g	286	hydrogen, liquid, at plant
Material	Ammonia	0.085g	246	ammonia, liquid, at regional storehouse
Material	Aluminum	1.150g	1056	aluminum, production mix, at plant
Material	Brass	0.050g	1066	brass, at plant
Material	Resin Glue	1.550g	1802	epoxy resin, liquid, at plant
Material	Solder paste	0.150g	10800	flux, wave soldering, at plant

Stage	Material Used	Amount	Eco-ID	Ecoinvent Description
Material	Glass Bulb	22.54g	810	glass tube, borosilicate, at plant
Material	Getter	0.002g	311	phosphoric acid, industrial grade, 85% in H_2O
Material	Glass Flare	2.097g	810	glass tube, borosilicate, at plant
Material	Exhaust Tube	2.165g	810	glass tube, borosilicate, at plant
Material	Lead wire	0.100g	1178	wire drawing, copper
Material	Molybdenum support wire	0.013g	1116	molybdenum, at regional storage
Material	Filament - Tungsten	0.010g	1142	rhodium, at regional storage
Production	Power	0.372g	6693	electricity mix for China
Production	Manufacturing	38.2g	10169	assembly, LCD screen
Material	Packaging	40.0g	1698	packaging, corrugated board, mixed fiber, single wall, at plant
Transport	Sea – 78.2g	10,000 km	1968	transport, transoceanic freight ship
Transport	Road – 78.2g	1000 km	1943	transport, truck >16t, fleet average
Use	Energy in use	90.0 kWh	6694	electricity mix for the U.S.
End of Life	Lamp, Recycling	10%	10977	disposal, treatment of CRT glass
End of Life	Lamp, Landfill	90%	2071	disposal, glass, 0% water, to inert material landfill
End of Life	Package, Recycling	30%	1693	corrugated board, recycling fiber, single wall, at plant
End of Life	Package, Landfill	70%	2077	disposal, packaging cardboard, 19.6% water, to inert material landfill

Overall, there were very good matches between the material used in the incandescent lamp and the options available in the Ecoinvent database. All of the gases used in the manufacturing and filling of the lamp were available, the metals and the glass were prepared. It should be noted that there are two different electricity values used in the analysis – there is a mix of electricity for China which is used at the manufacturing stage and a mix of electricity for the U.S. which is used for the energy in use stage. It is important that the energy in use stage reflect the mix where the lamp is being used because the magnitude of the impact associated with the electricity consumed during the use phase is later found to be the dominant factor in the environmental impact associated with this lamp. The recycling levels are meant to represent levels that would be commonly found in the U.S. for the different materials – the lamp and its packaging.

Comparing our findings to those presented in the Part 1 report, there is very good alignment for the energy-in use phase of the incandescent lamp which represents on average 93% of the impacts associated with this lamp. In Part 1, it was reported that the primary energy in use 15,100 MJ per 20 megalumen-hours of lighting service. In Part 2, we calculate 14,960 MJ for the same lighting service (converted using an average power plant heat rate of 10,633 BTU/kWh for 2011 (DOE, 2012c)). This shows that for the most important stage of the LCA, there is very good alignment between the two studies.

5.5 Compact Fluorescent Lamp Analysis

In addition to comparing the LED lamp against an incandescent lamp, it is also important to compare the LED lamp with the most common energy-efficient light source used in the U.S. today, a CFL. The CFL is a miniaturized version of the large linear tube fluorescent systems commonly found in commercial office buildings. The linear tube has been bent and twisted to conform to a smaller form-factor and the electronic ballast is contained in the base of the lamp, rather than being a separate component wired to sockets. The glass tube is permanently attached to the lamp base / ballast, and the system is designed to operate for approximately 8,000 hours, after which the entire lamp is either recycled or disposed.

The inventory of materials and processes presented in the table below were developed for a 15 watt integrally-ballasted CFL. The table below presents the materials used in manufacturing the lamp and ballast. The lamp itself weighs 153 grams and the card-stock packaging was measured at 81 grams, taken together the lamp inside the box totals approximately 234 grams.

The table estimates the transport of the lamp from China to the U.S. by sea and then a further 1000 kilometers distribution within the U.S. The table presents the energy consumed by the lamp over its lifetime – specifically, 15 watts times 8000 hours, or 120 kilowatt-hours. Finally, in the end of life stage, the table presents some estimates of the rates of recycling, with the CFL being recycled 20% of the time and the packaging 30% of the time. The middle column of the table specifies the quantity of material used (presented with the units), and finally, the material or process in the Ecoinvent database to which it was matched is provided. The table shows both the unique Ecoinvent ID for each matched material or process and the database description.

Table 5-12. LCA Inventory for the 15 Watt Integrally Ballasted Compact Fluorescent Lamp

Stage	Material Used	Amount	Eco-ID	Ecoinvent Description
Material	Argon gas	0.004g	252	argon, liquid, at plant
Material	Nitrogen gas	0.119g	300	nitrogen, liquid, at plant
Material	Oxygen gas	0.159g	301	oxygen, liquid, at plant
Material	Hydrogen gas	0.002g	286	hydrogen, liquid, at plant
Material	Neon gas	0.0004g	294	krypton, gaseous, at plant
Material	Noble Earths	0.001g	6954	rare earth concentrate, 70% REO, from bastnasite, at beneficiation
Material	Yttrium Oxide	1.37g	6954	rare earth concentrate, 70% REO, from bastnasite, at beneficiation
Material	Ammonia	0.13g	246	ammonia, liquid, at regional storehouse
Material	Nitric acid	7.9g	299	nitric acid, 50% in H2O, at plant
Material	Sulfuric acid	1.67g	350	sulfuric acid, liquid, at plant
Material	Aluminum Oxide	0.008g	244	aluminum oxide, at plant
Material	Lead	0.19g	1103	lead, at regional storage

Stage	Material Used	Amount	Eco-ID	Ecoinvent Description
Material	Copper	0.402g	1084	copper, primary, at refinery
Material	Nickel	0.003g	1121	nickel, 99.5%, at plant
Material	Brass	1.65g	1066	brass, at plant
Material	Cast iron	0.029g	1069	cast iron, at plant
Material	Chromium	0.0002g	1072	chromium steel 18/8, at plant
Material	Mercury	0.004g	1111	mercury, liquid, at plant
Material	Capacitor	40 pcs.	7010	capacitor, SMD type, surface-mounting, at plant
Material	Coil miniature	3 pcs.	10155	inductor, miniature RF chip type, MRFI, at plant
Material	Diode SMD	40 pcs.	7075	diode, glass-, SMD type, surface mounting, at plant
Material	PWB	3.7g	10995	printed wiring board, surface mount, lead-free surface, at plant
Material	Resistor SMD	40 pcs.	7068	resistor, SMD type, surface mounting, at plant
Material	Thermistor, NTC	0.19g	7068	resistor, SMD type, surface mounting, at plant
Material	Transistor power large	3.70g	7113	transistor, wired, big size, through-hole mounting, at plant
Material	Resin Glue	4.5g	1802	epoxy resin, liquid, at plant
Material	Solder paste	0.3g	10800	flux, wave soldering, at plant
Material	Glass Tube	1.20g	810	glass tube, borosilicate, at plant
Material	Housing top & bottom (PBTP)	2.39g	1827	polyethylene terephthalate, granulate, amorphous, at plant
Production	Natural Gas	10.7kg	8338	metal working factory operation, heat energy from natural gas
Production	Power	3.13MJ	6693	electricity mix for China
Production	Manufacturing	153g	10169	assembly, LCD screen
Material	Packaging	81g	1698	packaging, corrugated board, mixed fiber, single wall, at plant
Transport	Sea - 234g	10000km	1968	transport, transoceanic freight ship
Transport	Road - 234g	1000km	1943	transport, truck >16t, fleet average
Use	Energy in use	120 kWh	6694	electricity mix for the U.S.
End of Life	Lamp, Recycling	20%	10977	disposal, treatment of CRT glass
End of Life	Lamp, Landfill	80%	2071	disposal, glass, 0% water, to inert material landfill
End of Life	Package, Recycling	30%	1693	corrugated board, recycling fiber, single wall, at plant
End of Life	Package, Landfill	70%	2077	disposal, packaging cardboard, 19.6% water, to inert material landfill

Overall, the CFL is a complex system which includes the lamp, cathodes, a ballast, housing and a socket. Across the list of materials and processes identified in manufacturing a CFL, there were good matches in the Ecoinvent database. For example, the components in the ballast were able to be matched one-for-one with exactly the same component selected from the Ecoinvent database. As with the previous lamps discussed, this table shows two different electricity values used in the analysis – there is a mix of electricity for China which is used at the manufacturing stage and a mix of electricity for the United States which is used for the energy in use stage. This differentiation is important because the magnitude of the impact associated with the electricity consumed during the use phase is later shown to be a significant factor in the environmental impact associated with this lamp. Finally, the recycling levels are meant to represent levels that would be commonly found in the U.S. Compared with incandescent, it was assumed that there is a slightly higher recycling rate of the lamp (20%) because of the mercury in the glass tube.

Comparing our findings for this lamp to those presented in the Part 1 report, there is very good alignment for the energy-in use phase of the incandescent lamp which represents on average 78% of the impacts. In Part 1, it was reported that the primary energy in use 3,780 MJ per 20 megalumen-hours of lighting service. In Part 2, we calculate 4,079 MJ for the same lighting service (converted using an average power plant heat rate of 10,633 BTU/kWh for 2011 (DOE, 2012c)). This shows that for the most important stage of the LCA, we are estimating approximately 8% higher energy consumption for the energy in use stage of the LCA.

6 Life Cycle Impact Assessment Indicators

This section of the report discusses the indicators that were selected from the Ecoinvent database for this study. The inventories presented in Chapter 5 are combined with impact data from the Ecoinvent database to determine the levels of environmental impact. For this study, DOE wanted to make sure the assessment quantified impacts associated with air/climate, water, soil and resources. There were fifteen indicators chosen for this study, as shown in Table 6-1. After the table, a brief description of each of these indicators is provided.

Table 6-1. LCA Environmental Indicators Selected for this Analysis

	Abbr.	Name	Indicator	Ecoinvent Indicator	Units
Air / Climate	GWP	Global Warming Potential	greenhouse gas emissions	global warming potential (GWP100a) [CML2001]	kg CO_2-eq
	AP	Acidification Potential	air pollution	acidification potential [CML2001]	kg SO_2-eq
	POCP	Photochemical Ozone Creation Potential	air pollution	photochemical oxidation [CML2001]	kg O_3 formed
	ODP	Ozone Depleting Potential	air pollution	stratospheric ozone depletion (ODP10a)	kg CFC11-eq
	HTP	Human Toxicity Potential	toxicity	human toxicity (HTP100a) [CML2001]	kg 1,4-DCB-eq
Water	FAETP	Freshwater Aquatic Ecotoxicity Potential	water pollution	freshwater aquatic ecotoxicity (FAETP100a)	kg 1,4-DCB-eq
	MAETP	Marine Aquatic Ecotoxicity Potential	water pollution	marine aquatic ecotoxicity (MAETP100a) [CML2001]	kg 1,4-DCB-eq
	EP	Eutrophication Potential	water pollution	eutrophication potential [CML2001]	kg PO_4-eq
Soil	LU	Land Use	land use	land use [CML2001]	m^2a
	EDP	Ecosystem Damage Potential	biodiversity impacts	ecosystem damage potential [EDP]	points
	TAETP	Terrestrial Ecotoxicity Potential	soil degrad. & contamination	terrestrial ecotoxicity (TAETP100a) [CML2001]	kg 1,4-DCB-eq
Resources	ARD	Abiotic Resource Depletion	resource depletion	depletion of abiotic resources [CML2001]	kg Sb-eq
	NHWL	Non-Hazardous Waste Landfilled	non-hazardous waste	landfilling of bulk waste [EDIP2003]	kg waste
	RWL	Radioactive Waste Landfilled	hazardous waste	landfilling of hazardous waste [EDIP2003]	kg waste
	HWL	Hazardous Waste Landfilled	hazardous waste	landfilling of radioactive waste [EDIP2003]	kg waste

In the above table, the far-right column identifies the units in which each of these environmental indicators are measured. The abbreviation "eq" stands for equivalents which will often be used when more than one pollutant can cause a particular impact. For example, global warming is attributed to a number of gases, including carbon dioxide (CO_2) and methane (CH_4); however emissions are reported for this indicator simply in units of "kg of CO_2 equivalents." On that basis, CO_2 is said to have a global warming potential (GWP) of one because one kg of CO_2 has the warming potential of itself, but methane has a GWP of 25 (one kg of CH_4 has the warming potential of 25 kg of CO_2). By using equivalent values, it simplifies the outputs of the LCA and facilitates comparisons between studies. Several other criteria are reported in a similar way, notably the toxicity criteria, which are assessed relative to the toxicity of 1,4-DiChloroBenzene (1,4-DCB), a known carcinogenic substance.

The following material provides a brief overview of each of the 15 environmental criteria against which the incandescent, CFL and LED lamps are assessed.

Indicator: Global Warming Potential (GWP)
Measurement Units: kilograms of carbon dioxide (CO2) equivalents
Description: This indicator is a measurement of activities associated with the life cycle of the product that alter the chemical composition of the atmosphere through the build-up of greenhouse gases, primarily carbon dioxide, methane, and nitrous oxide. As these and other heat-trapping gases increase their concentration, the heat-trapping capability of the earth's atmosphere will also increase, triggering global climate change and associated environmental impacts.

Indicator: Acidification Potential (AP)
Measurement Units: kilograms of sulfur dioxide (SO2) equivalents
Description: This indicator is a measure of the air pollution (mainly ammonia, sulfur dioxide and nitrogen oxides) caused by the product's life cycle which contributes to the deposition of acidic substances. The resultant 'acid rain' is best known for the damage it causes to forests and lakes. However, less well known impacts are the ways acidification affects freshwater and coastal ecosystems, soils and even ancient historical monuments. Acid deposition can also increase the environmental mobility of metals, resulting in the pollution of water sources and increased uptake of metals (e.g., mercury) by biota.

Indicator: Photochemical Ozone Creation Potential (POCP)
Measurement Units: kilograms of ozone (O3) formed
Description: This indicator is a measure of the photochemical smog generated during the product's life cycle. Common sources include automobile internal combustion engines, as well as the increased use of fossil fuels for heating, industry, and transportation. These activities lead to emissions of two major primary pollutants, volatile organic compounds (VOCs) and nitrogen oxides. Interacting with sunlight, these primary pollutants convert into various hazardous chemicals known as secondary pollutants – namely peroxyacetyl nitrates (PAN) and ground-level (tropospheric) ozone. These secondary pollutants cause what is commonly referred to as "urban smog."

Indicator: Ozone Depleting Potential (ODP)
Measurement Units: kilograms of CFC-11 equivalents
Description: This metric quantifies the ozone depleting potential of the product during its life cycle. Although ground-level ozone is a pollutant, stratospheric ozone is beneficial, protecting the earth from excessive amounts of ultraviolet light. The stratospheric ozone layer is attacked by free radical catalysts, some of which are produced by many man-made chemicals such as chlorofluorocarbons (CFCs) which were used as a blowing agent in aerosols and insulation and as a working fluid in refrigerator compressors. This indicator adjusts all ozone depleting chemicals associated with the UEL to the equivalent level of emissions of these harmful chemicals.

Indicator: Human Toxicity Potential (HTP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator attempts to quantify the air, water and soil emissions associated with the product's life cycle that may be detrimental to human health. The toxicological factors are calculated using scientific estimates for the acceptable daily intake or tolerable daily intake of the toxic substances, but are still at an early stage of development, so can only be taken as an indication and not as an absolute measure of the toxicity potential. The measurement units are in equivalents of 1,4-dichlorobenzene, a known carcinogen.

Indicator: Freshwater Aquatic Ecotoxicity Potential (FAETP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator is very similar to human toxicity potential, but combines factors associated with the maximum tolerable concentrations of different toxic substances in water by freshwater aquatic organisms.

Indicator: Marine Aquatic Ecotoxicity Potential (MAETP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator is analogous to FAETP, combining factors associated with the maximum tolerable concentrations of different toxic substances in water, but refers to marine aquatic organisms.

Indicator: Eutrophication Potential (EP)
Measurement Units: kilograms of phosphate (PO4) equivalents
Description: Nitrates and phosphates are essential for life, but increased concentrations in water can encourage excessive growth of algae, reducing the oxygen within the water and damaging ecosystems – a phenomenon known as eutrophication.

Indicator: Land Use (LU)
Measurement Units: square meters per year (m2a), the product of m2 area and years
Description: Land use is an economic activity that generates large benefits for human society, but it also has negative impacts on the environment. The occupation of a location by an industrial facility precludes the return of that site to a more natural environment, including availability for wildlife. The indicator captures the impact on both the area involved and the number of years over which that occurs.

Indicator: Ecosystem Damage Potential (EDP)
Measurement Units: points
Description: Biodiversity has been negatively influenced by intensive agriculture, forestry and the increase in urban areas and infrastructure. This indicator attempts to provide some measure of that impact. It combines land-use and land transformation (both to and from industrial uses), and assigns characterization factors to account for the relative impact of the land usage.

Indicator: Terrestrial Ecotoxicity Potential (TAETP)
Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents
Description: This indicator is very similar to the previous toxicity potentials, but refers to the maximum tolerable concentrations of different toxic substances by terrestrial organisms.

Indicator: Abiotic Resource Depletion (ARD)
Measurement Units: Equivalent kilograms of the scarce element, antimony (Sb)
Description: The current levels of global resource consumption are widely acknowledged to be unsustainable. Abiotic resources are natural, and essentially limited, resources, such as iron ore, crude oil and natural gas, as opposed to renewable, biotic sources such as biomass. ARD impacts are reported against the remaining global inventory of antimony (Sb), a relatively scarce element.

Indicators: Non-Hazardous Waste Landfilled (NHWL), Radioactive Waste Landfilled (RWL), and Hazardous Waste Landfilled (HWL)
Measurement Units: Kilograms of each of these three land-fill processes
Description: For the products being considered in this LCA, these indicators all seek to quantify the amount of materials sent to landfill, split between three categories – non-hazardous waste, radioactive waste and hazardous waste.

7 Life Cycle Assessment Results

Having identified the materials and processes being consumed for each of the lamp types in Chapter 5 and selecting the fifteen environmental indicators in Chapter 6, this chapter presents the results of the analysis. The first review is to determine which stages of the life-cycle assessment are significant and which ones are negligible from an environmental impacts point of view. This analysis is important to inform the sensitivity analysis, which will investigate significant assumptions and test whether conclusions drawn are robust to plausible variations in the underlying data.

For each lamp type, the LCA impacts are calculated separately for the raw materials, the manufacturing, the transport (by sea and by road), the power consumed during the lamp's operating life and finally the end of life. The following series of tables and bar charts present the LCA results for each lamp type, broken down by these LCA stages. The values shown are in the units presented in Chapter 6 (and repeated below), but normalized to represent the impact associated with 20 megalumen-hours of light. This quantity of lighting service was used in DOE's Part 1 study and is equal to the light output of the 12.5 Watt LED lamp (2012) over its rated lifetime.

GWP	Global Warming Potential	kg CO_2-eq
AP	Acidification Potential	kg SO_2-eq
POCP	Photochemical Ozone Creation Potential	kg O_3 formed
ODP	Ozone Depleting Potential	kg CFC11-eq
HTP	Human Toxicity Potential	kg 1,4-DCB-eq
FAETP	Freshwater Aquatic Ecotoxicity Potential	kg 1,4-DCB-eq
MAETP	Marine Aquatic Ecotoxicity Potential	kg 1,4-DCB-eq
EP	Eutrophication Potential	kg PO_4-eq
LU	Land Use	m^2a
EDP	Ecosystem Damage Potential	points
TAETP	Terrestrial Ecotoxicity Potential	kg 1,4-DCB-eq
ARD	Abiotic Resource Depletion	kg Sb-eq
NHWL	Non-Hazardous Waste Landfilled	kg waste
RWL	Radioactive Waste Landfilled	kg waste
HWL	Hazardous Waste Landfilled	kg waste

Table 7-1. Life Cycle Impacts of the 60W Incandescent Lamp

Incandescent	Air					Water		
LCA Stage	GWP	AP	POCP	ODP	HTP	FAETP	MAETP	EP
Raw Materials	6.28	0.90049	0.000604	0.00000069	3.224	2.9873	11.026	0.05847
Manufacturing	7.77	0.06905	0.000796	0.00000030	4.373	0.0405	0.901	0.02756
Transport	0.28	0.00387	0.000043	0.00000004	0.098	0.0017	0.107	0.00053
Energy in Use	1017.12	6.93390	0.044379	0.00001008	197.746	18.5601	99.647	1.85966
Disposal	0.19	0.00059	0.000035	0.00000003	0.045	0.0011	0.017	0.00031
TOTAL	1031.64	7.90790	0.045857	0.00001114	205.486	21.5907	111.698	1.94653

Incandescent	Soil			Resources			
LCA Stage	LU	EDP	TAETP	ARD	NHWL	RWL	HWL
Raw Materials	1.7476	1.1385	0.002262	0.0499	2.060	0.0003923	0.0007504
Manufacturing	0.7402	0.5534	0.001446	0.0447	2.321	0.0000822	0.0002103
Transport	0.0033	0.0026	0.000051	0.0020	0.019	0.0000044	0.0000038
Energy in Use	20.2769	15.2903	0.120488	7.5409	30.601	0.0421082	0.0224757
Disposal	0.0198	0.0122	0.000134	0.0014	0.949	0.0000024	0.0000032
TOTAL	22.7878	16.9970	0.124381	7.6389	35.950	0.0425895	0.0234434

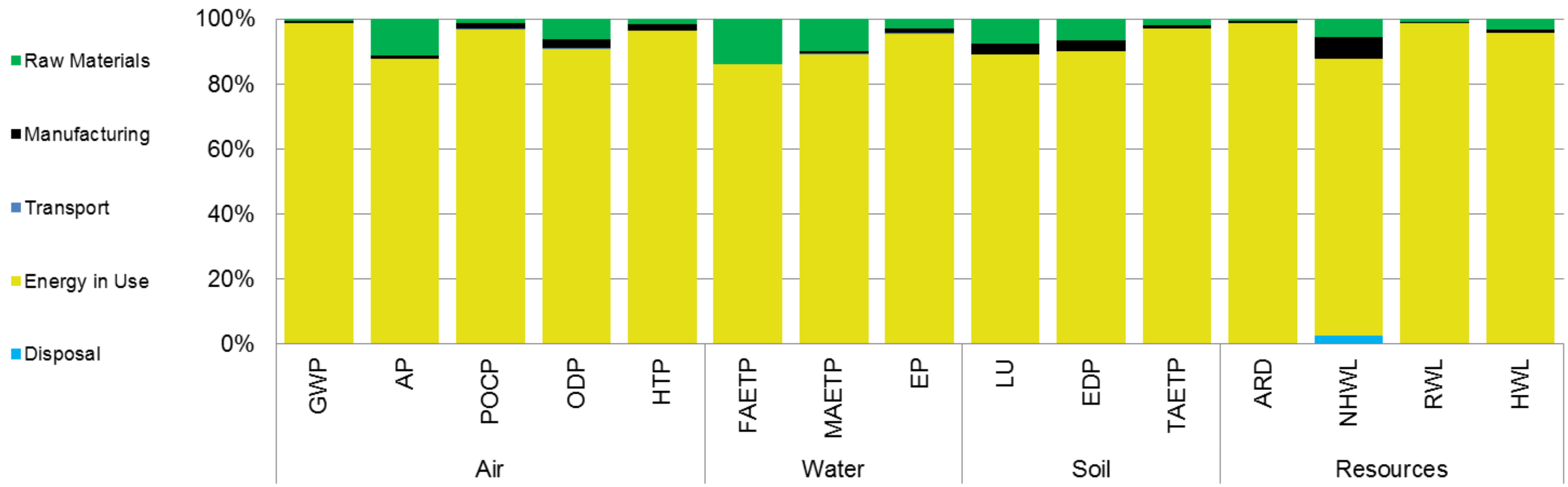


Figure 7-1. Proportions of the Life Cycle Impacts for the 60W Incandescent Lamp

Table 7-2. Life Cycle Impacts of the Compact Fluorescent Lamp

CFL LCA Stage	Air GWP	Air AP	Air POCP	Air ODP	Air HTP	Water FAETP	Water MAETP	Water EP
Raw Materials	10.680	0.29225	0.002879	0.00000117	9.007	0.5182	6.9088	0.10631
Manufacturing	16.560	0.08449	0.001215	0.00000120	4.677	0.3486	2.2256	0.03657
Transport	0.173	0.00237	0.000026	0.00000002	0.060	0.0010	0.0654	0.00032
Energy in Use	277.380	1.89095	0.012103	0.00000275	53.928	5.0615	27.1750	0.50715
Disposal	0.086	0.00029	0.000016	0.00000001	0.020	0.0005	0.0077	0.00014
TOTAL	304.879	2.27035	0.016239	0.00000515	67.692	5.9298	36.3825	0.65049

CFL LCA Stage	Soil LU	Soil EDP	Soil TAETP	Resources ARD	Resources NHWL	Resources RWL	Resources HWL
Raw Materials	1.0292	0.7001	0.013140	0.08395	1.382	0.000801	0.001169
Manufacturing	0.7215	0.5433	0.002536	0.08566	2.995	0.000239	0.000350
Transport	0.0020	0.0016	0.000031	0.00121	0.012	0.000003	0.000002
Energy in Use	5.5297	4.1698	0.032858	2.05648	8.345	0.011483	0.006129
Disposal	0.0085	0.0052	0.000057	0.00063	0.555	0.000001	0.000001
TOTAL	7.2909	5.4200	0.048622	2.22793	13.289	0.012527	0.007651

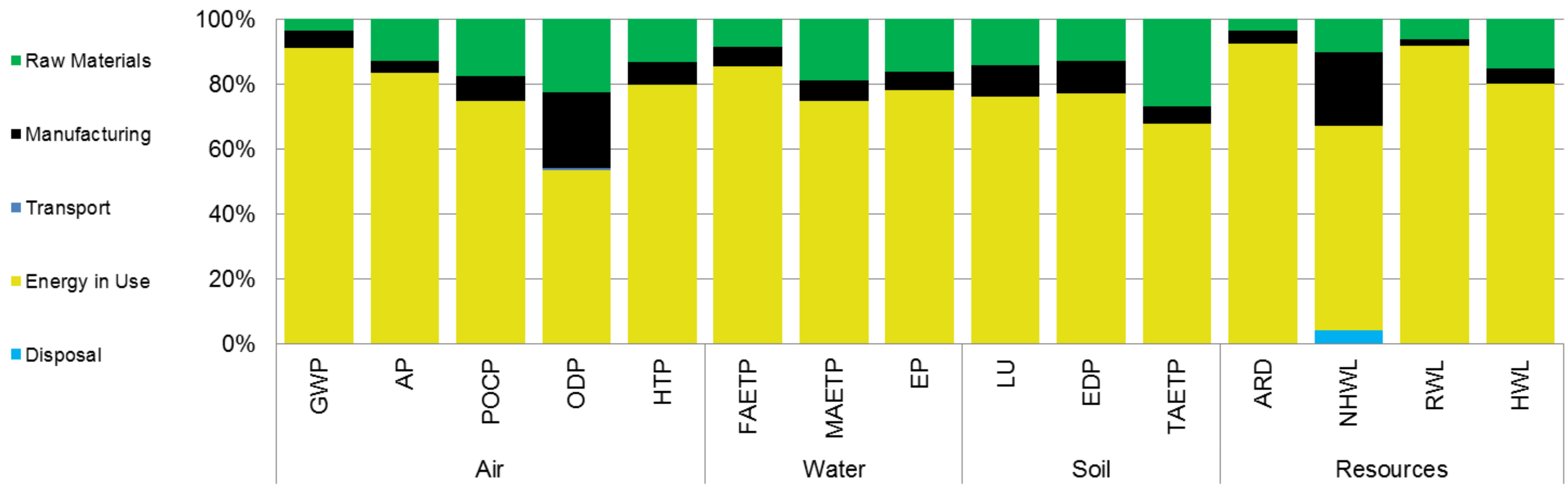


Figure 7-2. Proportions of the Life Cycle Impacts for the Compact Fluorescent Lamp

Table 7-3. Life Cycle Impacts of the 2012 LED Lamp

LED-2012	Air					Water		
LCA Stage	GWP	AP	POCP	ODP	HTP	FAETP	MAETP	EP
Raw Materials	12.752	0.118812	0.0020015	0.0000013575	13.2821	0.376537	6.4255	0.09046
Manufacturing	3.450	0.031194	0.0003134	0.0000000989	1.4660	0.015090	0.3198	0.00939
Transport	0.052	0.000708	0.0000078	0.0000000064	0.0180	0.000310	0.0196	0.00010
Energy in Use	234.756	1.600375	0.0102428	0.0000023255	45.6406	4.283750	22.9991	0.42922
Disposal	0.015	0.000059	0.0000027	0.0000000025	0.0035	0.000091	0.0014	0.00002
TOTAL	251.025	1.751148	0.0125682	0.0000037908	60.4102	4.675778	29.7654	0.52919

LED-2012	Soil			Resources			
LCA Stage	LU	EDP	TAETP	ARD	NHWL	RWL	HWL
Raw Materials	0.45011	0.33650	0.0069973	0.08918	4.3440	0.0008670	0.0028337
Manufacturing	0.26894	0.20316	0.0005715	0.02003	0.7873	0.0000281	0.0000658
Transport	0.00060	0.00048	0.0000093	0.00036	0.0035	0.0000008	0.0000007
Energy in Use	4.68000	3.52906	0.0278091	1.74047	7.0628	0.0097188	0.0051875
Disposal	0.00140	0.00085	0.0000089	0.00011	0.1692	0.0000002	0.0000003
TOTAL	5.40105	4.07005	0.0353961	1.85015	12.3668	0.0106149	0.0080880

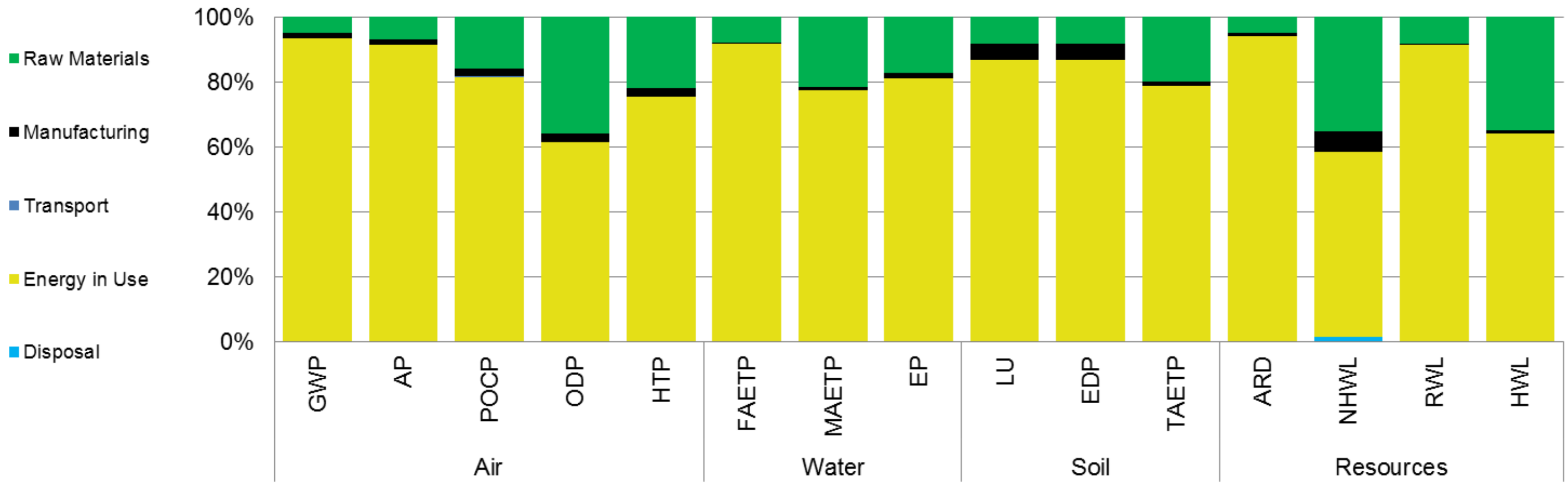


Figure 7-3. Proportions of the Life Cycle Impacts for the 2012 LED Lamp

Table 7-4. Life Cycle Impacts of the 2017 LED Lamp

LED-2017	Air					Water		
LCA Stage	GWP	AP	POCP	ODP	HTP	FAETP	MAETP	EP
Raw Materials	6.995	0.059638	0.000980	0.000000856	7.5722	0.24578	4.0410	0.056569
Manufacturing	1.900	0.017255	0.000167	0.000000050	0.7461	0.00794	0.1658	0.004804
Transport	0.027	0.000365	0.000004	0.000000003	0.0093	0.00016	0.0101	0.000050
Energy in Use	113.837	0.776046	0.004967	0.000001128	22.1318	2.07726	11.1526	0.208135
Disposal	0.013	0.000046	0.000002	0.000000002	0.0031	0.00008	0.0012	0.000022
TOTAL	122.772	0.853350	0.006120	0.000002039	30.4625	2.33122	15.3707	0.269580

LED-2017	Soil			Resources			
LCA Stage	LU	EDP	TAETP	ARD	NHWL	RWL	HWL
Raw Materials	0.2547	0.18857	0.004386	0.04949	3.5353	0.0004879	0.0011664
Manufacturing	0.1404	0.10642	0.000306	0.01106	0.4023	0.0000144	0.0000327
Transport	0.0003	0.00025	0.000005	0.00019	0.0018	0.0000004	0.0000004
Energy in Use	2.2694	1.71130	0.013485	0.84398	3.4249	0.0047128	0.0025155
Disposal	0.0013	0.00080	0.000009	0.00010	0.0826	0.0000002	0.0000002
TOTAL	2.6661	2.00734	0.018191	0.90482	7.4469	0.0052157	0.0037152

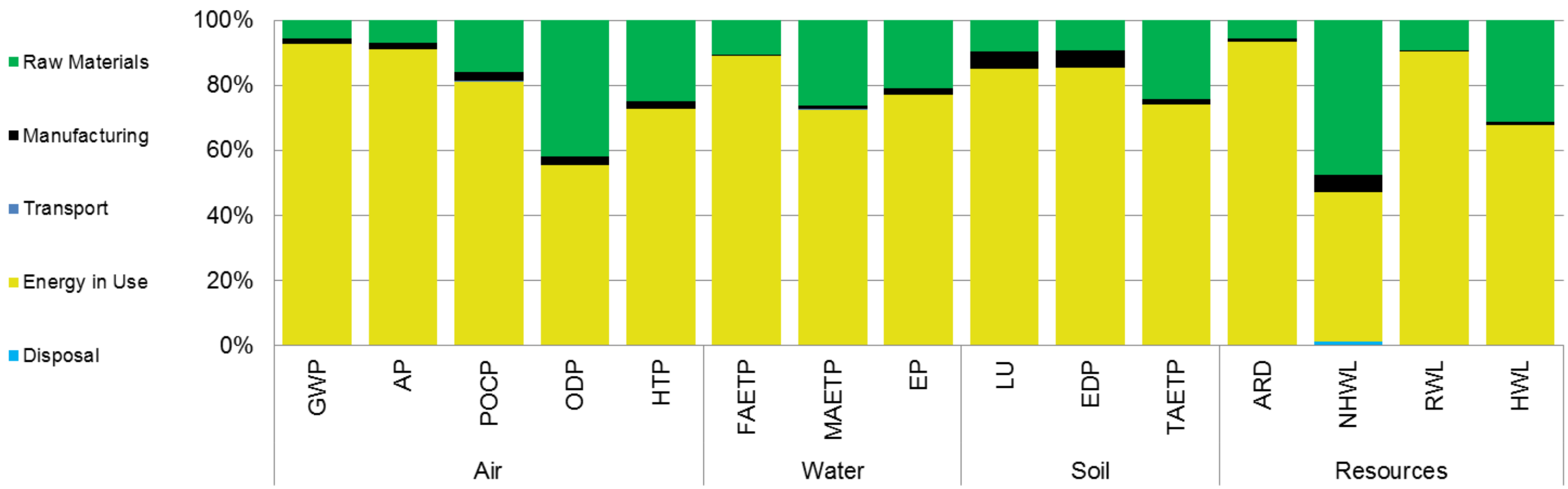


Figure 7-4. Proportions of the Life Cycle Impacts for the 2017 LED Lamp

7.1 Discussion of Life Cycle Assessment Results

The four sets of results clearly show that the factor that dominates the majority of the environmental indicators considered is ‘energy in use’ which is depicted in each figure with yellow shading. The proportion of impact attributable to energy in use is particularly high for the 60 watt incandescent lamp, where energy in use constitutes an average 93% of the fifteen impacts over the lifetime of the lamp. The next most significant stage of the assessment is the raw materials which constitute on average about 5% of the total impact, ranging from 13.8% for freshwater aquatic ecotoxicity potential to 0.6% for abiotic resource depletion. Manufacturing is the third most significant step in the LCA, with an average impact over the fifteen indicators of approximately 1.8%. The remaining two LCA steps – disposal and transport – constitute 0.2% and 0.1% respectively, although the majority of the disposal impact is in non-hazardous waste landfilled, where it represents 2.6% of that impact. Transportation was found to be virtually negligible, even though the lamps in their packaging have traveled over 11,000 kilometers from factory to home.

For the CFL, the largest contributor to environmental impacts is energy, which represents at most 92.3% of the impact (for abiotic resource depletion) and at least 53.4% (for ozone depleting potential). On average, energy in use represents about 78% of the impact of a CFL. The next most significant stage of the LCA is the raw materials, representing on average 13.6% of the impacts, with terrestrial ecotoxicity potential being the most impacted with 23.3% overall. Manufacturing is the third most impactful step in the LCA, with an average impact of approximately 8.2% overall. The remaining two LCA steps – disposal and transport – constitute 0.3% and 0.1% respectively, although the majority of the disposal impact is in non-hazardous waste landfilled, where it represents 4.2% of that impact. As with the incandescent lamp, the impact associated with transport was found to be virtually negligible, even though the packaged CFLs travel over 11,000 kilometers from factory to home.

For the LED lamp in 2012, the largest contributor to environmental impact is energy in use, which represents an average of 81% across the fifteen indicators. The proportion of impact varies from a high of 94.1% for abiotic resource depletion to a low of 57.1% for non-hazardous waste landfill. The second most significant impact is the raw materials used in manufacturing the LED lamp. These include a range of components, the LEDs and the large heat sink. On average the impact from the raw materials is 16.8%, with a high of 35.8% (for ozone depleting potential) and a low of 4.8% (for abiotic resource depletion). Manufacturing is the third most impactful step in the LCA, with just 2.3% and the disposal and transport impacts are extremely low, both less than 0.1%. As with the incandescent lamp and CFL, the packaged LED Lamp is assumed to be transported over 11,000 kilometers by sea and road, but the impacts are virtually negligible.

For the LED lamp in 2017, the profile is similar to that of the 2012 lamp, however the significance of energy is diminished due to the fact that this lamp is considerably more efficacious. For this reason, the other impacts are able to gain a slightly higher proportion of the relative impact for each of the fifteen categories considered. In this analysis, energy in use represents an average of 78.2% of the impact, followed by raw materials at 19.3% and manufacturing at 2.3%. The transportation and disposal of the lamp are negligible, at less than 0.2% each.

7.2 Comparative Results Between the Lamps

As well as understanding which parts of the life cycle are the main contributors to the overall environmental impacts of each lamp analyzed, it is also important to compare the lamps themselves to determine which have the smallest overall impact. The results of that analysis are presented in this subsection of the report.

The table below presents the environmental impacts associated with air and climate for each of the lamp types. Within each of the impact indicators, the values presented are comparable between the different lamp types because the lighting service has been normalized to represent 20 Mlm-hr of light output.

Table 7-5. Air-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service

Lamp Type	Global Warming Potential (GWP)	Acidification Potential (AP)	Photochemical Oxidation (POCP)	Stratospheric O_3 depletion (ODP)	Human Toxicity Potential (HTP)
	kg CO2-Eq	*kg SO2-Eq*	*kg formed O_3*	*kg CFC-11-Eq*	*kg 1,4-DCB-Eq*
Incandescent	1031.640	7.90790	0.0458570	0.0000111	205.4860
CFL	304.879	2.27035	0.0162390	0.0000052	67.6920
LED-2012	251.025	1.75115	0.0125682	0.0000038	60.4102
LED-2017	122.772	0.85335	0.0061200	0.0000020	30.4625

For global warming potential, the incandescent lamp has the largest CO_2-equivalent emissions, with over one tonne of emissions associated with the functional unit of 20 million lumen-hours of light. The CFL lamp represents a 70% reduction over the incandescent lamp for equivalent lighting service. The LED lamps are even better, offering a 76% reduction with the 2012 lamp and an 88% savings with the 2017 lamp.

For acidification potential, the trend is similar. The incandescent lamp causes the greatest impact, with 7.9 kilograms of sulfur dioxide equivalent emissions for 20 megalumen-hours of light. The CFL offers a reduction of 71% over the incandescent and the two LED lamps offer a 78% and 89% reduction respectively, greatly reducing the acidification potential.

Photochemical oxidation leads to urban smog, and the emissions of this air pollutant are the most severe with the incandescent lamp. That lamp will emit approximately 46 grams of ozone for the functional unit of light output. The CFL and both LED lamps offer savings over that baseline of 65%, 73% and 87% respectively.

Stratospheric ozone depletion potential is highest with the incandescent baseline lamp. The other, more efficacious lamps, offer savings potentials of between 53% and 82% when compared with the incandescent baseline.

For human toxicity potential, the lamp with the highest impact for the functional unit of light output is the incandescent lamp. The CFL offers a 67% reduction over incandescent and the two LED lamps offer a 71% and 85% savings potential in 2012 and 2017 respectively.

The following table presents the environmental impacts associated with water-related indicators for each of the lamp types, normalized for 20 Mlm-hr of light output.

Table 7-6. Water-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service

Lamp Type	**Freshwater Aquatic Ecotoxicity Potential (FAETP)**	**Marine Aquatic Ecotoxicity Potential (MAETP)**	**Eutrophication Potential (EP)**
	kg 1,4-DCB-Eq	*kg 1,4-DCB-Eq*	*kg PO4-Eq*
Incandescent	21.5907	111.6980	1.9465
CFL	5.9298	36.3825	0.6505
LED-2012	4.6758	29.7654	0.5292
LED-2017	2.3312	15.3707	0.2696

For freshwater aquatic ecotoxicity potential, the incandescent lamp has the largest impact, with over three times the impact of the CFL and ten times the impact of the LED in 2017. The units for this environmental indicator are reported in equivalent kilograms of "1,4-DCB" which is 1,4-DiChloroBenzene, a known carcinogen. The LED lamp in 2012 offers a 78% reduction in this impact compared to the incandescent lamp.

For marine aquatic ecotoxicity potential, the trend is similar. The incandescent lamp causes the greatest impact, with 112 kilograms of 1,4-DiChloroBenzene equivalent emissions for 20 megalumen-hours of light. The CFL offers a reduction of 67% over the incandescent and the two LED lamps offer a 73% and 86% reduction respectively, greatly reducing this environmental damage potential.

Eutrophication potential is the last indicator of water-related impacts, measuring the impact in terms of kilograms of phosphate equivalents that could cause excessive algal growth in waterways reducing oxygen in the water and damaging the ecosystem. The incandescent lamp will emit approximately 2 kilograms of phosphate equivalents over the 20 megalumen-hour lighting service functional unit. The CFL is approximately 67% less than that with 0.65 kg, and the two LED lamps are even lower at 0.53 kg and 0.27 kg in 2012 and 2017 respectively. The 2017 LED lamp represents an 8-fold reduction in the damages measured by this environmental indicator.

The following table presents the environmental impacts associated with soil-related indicators for each of the three lamp types, normalized for 20 Mlm-hr of light output.

Table 7-7. Soil-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service

Lamp Type	Land Use (LU)	Ecosystem Damage Potential (EDP)	Terrestrial Ecotoxicity (TAETP)
	m^2a	*points*	*kg 1,4-DCB-Eq*
Incandescent	22.7878	16.9970	0.1244
CFL	7.2909	5.4200	0.0486
LED-2012	5.4011	4.0701	0.0354
LED-2017	2.6661	2.0073	0.0182

Land use is a measure of impact on both the area involved and the number of years over which that impact occurs. Of the lamps considered, the incandescent lamp has the largest impact, with a value three times higher than the CFL and four times higher than the LED in 2012. The land use equivalent for an incandescent lamp providing 20 megalumen-hours of lighting service is 22.8 square meters per year. For the same lighting service, a CFL reduces that impact by 68%. The LED lamps reduce it further still, to only 5.4 square meters with the 2012 lamp and 2.5 square meters in 2017. These levels represent a 76% and 88% reduction respectively when compared to the incandescent lamp.

For ecosystem damage potential, the trend is similar. The incandescent lamp causes the greatest impact, with 17 points of ecosystem damage potential over the functional unit. The CFL offers a 68% reduction over the incandescent and the two LED lamps offer a 76% and 88% reduction respectively, greatly reducing the ecosystem damage potential.

Terrestrial ecotoxicity is measured in the 1,4-dichlorobenzene equivalents. The incandescent lamp was found to cause the release of 0.12 kilogram equivalents of this carcinogen. Compared to that impact, the CFL offers a reduction of 61%, lessening the impact to only 0.05 kilogram equivalents. The two LED lamps are even lower at 0.035 kg and 0.018 kg in 2012 and 2017 respectively. The 2017 LED lamp represents an 85% reduction over the incandescent lamp benchmark for the damages measured by this environmental indicator.

The following table presents the four resource-related environmental indicators that were assessed for each of the three lamp types, normalized for 20 Mlm-hr of light output.

Table 7-8. Resource-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service

Lamp Type	Abiotic Resource Depletion (ARD)	Non-Hazardous Waste Landfill (NHWL)	Radioactive Waste Landfill (RWL)	Hazardous Waste Landfill (HWL)
	kg antimony-Eq	*kg waste*	*kg waste*	*kg waste*
Incandescent	7.6389	35.9500	0.0426	0.0234
CFL	2.2279	13.2890	0.0125	0.0077
LED-2012	1.8502	12.3668	0.0106	0.0081
LED-2017	0.9048	7.4469	0.0052	0.0037

For the first of the resource-related environmental impacts, abiotic resource depletion potential has the largest depletion of the metric used for this environmental indicator, kilograms of antimony equivalents depleted. The incandescent lamp's impact is approximately 7.6 kilograms, while the more efficient lamp types offer a 71% (CFL) to 88% (LED in 2017) reduction over that baseline.

For non-hazardous waste landfill, the trend is similar. The incandescent lamp causes the greatest impact, with 36 kilograms of non-hazardous waste equivalents for the functional unit of 20 megalumen-hours of light. The CFL offers a reduction of 63% over the incandescent and the two LED lamps offer a 66% and 79% reduction respectively, greatly reducing the impact for this metric.

For radioactive waste landfill, the proportions of the reduction are nearly identical to that of the abiotic resource depletion potential. The incandescent lamp generates 43 grams of radioactive waste landfill equivalents, where the CFL and both LED lamps case the generation of substantially less waste. The CFL offers a reduction of 71%, to just 12 grams per 20 megalumen-hours of lighting service. The LED lamp in 2012 offers a 75% savings at 11 grams and the 2017 lamp offers a substantial savings of 88% savings at just 5 grams of radioactive waste landfill generated for the same light output.

For hazardous waste landfill, the trend is similar but not exactly the same. The incandescent lamp still has the largest impact, with 23 grams of hazardous waste landfill generated. The LED in 2012 has the next lower impact, with 8.1 grams, a 65% reduction. The CFL lamp is slightly lower than the LED with 7.7 grams, which represents a reduction of 67% over the baseline. And finally, the LED in 2017 has the lowest impact overall, with only 3.7 grams of hazardous waste landfill, a reduction of 84%. The reason that the LED lamp in 2012 has a slightly higher impact than the CFL is due to the large aluminum heat sink, which represents 20% of the total impact measured for this metric. While these are the mean values reported, the difference between the two is within the error margin for this study. Please see Annex A for a sensitivity analysis on this particular environmental indicator (i.e., Hazardous Waste Landfill).

Setting the other stages of an LCA to one side, if a comparison is performed simply between the raw material inputs of the lamp types studied in this analysis, the distribution of environmental impacts tends to be greater for the more efficient lamps because they are more complex systems. The CFL and LED lamps both make use of technology in order to reduce the watts of power consumed when producing light. Since the energy-in-use is the dominant LCA stage in terms of impacts (see Figures 7-1 through 7-4), the greater raw material impacts are justified on a life-cycle basis because these lamps reduce the overall environmental impacts associated with the same lighting service. In the future, improvements in LED manufacturing technology will improve efficacy and reduce costs facilitating the added benefit of lower impacts in almost all respects than any of the competing products on a life-cycle basis, even before accounting for the energy consumed in use.

7.3 Summary of the Environmental Impacts

To facilitate simpler interpretation of the results across the four lamps and the fifteen environmental indicators, the results are also presented in two 'spider graphs' shown in Figure 7-5 and Figure 7-6. Each radial line on the chart represents a different environmental impact, and the impacts are grouped into four categories – air (orange), water (blue), soil (green) and resources (yellow). For each impact, whichever lamp has the largest impact is plotted at the outer circumference, and the other products are then normalized to that impact. Therefore, the distance from the center of the spider graph represents the severity of the impact relative to that worst performer. The relative position of the points for the other lamps demonstrates their relative environmental impact to that maximum. Therefore, the closer each point is to the center of the graph, the smaller that particular impact. Those lamps with most of their plotted impacts close to the center of the web are generally the best performers from an environmental perspective.

It is clear from Figure 7-5 that the incandescent lamp has the highest impact per unit lighting service of all the sources considered (it occupies all of the outermost points on the chart). This result is intuitive because this lamp has the lowest efficacy of all the lamps considered and energy in use was already identified as the most significant indicator of environmental impact.

In all but one environmental indicator category (i.e., hazardous waste landfill), the next worst performer is the CFL, followed by the LED lamp in 2012 and then the LED lamp in 2017. The actual difference between the CFL and the LED for the hazardous waste to landfill category is 0.4 grams. The reason that the LED lamp in 2012 has a slightly higher impact than the CFL is due to the large aluminum heat sink, which represents 20% of the total impact measured for this metric.

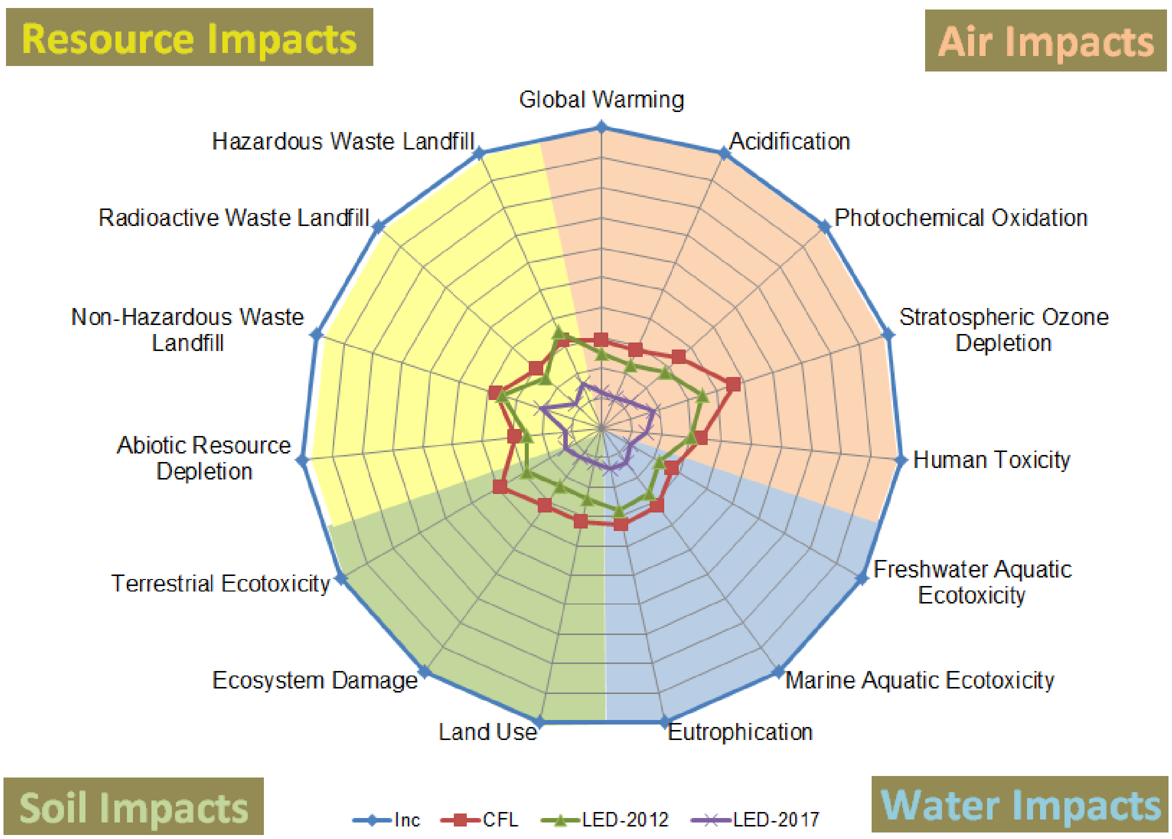


Figure 7-5. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to Incandescent

The incandescent lamp has the highest impact per unit lighting service of all the lamps considered. This finding is not a function of the material content, as the incandescent lamp has the lowest mass and is least complex lighting system. Rather, it represents the very low efficacy of this light source, where large quantities of energy are required to produce light. The high energy consumption per unit light output causes substantial environmental impact and results in the incandescent lamp being the most environmentally harmful across all fifteen impact measures.

The next worst performer is the compact fluorescent lamp, which has substantially lower impacts than incandescent, but is slightly more harmful than the 2012 integrally ballasted LED lamp. This is true in all but one category – hazardous waste landfill – where the large aluminum heat sink causes the impacts to be slightly greater for the LED lamp than for the CFL. The best performing light source is the projected LED lamp in 2017, which takes into account several projected improvements in LED manufacturing, LED performance and driver electronics.

Figure 7-6 presents the same findings shown in Figure 1-1, but the graph has been adjusted to remove the incandescent lamp and provide the impacts relative (primarily) to the CFL.

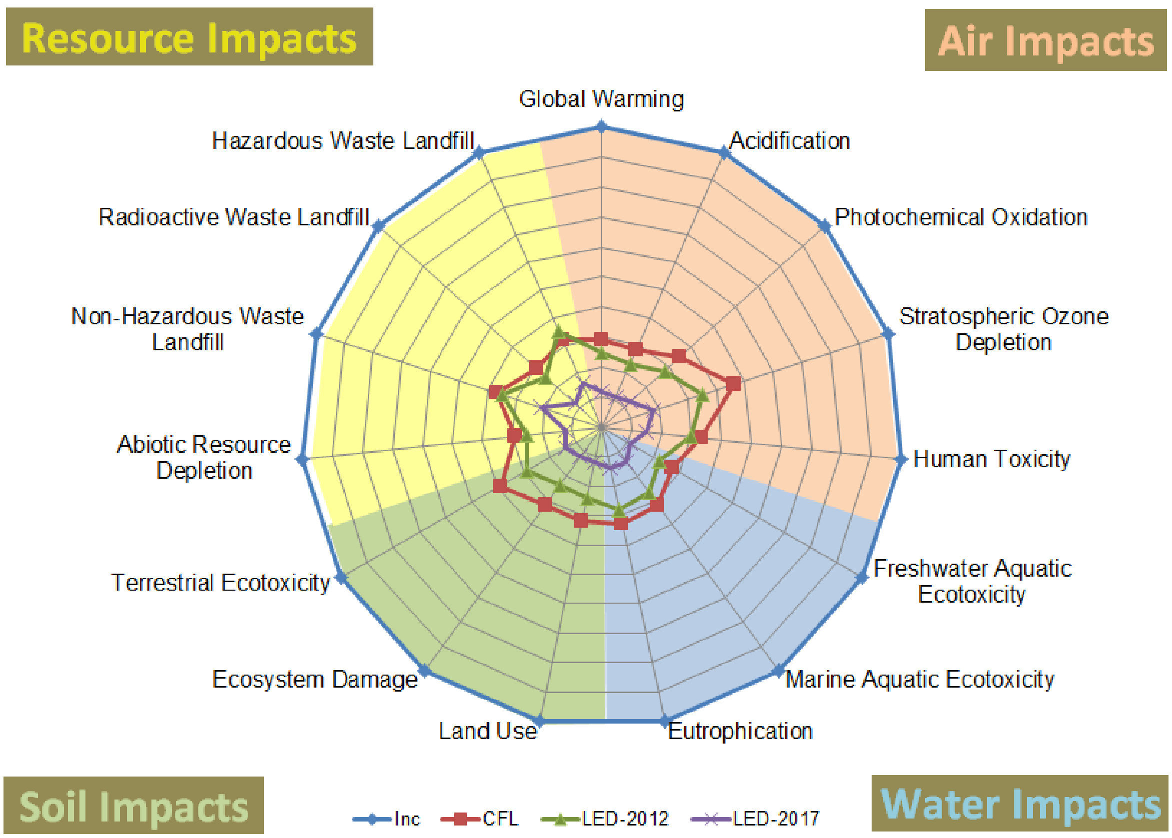


Figure 7-6. Life-Cycle Assessment Impacts of the CFL and LED Lamps Analyzed (Detail)

Overall, the impacts of the LED lamp in 2017 are significantly less than the incandescent, and about 70% lower than the CFL and approximately 50% lower than the LED lamp in 2012, which itself is the best available technology in 2012. The important finding from these graphs is not necessarily the minor relative differences between the CFL and LED lamps, but instead the very significant reduction in environmental impacts that will result from replacing an incandescent lamp. Environmental impact reductions on the order of 3 to 10 times are possible across the indicators through transitioning the market to these more efficacious light sources. These reductions are largely due to the reduction in energy consumption per unit light delivered in 2017. Thus, due to the dominant role of energy consumption in driving the impacts, continued focus on efficacy targets and incentives is appropriate. Furthermore, the greatest environmental impact after energy in-use for the LED sources is the aluminum heat sink, which would be reduced as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat).

7.3.1 Comparison with DOE Part 1 Study Findings

As discussed in Chapter 2 of this report, DOE published Part 1 of this LCA study earlier in 2012 (DOE, 2012a). The Part 1 study reviewed existing LCA literature, focusing on the energy consumed in manufacturing and use of the lamps studied. The report compared existing life-cycle energy consumption of an LED lamp to that of an incandescent lamp and a CFL based on ten key published studies.

As shown in Figure 2-1 of this report, the Part 1 report found that the life cycle energy consumption of LED lamps and CFLs to be similar at approximately 3,900 MJ per 20 million lumen-hours of lighting service. Incandescent lamps were found to consume approximately four times more energy (approximately 15,100 MJ per 20 million lumen-hours).

In Figure 7-7, the equivalent findings of the Part 2 study are presented. In general, these findings largely corroborated the Part 1 study results with only very slight differences. For incandescent lamps, the power consumption in Part 2 was less than 1% lower than the Part 1 result. For CFLs, the Part 1 finding was 4.3% lower than the Part 2. For LED lamps, the Part 2 study was found to be lower than Part 1, however this is to be expected as the Part 2 study is the first of its kind considering this relatively new lamp and the Part 1 study is considering lamps that were analyzed in LCA studies already published.

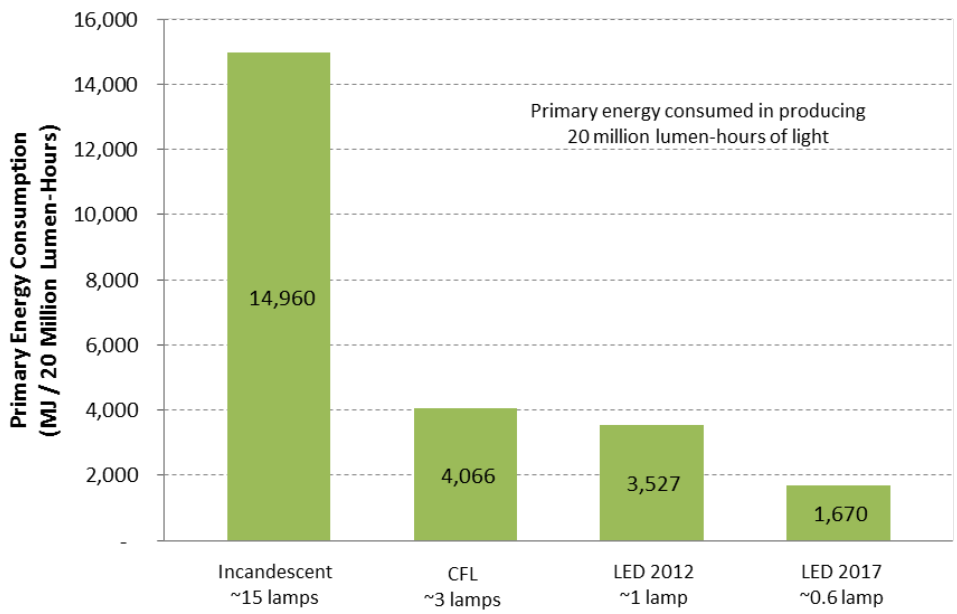


Figure 7-7. Life Cycle Assessment Primary Energy for Lamps in Part 2 Study

7.4 Data Quality Assessment

This section of the report considers the quality of the data underpinning the analysis. To document the quality of the data collected in this life cycle inventory, the table below was prepared to rate each data source based on key data quality criteria.

Table 7-9. Data Quality Ranking Based on Highest Value for this Goal and Scope (5 high, 1 low)

Reference	Time Related Coverage	Geographical Coverage	Technology Coverage	Precision of the Data	Completeness of the Data
Yole Develop.	4	5	4	5	5
OSRAM input	2	5	3	5	5
DEFRA LCA	2	4	3	5	4

In terms of the time-related coverage, the OSRAM life-cycle assessment (OSRAM, 2009) and the DEFRA study (DEFRA, 2009) were both published in 2009 and therefore represent LED technology from 2008 and 2009. These two studies are given a relatively low ranking on a time-scale due to the very rapid evolution of LED technology, which is experiencing significant change in both the manufacturing processes and the performance of the technology itself. The Yole research that was shared with this team, on the other hand, represents InGaN white-light LED production from the 2010 – 2011 time period, so it represents technologies and processes that are closer to those used in 2012.

In terms of geographical coverage, all of the studies scored relatively high. Yole's research is modeling the manufacturing processes of one of the major LED manufacturers in the world, therefore this is clearly given the highest score for global coverage. OSRAM retails product in over 150 countries around the world, so their LCA is about a technology that is global in nature, even if it has only been introduced in a few markets initially. The DEFRA study is given a slightly lower score because its focus was the UK market, drawing examples of products – as much as possible – from the UK. Many of these same or similar products are available elsewhere in the world, however the focus is on the UK and so the geographical coverage score is a 4.

In terms of technology coverage, the scores reflect the age of each of the data sources as well as the content contained therein. The Yole research is reflective of a recent manufacturing process for a high-volume, globally available LED technology. However it only characterizes the process and performance of this one manufacturer, and therefore isn't representative of all the technologies and approaches followed in the market. For this reason, the study is given a 4. For the OSRAM and DEFRA studies, these are both slightly dated, so the technologies being discussed and characterized in these reports are slightly out of date on a technological basis, resulting in a score of 3 for both.

In terms of the precision of the data, each study is given a 5 because they are all considered to be thoroughly researched, documented and peer-reviewed. The presentation in each case is clear and concise, and is easy to analyze and adapt to this work. Hence they are all given the top score for this data quality criterion.

Finally, on completeness of the data, the Yole research is given top marks again because the study offers a highly detailed and rigorous process analysis. The research team at Yole Développement includes several process engineers, solid-state scientists and researchers with industry experience. Given that level of technical expertise in-house, we find that the product of their research institute to be complete for the purposes of this study. Similarly, the OSRAM study is given top marks because it is the first LCA that we are aware of that was published by one of the global manufacturers of LEDs. In preparing their work, OSRAM drew upon a wide range of expertise from within their company, and ensured that the detail included in their resulting report was highly rigorous and accurate. OSRAM confirms this fact by demonstrating that this study was peer-reviewed by three independent experts who are familiar with LCA science. The DEFRA report is given 4 out of 5 because it relies on secondary sources of information for some of the lamps analyzed which are not complete. This became clear, for example, studying the baseline incandescent lamp and CFL which are cross-referenced to other studies.

7.4.1 Comparison of Ecoinvent LED with DOE LED Impact Estimates

As discussed earlier in this report, the Ecoinvent database version 2.2 already contains an entry for an LED. The Ecoinvent LED record covers raw material input and production of 5 millimeter LEDs for hole-through mounting technology. The LEDs modeled in the Ecoinvent database are commonly used in the information and communication technology industries and have a typical weight of 0.35 grams per unit. The impact assessment takes into account average diode production technology, including the diode wafer production (i.e., cleaning, masking, etching, doping, oxidizing, and metal deposition) and the final assembly of the diode (wafer sawing, die bonding, molding, trimming and forming). While this is a very good record for an indicator LED, it does not represent a high-brightness LED and also is based on LED manufacturing technology from 2007 and 2008, rather than the equipment being used today.

In Chapter 5 of this report, the authors present their characterization of the LED manufacturing process. LED manufacturing is an interim step in the production of an LED lamp which is ultimately what this study is investigating. However, for the purposes of understanding how much LED technology has improved and/or is different relative to the Ecoinvent LED that already exists in database version 2.2, the authors prepared a comparison of the environmental impacts associated with these two LEDs. Due to the fact that one LED is a 5 millimeter indicator lamp and the other is a high-brightness LED used in general illumination applications, the impacts need to be normalized for light output from the device. The indicator lamp was found to have a light output of 4 lumens, whereas the high-brightness LED was found to have a light output of 70 lumens (Philips, 2012).

The following table presents the comparison between the Ecoinvent LED and the InGaN LED manufactured for use in the Philips EnduraLED lamp. The table shows the significant reduction in the environmental impacts on a per-lumen basis that have been achieved between the 2007 Ecoinvent assessment and the 2011 technology that was assessed in this model. Overall, the average reduction in impact is 94.5%.

Table 7-10. Comparison of Ecoinvent LED and this Study's LED Manufacturing Impacts

Ecoinvent Indicator	Units	Ecoinvent LED* (2007)	DOE LED (2011)	Reduced Impact %
Global Warming Potential	kg CO2-Eq	0.0268	0.00155	92.3%
Acidification Potential	kg SO2-Eq	0.000131	0.0000105	89.3%
Photochemical Ozone Creation Potential	kg formed ozone	0.00000318	0.000000105	95.6%
Ozone Depleting Potential	kg CFC-11-Eq	2.33E-09	2.86E-11	98.4%
Human Toxicity Potential	kg 1,4-DCB-Eq	0.00613	0.000192	95.8%
Freshwater Aquatic Ecotoxicity Potential	kg 1,4-DCB-Eq	0.000129	0.00000402	95.9%
Marine Aquatic Ecotoxicity Potential	kg 1,4-DCB-Eq	0.00317	0.0000829	96.5%
Eutrophication Potential	kg PO4-Eq	0.0000841	0.00000193	96.9%
Land Use	m2a	0.000571	0.0000446	89.6%
Ecosystem Damage Potential	points	0.000444	0.0000352	89.4%
Terrestrial Ecotoxicity Potential	kg 1,4-DCB-Eq	0.00000535	0.000000213	94.7%
Abiotic Resource Depletion	kg antimony-Eq	0.000199	0.0000084	94.4%
Non-Hazardous Waste Landfilled	kg waste	0.00139	0.0000863	91.7%
Radioactive Waste Landfilled	kg waste	0.00000233	2.64E-08	98.5%
Hazardous Waste Landfilled	kg waste	0.00000065	9.14E-09	98.1%
			Average:	94.5%

* The Ecoinvent database unique ID for the "light emitting diode, LED", at plant is 7077.

Thus, on a lumen output basis, it would appear that high-brightness LEDs manufactured in 2011 are significantly less harmful for the environment than the 5mm indicator LEDs that were produced in 2007.

8 Critical Review

Input solicited from several lighting experts and manufacturers during the course of the project has provided the critical peer review section of the LCA. This report will be circulated in draft form to allow additional comments from industry prior to finalizing the study results.

Early review by manufacturers confirmed that the assumptions in this report are realistic, and they indicated that many of the manufacturing processes are already more efficient than those documented in this report. Other reviewers indicated that the chemical and energy use documented in this report for the MOCVD process appears to be reasonable.

9 Recommendations

This report and the Part 1 study (DOE 2012a) together provide a full summary of LED LCA work to date. This analysis documents the manufacturing process in a publicly-accessible medium for external review and comment, which will enable the LCA and lighting research communities to continue refining the research.

Several recommendations for future work have been highlighted by the study:

1. Work with manufacturers to reduce the size of aluminum heat sinks and/or find alternative materials and configurations to reduce the mass. The aluminum heat sinks contribute significantly to upstream waste and energy consumption. Manufacturers are testing a variety of new techniques to improve heat transfer, which may result in more environmentally friendly products with smaller heat sinks.

2. Work with manufacturers to meet the DOE targets for efficacy and performance that will make LED lighting solutions dramatically better than CFLs for the full life cycle environmental impacts. This may include, for example, creating the “L-Prize Mark II” to further encourage innovation and improvement in the efficacy of LED lamps, as the energy-in-use phase has proven to have the most significant environmental impact of all those analyzed.

3. Encourage academic and industry studies of and programs for recycling to improve end of life options for LED products. The heat sink represents a significant cost opportunity for recycling programs.

4. Revisit the manufacturing process documented in this report periodically to account for improvements to the process, which may further reduce the environmental impacts of LED systems.

5. Encourage Ecoinvent to establish a new category of ‘high brightness LED’ for the Ecoinvent database which reflects 2012 LED manufacturing technology as opposed to the 2007 indicator light LED that is currently in the database.

The last part of this study (Part 3) will provide additional insight about the disposal of the products by testing LEDs for disposal thresholds. This part of the study will provide a useful “check” on the actual environmental impact of one LED lamp and compare it to the benchmark provided by EPA and other regulatory groups.

10 APPENDIX A: Sensitivity Analysis

This section provides an overview of an analysis that was conducted to quantify the sensitivity of the results to possible changes in the assumptions or estimates underpinning the model. One option for dealing with this uncertainty is simply to make an estimate of the unknown parameters. This is a pragmatic approach to arriving at an answer, but creates uncertainty about the reliability of the results. A sensitivity analysis aims to explore the sensitivity of the results and conclusions to these underlying assumptions, and thereby provide comment on the confidence in the results.

A Monte Carlo analysis is a useful tool for checking confidence in estimates and assumed values. With this tool, the user stipulates which parameters will be variables, and specifies the distribution for each of those parameters. The Monte Carlo analysis then performs multiple calculations, each time randomly generating a value from within the defined range and using it to generate results from a run of the model. The final output of a Monte Carlo analysis is a distribution of results instead of a single point result. By plotting histograms of the distributions for the different lamp types analyzed, it is possible to determine, by the amount of overlap, a level of confidence in the results.

A Monte Carlo sensitivity analysis was run on the LCA model varying the lifetime of each of the lamps, the efficacy and the percentage recycling at end of life. The calculations were performed in the Microsoft Excel workbook that had been created, using the Oracle Crystal Ball software plug-in. Table A-1 presents the parameters chosen for the simulation. All were modeled using a normal distribution, and the means and standard deviations (SD) of the distributions are also shown. A total of 10,000 runs of the model were conducted for this sensitivity analysis.

Table A-1. Parameters of Normal Distributions Used in the Monte Carlo Sensitivity Analysis

Incandescent	**Mean**	**Standard Deviation**	**Units**
Efficacy	15	1	lumens/watt
Lifetime	1500	100	hours
Recycling Lamp	0.1	0.025	percent recycled
Recycling Packaging	0.3	0.05	percent recycled
Compact Fluorescent Lamp	**Mean**	**Standard Deviation**	**Units**
Efficacy	55	5	lumens/watt
Lifetime	8000	1000	hours
Recycling Lamp	0.2	0.025	percent recycled
Recycling Packaging	0.3	0.05	percent recycled
Light Emitting Diode 2012	**Mean**	**Standard Deviation**	**Units**
Efficacy	65	7	lumens/watt
Lifetime	25000	5000	hours
Recycling Lamp	0.2	0.025	percent recycled
Recycling Packaging	0.3	0.05	percent recycled
Light Emitting Diode 2017	**Mean**	**Standard Deviation**	**Units**
Efficacy	134	15	lumens/watt
Lifetime	40000	5000	hours
Recycling Lamp	0.2	0.025	percent recycled
Recycling Packaging	0.5	0.1	percent recycled

Results

The general form of the results is depicted in Figure A-1, which shows the predicted future global warming potential of the four lamps analyzed in this report. The plot is based on 10,000 runs of the model varying the input assumptions shown in Table A-1. From this graph, it is clear that the incandescent lamp has the highest impact for global warming potential with a mean at 51 kg CO2-equivalents per million lumen hours and a standard deviation of 3.5 kilograms. The CFL has a mean of 15.2 kg CO2-equivalents per million lumen hours with a much tighter standard deviation of 1.4 kilograms. The LED 2012 lamp has virtually the same shape as the CFL and the same standard deviation, but its mean has shifted lower to 12.5 kg CO2-equivalents. Finally, the LED 2017 lamp has the tightest distribution of results, with a mean of 5.7 kg and a standard deviation of only 0.6 kg.

This finding strengthens the overall outcome of this study, providing more assurance that varying the inputs to the degree they are in Table A-1 does not change the overall finding and prioritization of impacts for this environmental indicator. And, while this graph only presents the impacts in terms of global warming potential, the outcome is similar for the other 14 indicators.

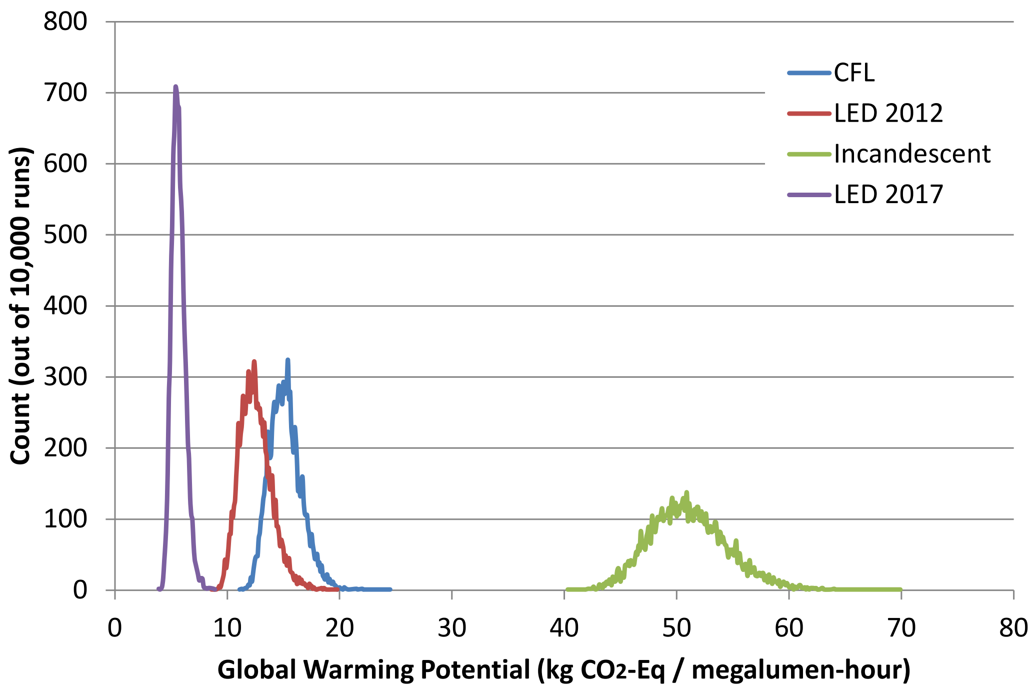


Figure A-1 Scatter Plot of Results for Monte Carlo Analysis of Global Warming Potential

Figure A-2 presents the scatter plot of results for the Monte Carlo analysis of Hazardous Waste Landfill. This is the environmental indicator which found that LED lamps in 2012 had slightly more impact than CFLs (see Figure 7-6). Using the same range of input variables given in Table A-1, the following graph was prepared for the Hazardous Waste Landfill indicator.

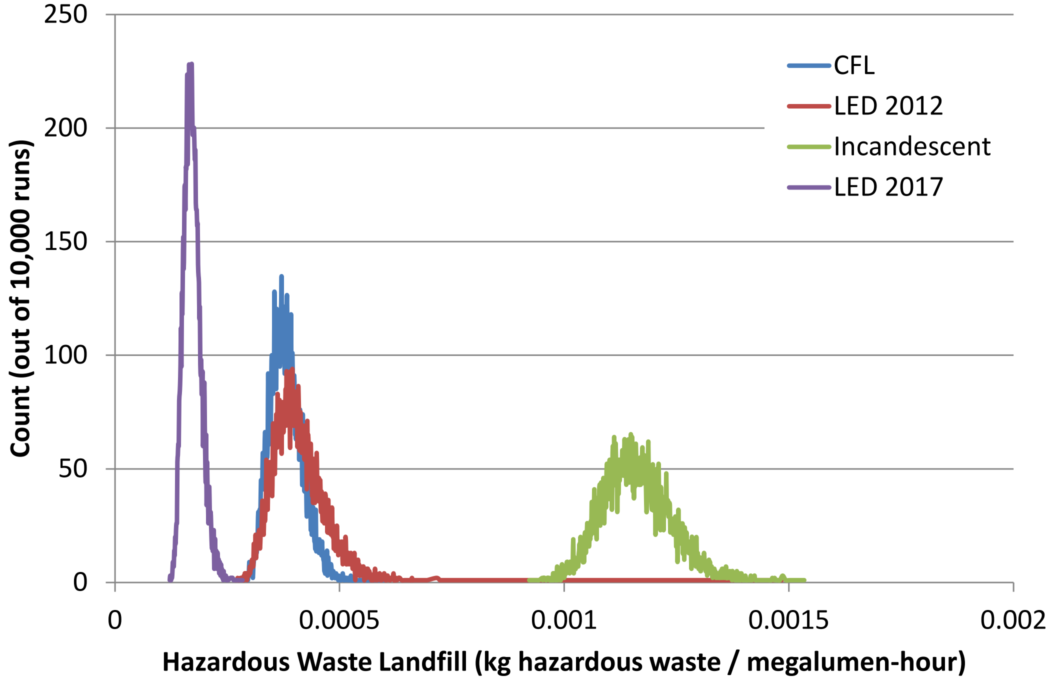


Figure A-2 Scatter Plot of Results for Monte Carlo Analysis of Hazardous Waste Potential

The shape and overlapping nature of the two graphs are slightly different. The LED has a mean of 0.41 grams of hazardous waste per megalumen-hour with a standard deviation of 0.06 grams. The CFL has a mean of 0.38 grams of hazardous waste with a standard deviation of just 0.04 grams. The mean values of the two lamp types are extremely close and the area described under the two scatter plots of results is very similar. To get a more detailed view of these two lamps, we remove the incandescent lamp and the LED 2017 lamp, as shown in Figure A-3.

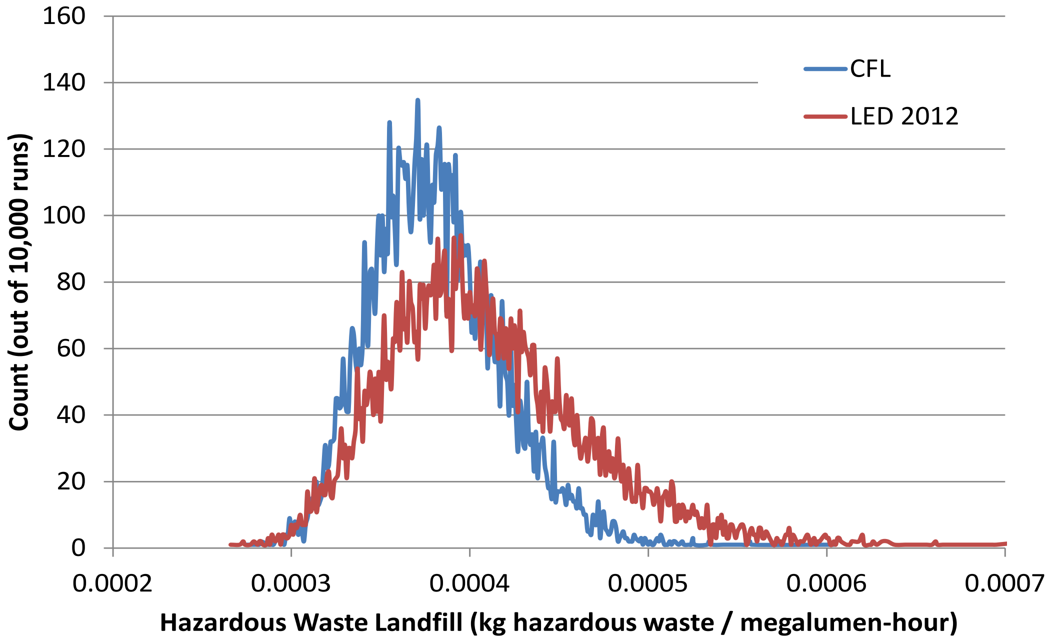


Figure A-3 Scatter Plot of Results for CFL and LED 2012 of Hazardous Waste Potential

In Figure A-3, by zooming in on this section of the X-axis and removing the other lamp types from the plot, it becomes easier to focus on a comparison between these two distributions. There is reasonably good overlap to the left of the two plots, which represents those lamps having lower hazardous waste landfill impacts. The mean values for these two scatter plots are different, but the CFL lamp is only 7% lower than the LED 2012. The reason for this difference is because of the right hand part of the two curves, where the LED lamp has a longer tail stretching out to the right. Referring back to Figure A-2, it is important to note that the LED lamp in 2017 has significantly lower hazardous waste landfill impact when compared to CFLs. This is due to the projected improvements in efficacy and the associated reduction in the mass of the aluminum heat sinks used in the 2017 LED lamp design.

In conclusion, the Monte Carlo sensitivity analysis shows that the incandescent lamp has, by a considerable margin, the largest environmental impact and thus represents the least preferred lighting option. Due to the great impact associated with energy-in use, changing to a more efficient lamp will reduce impacts, with LED lamps in 2012 being a better option on a LCA basis than CFLs. LED lamps in 2017 represent a significantly better lighting option, with much lower environmental impacts.

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