



Sustainable LED Fluorescent Light Replacement Technology

Final Report

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Table of Contents

Section	Page
Acronyms and Abbreviations	v
1. Executive Summary	1
1.1 Project Partners	2
2. Background	3
2.1 Project Goals and Objectives	3
2.2 Relevance to DOE Goals	4
3. Project Methodology	5
4. Project Results and Benefits	7
4.1 Phase 1 – “As-Is” Analysis	7
4.2 Phase 2 – Development	9
5. Using the Sustainable LED Product Design Guide	15
6. Conclusions and Opportunities for Further Work	19
7. Technology Transfer Activities	21
Appendix A – Tested Lamps	A-1
Appendix B – Environmental Impact Values and Documentation	B-1
Appendix C – Sustainable LED Product Design Guide	C-1
Appendix D – Presentation Materials	D-1

Acronyms and Abbreviations

BOM	Bill-of-Materials	LCIA	life cycle impact assessment
CFL	compact fluorescent lamp	LED	light-emitting diodes
CRI	color rendering index	NCMS	National Center for Manufacturing Sciences
DOE	Department of Energy	REACH	Registration, Evaluation, Authorization and Restriction of Chemical Substances
EOL	end-of-life	RoHS	Restriction of Hazardous Substances
EU	European Union	SSL	solid state lighting
GHG	greenhouse gas	U.S.	United States
LCA	life cycle assessment		
LCI	life cycle impact		

1. Executive Summary

Solid-state lighting, using light-emitting diodes (LEDs), has great energy saving potential over conventional incandescent and fluorescent lamps currently in use. However, although there are great energy savings in the use-phase of the lamps, the remainder of the product lifecycle is not so cut-and-dried. LED products rely on on-board or sometimes off-board power supplies and other electronic circuits. Aluminum heat sinks may be required for heat management to maintain long lifetimes. Adhesives or fasteners are necessary to hold all the constituent components together. All of this added complexity has an environmental footprint, especially when considered against the relative simplicity of fluorescent tubes and screw-in incandescent bulbs. Only by evaluating the entire product lifecycle, from raw material extraction to manufacturing to use through end-of-life, can the overall ecological impacts of the lamps be determined.

Illumisys and the National Center for Manufacturing Sciences (NCMS) partnered on a three-year project awarded by the United States (U.S.) Department of Energy (DOE), to quantify the impacts of LED lamps, incandescent lamps and fluorescent benchmark lamps over a product lifecycle – i.e. to develop a sustainable design and manufacturing strategy that addresses product manufacturing, use, recycling and disposal scenarios for LED-based lighting. Based on the knowledge gained from extensive product tear-down studies of fluorescent and screw-in lighting products, lifecycle assessment tools, and accelerated lifecycle testing protocols, an interactive Sustainable LED Design Guide has been developed to aid architectural and lighting designers and engineers in making design decisions that consider three important environmental impacts (greenhouse gas

emissions, energy use and mercury emission) across all phases of the life of an LED lighting product. Critical information developed for the lifecycle analysis and product feature comparisons is the useful life of the lighting product as well as its performance. The Design Guide is available at www.ncms.org, and was developed based on operational and durability testing of a variety of lighting products including power consumption, light output, and useful life of a lamp in order to allow a more realistic comparison of lamp designs.

This report describes the main project tasks, results and innovative features of the lifecycle assessment (LCA)-based design tools, and the key considerations driving the sustainable design of LED lighting systems. The Design Guide incorporates the following three novel features for efficiently evaluating LED lighting features in value-chains:

- **Bill-of-Materials (BOM) Builder** – Designers may import process data for each component and supply functional data for the product, including power, consumption, lumen output and expected useful life.
- **Environmental Impact Review** – Designs are comparable across lifecycle phases, subsystems, and environmental impact category, and can be normalized to a user-defined functional unit.
- **Drill-down Review** – These provide an in-depth look at individual lamp designs with the ability to review across subsystem or lifecycle phase.

As part of the dissemination effort, and to solicit input for validation of the Guide, Illumisys and NCMS staff presented the project at five industry events, with a sixth technical presentation planned in late October 2011.

1.1 Project Partners

Illumisys is a Troy, Michigan-based company focused on next generation solid-state lighting technology. The company was formed in 2007 as a spinoff venture and wholly-owned subsidiary of Altair Engineering, Inc. with initial products based on Altair's intellectual property for the direct replacement of fluorescent light tubes with LED lamps.

NCMS is a not-for-profit organization, based in Ann Arbor, Michigan and a premier provider of

collaborative research, information, knowledge and expertise to the North American manufacturing and defense community. Backed by over 300 corporate members, NCMS has spearheaded numerous advancements – in advanced materials, alternative energy, electronics, high-performance computing, rapid prototyping, nanomanufacturing, enterprise integration and sustainability – all focused on enhancing the nation's manufacturing competitiveness in the global economy.

2. Background

It is estimated that lighting accounts for 25% of the total electricity usage by residential and commercial consumers in the U.S., and is responsible for 10% of all U.S. carbon dioxide emissions. The DOE estimates that lighting-based energy consumption can be reduced by at least 20% by 2030 through the use of solid-state LED based lighting.¹ LEDs are the fastest growing category of lighting technology that can counter problems related to mercury and light quality which are inherent in fluorescent lighting systems. LEDs contain no mercury or hazardous materials, and consume up to 90% less energy with no significant radiant heat or ultraviolet radiation. There have been tremendous strides in LED technology and cost reduction in recent years, with many new lighting products entering the marketplace that claim to provide lumen outputs and color temperatures matching the brightness and quality of conventional light sources. There is a high level of concern in the U.S. LED Industry to take concerted steps to defend against poor-quality LED products offering unwarranted claims of sustainability, in order to address allegations of “greenwashing.” This project was organized to raise the industry stakeholders’ interest in sustainability and environmental awareness, which are a necessary component of doing business, to assure the long-term competitiveness of the industry in the U.S. The project partners have addressed these issues by providing useful systems-level approaches and data-driven tools for guiding design and manufacturing decisions.

Preliminary investigations identified some key examples of design decisions that may influence the lifecycle impacts of the product that are

comparable to the use-phase impacts. Among them were:

- *Raw materials and manufacturing* – LED lifetime is directly affected by ambient temperatures. As a result, LED lighting products require substantial heat-sinks of aluminum or other thermally conductive material. The cradle-to-gate energy required to produce the heat sink, which is estimated at approximately 200 MJ per kg, is comparable to the energy consumed during several thousand hours of product use, and is thus, a significant factor in a lifecycle evaluation as proposed in this project.
- *Upgradability* – The ability to change out the LED devices for newer models while retaining much of the remaining fixture will have significant lifecycle advantages. However, this serviceability must be designed into the initial product, and involves tradeoffs in cost and convenience addressed in this project.
- *End-of-life* – LED lighting products do not contain mercury, and generally meet Restriction of Hazardous Substances (RoHS) compliance. However, LEDs do contain a wide variety of less common materials. New regulatory requirements, such as the REACH regulation in the European Union (EU), may affect the supply and availability of certain materials, and have consequences related to extended producer responsibility that will incur obligations for the manufacturer, and will limit disposal options for the consumer, at end-of-life.

This project analyzed the effect of such factors on the lifecycle performance of LED products.

¹ Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy, Washington, DC, February 2010.

2.1 Project Goals and Objectives

While the solid-state lighting (SSL) LED technology itself provides the environmental benefits of reduced energy use and, by extension, greenhouse gas emissions in the use-phase, the electronics, thermal management, and optical components have the potential to impact the environment during the other phases of the product lifecycle.

The main objective of this project was to evaluate alternative designs for solid-state lighting products over the entire product lifecycle with regard to key sustainability impact categories, including energy usage and greenhouse gas emissions. One expected outcome was the consolidation of key findings, measurements and lifecycle analyses for the development of a best practices guideline for eco-friendly LED product design that takes into account the current and future needs of LED lamps. By providing guidance to lighting designers, good design decisions can be made that help in reducing the environmental impact of the product in key phases: raw material extraction, product manufacturing, and end-of-life.

Rather than deliver a white paper outlining how to make good decisions or provide complicated lifecycle-based calculations, the partners opted to develop a public-domain Sustainable LED Product Design Guide via an online accessible web application that would simplify decision-making and be accessible to a broader audience of stakeholders. Allowing a user to develop simple BOM of their designs and get immediate visual feedback on the impacts of their material and process selection provides opportunities for quickly creating “what-if” scenarios. With the interactive ability to compare the sources of impacts by category, lifecycle phase, or product subsystems, a user could identify the primary sources of the impacts and design them out of the product.

2.2 Relevance to DOE Goals

The DOE *Solid-State Lighting Multi-Year Program Plan* (March 2006) specifically identifies cost (measured in dollars per kilolumen) and performance (measured in lumens per watt) as the immediate barriers to near-term adoption of solid-state lighting for general illumination applications. The global community is demanding that products be designed and manufactured in ways that help ensure sustainability by minimizing environmental impact throughout a product’s lifecycle. Simultaneously, the lighting industry faces the daunting task of re-educating consumers and other manufacturing stakeholders on how to achieve greater sustainability and to produce the same amount of light with fewer watts.

The Sustainable LED Product Design Guide provides a widely-accessible, user-friendly tool which allows designers of LED lighting products to choose materials and processes based on reduced energy use, greenhouse gas emission, and mercury emission. The environmental impacts can be compared across multiple design concepts or against benchmark lighting products, and across lifecycle phases. These unique capabilities of the tool address the mission of the DOE SSL Program by helping designers to reduce lifecycle energy consumption of solid-state lighting products beyond just the use-phase, while also reducing exposure to environmental risk factors such as climate change and toxicity.

Beyond reduction of impacts through the selection of materials and manufacturing processes, performance characteristics of the lighting products are considered in the Guide, allowing the balance of design against light output, power draw, and lamp life e.g. the impacts associated with additional aluminum for thermal management might be far outweighed by a resulting extension of lamp life.

3. Project Methodology

Life Cycle Assessment (LCA) is a methodology to develop an aggregate estimate of the environmental impacts by all of the processes that contribute to the raw materials, manufacturing, transportation, use, and end-of-life scenarios of a product or process.

The approach adopted to achieve the project objectives consisted of two project phases, executed in four technical tasks to perform systematic Life Cycle Impact Assessment (LCIA)-based database development and Design Guide development activities involving:

- Extensive product tear-downs of selected 16 LED, fluorescent and screw-in lighting products for material and manufacturing studies.
- Development of framework and databases for lifecycle assessment and impact information
- Accelerated lifecycle testing of products as input for design alternative exploration and analysis
- Development of user interface tools for dissemination of LCA-based sustainability information on the selected lighting products via web media.

The Statement of Work consisted of the following:

- Phase 1 – “As-Is” Analysis

Task 1.0 – Material and Manufacturing Analysis

Task 2.0 – Lifecycle Assessment

- Phase 2 – Development

Task 3.0 – Design Alternative Exploration and Analysis

Task 4.0 – Best Practices Guide Development

While the majority of technical tasks were performed at Ilumisys, overall project oversight and management was provided by NCMS. Detailed quarterly progress reports were filed by NCMS during the project.

This final report provides the highlights of the above tasks with significant results that include:

- (a) Test measurements and graphical results from product lifecycle testing (Appendix A)
- (b) Environmental impact values derived (with key data sources) (Appendix B)
- (c) User manual for the Sustainable LED Product Design Guide – a web-based tool hosted by NCMS at www.ncms.org (Appendix C)
- (d) Sample slide presentation of the Guide for industry outreach (Appendix D).

4. Project Results and Benefits

4.1 Phase 1 – “As-Is” Analysis

Task 1.0 – Material and Manufacturing Analysis

Ilumisys identified and procured 16 different product samples (screw-in incandescent bulbs and fluorescent lamps), and then performed systematic tear-down studies on each sample as part of the analysis work. The complete product list is provided in Appendix A.

BOM templates developed in Excel were populated with materials and manufacturing process information for these 16 different product samples so that LCA-based comparison studies could begin. The product list included three Ilumisys products for comparing to benchmarks during new product tests and BOM population.

The common lamp assembly structure developed that was used in completing the BOMs for all benchmark lamps consisted of the following five subsystems:

1. Electronic and Electrical Components
2. Optical Components
3. Thermal Management Components
4. Fixture Interface Components
5. Miscellaneous Mechanical Components.

All of the constituent processes in the raw material and manufacturing phases were identified to the best judgment of the Ilumisys engineers. For example, the heat sink for a given lamp might be identified as an aluminum casting with machining and anodizing operations. This would constitute aluminum extraction (raw material phase), aluminum casting (manufacturing phase), aluminum machining (manufacturing), and anodizing (manufacturing). The required measurable for these processes would be the part mass for the

extraction, casting, and machining processes, and surface area for the anodizing process.

The focus of such analyses was on screw-in incandescent-replacement type lamps and 4-foot linear fluorescent replacement lamps. In each case, where possible, four units were purchased. Two of each model of the lamps were designated for testing, one was used for disassembly and one spare was kept for any other uses that might arise such as unexpected failures of test lamps. Initially, lamps that had been tested in the CALiPER program were selected so any additional data points might be available. As new products came on the market that might incorporate different design concepts or vastly improved function, these products might be purchased for analysis.

Once a lamp had been disassembled, its components were identified, classified into common subsystem designations, and measured for the lifecycle metrics appropriate for that component. This identified the use-phase impacts of the product.

Finally, an end-of-life scenario was assigned. The default assumption for all products was landfill. This was applied on the total product mass. LCA impacts were also available for incineration. With further development, scenarios could be generated for recycling and remanufacturing. These scenarios are more complex and would require further study.

An additional data point was required for each product in order to compare different products in a normalized manner. With the light output identified for each product, products can be compared based on a normalized functional unit, namely lumen-hours.

The power draw, light output, and life expectancy of the products were initially taken from manufacturer claims. It has been clear

from the DOE sponsored CALiPER testing that manufacturer claims often differ from reality. Where possible, in the initial analyses, CALiPER results were used for light output and power draw. In order to determine consistent, long-term performance of the lamps, Ilumisys tested all products in their lighting lab. The details of the testing are outlined in the next section.

Task 2.0 – Lifecycle Assessment

Lifecycle assessment is a measure of the environmental impacts by all of the processes that contribute to the raw materials, manufacturing, transportation, use, and end-of-life scenarios of a product or process.

With NCMS support, information was extracted for populating the BOMs using query tools from two commercial life cycle impact (LCI) inventory databases: GaBi (PE database) and ecoInvent (SimaPro), and added to the Excel template – the majority of the lamp materials, other than electronics components, had data derived from GaBi that was included in the BOM template.

As the benchmark lamps were disassembled and cataloged, Ilumisys identified the materials and processes used to produce them, using GaBi and SimaPro LCI databases to provide “most representative” numbers as starting points for assessing the impacts of those materials and processes in three impact categories incorporated in the Material Data Feeder spreadsheet:

- Energy use (measured in kW)
- Greenhouse gas emissions (measured in 100-year equivalence of kg CO₂)
- Mercury emissions (measured in mg).

Ilumisys and NCMS supplemented the information obtained from these two commercial databases by researching other

independent measures of the inherent variability of the data, including such factors as:

- Variations in fuel heating value and carbon content
- Geographical variations in carbon intensity and electrical grid mix.

Addressing Inherent Variability in LCI Data

Periodic brainstorming meetings were held at NCMS with multi-disciplinary staff and internal sustainability and engineering experts at both organizations to identify possible strategies for calculating inherent and statistical variability and uncertainty in LCI data, so as to adopt robust methods for approximating the ranges of possible impact values. The goal was mainly to raise questions and thereby flag issues that may not have been fully considered. For example, when considering unaccounted carbon dioxide emissions from the core factors, SimaPro indicated 12.2 kg CO₂ emissions versus PE database’s mean value was 8.9 kg CO₂.

Factors contributing to the variability in setting boundaries or ranges of the lifecycle impact categories (i.e. greenhouse gas emissions, energy and mercury emissions) included:

- Use of two different (independent) databases (ecoInvent and PE) often due to different methods, or missing values or results available from only one database)
- Variance of fuels (e.g. different coals have been very different heating values)
- Feedstocks (e.g. unknown locations for transportation of materials and products)
- Transportation (unknown locations for transportation of materials and products)
- Process efficiency (well-defined versus vaguely defined processes, much data is based on European averages, whereas many of the lamps being evaluated are made in China).

The NCMS-recommended strategy for setting ranges (obtained from the two commercial LCI databases) was to use a “minimum-of-the-minimums, maximum-of-the-maximums” approach. This was done to approximate the inherent variability of impacts based on geography, process efficiency, etc. The primary driver to calculating this range was the variability of heating value and carbon content of the fossil fuels consumed in each of the processes. This approach, sometimes, did not account for the cases when data was only available from one of the two sources. In such cases, the “most representative” values for each impact were combined to develop a range, specified by a “maximum” (worst expected) and “minimum” (best feasible) value.

The BOM was set up in such a way that, as each product had its materials and processes identified, the lifecycle data was automatically filled in by way of a “data feeder” sheet. As LCI data was added and refined, the updates were thereby propagated immediately to all BOMs.

About 15% of cells in the Material Data Feeder Spreadsheet initially lacked data for the LCA model, for which the criticality of the “missing” data was assessed by Ilumisys. Examples of data needs that were resolved included:

- Tungsten (used in conventional bulb filaments)
- Silicone (used in adhesives and insulation from wiring used in LEDs) – Ilumisys required data on end-of-life stage for these materials.

4.2 Phase 2 – Development

Task 3.0 – Design Alternative Exploration and Analysis

Due to the volume of products included in durability tests, Ilumisys invested its own resources to develop an in-house laboratory so as to more efficiently and economically conduct light testing. This lab was operational in mid-

March 2010 with all testing components and instrumentation/data acquisition systems in place. Thereafter, product testing began in order to obtain real numbers for the functional lamp units under test.

Because the desired performance data included life expectancy of the lamps, long-term testing was needed to replace the manufacturer-claimed information. The Ilumisys team researched the test methods used in LM-79, LM-80, and Energy Star programs. Ilumisys employed a 5-foot diameter integrating sphere for testing linear fluorescent replacement lamps and a smaller 18” diameter integrating sphere for screw-in lamps. Lamps were stored in temperature-controlled boxes with a design based on the descriptions in Energy Star test documents. The box ambient temperature was maintained at 45°C and lamps were cycled continuously at 3 hours on, 20 minutes off (90% ON, 10% OFF). Four thermocouples were used in each box to assure that temperatures were maintained. Where necessary, 60W and 100W lamps were used to aid in maintaining the temperature. All lamps were separated by baffles as outlined in the Energy Star documents.

All lamps were “staged” outside their box for 1 hour prior to measure light output. They were left ON in 20°C ambient temperature in the lab before being moved quickly into the integrating sphere. Lamps were tested more frequently in the early part of the project (approximately twice per week) and less frequently later in the project (approximately twice per month). At the time of the writing of this report, lamps had been powered ON for approximately 8,000 hours (one calendar year of continuous use would be 8,760 hours).

The following metrics were collected in the product testing:

- Power consumption
- Current draw
- Power factor

- Luminous flux (light output)
- Color rendering index (CRI)
- Color temperature
- Chromaticity.

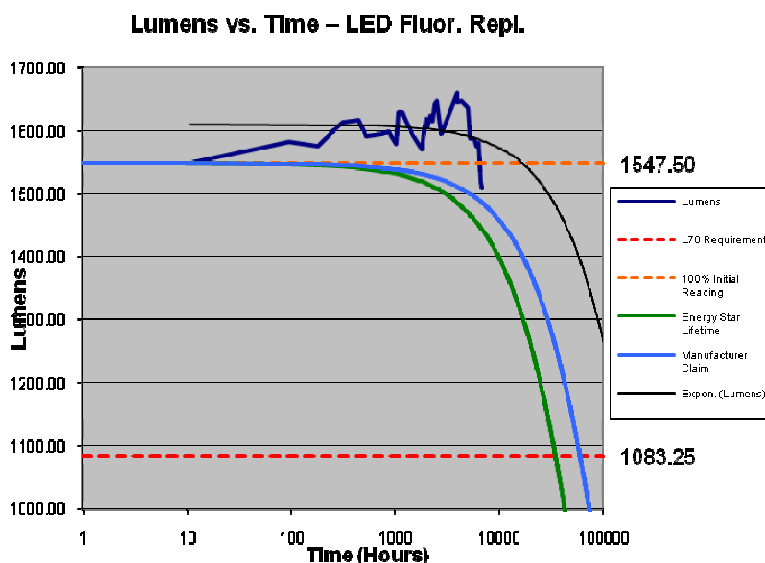
To conduct photometric testing of the lamps, Illumisys constructed a 62" diameter integrating sphere in which to place the lamps while the spectrometer took the light readings. The purpose of an integrating sphere was to disperse the light from the lamps so that there was an even distribution over the sphere surface so that the spectrometer could measure a non-directional radiation of the light. Utilizing a standard lamp that was calibrated at an outside lab, Illumisys was able to calibrate the integrating sphere setup.

Using the L70 specification of 70% light output as the end-of-life condition, Illumisys identified the real useful life of the lamps, either through direct measurement (if that condition was reached), or by extrapolation (if this condition was not reached within project timing). To this point we have used the manufacturer claims of light output and lifetime to define the functional units of the lifecycle analysis. This testing yielded more accurate numbers.

Samples of the charts compiled for a single lamp are shown in Figures 1 and 2. Charts of all tested lamps are provided in Appendix A.

As can be seen in Figure 1, curves were included showing manufacturer's claim (where applicable) and the Energy Star requirement for lamp life. For fluorescent lamps, the Energy Star life requirement was assumed to be 35,000 hours which is the commercial lamp requirement (note that at time of writing, an Energy Star standard has not been set for linear fluorescent replacement applications). For screw-in lamps, the 25,000 hour residential requirement was used. Also identified was the "L70" line which represents 70% of the initial lumen output. This is the generally accepted failure criteria for lighting. In cases where lamps did not fail within the timeframe of the project, data was extrapolated for populating the BOM with the other lamp information.

Chromaticity X and Y values identify the color temperature of the tested lamp. Figure 2 shows a scatter of the chromaticity values measured over the test period.



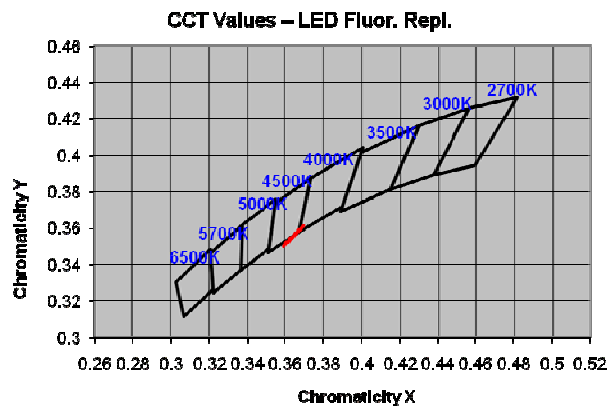


Figure 2. Example Chromaticity Chart

LCA-Based Environmental Impact Database Generation

A database of processes was generated by using the PE Database in GaBi and the ecoInvent Database in SimaPro. Processes expected to be used in the production of LED lamp components were identified in these databases and used to build a data feeder for the BOMs to be generated in the As-Is Analysis and in the Sustainable LED Product Design Guide tool. The data feeder sheet with the sources of the data cited is included in Appendix B.

The processes were divided into groupings corresponding to three lifecycle phases: production, use, and end-of-life. The production phase includes all raw material extraction and material processing processes. The use-phase represents the energy consumed in powering the lamp, and the end-of-life phase represents the disposal scenario for the lamp.

The environmental impacts chosen for measurement in this project were greenhouse gas emissions, energy consumption, and mercury emission.

Greenhouse gas emissions were chosen as an impact category due to the focus today on climate change. The oft-heard question about the environmental metric for products is “what is the carbon footprint?” It was clear that any designer would be interested in knowing the

aspects of their design which contribute to this impact category.

Energy consumption is a category that seems to have great influence over many other categories. If the amount of energy required over the lifecycle is reduced, generally the greenhouse gas and toxic emissions are also reduced. Energy consumption was included in this Guide as an impact which could be focused on by the designer as a primary indicator of environmental impacts.

Finally, mercury emission was considered due to the relevance in the lighting industry because of its use in fluorescent lamps. Often in marketing LED products, the lack of mercury is touted as a benefit over linear fluorescent or compact fluorescent lamps (CFL). Including mercury in the As-Is Analysis and in the Guide would demonstrate the veracity of this claim. Though LED lamps do not contain mercury, mercury can be emitted to the environment in the production or use-phases of the lifecycle through the use of energy produced in fossil fuel power plants.

In the development of the database of impacts, data was not available for all expected processes that relate to the design of an LED lamp. Additionally, some of the data seemed to be unrealistic. In some cases, surrogate data was used by means of studies of the lamps considered in the As-Is phase of the project.

For example, the LCA data for populated circuit boards is based on those assemblies as used in computer and telecommunications products. The circuit boards used these devices tend to be densely populated and contain many gold-containing components. Gold production results in a high release of mercury according to the LCA documentation. Rather than use the data for populated circuit boards, the project team created new values based on an average of the individual electronic components for a representative sampling of products and used

these new values in the data feeder for the Guide.

All impact values and documentation are included in Appendix B of this report.

BOM Development

A sample of each of the purchased lamps was disassembled and each of the components were weighed and tallied into the BOM. All components were divided into one of the following subsystems:

- Electrical and Electrical Components
- Optical Components
- Thermal Management Components
- Fixture Interface Components
- Miscellaneous Mechanical Components.

By associating each part with one of the above subsystems, lamps could be compared against common subsystems allowing the designer to understand the parts of the lamp assembly driving the highest impacts.

For each component entered into the BOM, the associated processes in producing that part were identified. Additionally, the energy consumed during the lamp's life was recorded by multiplying the measured power consumption by the measured (or extrapolated) life. The lamp was also assigned a disposal scenario.

All of the above information allowed impacts to be calculated against each of the lifecycle phases. Different products or concepts could then be compared against each phase of the lifecycle.

Another factor against which different products could be compared was in performance. By considering the lamp life and the lamp light output, different designs could be compared against different functional units. For example, two lamps could be compared on a basis of energy consumption per lumen or, greenhouse gas emissions per lumen-hour. This allowed products with different performance

characteristics to be compared in a relative manner.

A more practical example was in the comparison of an LED screw-in lamp to that of a standard incandescent. An incandescent lightbulb has very low impacts in the production phase when compared to a much more complicated LED lamp. Additionally, the LED lamp may put out less light than the incandescent. However, the life of the LED lamp might be many times greater than that of the incandescent lamp.

Figure 3 illustrates the condition where an incandescent lamp puts out twice as much light as an LED lamp. This would suggest that since two LED lamps are required to achieve the same lighting levels, that the impacts then must be doubled with the LED lamp. However, in this example, we see that the life of the LED lamp is 30 times as long as that of the incandescent lamp. If the environmental impacts of these two lamps were compared per lumen-hour, we would have to consider the impacts of 15 incandescent lamps to each LED lamp. Functional units are also valuable for a lamp designer to consider the benefits of adding material to make a lamp last longer or put out

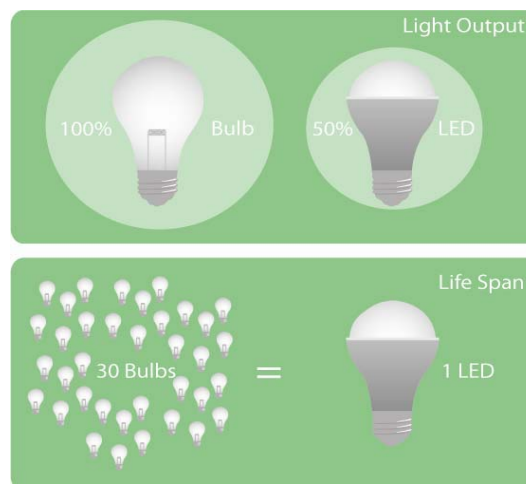


Figure 3. Illustration of the Application of Functional Units

more light, and the resultant impacts on the environment.

Trends Identified During As-Is Analysis

Several general observations could be made about the environmental impacts associated with design attributes of the lamps. The greatest impacts came from the use-phase of the lamps from the energy consumed to power them. The use-phase accounted for the vast majority of the impacts.

In the production phase, it was seen that the electronics components in ballasted (self- or remotely-ballasted) lamps contributed greater impacts in general than other subsystems.

Other trends, such as the use of glass lenses rather than plastic, can be identified in review of the tested lamps.

Length of life of the lamps was another major determinant of impacts when lamps were compared against one another. For example, it might be worth adding additional heat sink mass or revising electronic components to lengthen life, even if it might mean greater production-phase impacts to those subsystems, if this could result in longer lamp life.

Task 4.0 – Best Practices Guide Development

Section 5 explains the Guide developed during the project in more detail.

5. Using the Sustainable LED Product Design Guide

There are two sections to the Guide: BOM input and Reporting/Review. The Guide already contains data on existing lamp designs, including incandescent and fluorescent benchmarks, as well as LED lamps that were available during the course of the project.

First, we will review the BOM Building Sheet. Figure 4 shows the BOM sheet for a CFL bulb. In order to create a new BOM in the tool, the user first identifies some basic information about the lamp as shown in Figure 5.

13W CFL Screw-In Lamp			Use and End of Life Impacts for Lamp			Total Use and End of Life Impacts per Lumen-Hr			Total Use and End of Life Impacts per Hour of Use		
Lamp Weight (kg)	0.057151		GHG Emission (kg CO2)	Energy Consumption (MJ)	Mercury Emission (mg)	GHG Emission (kg CO2 Eq)	Energy Consumption (MJ/lumen-hr)	Mercury Emission (mg/lumen-hr)	GHG Emission (kg CO2 Eq)	Energy Consumption (MJ/hr)	Mercury Emission (mg/hr)
Power Use (W)	12.1		28.414111	465.71319	0.5312766	3.72098E-06	6.09876E-05	6.95734E-08	0.002583101	0.042337563	4.82979E-05
Life (hours)	11000	kWh	0.0400057	0.0179454	0.0822974	5.23895E-09	2.35005E-09	1.07773E-08	3.63688E-06	1.6314E-06	7.48159E-06
Lumen Output	694.2										
Location of Use	US										
Lamp End of Life Scenario	Waste Disposal										
Lamp Type	Screw-In Replacement										
Lamp Subsystem/Component			Total Production Impacts for Lamp Lvl			Total Production Impacts per Lumen-Hour			Total Production Impacts per Hour of Use		
			GHG Emission (kg CO2)	Energy Consumption (MJ)	Mercury Emission (mg)	GHG Emission (kg CO2 Eq)	Energy Consumption (MJ/lumen-hr)	Mercury Emission (mg/lumen-hr)	GHG Emission (kg CO2 Eq)	Energy Consumption (MJ/hr)	Mercury Emission (mg/hr)
Thermal Management			0	0	0	0	0	0	0	0	0
Electrical/Electronic Components			0.0048637	0.0989319	0.001224	6.36925E-10	1.29556E-08	1.60286E-10	4.42154E-07	8.99381E-06	1.11271E-07
Base Wire			0.0004819	0.0022077	0.0001606	5.4914E-11	1.6402E-09	2.2191E-11	5.5940E-08	1.1044E-06	1.5494E-08
Base Pad			0.0004503	0.0020497	0.0001549	4.8219E-11	1.6170E-09	1.9214E-11	5.1594E-08	4.7323E-07	1.0449E-08
Base Pad Wire			0.000709167	0.0012541	0.00012431	2.2391E-10	8.2544E-09	1.9108E-11	1.8544E-07	3.4477E-06	8.5814E-08
Circuit			0.000289419	0.00171791	0.00013041	2.1011E-10	5.4919E-09	4.1019E-11	1.6323E-07	3.7418E-06	2.6417E-08
Optical Components			0.0641042	1.1036488	0.0465582	8.39478E-09	1.44529E-07	8.46701E-08	5.82766E-06	0.000100332	5.8778E-05
Mercury			0.000471719	0.00703241	0.0000041	6.1774E-11	9.2094E-10	8.43387E-08	4.0133E-08	6.3932E-07	5.8548E-05
Phosphor			0.063628531	1.09616122	0.002554039	9.3339E-09	1.4340E-07	3.3446E-10	5.7047E-06	9.9424E-05	2.3211E-07
Lamp											
Fixture Interface Components			0.0187727	0.3238316	0.0041775	2.45839E-09	4.24074E-08	5.47071E-10	1.70661E-06	2.94392E-05	3.79777E-07
Edison screw base assembly			0.018772744	0.323831623	0.004177546	2.45839E-09	4.24074E-08	5.47071E-10	1.70661E-06	2.94392E-05	3.79777E-07
Miscellaneous Mechanical Components			0.0520848	1.4266531	0.0035003	6.82078E-09	1.86829E-07	4.58382E-10	4.73498E-06	0.000129697	3.18209E-07
Glu			0.010493339	0.192423037	0.0005410	1.3748E-09	2.5191E-08	2.01907E-10	9.54394E-07	1.7493E-05	1.4014E-07
Plastic cover cap			0.016148103	0.49948182	0.000791013	2.202E-09	4.9302E-08	1.03702E-10	1.62163E-06	4.8241E-05	7.19191E-07
Plastic cover base			0.024771891	0.735912302	0.00164606	3.4037E-09	9.62774E-08	1.82773E-10	2.2519E-06	6.6327E-05	1.0419E-07
Lamp Production			0.1398255	2.9530754	0.65546	1.83109E-08	3.86721E-07	8.58359E-08	1.27114E-05	0.000268461	5.95873E-05
Totals Over Product Lifecycle			28.593942	468.684214	1.2690341	3.74452E-06	6.13766E-05	1.66187E-07	0.002599449	0.042607656	0.000115367
Lamp Production			0.1398255	2.9530754	0.65546	1.83109E-08	3.86721E-07	8.58359E-08	1.27114E-05	0.000268461	5.95873E-05
Lamp Energy Use			0.0400057	0.0179454	0.0822974	5.23895E-09	2.35005E-09	1.07773E-08	3.63688E-06	1.6314E-06	7.48159E-06
Lamp End of Life			0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

Figure 4. BOM Build Sheet for CFL Benchmark Bulb

13W CFL Screw-In Lamp	
Lamp Weight (kg)	0.057151
Power Use (W)	12.1
Life (hours)	11000
Lumen Output	694.2
Location of Use	US
Lamp End of Life Scenario	Waste Disposal
Lamp Type	Screw-In Replacement

Figure 5. Lamp Information Panel

The tan-highlighted cells indicate user input areas. The entries for power use, life, and lumen output for the pre-populated lamps in the Guide are based upon lab testing of the example lamps. The Life entry is based upon L70 failure criteria and in cases where tested lamps have not declined to 70% output, values are extrapolated on an exponential decay.

In the User-Defined lamp BOMs, the Lamp Type has been assigned already. In all example lamps, the End-of-Life Scenario is assumed to be landfill. Incineration is the other option. Any future extension of the project could allow recycling and remanufacturing scenarios to be included.

Next, the user may assign the components in their BOM to the subsystems defined in the sheet. These subsystems define the production phase of the product lifecycle.

In Figure 6, one example of a subsystem area on the BOM entry sheet is shown. The user identifies the components in that subsystem in the first column. In the following four columns, drop-down menus allow the material class, material, primary, and secondary processes to be assigned. The processes are discrete, so if a heat sink is made of cast aluminum and anodized, two line items must be created:

NonFerro -> Aluminum -> Cast -> None

NonFerro -> Aluminum -> Cast -> Anodized

Next the user assigns the quantity of the line item within the assembly, and assigns a mass per component. This information allows the Guide to assign impacts to the production phase of the lamp design.

When the new BOM has been populated, the user may open the “LED Sustainable Design Guide” tab to review the impacts charts. The charts show the production, use, and end-of-life phases in different colors, with the production phase shown in different shades identifying the subsystems. A chart Control Panel allows the user to consider the total lamp lifecycle impacts or to compare lamps normalized to impacts per hour or impacts per lumen-hour. Using these controls, the user may identify the importance of light output and longevity of the lamp design in reducing the impacts over the lifecycle. Additionally, the user may turn on or turn off each phase of the lifecycle to focus the data to the area most critical to the designer (Figure 7).

An example of the Greenhouse Gas Emission chart for screw-in lamps are shown in Figures 8 – 10, illustrating the effects of the chart controls.

Electrical/Electronic Components							
Bare Wire	NonFerro	Copper	Copper Wire	None	Weight	1	0.000122 kg
Standoff	Other	Fasteners	Steel Fastener	None	Weight	4	0.00002775 kg
Insulated Wires	Other	Insulated Wire	PVC Insulated	None	Weight	1	0.000439 kg
Circuit	Electronics	Circuit Components	Populated Thru	None	Weight	1	0.014115 kg

Figure 6. Example Subsystem Component Entry

Chart Controls	Select from the drop-down menus below
Total Impacts or Normalized	Total Impacts Over Lamp Life
Include Lamp Production Phase?	Yes
Include Lamp Use Phase?	Yes
Include Lamp End of Life Phase?	Yes

Figure 7. Chart Control Panel

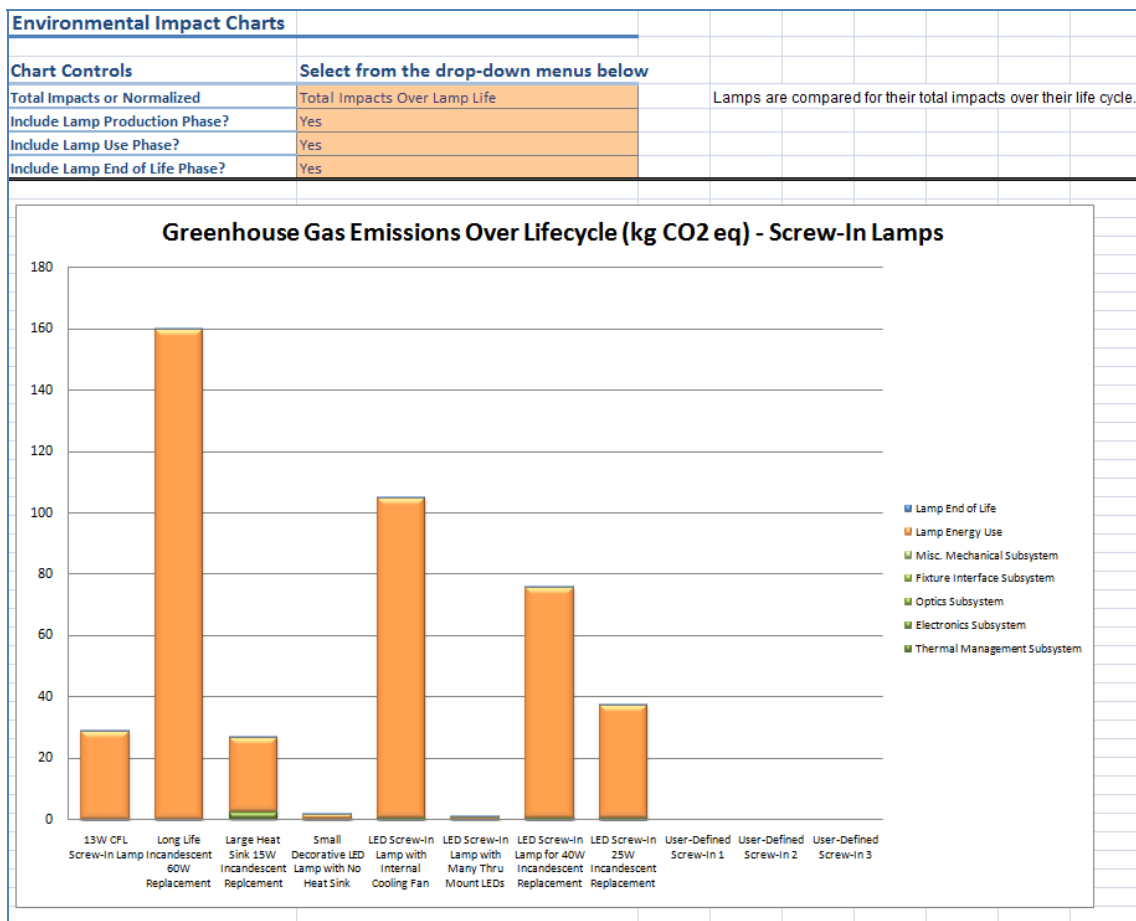


Figure 8. Greenhouse Gas Emissions Chart Showing Total Lifecycle Impacts

Figure 8 shows the total lifecycle impact for each of the lamps. Products with high power use and/or long life will show high impacts in the case in the use-phase. The use-phase is the dominant source of greenhouse gas emissions, and so little can be learned in this chart about the production and end-of-life phases.

Figure 9 shows the same chart as Figure 8, however, the use-phase data is omitted per the control panel. This allows a better look at the per-lamp impacts from the production and end-of-life phases.

By looking at only the per-lamp impacts, we are not reviewing a complete picture. If we consider the longevity and/or the light output of the lamp, the user may make better design decisions. While there are very small impacts resulting from the production and disposal of an incandescent lightbulb due to its very basic

design, the quantity of incandescent lightbulbs required to produce a given amount of light over the period of a very long-lasting LED lamp's life amplifies these impacts. By considering impacts normalized on a per lumen-hour basis, more information is available to the designer to make better design decisions.

Figure 10 illustrates the important of light output and longevity in reducing the per lumen-hour impacts of a lamp.

Charts shown in the LED Sustainable Design Guide tab include Greenhouse Gas Emissions, Energy Use, and Mercury Emissions for Screw-In and T8 lamps. All six charts will update simultaneously by manipulation of the control panel.

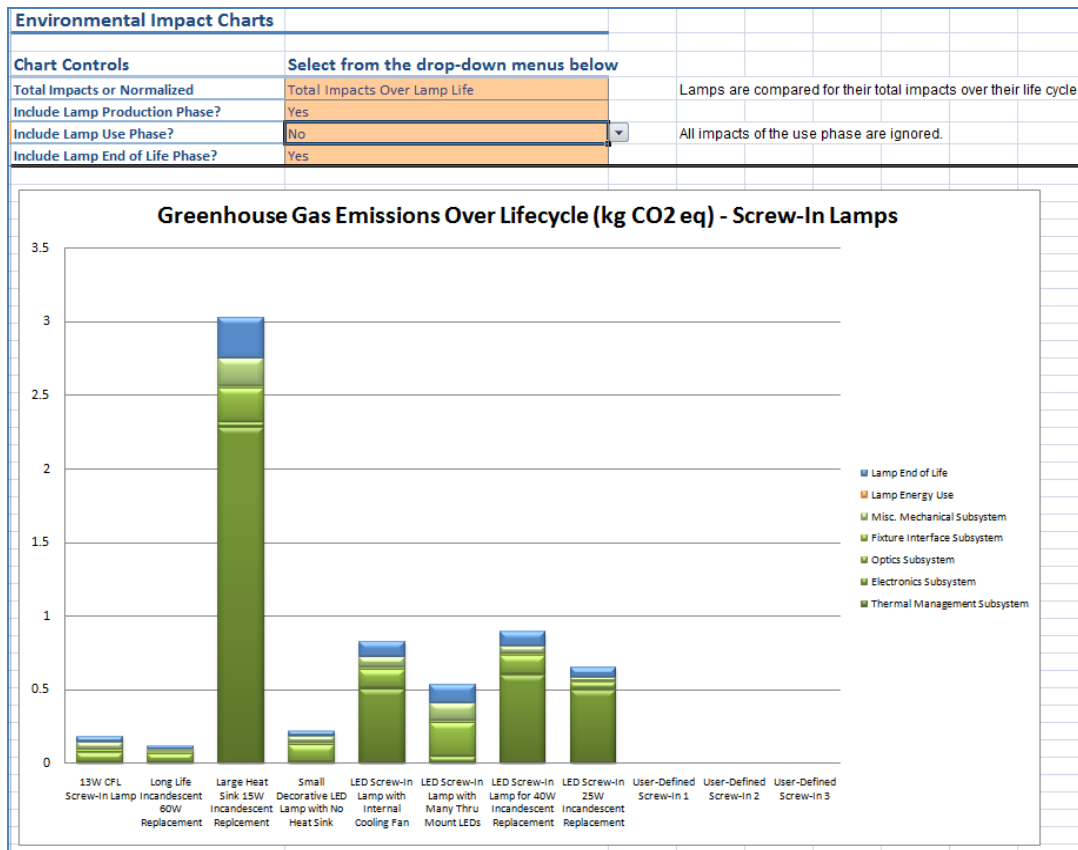


Figure 9. Greenhouse Gas Emissions Chart Showing Impacts in Production and End-of-Life Phases Only

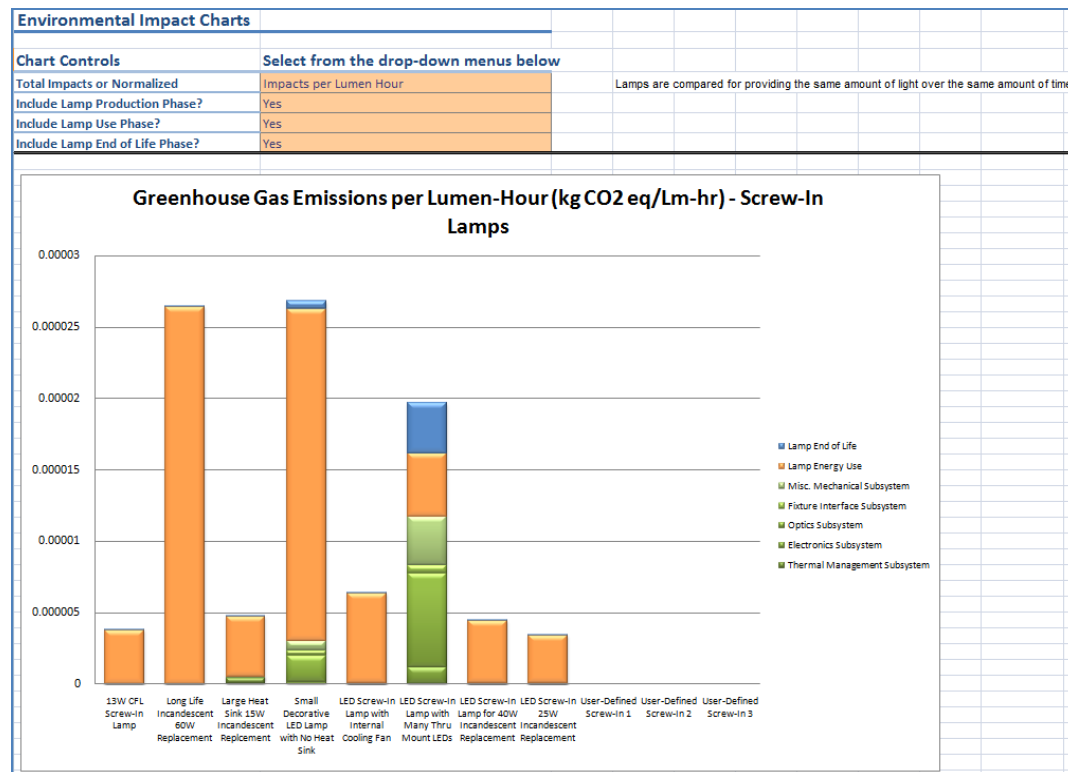


Figure 10. Greenhouse Gas Emissions Chart Showing All Lifecycle Phases Normalized to Lumen-Hours

6. Conclusions and Opportunities for Further Work

6.1 Process Database Improvements

One of the limits of the Guide is the overall quality of the LCA data in the process database. In some cases, LCI data for some processes was either unavailable or inappropriate for the application. Often, these issues are present in the electrical circuit components. In particular, the LCI data for the LEDs that are most commonly used in quality LED lighting products is missing. Further LCA studies, beyond the default data available in SimaPro and GaBi, would strengthen the underlying data feeding the Guide.

6.2 Additional Impact Categories

There are many other environmental impact categories that could be considered within the Guide with further research and data gathering. Water use, for example, is a category expected to be coming more to the forefront. This is a

complex category which is the subject of much debate in how it is best evaluated. Other toxicity factors beyond mercury emission would add value to the Guide as well.

Further, a non-environmental, but still quite relevant impact of a product design is cost. Adding cost as a decision criteria alongside the environmental impacts would make the tool more useful to a designer in a real product design environment.

6.3 Additional Lamp Form Factors

Although the Guide, in its current form, should be useful for lamp form factors beyond screw-in replacement and linear fluorescent replacement lamps, further review of these other lamp types may identify other materials and processes that need to be added to the database.

7. Technology Transfer Activities

Publications/Presentations

- [1] “Sustainable LED Fluorescent Light Replacement Technology Project,” presentation by Dr. Manish Mehta at NIST Workshop on Sustainable Manufacturing, October 7, 2009, Gaithersburg, MD.
- [2] Project information exchange regarding strategies for addressing inherent variability of LCI for LEDs and electronics held with Ms. Joel Todd, Chairperson of LEED Steering Committee, U.S. Green Building Council, January 28, 2010.
- [3] “Achieving Sustainable LED Lighting: A Product Design Guide,” June 14 Presentation by James M. Amrine Jr., and Dr. Manish Mehta at NeoCon 2010, The Merchandize Mart, Chicago, IL.
- [4] “Achieving Sustainable LED Lighting: A Product Design Guide,” invited presentation by James M. Amrine Jr., and Dr. Manish Mehta to the South-East Michigan Sustainable Business Forum, September 16, 2010, Dearborn, MI.
- [5] “A Product Design Guide for Achieving Sustainable LED Lighting Systems,” by James Amrine Jr. and Dr. Manish Mehta, presented at 2011 Electronics and Sustainability Symposium, March 23-24, 2011, Champaign, IL.
- [6] “A Product Design Guide for Achieving Sustainable LED Lighting Systems,” by James Amrine Jr. and Dr. Manish Mehta, accepted for presentation at Michigan Green Chemistry Conference, October 27, 2011, Ann Arbor, MI.

Appendix A –Tested Lamps

The following pages identify the lamps for which testing was conducted and against which the Guide was developed.

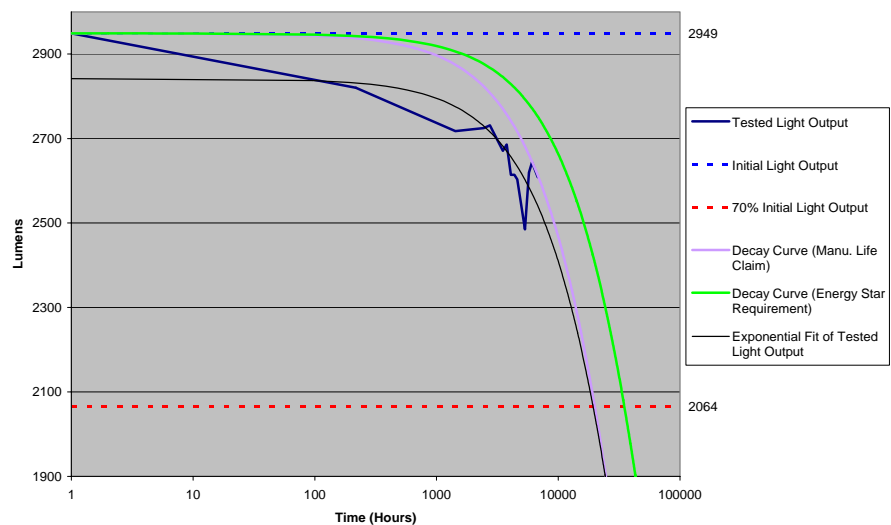
Ilumisys Reference #	FLUOR-001D
Manufacturer	Philips
Model	F40T12 Alto
Description	40W T12 Fluorescent Tube
Power Supply Voltage/Device	Philips Advance AmbiStar RELB-1S40SC T12 Ballast (120Vac Input)
Ilumisys Initial Test Date	8/17/10
Ilumisys Final/ Recent Test Date:	8/17/11
CALiPER Reference #	08-30
CALiPER Test Round	5
CALiPER Test Date	5/08

	Manufacturer Claim	Test Results	CALiPER Results^Δ
Initial Light Output (Lumens)	3,200	2,949	3,101
70% Initial Output (Lumens)	2,240	2,064	
Current Output (Lumens)		2,613	
Life Expectancy* (Hours)	20,000	19,373	
Correlated Color Temperature (K)	4,100	4,768	2,884
Color Rendering Index (R₉)	70	74	84
Power (Watts)	40	40	39.0

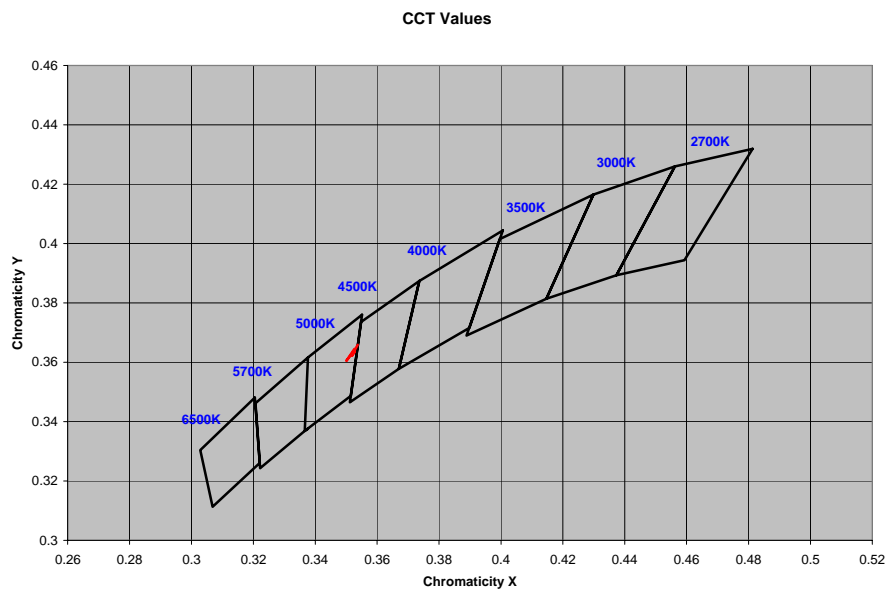
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.

^Δ The color temperature of the CALiPER tested device was different than that of Ilumisys testing.





FLUOR-001D Lumens vs. Time



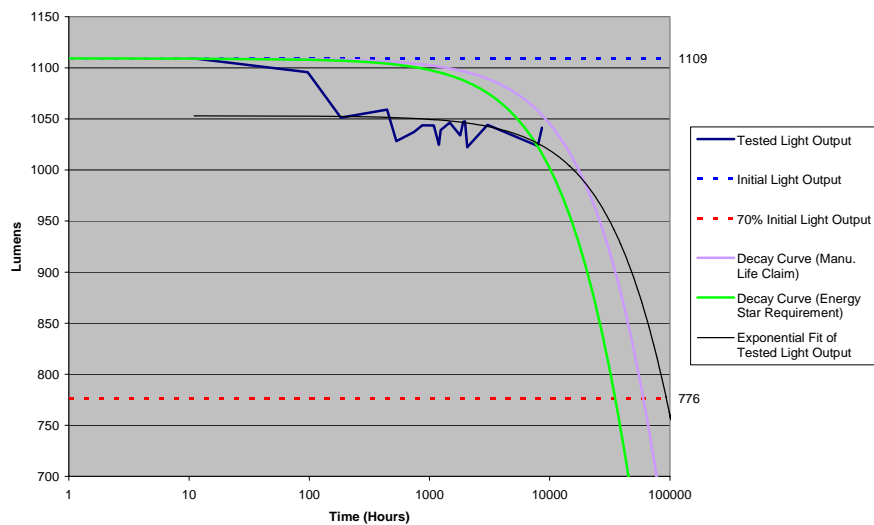
FLUOR-001D Chromaticity Chart

Illumisys Reference #	FLUOR-002A
Manufacturer	Illumisys
Model	MK1
Description	Ballast Powered LED Fluorescent-Replacement
Power Supply Voltage/Device	Philips 120-277Vac Advance Centium ICN-1P32-N
Illumisys Initial Test Date	4/14/10
Illumisys Final/ Recent Test Date:	8/17/11
CALiPER Reference #	09-13AB
CALiPER Test Round	9
CALiPER Test Date	6/23/09

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	1,200	1,109	1,407
70% Initial Output (Lumens)	840	776.3	
Current Output (Lumens)		1,098	
Life Expectancy* (Hours)	60,000	93,446	
Correlated Color Temperature (K)	4,200	4,294	3,758
Color Rendering Index (R_a)	75	79	76
Power (Watts)	28	25	32

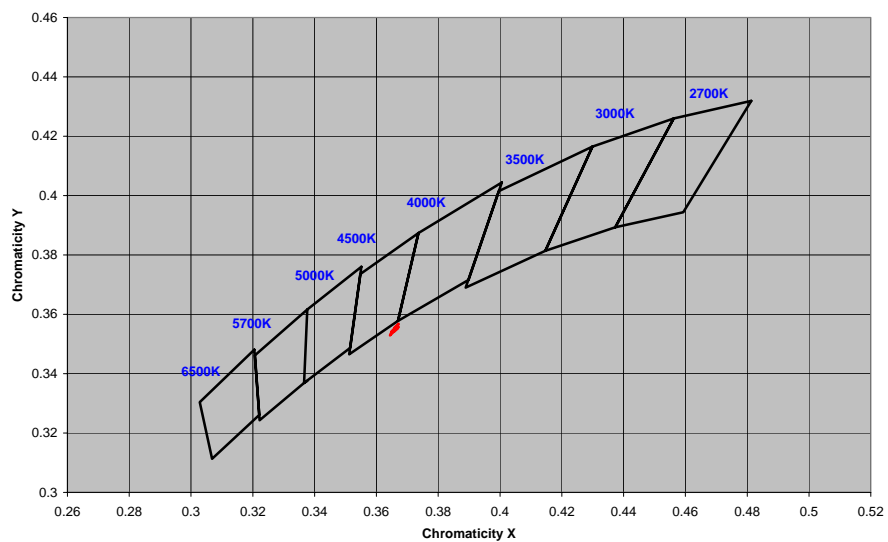
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





FLUOR-002A Lumens vs. Time

CCT Values



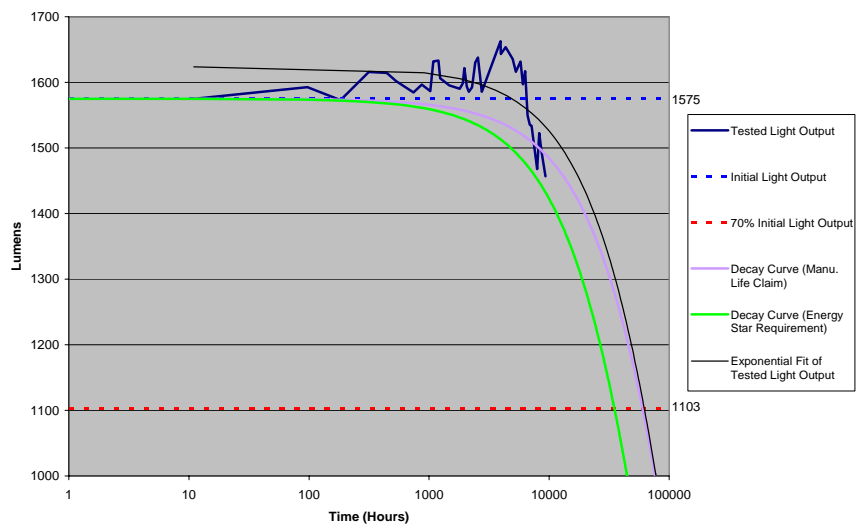
FLUOR-002A Chromacity Chart

Illumisys Reference #	FLUOR-003A
Manufacturer	Illumisys
Model	MK2
Description	Line Voltage LED Fluorescent-Replacement
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/14/10
Illumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	09-107
CALiPER Test Round	11
CALiPER Test Date	7/6/10

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	1,500	1,575	1,539
70% Initial Output (Lumens)	1,050	1,103	
Current Output (Lumens)		1,489	
Life Expectancy* (Hours)	60,000	62,020	
Correlated Color Temperature (K)	4,200	4,346	3,548
Color Rendering Index (R_a)	75	77	73
Power (Watts)	22	22	22

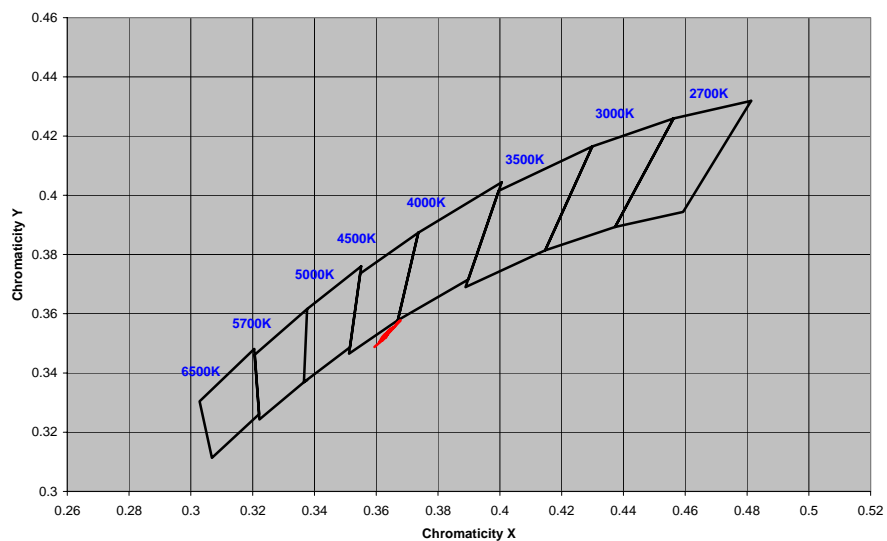
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





FLUOR-003A Lumens vs. Time

CCT Values



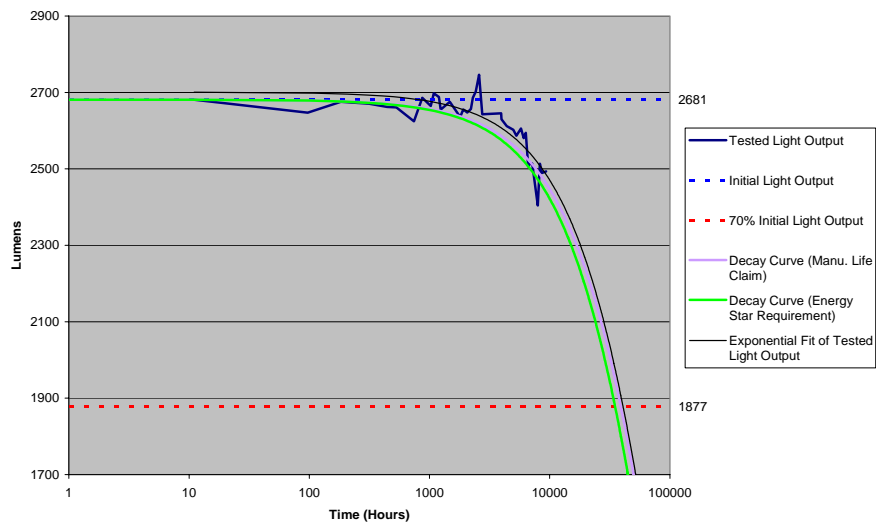
FLUOR-003A Chromaticity Chart

Illumisys Reference #	FLUOR-004D
Manufacturer	Philips
Model	F32T8/TL841 Plus
Description	Philips Alto 32W T8 Fluorescent Tube
Power Supply Voltage/Device	Philips Advance Centium ICN- 1P32-N T8 Ballast 120-277 Vac
Illumisys Initial Test Date	4/14/10
Illumisys Final/ Recent Test Date:	8/17/11
CALiPER Reference #	08-28
CALiPER Test Round	5
CALiPER Test Date	5/08

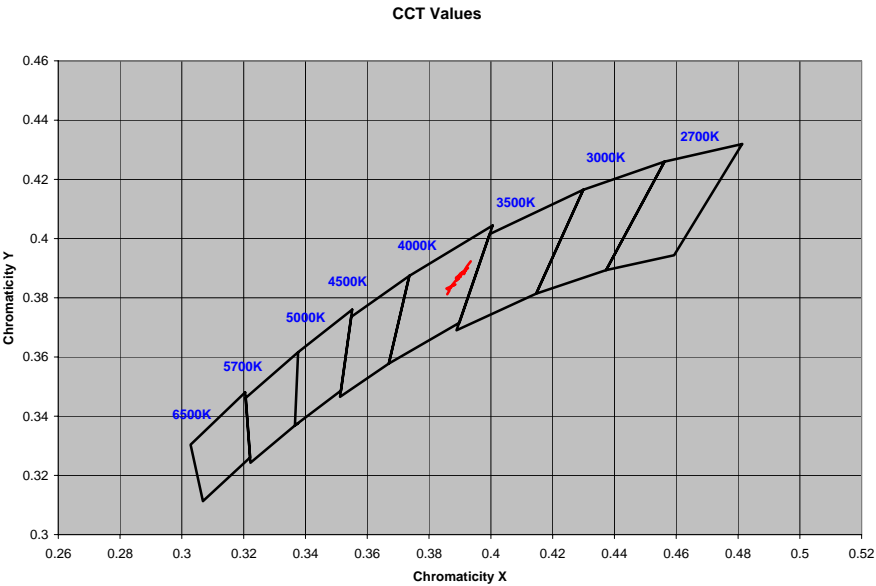
	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	2,950	2,681	3,081
70% Initial Output (Lumens)	2,065	1,877	
Current Output (Lumens)		2,510	
Life Expectancy* (Hours)	39,000	40,790	
Correlated Color Temperature (K)	4,100	3,829	3,932
Color Rendering Index (R_a)	85	78	81
Power (Watts)	32	32	32

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





FLUOR-004D Lumens vs. Time



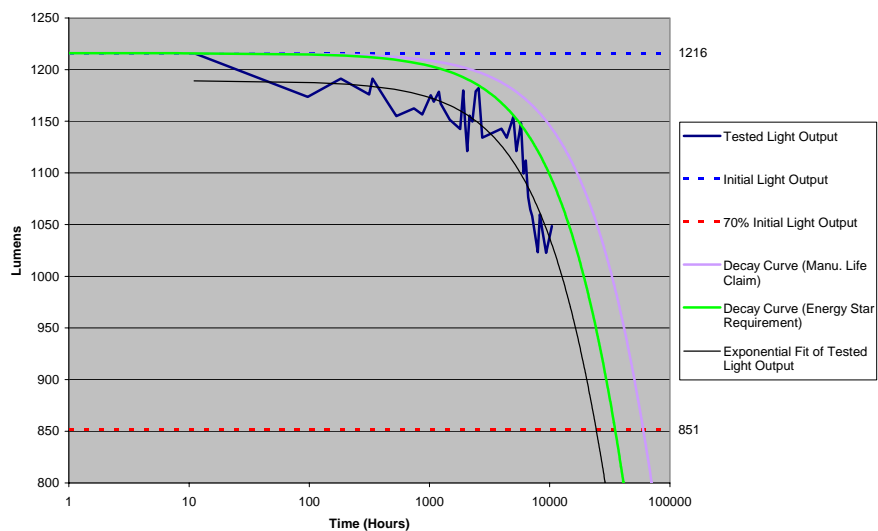
FLUOR-004D Chromacity Chart

Illumisys Reference #	FLUOR-005C
Manufacturer	SeeSmart LED, Inc.
Model	2700K LED Tube Light 15W
Description	4' Clear Lens Warm White LED Fluorescent-Replacement
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/16/10
Illumisys Final/ Recent Test Date:	8/17/11
CALiPER Reference #	09-04
CALiPER Test Round	9
CALiPER Test Date	6/09

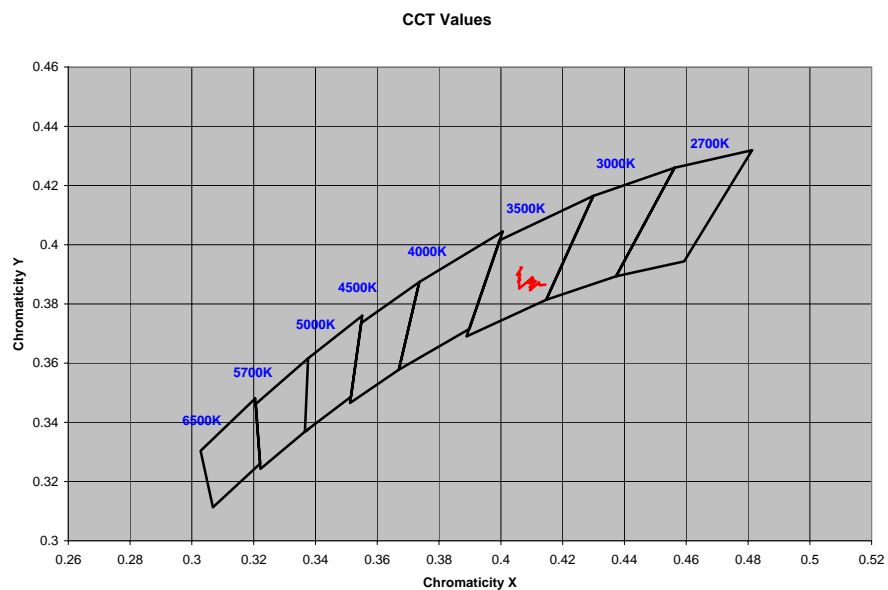
	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	1,500	1,216	1,218
70% Initial Output (Lumens)	1,050	851	
Current Output (Lumens)		1,048	
Life Expectancy* (Hours)	100,000	24,400	
Correlated Color Temperature (K)	2,700	3,403	3,221
Color Rendering Index (R_a)	–	70	66
Power (Watts)	15	16	16

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





FLUOR-005C Lumens vs. Time

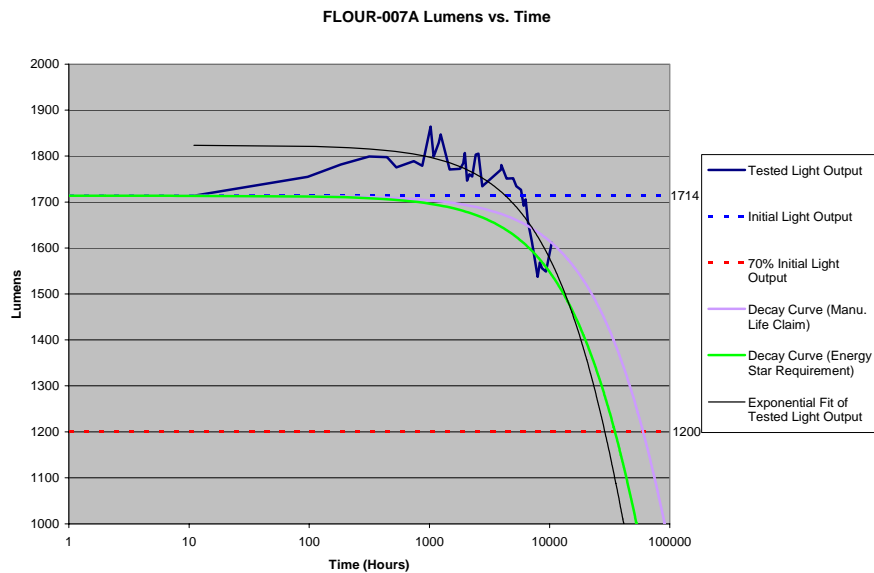


FLUOR-005C Chromacity Chart

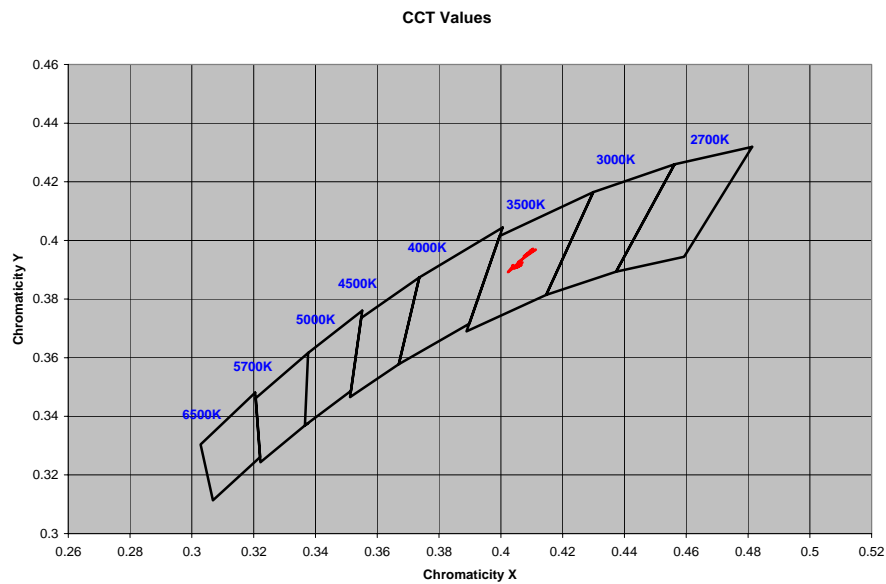
Illumisys Reference #	FLUOR-007A
Manufacturer	Illumisys
Model	MK2 Glass Cover
Description	Line-Voltage LED Fluorescent-Replacement (Glass)
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/14/10
Illumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	–
CALiPER Test Round	–
CALiPER Test Date	–

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	1,200	1,714	–
70% Initial Output (Lumens)	840	1,200	
Current Output (Lumens)		1,611	
Life Expectancy* (Hours)	60,000	28,831	
Correlated Color Temperature (K)	3,500	3,499	–
Color Rendering Index (R_a)	70	70	–
Power (Watts)	22	25	–

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.



FLOUR-007A Lumens vs. Time



FLOUR-007A Chromacity Chart

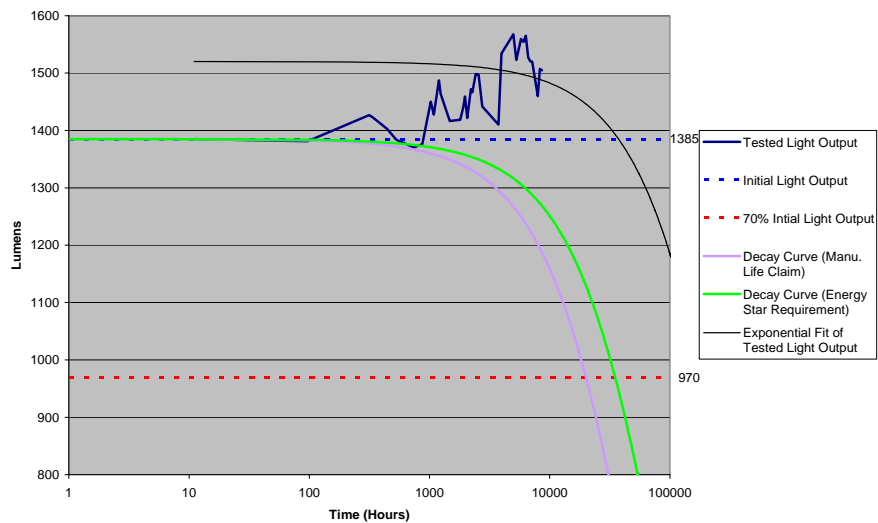
Illumisys Reference #	FLUOR-010D
Manufacturer	Lead Sun
Model	LS404272
Description	15W External Driver LED Fluorescent-Replacement
Power Supply Voltage/Device	LS472331.0 100-240Vac Input – 15-34V/480mA Output (Proprietary LED Driver)
Illumisys Initial Test Date	4/16/10
Illumisys Final/ Recent Test Date:	5/28/11
CALiPER Reference #	–
CALiPER Test Round	–
CALiPER Test Date	–

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	1,400	1,385	
70% Initial Output (Lumens)	980	970	
Current Output (Lumens)		1,504	
Life Expectancy* (Hours)	–	8,668 ^a	
Correlated Color Temperature (K)	4,500-5,500		
Color Rendering Index (R_a)	–		
Power (Watts)	15	18	

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.

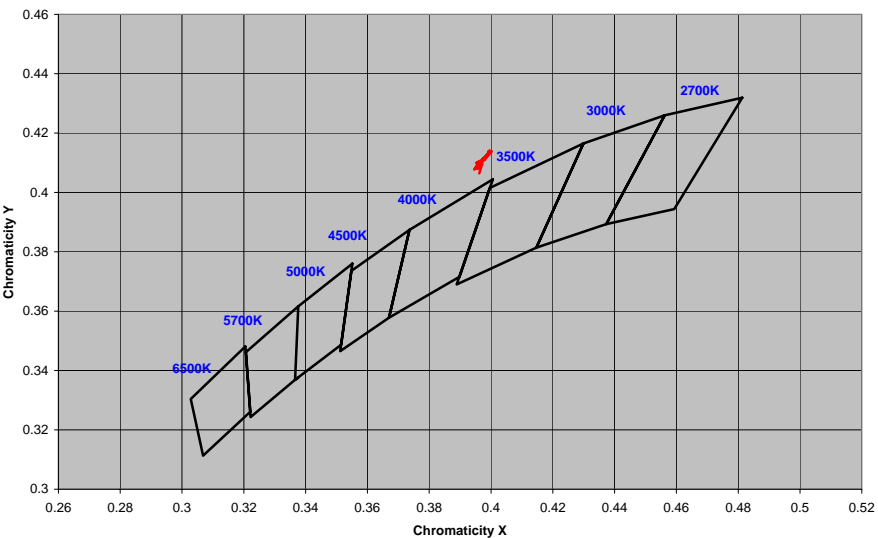
^a This bulb was incidentally damaged at this level many hours before it reached its end of life and testing was complete.





FLUOR-010D Lumens vs. Time

CCT Values



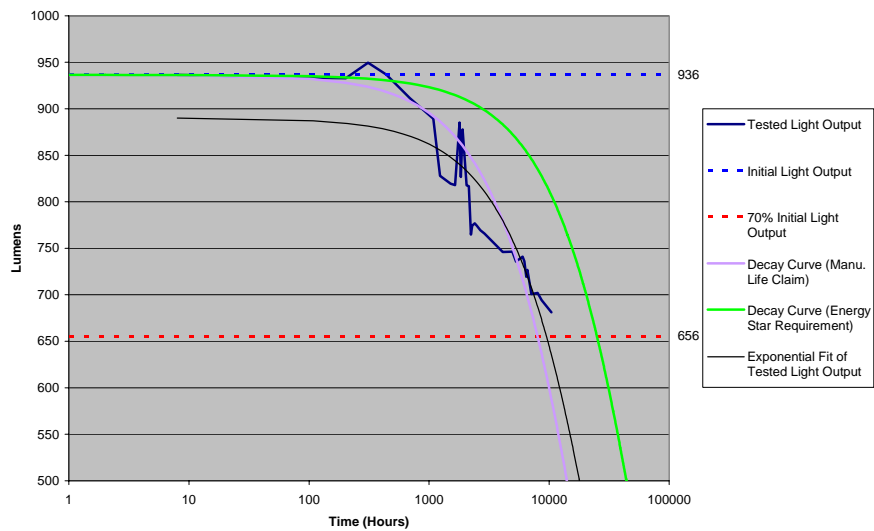
FLUOR-010D Chromacity Chart

Ilumisys Reference #	INCAN-001D
Manufacturer	GE
Model	16460
Description	GE CFL 13W Spiral Bulb
Power Supply Voltage/Device	120Vac
Ilumisys Initial Test Date	4/19/10
Ilumisys Final/Recent Test Date:	8/19/11
CALiPER Reference #	08-27
CALiPER Test Round	5
CALiPER Test Date	4/08

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	825	936	806
70% Initial Output (Lumens)	578	655	
Current Output (Lumens)		681	
Life Expectancy* (Hours)	8,000	9,465	
Correlated Color Temperature (K)	2,700	2,695	2,703
Color Rendering Index (R_a)	–	81	82
Power (Watts)	13	12	12

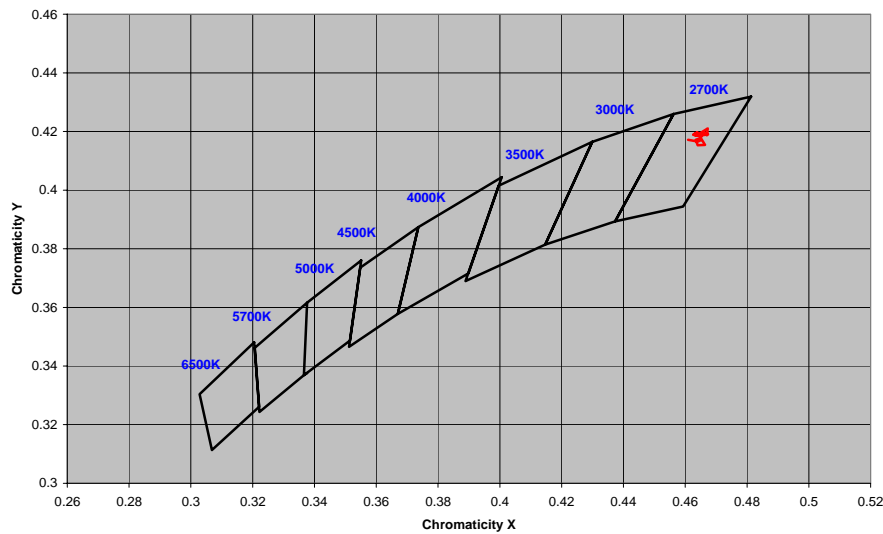
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





INCAN-001D Lumens vs. Time

INCAN-001D CCT Values



INCAN-001D Chromacity Chart

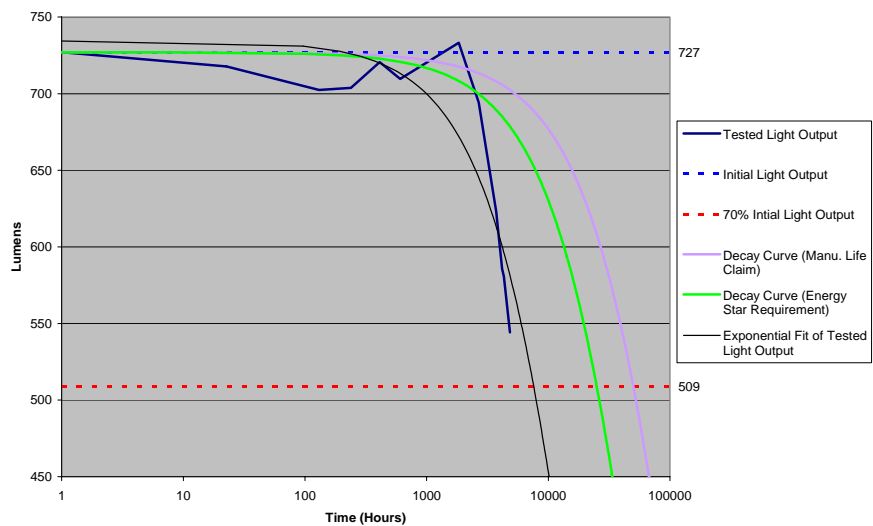
Illumisys Reference #	INCAN-002C
Manufacturer	WDM
Model	WDM 15W
Description	15W Large Heat-sink LED Screw-in
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	8/5/10
Illumisys Final/ Recent Test Date:	3/17/11
CALiPER Reference #	08-132
CALiPER Test Round	7
CALiPER Test Date	12/1/08

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	750	727	466
70% Initial Output (Lumens)	525	509	
Current Output (Lumens)		544	
Life Expectancy* (Hours)	50,000	4,839 ^a	
Correlated Color Temperature (K)	3,500	5,483	3,743
Color Rendering Index (R₉)	–	70	68
Power (Watts)	15	14	14

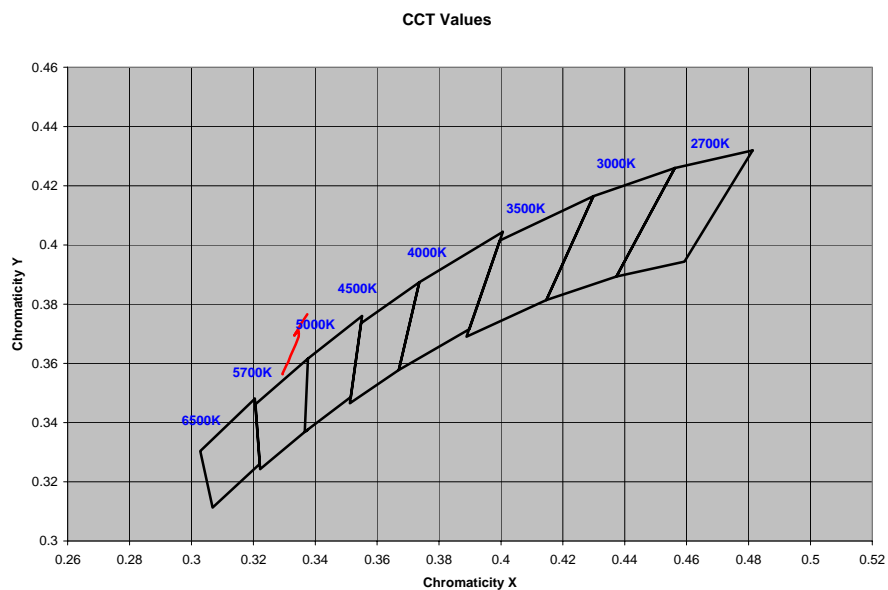
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.

^a Device failed at this level many hours before testing was completed.





INCAN-002C Lumens vs. Time



INCAN-002C Chromacity Chart

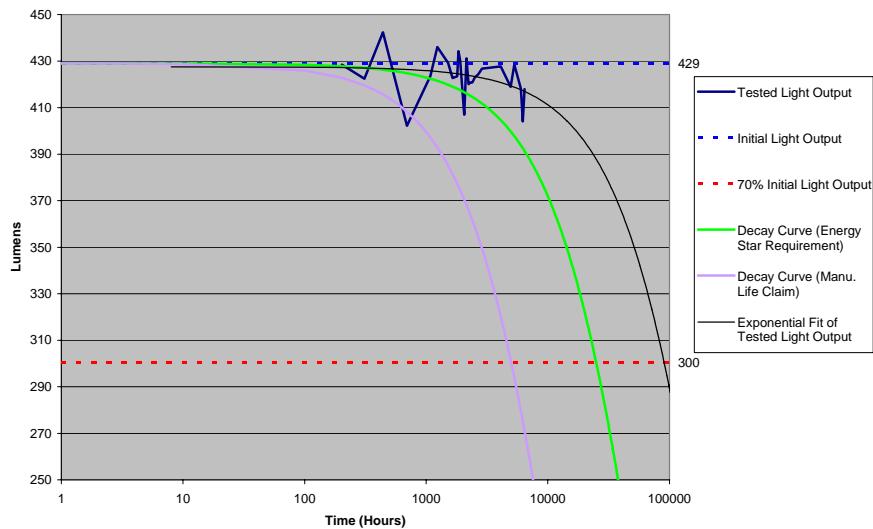
Illumisys Reference #	INCAN-005D
Manufacturer	SLI
Model	60134
Description	Incandescent Long-Life 130V
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/19/10
Illumisys Final/Recent Test Date:	2/14/11
CALiPER Reference #	08-04
CALiPER Test Round	5
CALiPER Test Date	4/08

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	466	429	353
70% Initial Output (Lumens)	325	300	
Current Output (Lumens)		418	
Life Expectancy* (Hours)	5,000	6,439 ^a	
Correlated Color Temperature (K)	–	2,565	2,491
Color Rendering Index (R_a)	–	98	99
Power (Watts)	60	52	55

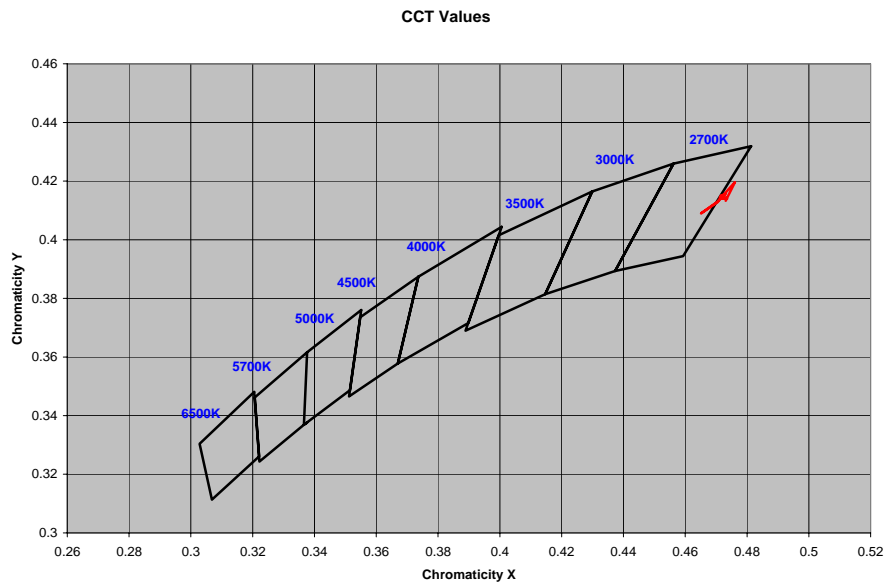
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.

^a Device failed at this level many hours before testing was completed.





INCAN-005D Lumens vs. Time



INCAN-005D Chromacity Chart

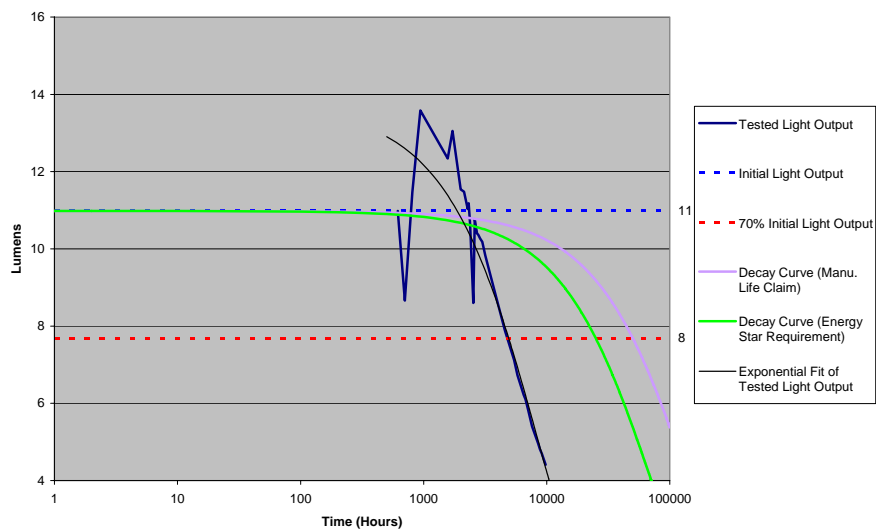
Ilumisys Reference #	INCAN-006A
Manufacturer	Mule Lighting
Model	LEDalux LED-CW-120-CL
Description	Decorative 1W LED Screw-in
Power Supply Voltage/Device	120Vac
Ilumisys Initial Test Date	4/18/10
Ilumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	07/12
CALiPER Test Round	2
CALiPER Test Date	5/16/07

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	–	11	20
70% Initial Output (Lumens)	–	8	
Current Output (Lumens)		4	
Life Expectancy* (Hours)	50,000	6103 ^a	
Correlated Color Temperature (K)	–	13,073	25,263
Color Rendering Index (R₉)	–	79	79
Power (Watts)	<1	1	1.5

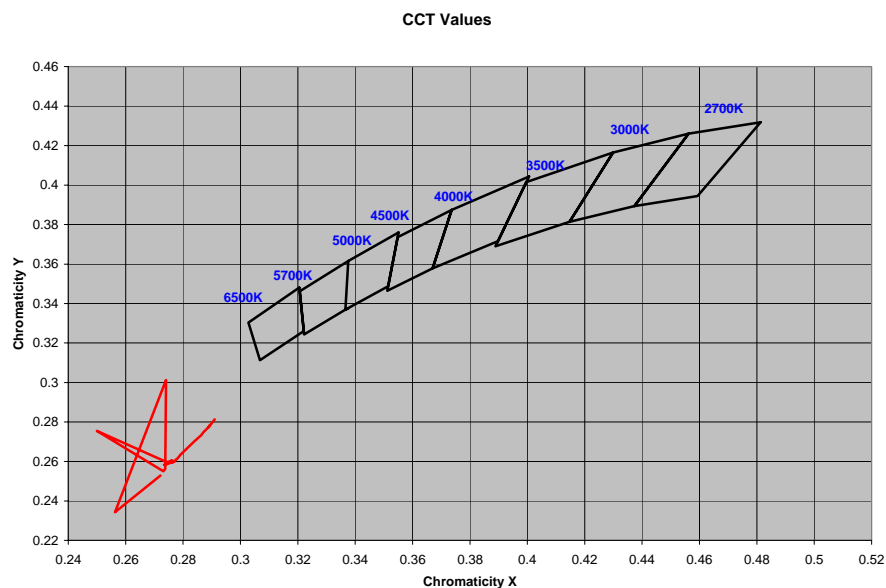
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.

^a It is estimated the device performance fell below 70% initial output at this level for many hours.





INCAN-006A Lumens vs. Time



INCAN-006A Chromacity Chart

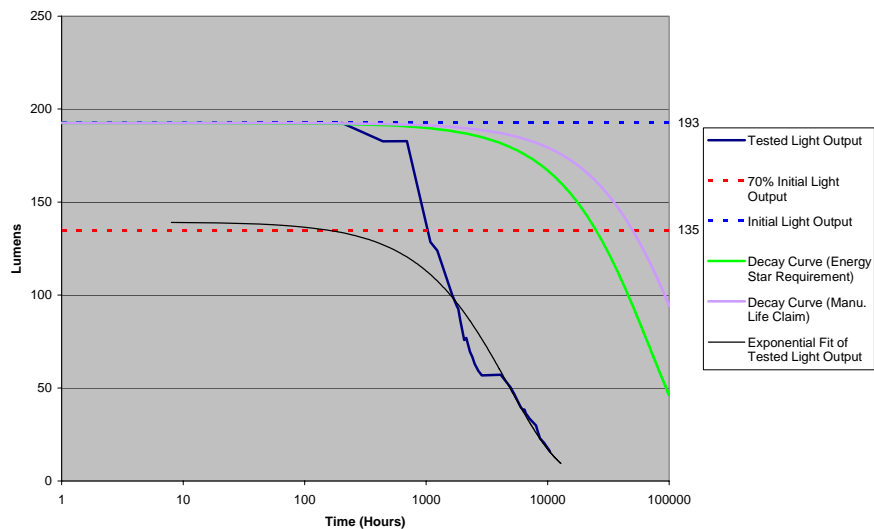
Illumisys Reference #	INCAN-008D
Manufacturer	GBL LED Lighting
Model	150 LED E26-D5X30LED-CLR
Description	150 LED Screw-in Bulb
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/20/10
Illumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	08/80
CALiPER Test Round	6
CALiPER Test Date	8/08

	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	295	193	292
70% Initial Output (Lumens)	206.5	135	
Current Output (Lumens)		16	
Life Expectancy* (Hours)	50,000	513 ^a	
Correlated Color Temperature (K)	–	9,655	7,272
Color Rendering Index (R_a)	–	82	79
Power (Watts)	–	4	4.8

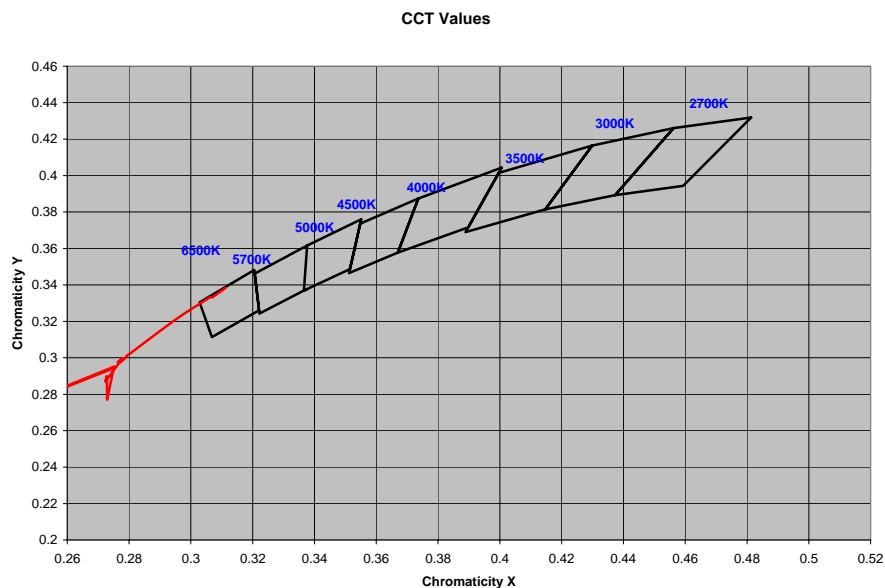
* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.

^a It is estimated the device performance fell below 70% initial output at this level for many hours.





INCAN-008D Lumens vs. Time



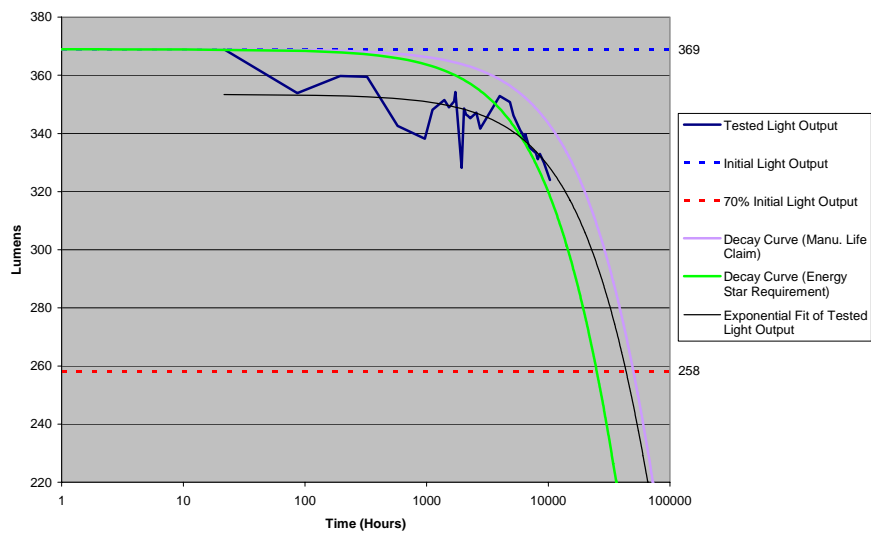
INCAN-008D Chromacity Chart

Illumisys Reference #	INCAN-015B
Manufacturer	Sylvania
Model	78779
Description	8W LED Screw-in (40W Replacement)
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/26/10
Illumisys Final/ Recent Test Date:	8/17/11
CALiPER Reference #	–
CALiPER Test Round	–
CALiPER Test Date	–

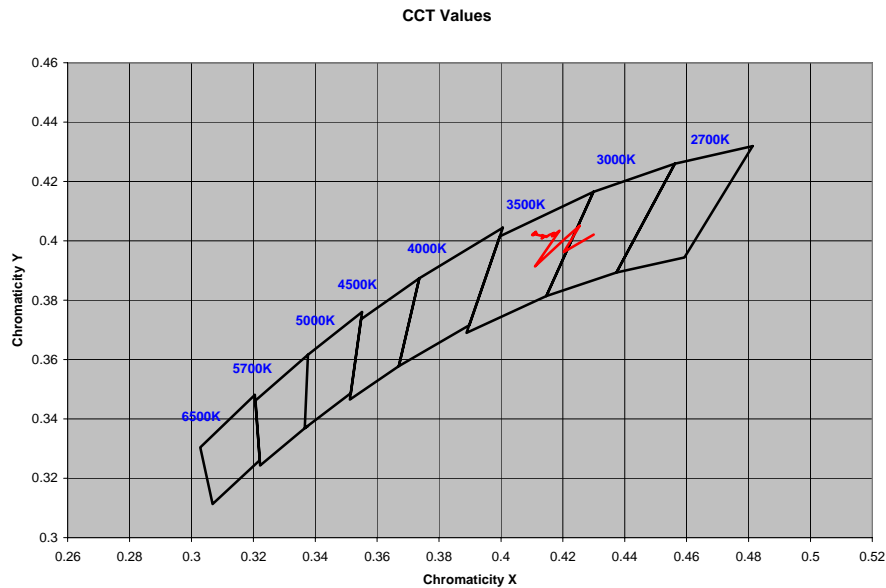
	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	390	369	–
70% Initial Output (Lumens)	273	258	
Current Output (Lumens)		323	
Life Expectancy* (Hours)	50,000	43,659	
Correlated Color Temperature (K)	3,000	3,396	–
Color Rendering Index (R_a)	85	83	–
Power (Watts)	8	8	–

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





INCAN-015B Lumens vs. Time



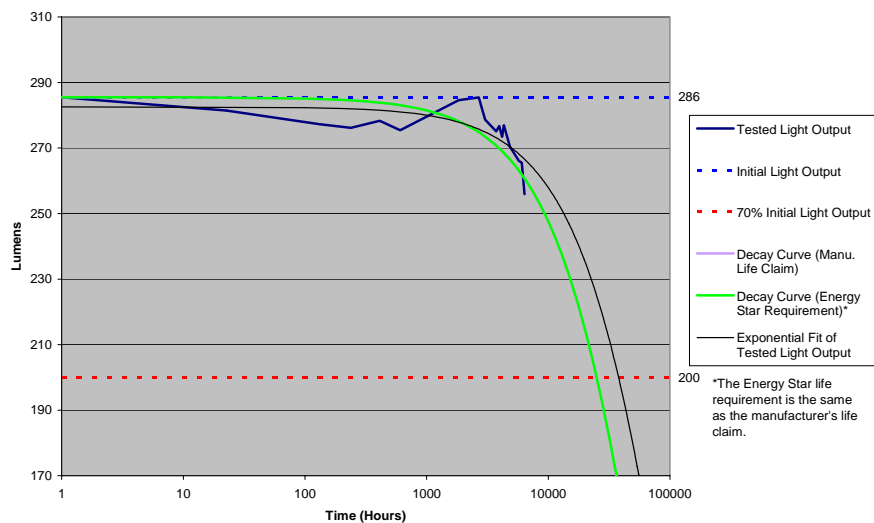
INCAN-015B Chromacity Chart

Illumisys Reference #	INCAN-017A
Manufacturer	Philips
Model	Ambient LED Indoor Bulb
Description	408369
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	8/5/10
Illumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	–
CALiPER Test Round	–
CALiPER Test Date	–

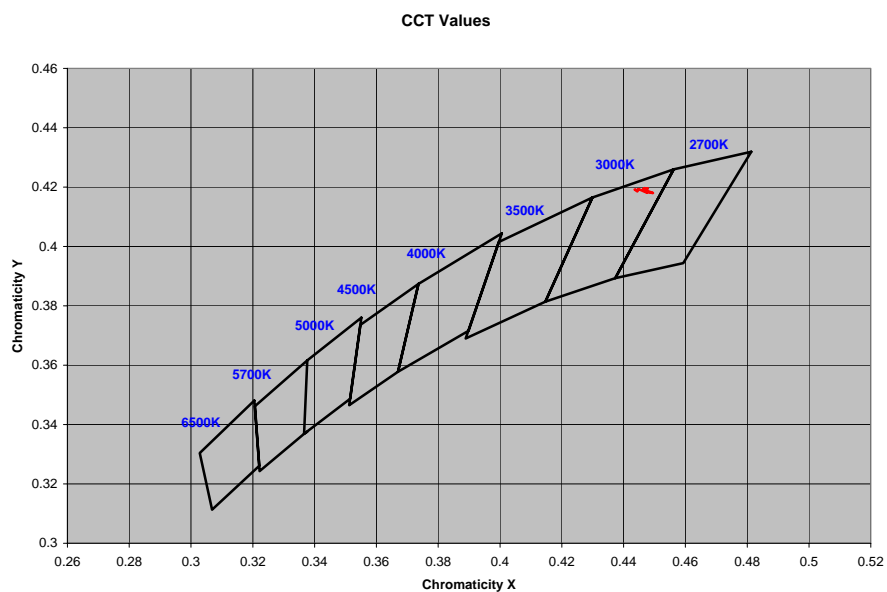
	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	240	286	–
70% Initial Output (Lumens)	168	200	
Current Output (Lumens)		256	
Life Expectancy* (Hours)	25,000	37,831	
Correlated Color Temperature (K)	3,000	2,969	–
Color Rendering Index (R_a)	–	83	–
Power (Watts)	5	5	–

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





INCAN-017A Lumens vs. Time



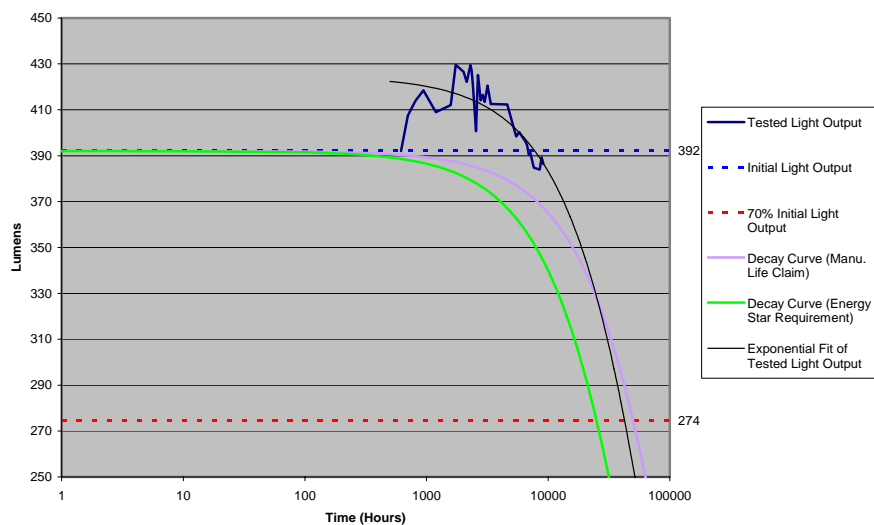
INCAN-017A Chromacity Chart

Illumisys Reference #	INCAN-007B
Manufacturer	Earth LED
Model	EvoLux S Warm White
Description	Warm White LED Screw-in
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	4/18/10
Illumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	08-92
CALiPER Test Round	6
CALiPER Test Date	8/08

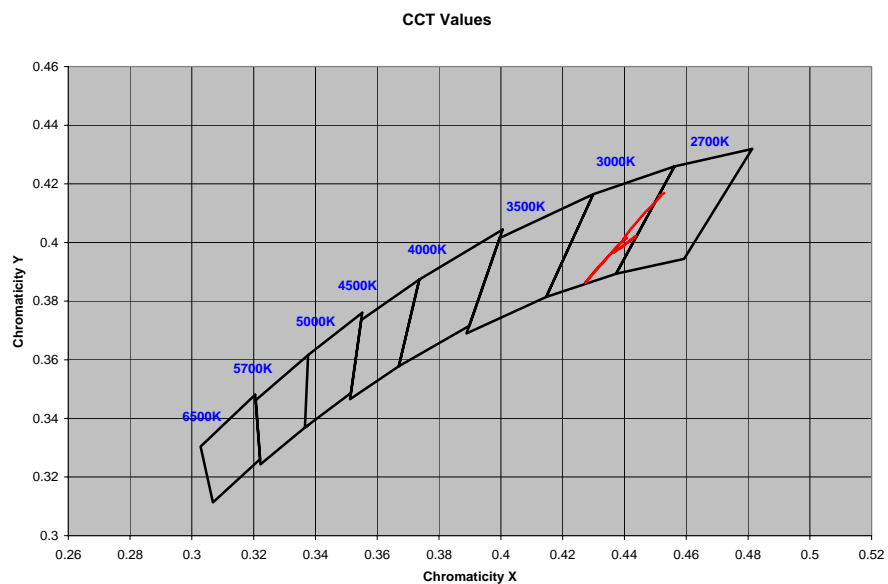
	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	500	392	403
70% Initial Output (Lumens)	350	274	
Current Output (Lumens)		378	
Life Expectancy* (Hours)	50,000	42,679	
Correlated Color Temperature (K)	3,000	2,906	3,143
Color Rendering Index (R_a)	80	83	49
Power (Watts)	13	12	12.9

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





INCAN-007B Lumens vs. Time



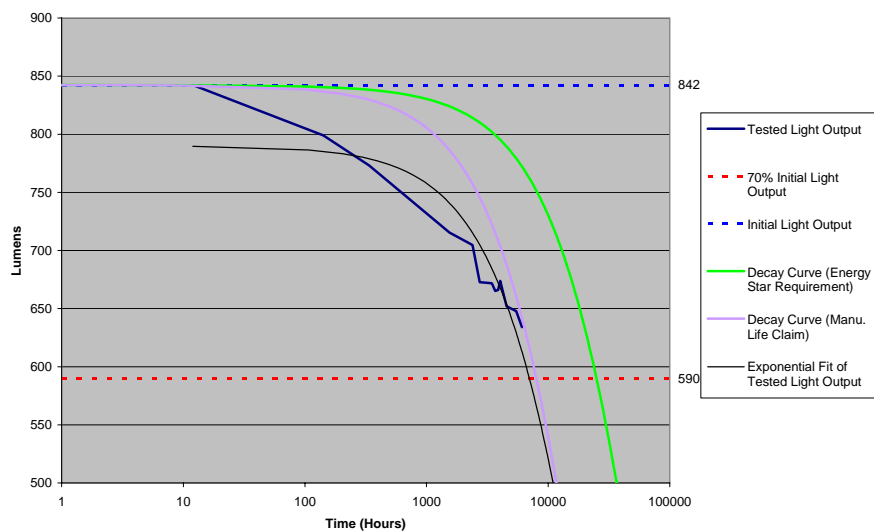
INCAN-007B Chromaticity Chart

Illumisys Reference #	INCAN-018B
Manufacturer	GE
Model	74198
Description	13W Spiral CFL
Power Supply Voltage/Device	120Vac
Illumisys Initial Test Date	8/18/10
Illumisys Final/Recent Test Date:	8/17/11
CALiPER Reference #	–
CALiPER Test Round	–
CALiPER Test Date	–

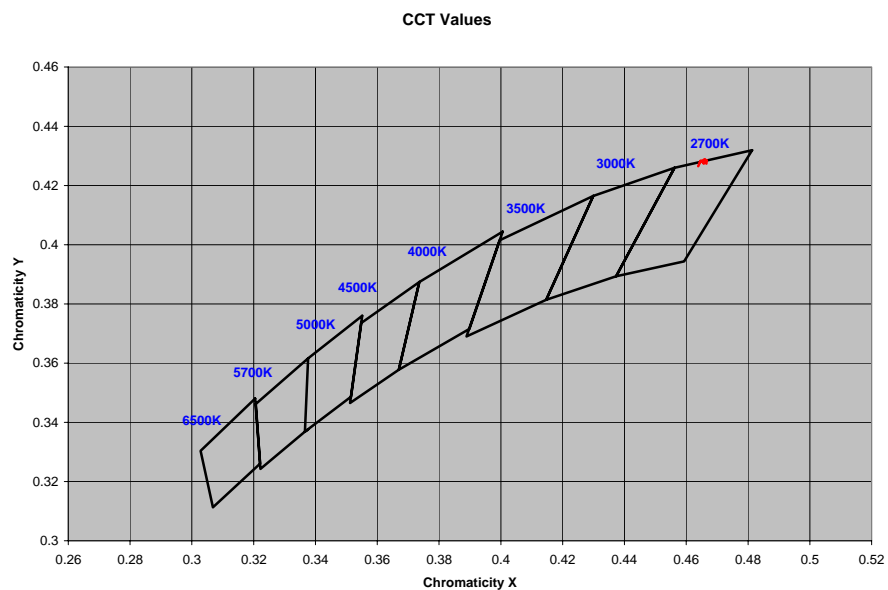
	Manufacturer Claim	Test Results	CALiPER Results
Initial Light Output (Lumens)	825	842	–
70% Initial Output (Lumens)	578	589	
Current Output (Lumens)		613	
Life Expectancy* (Hours)	8,000	7,003	
Correlated Color Temperature (K)	2,700	2,748	–
Color Rendering Index (R_a)	82	81	–
Power (Watts)	13	11	–

* Life expectancy for the test results is estimated using the exponential decay curve of the tested light output data and 70% of the initial output.





INCAN-018B Lumens vs. Time



INCAN-018B Chromaticity Chart

Appendix B – Environmental Impact Values and Documentation

Impact Values

Below are the environmental values used in the Sustainable LED Design Guide.

Material Class	Material	Primary Process	Secondary Process	Process Measurable	GHG (kg CO ₂ Eq)	Energy (MJ)	Mercury (mg)
Ferro	Steel	Steel Billet	None	Weight	1.815667096	28.22468773	0.635260656
Ferro	Steel	Steel Billet	Wire Drawing	Weight	2.147002536	32.37091735	0.983572346
Ferro	Steel	Steel Billet	Milling	Weight	3.080300952	46.90177909	1.051343551
Ferro	Steel	Steel Billet	Chrome Finish	Surface Area	2.1711783	43.4658086	0.15263142
Ferro	Steel	Steel Billet	Powder Coating	Surface Area	4.589747	86.1691345	0.44941253
Ferro	Steel	Stamped Primary Sheet	None	Weight	3.007681413	37.98300005	0.797583869
Ferro	Steel	Stamped Primary Sheet	Chrome Finish	Surface Area	2.1711783	43.4658086	0.15263142
Ferro	Steel	Stamped Primary Sheet	Powder Coating	Surface Area	4.589747	86.1691345	0.44941253
Ferro	Steel	Stamped Secondary Sheet	FerroSteel Stamped SecondarySheet	Weight	1.500230029	16.2514765	0.085157306
Ferro	Steel	Stamped Secondary Sheet	Chrome Finish	Surface Area	2.1711783	43.4658086	0.15263142
Ferro	Steel	Stamped Secondary Sheet	Powder Coating	Surface Area	4.589747	86.1691345	0.44941253
Ferro	Steel	Stamped Unspecified Sheet	None	Weight	2.614044871	28.8449788	0.797583869
Ferro	Steel	Stamped Unspecified Sheet	Chrome Finish	Surface Area	2.1711783	43.4658086	0.15263142
Ferro	Steel	Stamped Unspecified Sheet	Powder Coating	Surface Area	4.589747	86.1691345	0.44941253
NonFerro	Aluminum	Cast Primary Aluminum	None	Weight	12.73806314	206.9299699	0.270352713
NonFerro	Aluminum	Cast Primary Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Cast Primary Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Cast Primary Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Cast Primary Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Extruded Primary Aluminum	None	Weight	13.26611266	218.3858213	0.30333773
NonFerro	Aluminum	Extruded Primary Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Extruded Primary Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Extruded Primary Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Extruded Primary Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Billet Primary Aluminum	None	Weight	12.29078358	198.5148286	0.259572984
NonFerro	Aluminum	Billet Primary Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Billet Primary Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Billet Primary Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864

Material Class	Material	Primary Process	Secondary Process	Process Measurable	GHG (kg CO ₂ Eq)	Energy (MJ)	Mercury (mg)
NonFerro	Aluminum	Billet Primary Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Cast Secondary Aluminum	None	Weight	1.376646768	24.90149175	0.187863233
NonFerro	Aluminum	Cast Secondary Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Cast Secondary Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Cast Secondary Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Cast Secondary Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Extruded Secondary Aluminum	None	Weight	1.904696293	36.35734318	0.220848249
NonFerro	Aluminum	Extruded Secondary Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Extruded Secondary Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Extruded Secondary Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Extruded Secondary Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Billet Secondary Aluminum	None	Weight	0.929367214	16.4863505	0.177083503
NonFerro	Aluminum	Billet Secondary Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Billet Secondary Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Billet Secondary Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Billet Secondary Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Cast Production Mix Aluminum	None	Weight	9.000655754	144.9634819	0.302132928
NonFerro	Aluminum	Cast Production Mix Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Cast Production Mix Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Cast Production Mix Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Cast Production Mix Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Extruded Production Mix Aluminum	None	Weight	9.528705279	156.4193333	0.335117944
NonFerro	Aluminum	Extruded Production Mix Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Extruded Production Mix Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Extruded Production Mix Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Extruded Production Mix Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Billet Production Mix Aluminum	None	Weight	8.5533762	136.5483407	0.291353198
NonFerro	Aluminum	Billet Production Mix Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Billet Production Mix Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Aluminum	Billet Production Mix Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Billet Production Mix Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Aluminum	Drawn Aluminum	None	Weight	11.38724456	190.5023852	0.278540064
NonFerro	Aluminum	Drawn Aluminum	Machining	Weight	0.904047712	13.77555958	0.056505831
NonFerro	Aluminum	Drawn Aluminum	Anodizing	Surface Area	4.1081486	80.4417333	0.36007964

Material Class	Material	Primary Process	Secondary Process	Process Measurable	GHG (kg CO ₂ Eq)	Energy (MJ)	Mercury (mg)
NonFerro	Aluminum	Drawn Aluminum	Powder Coating	Surface Area	3.7361933	67.39207009	0.33612864
NonFerro	Aluminum	Drawn Aluminum	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Brass	Cast Brass	None	Weight	3.762849667	59.91918069	0.677826354
NonFerro	Brass	Cast Brass	Chrome Finish	Surface Area	2.1711783	43.4658086	0.15263142
NonFerro	Brass	Cast Brass	Tin Plating	Surface Area	3.3501117	58.01940624	0.28850761
NonFerro	Brass	Cast Brass	Enameling	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Brass	Sheet Rolled Brass	None	Weight	4.664183632	78.34379382	0.742007615
NonFerro	Brass	Sheet Rolled Brass	Chrome Finish	Surface Area	4.1081486	80.4417333	0.36007964
NonFerro	Brass	Sheet Rolled Brass	Tin Plating	Surface Area	8.6750434	182.720006	0.70488909
NonFerro	Brass	Sheet Rolled Brass	Enameling	Surface Area	0.146636779	3.184760172	0.007150525
NonFerro	Copper	Copper Wire	None	Weight	5.318855091	100.1669913	1.38938936
Plastics	ABS	Injection Molded ABS	None	Weight	4.858731219	120.46228	0.120746251
Plastics	ABS	Extruded ABS	None	Weight	4.01525608	102.4547768	0.091408998
Plastics	PVC	Injection Molded PVC	None	Weight	3.066171271	91.00052007	0.144399742
Plastics	PVC	Blow Molded PVC	None	Weight	2.744336675	88.5828133	0.14703004
Plastics	PVC	Extruded PVC	None	Weight	2.222696131	72.99301696	0.11506249
Plastics	Acrylic	Injection Molded Acrylic	None	Weight	7.299667581	157.0742597	0.146972393
Plastics	Acrylic	Blow Molded Acrylic	None	Weight	6.977832985	154.6565529	0.149602691
Plastics	Polycarbonate	Injection Molded Polycarbonate	None	Weight	8.36124089	158.2831065	0.677413273
Plastics	Polycarbonate	Blow Molded Polycarbonate	None	Weight	8.039406295	155.8653997	0.68004357
Plastics	Polycarbonate	Extruded Polycarbonate	None	Weight	7.51776575	140.2756033	0.64807602
Plastics	Rubber	Molded Rubber	None	Weight	3.013579066	97.65598074	0.08562702
Plastics	Polypropelene	Injection Molded Polypropelene	None	Weight	3.058698084	104.5752414	0.087275663
Plastics	Polypropelene	Blow Molded Polypropelene	None	Weight	2.753688034	102.5207032	0.090278013
Plastics	Polypropelene	Extruded Polypropelene	None	Weight	2.23204749	86.93090685	0.058310462
Glass and Ceramics	Glass	Glass Tube	None	Weight	3.284090168	56.59662635	0.131814563
Paper	Cardboard	Cardboard Sheet	None	Weight	0.82567448	29.94073804	0.057744944
Paper	Kraft Paper	Kraft Paper Sheet	None	Weight	-0.94070575	60.19813738	0.072827306
Electronics	Circuit Components	Populated SM PCB	None	Weight	0.153001714	2.931618675	0.022340826
Electronics	Circuit Components	Unpopulated SM PCB	None	Surface Area	282.47496	5441.992731	38.878574
Electronics	Circuit Components	Unpopulated SM PCB	Soldering - Lead Free	Surface Area	7.2936526	137.6922946	1.7052234
Electronics	Circuit Components	Unpopulated SM PCB	Soldering - Lead Containing	Surface Area	6.0504967	113.9800679	1.5989887
Electronics	Circuit Components	Populated Through Mount PCB	None	Weight	0.153001714	2.931618675	0.022340826
Electronics	Circuit Components	SMD Resistor	None	Weight	32.978617	636.082929	5.2443102
Electronics	Circuit Components	Metal Film Through Mount Resistor	None	Weight	32.978617	636.082929	5.2443102
Electronics	Circuit Components	Wirewound Through Mount Resistor	None	Weight	30.672732	591.907292	5.0370355
Electronics	Circuit Components	SMD Transistor	None	Weight	147.2454	2945.170993	15.626699
Electronics	Circuit Components	Through Mount Transistor	None	Weight	146.29456	2926.569262	15.61097
Electronics	Circuit Components	SMD Capacitor	None	Weight	59.81028	1147.877364	8.9218276
Electronics	Circuit Components	Through Mount Capacitor	None	Weight	51.102405	996.215663	6.3847818
Electronics	Circuit Components	Ring Core Inductor	None	Weight	43.870914	835.485269	6.5259277

Material Class	Material	Primary Process	Secondary Process	Process Measurable	GHG (kg CO ₂ Eq)	Energy (MJ)	Mercury (mg)
Electronics	Circuit Components	SMD Integrated Circuit Small	None	Weight	1018.5318	16302.96763	359.16752
Electronics	Circuit Components	SMD Diode	None	Weight	231.92488	4702.522543	19.329606
Electronics	Circuit Components	Through Mount Diode	None	Weight	231.19182	4685.986548	18.541785
Electronics	Circuit Components	SMD LED	None	Weight	231.92488	4702.522543	19.329606
Electronics	Circuit Components	Through Mount LED	None	Weight	231.19182	4685.986548	18.541785
Electronics	Other Electronic Components	Silicone Potting	None	Weight	2.6980774	62.63038164	0.24630457
Electronics	Other Electronic Components	Cooling Fan	None	Weight	11.901097	254.3552561	2.1100731
Electronics	Other Electronic Components	Fluorescent Lamp Ballast	None	Life	1.869034873	32.91482576	0.408868228
Other	Adhesives	Epoxy	None	Weight	7.585504804	139.0339859	1.114017364
Other	Adhesives	Thermal Adhesive	None	Weight	2.6980774	62.63038164	0.24630457
Other	Fasteners	Steel Fastener	None	Weight	3.110835263	46.90177909	1.051343551
Other	Fasteners	Brass Fastener	None	Weight	4.87102084	81.71177313	1.331914429
Other	Fasteners	Plastic Fastener	None	Weight	8.36124089	157.8805372	0.677413273
Other	Insulated Wire	PVC Insulated Wire	None	Weight	3.894912589	91.40237032	1.417837416
Other	Insulated Wire	Silicone Insulated Wire	None	Weight	3.053636983	64.55928151	0.943821178
Other	Chemicals and Minerals	Mercury	None	Weight	117.92968	1758.135349	161001.04
Other	Chemicals and Minerals	Tungsten Wire	None	Weight	22.81832859	248.0143005	0.115880345
Other	Chemicals and Minerals	Argon Gas	None	Weight	0.227980001	4.596129455	0.014263145
Assembled Components	Edison Screw Base Assembly	Steel Edison Base	None	Weight	1.407084522	20.06128553	0.309681255
Assembled Components	Edison Screw Base Assembly	Brass Edison Base	None	Weight	2.340741192	40.37800833	0.520891069

Energy	Energy Use	US Grid Mix	None	Energy	0.213479418	3.49897215	0.00399156
Energy	Energy Use	EU Grid Mix	None	Energy	0.146636779	3.184760172	0.007150525

End of Life	Waste Disposal	Landfill	None	Weight	0.7	0.314	1.44
End of Life	Waste Disposal	Incineration	None	Weight	0.00529	0.0923	0.00101
End of Life	Reclamation	Recycled	None	Weight	Data Not Available	Data Not Available	Data Not Available
End of Life	Reclamation	Remanufactured	None	Weight	Data Not Available	Data Not Available	Data Not Available

Impact Documentation

Below are the sources of the data used for the above environmental impact values.

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Ferro	Steel	Steel Billet	Average of values from SimPro and GaBi	Analyzing 1 kg 'Steel, low-alloyed, at plant/ RER S'	IPCC 2007 GWP 100a V1.01	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Steel cold rolled PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Ferro	Steel	Wire Drawing	Values from SimaPro	Analyzing 1 kg 'Wire drawing, steel/RER S'	IPCC 2007 GWP 100a V1.01	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Ferro	Steel	Milling	Average of values from SimPro and GaBi	Analyzing 1 kg 'Milling, steel, average/ RER S'	IPCC 2007 GWP 100a V1.01	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	GLO: Steel high-alloyed machining (0,47 kg shavings per 1 kg part) PE [b]	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Ferro	Steel	Chrome Finish	Values from SimaPro	Analyzing 1 m2 'Selective coating, copper sheet, black chrome/ RER S'	IPCC 2007 GWP 100a V1.02	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Ferro	Steel	Powder Coating	Values from SimaPro	Analyzing 1 m2 'Powder coating, steel/RER S'	IPCC 2007 GWP 100a V1.03	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Ferro	Steel	Stamped Primary Sheet	Average of values from SimPro and GaBi	Comparing 1 kg 'Steel, low-alloyed, at plant/RER S' with 1 kg 'Sheet rolling, steel/RER S'	IPCC 2007 GWP 100a V1.04	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Steel sheet (ECCS) BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Ferro	Steel	FerroSteel Stamped Secondary Sheet	Values from GaBi					DE: Steel sheet secondary (ECCS) BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Ferro	Steel	Stamped Unspecified Sheet	Average of average of Primary and Secondary values from SimPro and GaBi								

				SimaPro				GaBi			
Material Class	Material	Process Name	Description of Data Source	Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
NonFerro	Aluminum	Cast Primary Aluminum	Primary Aluminum Raw Material + Aluminum Casting								
NonFerro	Aluminum	Primary Aluminum Raw Material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Aluminum, primary, at plant/RER S'	IPCC 2007 GWP 100a V1.02	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Aluminum ingot mix PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Aluminum Casting	Average of values from SimPro and GaBi	Analyzing 1 kg 'Casting, bronze/CH S'	IPCC 2007 GWP 100a V1.03	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Aluminum die-cast part PE [b]	In this method, only electrical and thermal energy are reported. Impacts from thermal and electrical energy are added from those datasets identified in the following two line items.		
NonFerro	Aluminum	Electrical energy	Impact values from GaBi are used to populate impacts for Aluminum Casting					EU-25: Power grid mix PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Thermal energy - unspecified	Impact values from GaBi are used to populate impacts for Aluminum Casting. Because the source is not specified, all thermal energy sources are averaged.					Thermal energy from unspecified fuel	Values are averaged from the below thermal sources		
NonFerro	Aluminum	Thermal energy from coal	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from coal BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Thermal energy from diesel	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from diesel BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Thermal energy from gas	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from gas BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*

				SimaPro				GaBi			
Material Class	Material	Process Name	Description of Data Source	Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
NonFerro	Aluminum	Thermal energy from heavy fuel oil	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from heavy fuel oil BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Thermal energy from light fuel oil	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from light fuel oil BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Thermal energy from natural gas	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from natural gas BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Thermal energy from wood	Impact values are used to populate "Thermal energy - unspecified"					Thermal energy from wood BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Machining	Average of values from SimPro and GaBi	Analyzing 1 kg 'Milling, aluminum, average/ RER S'	IPCC 2007 GWP 100a V1.03	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Aluminum cast part machining (standard) PE [b]	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Anodizing	Values from SimaPro	Analyzing 1 m2 'Anodizing, aluminum sheet/RER S'	IPCC 2007 GWP 100a V1.04	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Aluminum	Powder Coating	Values from SimaPro	Analyzing 1 m2 'Powder coating, aluminum sheet/RER S'	IPCC 2007 GWP 100a V1.05	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Aluminum	Enameling	Values from SimaPro	Analyzing 1 m2 'Enameling/ RER S'	IPCC 2007 GWP 100a V1.06	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
NonFerro	Aluminum	Extruded Primary Aluminum	Sum of extruded aluminum process and Primary aluminum billet process	Analyzing 1 kg 'Section bar extrusion, aluminum/ RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Aluminum extrusion profile PE [pl]	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Billet Primary Aluminum	Average of values from SimPro and GaBi	Analyzing 1 kg 'Aluminum, primary, at plant/RER S'	IPCC 2007 GWP 100a V1.08	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Aluminum ingot mix PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Cast Secondary Aluminum	Sum of cast aluminum process and secondary aluminum billet process								
NonFerro	Aluminum	Extruded Secondary Aluminum	Sum of extruded aluminum process and secondary aluminum billet process								
NonFerro	Aluminum	Billet Secondary Aluminum	Average of values from SimPro and GaBi	Analyzing 1 kg 'Aluminum, secondary, from old scrap, at plant/ RER S'	IPCC 2007 GWP 100a V1.08	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Aluminum ingot secondary BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Aluminum	Cast Production Mix Aluminum	Sum of cast aluminum process and production mix aluminum billet process								
NonFerro	Aluminum	Extruded Production Mix Aluminum	Sum of extruded aluminum process and production mix aluminum billet process								
NonFerro	Aluminum	Billet Production Mix Aluminum	Values from SimaPro	Analyzing 1 kg 'Aluminum, production mix, at plant/RER S'	IPCC 2007 GWP 100a V1.08	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Aluminum	Drawn Aluminum	Average of values from SimPro and GaBi	Analyzing 1 kg 'Deformation stroke, cold impact extrusion, aluminum/ RER S'	IPCC 2007 GWP 100a V1.09	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Aluminum sheet deep drawing PE [b]	In this method, only electrical energy is reported. Impacts from electrical energy is added from those datasets identified Aluminum Electrical Energy line item above		

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
NonFerro	Brass	Cast Brass	Sum of cast brass process and brass raw material process								
NonFerro	Brass	Brass casting process	Values from SimaPro	Analyzing 1 kg 'Casting, brass/CH S'	IPCC 2007 GWP 100a V1.09	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Brass	Brass raw material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Brass, at plant/CH S'	IPCC 2007 GWP 100a V1.09	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Brass PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Brass	Chrome Finish	Values from SimaPro	Analyzing 1 m2 'Selective coating, copper sheet, black chrome/ RER S'	IPCC 2007 GWP 100a V1.10	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Brass	Tin Plating	Values from SimaPro	Analyzing 1 m2 'Tin plating, pieces/ RER S'	IPCC 2007 GWP 100a V1.11	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Brass	Enameling	Values from SimaPro	Analyzing 1 m2 'Enameling/ RER S'	IPCC 2007 GWP 100a V1.06	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
NonFerro	Brass	Sheet Rolled Brass	Sum of sheet rolled brass process and brass raw material process								
NonFerro	Brass	Brass sheet rolling	Average of values from SimPro and GaBi	Analyzing 1 kg 'Sheet rolling, copper/ RER S'	IPCC 2007 GWP 100a V1.06	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Aluminum sheet PE [pl]	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
NonFerro	Copper	Copper Wire	Sum of copper wire drawing process and copper raw material process								

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
NonFerro	Copper	Wire drawing	Average of values from SimPro and GaBi	Analyzing 1 kg 'Wire drawing, copper/ RER S'	IPCC 2007 GWP 100a V1.06	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Copper wire (0.06mm) PE [b]	In this method, only electrical and thermal energy are reported. Impacts from thermal and electrical energy are added from those datasets identified in the line items above for aluminum casting		
NonFerro	Copper	Raw material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Copper, primary, at refinery/ GLO S'	IPCC 2007 GWP 100a V1.06	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Copper mix (99,999% from electrolysis) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	ABS	Injection Molded ABS	Sum of ABS Raw Material and Injection Molding processes								
Plastics	ABS	Raw Material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S'	IPCC 2007 GWP 100a V1.06	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Acrylonitrile-butadiene-styrene granulate mix (ABS) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics		Injection Molding	Average of values from SimPro and GaBi	Analyzing 1 kg 'Injection molding/ RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Plastic injection molding part (unspecific) PE [b]	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	ABS	Extruded ABS	Sum of ABS Raw Material and Extruding processes								
Plastics		Extruding	Values from SimaPro	Analyzing 1 kg 'Extrusion, plastic pipes/RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Plastics	PVC	Injection Molded PVC	Sum of PVC Raw Material and Injection Molding processes								
Plastics	PVC	Raw Material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Polyvinyl-chloride, bulk polymerized, at plant/ RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Polyvinylchloride powder (PVC) BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	PVC	Blow Molded PVC	Sum of PVC Raw Material and Blow Molding processes								

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Plastics		Blow Molding	Average of values from SimPro and GaBi	Analyzing 1 kg 'Blow molding/ RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Polyethylene (PE-HD) blow molding PE [b]	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	PVC	Extruded PVC	Sum of PVC Raw Material and Extruding processes								
Plastics	Acrylic	Injection Molded Acrylic	Sum of Acrylic Raw Material and Injection Molding processes								
Plastics	Acrylic	Raw Material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Polymethyl methacrylate, beads, at plant/RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Polymethyl methacrylate granulate (PMMA) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	Acrylic	Blow Molded Acrylic	Sum of Acrylic Raw Material and Blow Molding processes								
Plastics	Poly-carbonate	Injection Molded Poly-carbonate	Sum of Poly-carbonate Raw Material and Injection Molding processes								
Plastics	Poly-carbonate	Raw Material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Poly-carbonate, at plant/RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Polycarbonate granulate (PC) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	Poly-carbonate	Blow Molded Poly-carbonate	Sum of Poly-carbonate Raw Material and Blow Molding processes								
Plastics	Poly-carbonate	Extruded Poly-carbonate	Sum of Poly-carbonate Raw Material and Extruding processes								
Plastics	Rubber	Molded Rubber	Average of values from SimPro and GaBi	Analyzing 1 kg 'Synthetic rubber, at plant/RER S'	IPCC 2007 GWP 100a V1.07	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Styrene-butadiene rubber mix (SBR) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*

				SimaPro				GaBi			
Material Class	Material	Process Name	Description of Data Source	Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Plastics	Polypropylene	Injection Molded Polypropylene	Sum of Polypropylene Raw Material and Injection Molding processes								
Plastics	Polypropylene	Raw Material	Average of values from SimPro and GaBi	Analyzing 1 kg 'Polypropylene, granulate, at plant/RER S'	IPCC 2007 GWP 100a V1.08	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Polypropylene granulate (PP) BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Plastics	Polypropylene	Blow Molded Polypropylene	Sum of Polypropylene Raw Material and Blow Molding processes								
Plastics	Polypropylene	Extruded Polypropylene	Sum of Polypropylene Raw Material and Extruding processes								
Glass and Ceramics	Glass	Glass Tube	Values from SimaPro	Analyzing 1 kg 'Glass tube, borosilicate, at plant/DE S'	IPCC 2007 GWP 100a V1.08	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Paper	Cardboard	Cardboard Sheet	Values from SimaPro	Analyzing 1 kg 'Packaging, corrugated board, mixed fiber, single wall, at plant/RER S'	IPCC 2007 GWP 100a V1.09	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Paper	Kraft Paper	Kraft Paper Sheet	Values from SimaPro	Analyzing 1 kg 'Kraft paper, unbleached, at plant/RER S'	IPCC 2007 GWP 100a V1.10	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Populated SM PCB	See additional information below **								
Electronics	Circuit Components	Unpopulated SM PCB	Values from SimaPro	Analyzing 1 m2 'Printed wiring board, surface mount, at plant/GLO S'	IPCC 2007 GWP 100a V1.10	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Soldering - Lead Free	Values from SimaPro	Analyzing 1 m2 'Mounting, surface mount technology, Pb-free solder/ GLO S'	IPCC 2007 GWP 100a V1.10	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Electronics	Circuit Components	Soldering - Lead Containing	Values from SimaPro	Analyzing 1 m2 'Mounting, surface mount technology, Pb-containing solder/ GLO S'	IPCC 2007 GWP 100a V1.11	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Populated Through Mount PCB	See additional information below **								
Electronics	Circuit Components	SMD Resistor	Values from SimaPro	Analyzing 1 kg 'Resistor, metal film type, through-hole mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.11	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Metal Film Through Mount Resistor	Values from SimaPro	Analyzing 1 kg 'Resistor, metal film type, through-hole mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.11	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Wirewound Through Mount Resistor	Values from SimaPro	Analyzing 1 kg 'Resistor, wirewound, through-hole mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.11	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	SMD Transistor	Values from SimaPro	Analyzing 1 kg 'Transistor, SMD type, surface mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.12	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Through Mount Transistor	Values from SimaPro	Analyzing 1 kg 'Transistor, wired, small size, through-hole mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.13	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	SMD Capacitor	Values from SimaPro	Analyzing 1 kg 'Capacitor, SMD type, surface-mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.14	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Through Mount Capacitor	Values from SimaPro	Analyzing 1 kg 'Capacitor, electrolyte type, < 2cm height, at plant/GLO S'	IPCC 2007 GWP 100a V1.15	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Electronics	Circuit Components	Ring Core Inductor	Values from SimaPro	Analyzing 1 kg 'Inductor, ring core choke type, at plant/ GLO S'	IPCC 2007 GWP 100a V1.16	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	SMD Integrated Circuit Small	Values from SimaPro	Analyzing 1 kg 'Integrated circuit, IC, logic type, at plant/GLO S'	IPCC 2007 GWP 100a V1.17	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	SMD Diode	Values from SimaPro	Analyzing 1 kg 'Diode, glass-, SMD type, surface mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.18	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Through Mount Diode	Values from SimaPro	Analyzing 1 kg 'Diode, glass-, through-hole mounting, at plant/GLO S'	IPCC 2007 GWP 100a V1.19	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	SMD LED	Values from SimaPro	Analyzing 1 kg 'Light emitting diode, LED, at plant/ GLO S'	IPCC 2007 GWP 100a V1.20	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Circuit Components	Through Mount LED	Values from SimaPro	Analyzing 1 kg 'Light emitting diode, LED, at plant/ GLO S'	IPCC 2007 GWP 100a V1.21	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Other Electronic Components	Silicone Potting	Values from SimaPro	Analyzing 1 kg 'Silicone product, at plant/RER S'	IPCC 2007 GWP 100a V1.22	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Other Electronic Components	Cooling Fan	Values from SimaPro	Analyzing 1 kg 'Fan, at plant/GLO S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Electronics	Other Electronic Components	Fluorescent Lamp Ballast	See additional information below **								
Other	Adhesives	Epoxy	Average of values from SimPro and GaBi	Analyzing 1 kg 'Epoxy resin, liquid, at plant/ RER S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Epoxy resin Plastics Europe	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Other	Adhesives	Thermal Adhesive	Values from SimaPro	Analyzing 1 kg 'Silicone product, at plant/RER S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Other	Fasteners	Steel Fastener	Sum of steel billet and machining processes								
Other	Fasteners	Brass Fastener	Sum of brass billet and machining processes								
Other	Fasteners	Plastic Fastener	Sum of polycarbonate raw material and injection molding processes								
Other	Insulated Wire	PVC Insulated Wire	Sum of PVC raw material, plastics extrusion, copper raw material, and copper wire drawing processes, based on measure weight of sample wire and insulation								
Other	Insulated Wire	Silicone Insulated Wire	Sum of silicone material, copper raw material, and copper wire drawing processes, based on measure weight of sample wire and insulation								
Other	Chemicals and Minerals	Mercury	Values from SimaPro	Analyzing 1 kg 'Mercury, liquid, at plant/GLO S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*				
Other	Chemicals and Minerals	Tungsten Wire	Sum of Tungsten raw material and copper wire drawing								
Other	Chemicals and Minerals	Tungsten Raw Material	Values from SimaPro	Analyzing 1 kg 'Tungsten I'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand					

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
Other	Chemicals and Minerals	Argon Gas	Average of values from SimPro and GaBi	Analyzing 1 kg 'Argon, crude, liquid, at plant/ RER S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	DE: Argon (gaseous) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Assembled Components	Edison Screw Base Assembly	Steel Edison Base	Sum of steel sheet, steel stamping, and glass products processes, based on sample components								
		Glass products	Average of values from SimPro and GaBi	Analyzing 1 kg 'Packaging glass, white, at plant/ RER S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	CH: Glass (white; packaging) BUWAL	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Assembled Components	Edison Screw Base Assembly	Brass Edison Base	Sum of brass raw material, brass sheet rolling, aluminum drawing, and glass products processes, based on sample components								

Energy	Energy Use	US Grid Mix	Average of values from SimPro and GaBi	Analyzing 1 MJ 'Electricity, production mix US/US S'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	US: Power grid mix PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
Energy	Energy Use	EU Grid Mix	Average of values from SimPro and GaBi	Analyzing 1 MJ 'Electricity, production mix RER/RER S'	IPCC 2007 GWP 100a V1.24	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	EU-25: Power grid mix PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*

End of Life	Waste Disposal	Landfill	Average of values from SimPro and GaBi	Analyzing 1 kg 'Landfill/ CH U'	IPCC 2007 GWP 100a V1.23	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Landfill (Municipal household waste; BE, DK) PE	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
-------------	----------------	----------	--	---------------------------------	--------------------------	---	------------	--	---	---	------------

Material Class	Material	Process Name	Description of Data Source	SimaPro				GaBi			
				Title	Method - GHG	Method - Energy	Method - Mercury	Title	Method - GHG	Method - Energy	Method - Mercury
End of Life	Waste Disposal	Incineration	Average of values from SimPro and GaBi	Analyzing 1 kg 'Incineration/ CH U'	IPCC 2007 GWP 100a V1.24	Cumulative Energy Demand V1.05 / Cumulative energy demand	Inventory*	RER: Household waste in municipal waste incinerator ELCD/PE-GaBi	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.] kg CO2-Equiv.	Energy renewable and non-renewable (gross calorific value) [MJ]	Inventory*
End of Life	Reclamation	Recycled	No values included in this release								
End of Life	Reclamation	Remanufactured	No values included in this release								

* Inventory: Indicates that Mercury values were calculated from adding all sources of mercury identified in the output inventory of the associated process. See example below:

Values from GaBi (example is from Primary Aluminum Raw Material):

Mercury (+II) [Heavy metals to air]	1.39394E-07	kg
Mercury (+II) [Heavy metals to fresh water]	1.19898E-08	kg
Mercury (+II) [Heavy metals to sea water]	1.5764E-09	kg
Mercury (+II) [Heavy metals to industrial soil]	3.00847E-12	kg
Sum	1.52964E-07	kg

Values from SimaPro (example is from Primary Aluminum Raw Material):

Impact category	Unit	Total	Aluminum, primary, at plant/RER S
Mercury	mg	0.4039905	0.4039905

** Impact information for populated circuit boards in the LCA software tools was based on circuits used in the computing and telecommunications industries. Circuit boards in these industries tend to be very densely populated when compared to what was found in the LED products considered in this project, skewing the impact values for this category. In order to create a more representative set of impact values, the circuits were inventoried for five different lamps and the sums of the impacts of their circuit components were averaged per total mass of the populated circuit board assemblies. The values in the table above represent these averages.

Appendix C – Sustainable LED Product Design Guide

The Sustainable LED Product Design Guide – a web-based tool is hosted by NCMS at www.ncms.org

Sustainable LED Product Design Guide

Available at www.ncms.org

User Manual

Rev 1

September 27, 2011



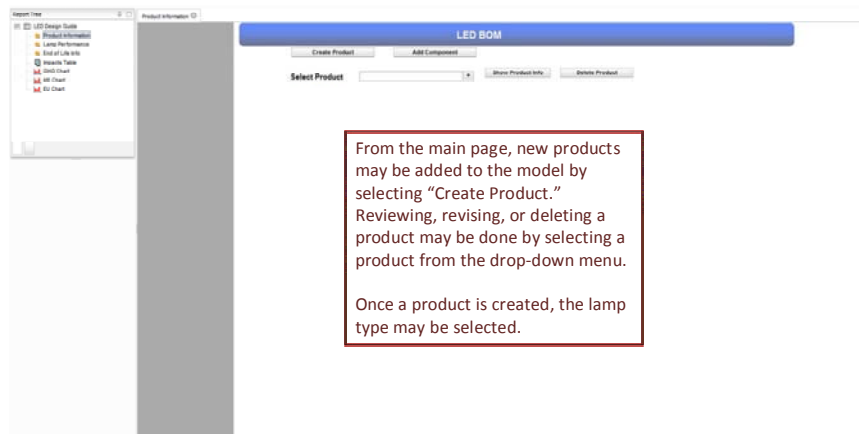
Overview

The intent of the *Sustainable LED Product Design Guide* is to aid designers of LED lighting products in making environmentally sustainable design decisions. This guidance is provided through comparison against existing or conceptual designs through an interactive charting environment. In order to compare a design concept against other products, the user follows this procedure:

- Create the new product
- Identify the product type
- Populate the Bill-of-Materials (BOM) of the product
- Assign materials and processes to the components in the BOM
- Assign the performance specifications of the product
- Identify the disposal scenario expected for the product
- Proceed to the charting dashboard to compare the environmental impacts of the design against other products in the guide
- Export PDF charts in order to report findings



Creating or Reviewing a Product



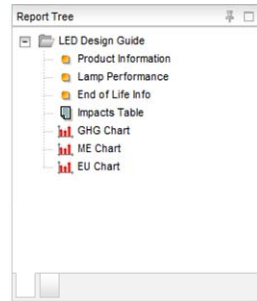
Populating the BOM

[illegible]

From the BOM page, components may be added and assigned to a subsystem. Once a component is added, materials and processes may be assigned by right-clicking the component and selecting “assign material.”



Assigning the Performance Specifications and End-of-Life Scenario to the Product

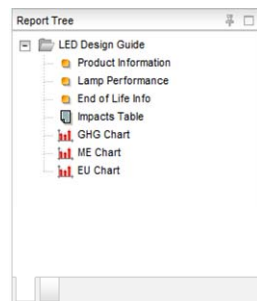


Use and End-of-Life Phase information may be assigned to the Lamp Product by selecting "Lamp Performance" or "End of Life" Info from the Report Tree.

The values input in these pages will calculate the Use and End-of-Life phase impact values and allow for comparing products across functional units.



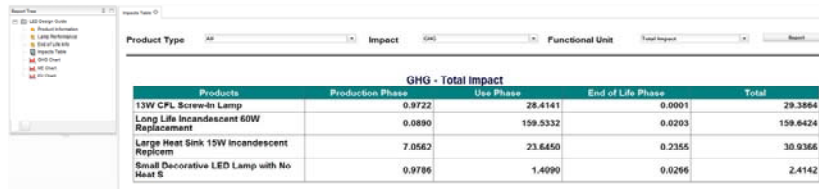
Product Review Reports



From the Report Tree, the user may view a comparison of products in table form ("Impacts Table") or in chart form. The charts and tables may be viewed for each of the three impact categories.



Environmental Impacts Table



The screenshot shows the 'Report Tree' on the left with options like 'Product Information', 'Life Cycle Impacts', 'GHG Table', 'GHG Chart', 'GHG Chart', and 'GHG Chart'. The main window displays the 'Impacts Table' with filters for 'Product Type' (All), 'Impact' (GHG), and 'Functional Unit' (Total Impact). The table shows GHG - Total Impact for various products across Production, Use, and End of Life phases.

Products	Production Phase	Use Phase	End of Life Phase	Total
13W CFL Screw-In Lamp	0.9722	28.4141	0.0001	29.3864
Long Life Incandescent 60W Replacement	0.0890	159.5332	0.0203	159.6424
Large Heat Sink 15W Incandescent Replacement	7.0562	23.6450	0.2355	30.9366
Small Decorative LED Lamp with No Heat S	0.9786	1.4090	0.0266	2.4142

The Impacts Table shows a tabular comparison of products' impacts.

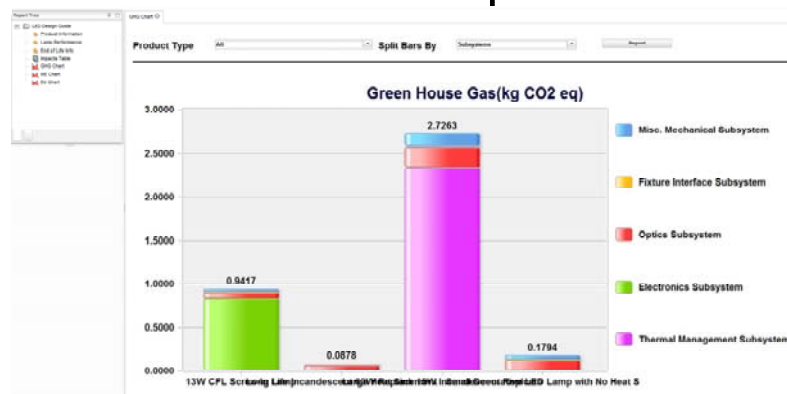
The user may choose to show all of the products of a given type, or all products in the "Product Type" field.

The user may select which impact category to compare products against in the "Impacts" field.

The user may choose to compare the impacts of the products for total lifecycle impacts, impacts per hour of use, or impacts per lumen-hour. The normalization factor may be selected in the "Functional Unit" field.



Environmental Impacts Charts



By choosing one of the impact category charts from the Report Tree, a visual report of the impacts of the various products is generated.

The bars may be divided by the subsystems for a comparison of Production Phase impacts, or by life cycle phase for a comparison of products across life cycle phases with the option of selecting a functional unit.



Exporting Reports to PDF Files



The icons at the top of the screen allow for exporting PDF files of the reports.

The first icon allows additional report pages to be created.

The second icon hides the Report Tree to maximize the viewing area for the charts and tables.

The third icon exports a PDF file of the currently active report page.

The fourth icon exports a PDF file for all of the tabs.

In order to create a report showing charts for all impact categories, new tabs would be created for each desired chart, and when complete, the fourth icon can be selected to export a report for the comparison of impacts.





Appendix D – Presentation Materials

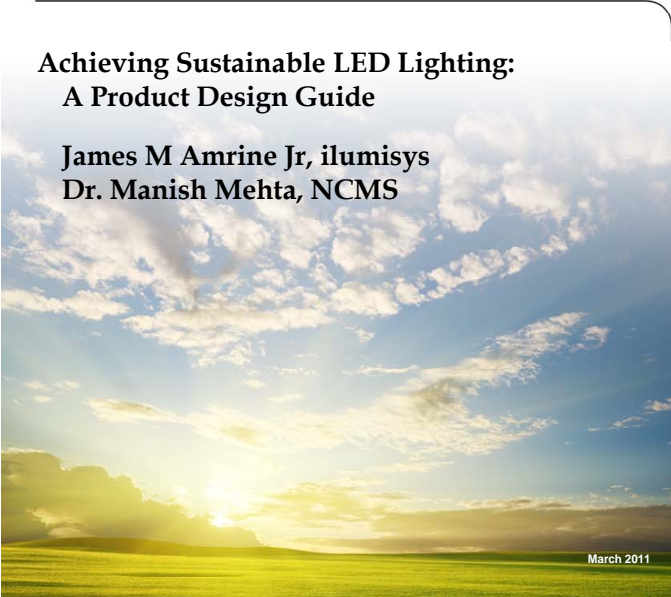
NCMS and Ilumisys presented the work done on this project at three different venues over the course of the project. The first was at the 2010 NeoCon conference in Chicago in June, 2010. The second was at the Southeast Michigan Sustainable Business Forum monthly meeting in September of 2010. The third presentation was given at the Sustainable Electronics Initiative conference in Champaign, IL in March 2011. The slides shown in Champaign are included below:

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Achieving Sustainable LED Lighting: A Product Design Guide

James M Amrine Jr, ilumisys
Dr. Manish Mehta, NCMS









March 2011


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Sustainable Lighting Product Development




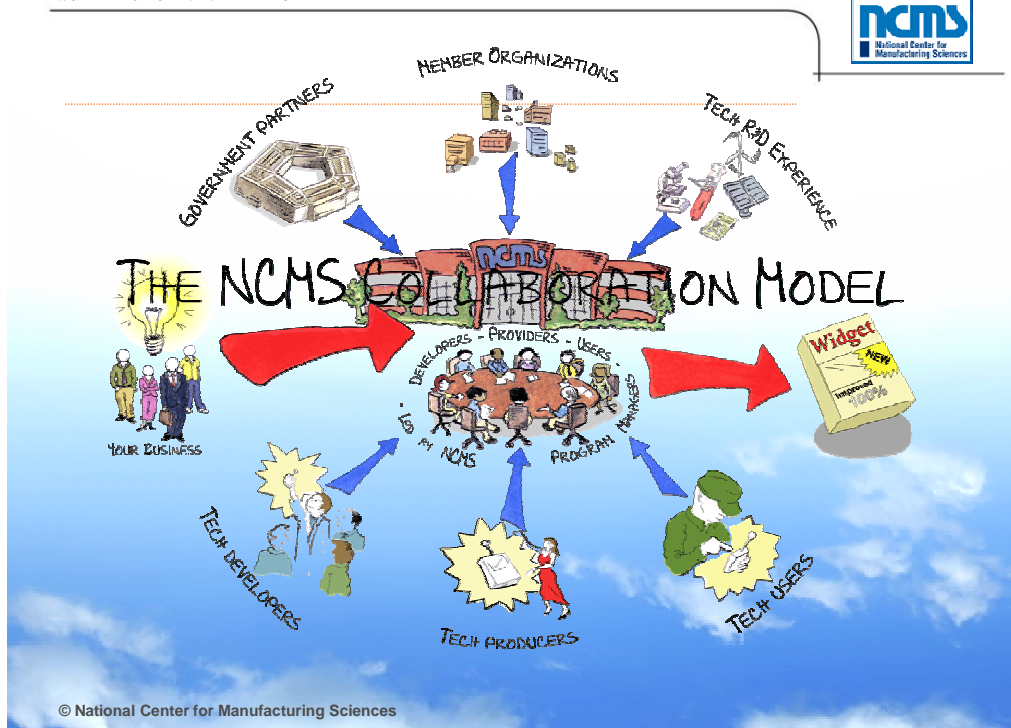
ilumisys is a Troy, Michigan-based company focused on next-generation solid-state lighting technology. The company was formed in 2007 as a spinoff venture and wholly owned subsidiary of Altair Engineering, Inc. with initial products based on Altair's intellectual property for the direct replacement of fluorescent light tubes with light-emitting diode (LED) lamps.



NCMS is a not-for-profit organization, based in Ann Arbor, MI, and a premier provider of collaborative research, information, knowledge and expertise to the North American manufacturing and defense community. Backed by over 350 corporate members, NCMS has spearheaded numerous advancements – in advanced materials, alternative energy, electronics, high performance computing, rapid prototyping/ manufacturing, enterprise integration and sustainability – all focused on enhancing the nation's manufacturing competitiveness in the global economy



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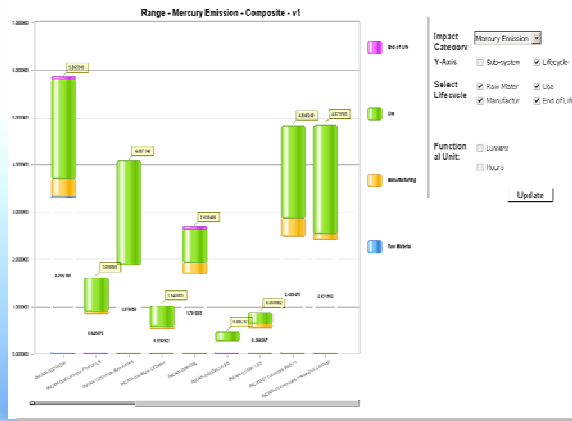
NCMS Sustainability Program

- DOE Programs in Lightweighting, Fuel Cells & Hydrogen
- DOE - Sustainable Light Emitting Diode Fluorescent Lamps (with ilumisys/Altair) – LCA-driven Design Guide/Web tool
- Operates 9 (of 14) EPA Compliance Assistance Centers (Web)
- EPA-LCA for VOCs in Paints & Coatings Web tool
- EPA - Sustainable Product Initiative
 1. Cradle-to-Gate Tools & Gate-to-Gate tools
 2. Remanufacturing Assessment Web tool
 3. Sustainable Automotive Materials Selection Guide tool
 4. National Green Vehicle Standard
 5. Multi-Attribute Sustainability Standards Guide (Web)

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Sustainable LED Product Development

Sustainable Lighting Design



U.S. Department of Energy sustainability of LED lighting products project

The U.S. Department of Energy (DOE) has contracted ilumisys and the National Center for Manufacturing Science (NCMS) to evaluate the sustainability of LED lighting products. ilumisys is conducting durability and output testing of numerous LED lighting products to define an evaluation process (including LCA).

The study findings will generate a best practices guide to allow LED product designers to make sustainable design decisions.

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Sustainable LED Product Development

Phase 1: As-Is Analysis



Select Products for Analysis

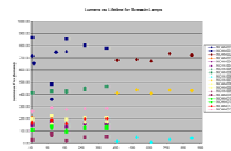


Several commercially-available LED lighting products were selected from two categories: screw-in incandescent replacement lamps and linear fluorescent replacement lamps.

Life Cycle Analysis

Products were disassembled and bills-of-material were generated, including all production-related processes. Life cycle analyses were performed for three impact categories.

Product Testing



Light output and useful lifetime testing were performed on each product to support the LCA results and to define the functional units used to compare products.

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Sustainable LED Product Development

Products Selected for Evaluation – Screw-In Replacements

GE 13W Spiral CFL (benchmark)



SLI 60W Incandescent (benchmark)



GBL 9W 150 LED



WDM 15W LED



Sylvania 8W LED



EvoLux S 13W LED



MR LED 2.3W



Luxterra 5W LED



Mule LEDalux 1W LED



Lemnis Pharos 4W LED



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Sustainable LED Product Development

Products Selected for Evaluation – Fluorescent Replacements

Philips F40T12 Alto 40W
& Philips F32T8 Alto 32W
(Benchmarks)



ilumisys Mk1 28W LED
& ilumisys Mk2 22W LED



SeeSmart 15W LED



Clean Light Green Light 17W LED



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Sustainable LED Product Development

What is Life Cycle Assessment?



Life Cycle Assessment or Analysis (LCA) is the evaluation of the environmental, economic, and/or social impacts of a product or process throughout its life.

The lifecycle phases considered in this program were:

- Raw Material Extraction/Manufacturing
- Use
- End of Life

Transportation was not considered due to lack of information on the products we are considering. An extension of this program may allow for the consideration of transportation within the LCA.

The program focus will be on select environmental impacts.

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Sustainable LED Product Development

LCA Impact Category Selection



Energy Consumption



Energy consumption was chosen as a general impact category to consider because many other impacts are driven by the energy required for each of the life cycle phases.

Greenhouse Gas Emission



With climate change at the forefront of the environmental discussion, greenhouse gas emissions (measured in kg CO₂ equivalence) was a clear choice for evaluation.

Mercury Emission



Because a frequent benefit cited for LEDs over fluorescent lighting is the lack of mercury, mercury released to the environment over the lifecycle was evaluated. Note that while incandescent and LED lamps contain no mercury, mercury is released in their use due to its emission in coal-fired power plants.



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Assumptions in the LCA Study

- Populated circuit boards were considered by weight as a unit rather than as each of the constituent components. This is driving higher-than-realistic impacts for the electronics package. We are developing our own metric from the LCA software tools and measurements on actual lamp circuits to replace these values. This high impact per mass is due to the LCA inventories using telecom circuits and PC motherboards as their standard.
- “Unspecified” categories were established for use of primary, secondary, and production mix metals. Worst case of these defines the value for the unspecified condition.
- Default assumption for metals was production mix, as discussions with metals industry experts indicated that there is very little primary metal used except in very specific applications. The same is true of 100% secondary materials.
- Waste in any forming process was left to the defaults in the LCA software tools. Not enough information was available to identify waste, therefore only the mass of the finished part was used for impact calculations.
- Lamps that required a standard external electronic ballast (fluorescent tubes and the ilumisys Mk1 tubes) had the ballast impacts included in their LCA. The contribution of the ballast was based on a rated life of 50,000 hours and the assumption that a ballast runs two lamps, so if a ballast runs lamps that have a life of 25,000 hours, 1/2 of the ballast impacts are included for a single lamp.
- Initially, useful life of the lamps, used in defining functional units, will be based on manufacturer claims. Lab testing will measure real life numbers and these will replace the other values as they become available.

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Product BOM Creation

Turning a bill-of-materials into a bill-of-processes...

No longer only a 65-gram heat sink, now it is...



GHG Emissions from production and end-of-life phases:
~1.12 kg CO₂ eq.



Extruding
~.06 kg CO₂ eq.



Raw Material Extraction
~.78 kg CO₂ eq.

Anodizing
~.27 kg CO₂ eq.



Machining
~.005 kg CO₂ eq.



Landfill
~.001 kg CO₂ eq.

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Product Testing

What is being tested, and why?

- Power consumption and useful life are needed to quantify the use phase in the life cycles of the lamps.
- Light output and useful life contribute to the functional unit against which products can be compared.
- Testing conditions are guided by best practices taken from Energy Star and IES LM-79 and LM-80 standards.
- Color temperature and color rendering index are also being measured.



62" integrating sphere for photometric testing



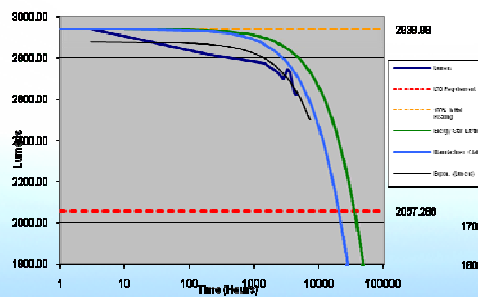
Lamps run continuously on a 3-hour on, 20-minute off cycle at 45°C inside of temperature control chambers

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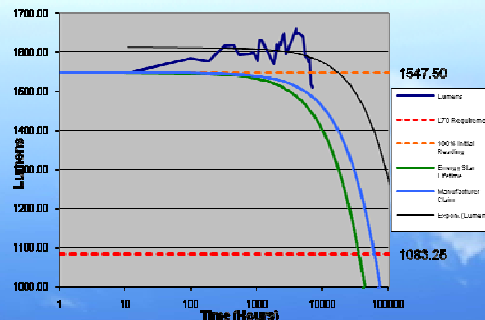


Some Preliminary Test Results – Lumens vs Time

Lumens vs. Time - T12 Benchmark



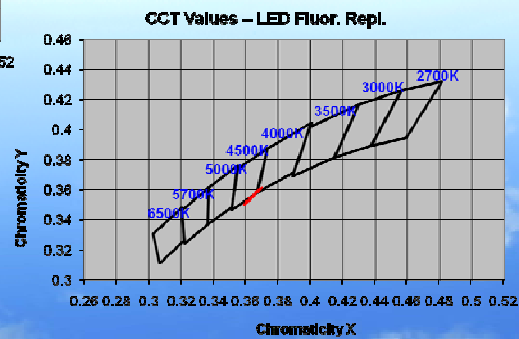
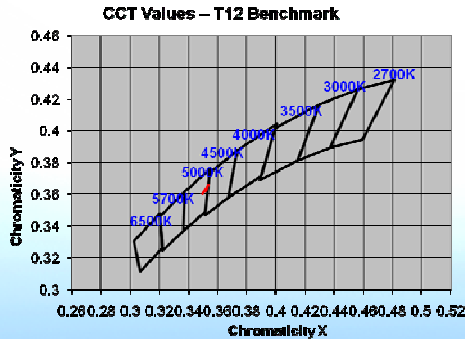
Lumens vs. Time - LED Fluor. Repl.



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Some Preliminary Test Results – CCT Over Time



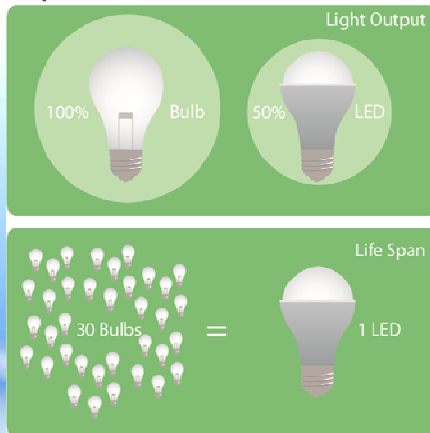
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Functional Units in LCA

Why are functional units important?

Allow comparisons of products with different levels of performance without penalizing better performing products that have higher impacts



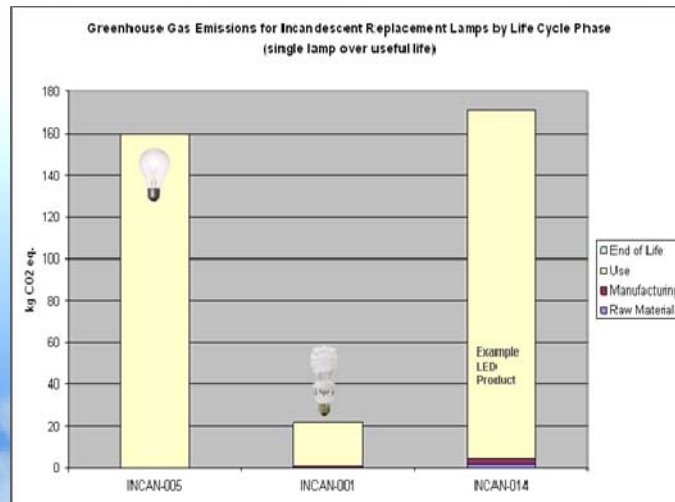
As an example, to get the same amount of light over the same period of use, it might require 15 incandescent lamps to equate to the performance over time of one LED lamp. Thus, in comparison, 15-times the impacts of the incandescent lamp are considered against a single LED lamp.

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Functional Units in LCA

When looking at single lamps, the LED lamps have very high impacts due to their complexity...

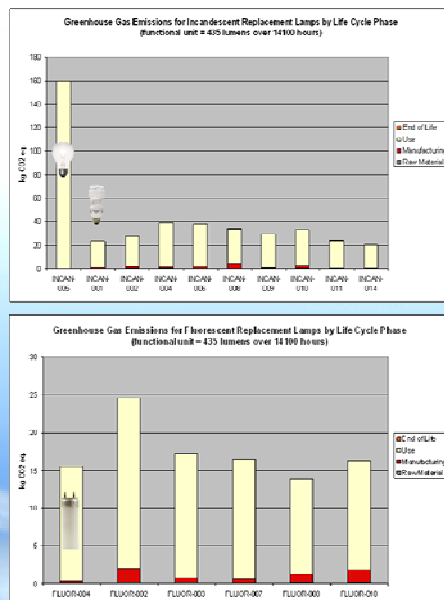


...but when compared against a functional unit, equivalent light output over a longer life reduces the impacts in achieving that quantity of light over time.

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Preliminary LCA Results – GHG Emissions



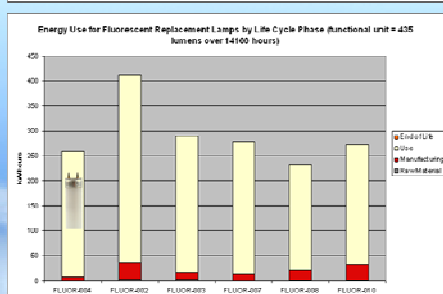
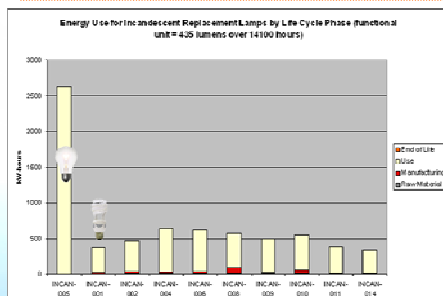
Initial Observations:

- The use phase dominates the Greenhouse Gas Emissions.
- The energy efficiency of fluorescent lamps define the path for LED lamp design.

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Preliminary LCA Results – Energy Use



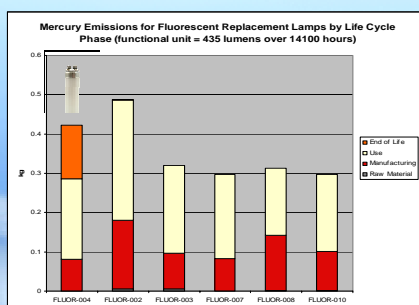
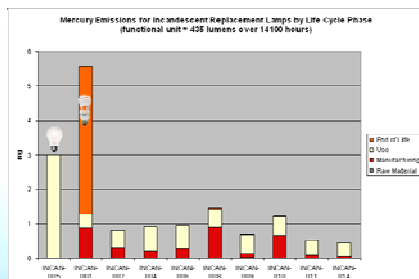
Initial Observations:

- The use phase dominates the Energy Use Impact.
- Energy Use tracks with GHG – GHG Emissions are directly related to Energy Use in all phases.

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Preliminary LCA Results – Mercury Emissions



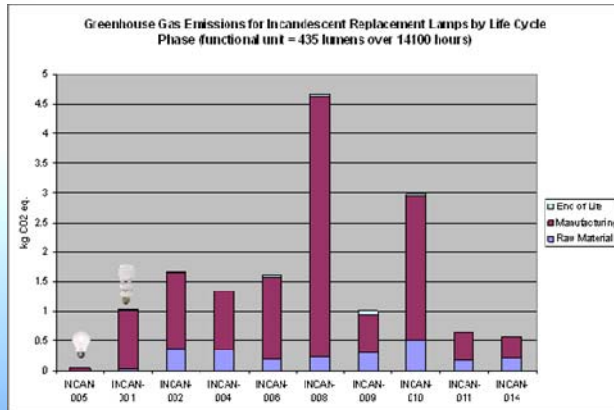
Initial Observations:

- The manufacturing stage plays a larger role in Mercury Emission than in other impact categories.
- The fluorescent products contain mercury which is accounted for at end-of-life.
- Mercury emission comes primarily from coal-fired plants as incandescent and LED products contain no mercury.
- Larger discrepancies are seen between data sources for Mercury Emission as compared to other impact categories.

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Preliminary LCA Results – Without the Use Phase



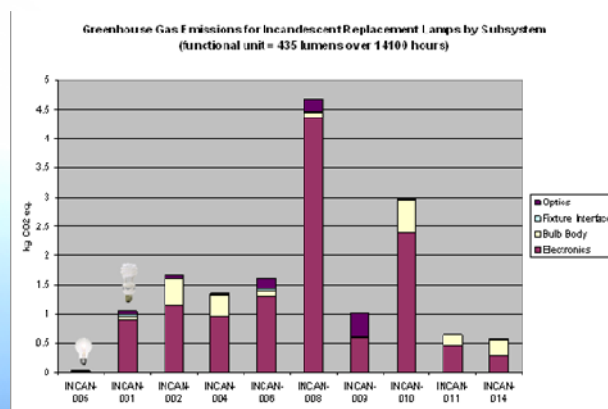
Initial Observations:

- Manufacturing is the phase with the second greatest potential for impact reductions, after improved efficacy of the lamp.
- The end-of-life phase remains as the phase with the lowest impacts.

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Preliminary LCA Results – Subsystem Review

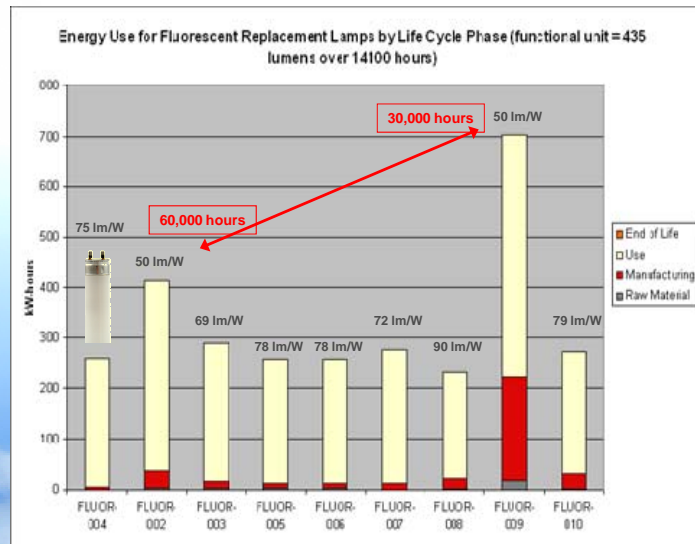


Again, ignoring the use phase:

- The majority of the impacts come from the Electronics Subsystem.
- Major contributors to GHG after the electronics are plastic lenses (Optics Subsystem) and large aluminum heat sinks (Bulb Body Subsystem).



Preliminary LCA Results – Importance of Efficacy



The greatest reductions in environmental impacts will come from improvements in lamp efficacy through increased efficiency of the LEDs.

Fluorescent is still strong in this area, but LEDs are gaining ground.

Lifetime is also critical.

Note that lifetime assumptions are based on manufacturer claims. These values will be updated as the data becomes available.



Sustainable LED Product Development

Creating a Best Practice Guide for Sustainable LED Lighting Products

The design guide, when complete will be available via the sustainability portal on the NCMS website. The frame work of the tool will be as follows:

