Life-Cycle Assessment of Energy and LED Lighting

8

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Executive Summary

The report *Review of the Life Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps* is the first installment of a larger U.S. Department of Energy (DOE) project to assess the life-cycle environmental and resource costs in the manufacturing, transport, use, and disposal of light-emitting diode (LED) lighting products in relation to comparable traditional lighting technologies. The assessment comprises three phases:

- Comparison of the total life-cycle energy consumed by LED and other lamp types based on existing life-cycle assessment (LCA) literature;
- An LCA study of an LED lamp considering both the direct and indirect material and process inputs to fabricate, ship, operate and dispose of the lamp; and
- The purchase, disassembly and chemical testing of LED and conventional lighting products to study whether potentially hazardous materials are present in concentrations that exceed hazardous waste regulatory thresholds.

The potential energy imbalance between upstream energy consumption and downstream energy savings has led several institutions to employ life-cycle analyses to quantify the life-cycle energy impacts of LED lighting. The purpose of this report is to estimate, from prior studies, the life-cycle energy consumption of an LED lamp product as compared to incandescent lamp and compact fluorescent lamp (CFL) technologies. This report analyzes several existing life-cycle assessment (LCA) studies, which include academic publications as well as manufacturing and independent research reports. This analysis answers three main questions:

- How much energy is consumed during each life-cycle phase of LED lamps (manufacture, transport, use, etc.)?
- How does the life-cycle energy consumption of LED lamps compare to that of incandescent lamp and CFL products?
- How might the life-cycle energy consumption of LED lamp products change in the future?

This report analyzes the energy consumption associated with three life-cycle phases: manufacturing, transportation, and use. The majority of data collected for this energy assessment of incandescent lamps, CFLs, and LED lamps is gathered from information provided in existing LCA reports. A total of ten publications provide the data and level of disaggregation necessary to develop a comprehensive analysis of the life-cycle energy for each lamp type.

Incandescent, CFL, and LED lighting products represent different lighting technologies each having varying performance characteristics. The ten life-cycle analyses considered an array of lamp products each having different specifications for each technology. Therefore, when estimating per lamp energy consumption, current performance characteristics are developed for the incandescent lamp and CFL based on the products analyzed in the cited studies. For the LED lamps, in order to provide as current of an analysis possible and to allow for an analysis of future products, the performance characteristics of the LED lamp are based on the 2011 DOE Solid State Lighting Multi Year Program Plan (DOE, 2011a).

Considering the lumen output and lifetime for each lamp it is apparent that these products are not perfectly equivalent. To provide the uniformity necessary to conduct a life-cycle energy analysis, a functional unit of “20 million lumen-hours” is selected. This functional unit represents the lighting service provided by a single 60 W LED lamp replacement over its lifetime. As the lifetimes of incandescent and compact fluorescent technologies are significant lower than that of LED technologies, a single incandescent lamp or CFL provides less lighting service than the functional unit value; thus, the life-cycle energy estimates are multiplied by the number of lamps needed to reach this equivalence.

The manufacturing phase estimates provided in the report encompass primary resource acquisition, raw material processing, manufacturing, and assembly. The manufacturing energy profile of incandescent lamps, CFLs, and LED lamps is developed solely based on data from existing LCA studies. This data includes direct estimates of manufacturing phase energy consumption, carbon dioxide emissions impacts due to manufacturing energy use, and data on disassembled lamp components (combined with the utilization of a life-cycle inventory database).

The transportation phase is defined as the transporting of a packaged lamp from the manufacturing facility to the retail outlet. All other transportation prior to this phase is assumed to be included in the manufacturing phase. Only a few studies analyzed the impacts of transportation to the retail outlet, and those that did provided minimal insight into their calculation assumptions. Hence, the energy consumption from transportation presented in this report is determined by separate analysis. To calculate the energy use due to the transportation, the manufacturing origin for each lighting technology is characterized. Then, based on the distance of transport, the type of transportation vehicle, and the estimated capacity of that vehicle, the total transportation energy use per functional unit is calculated.

The use phase energy consumption is calculated based on the assumed wattage and lumen output characteristics of the incandescent, compact fluorescent, and LED technologies analyzed. When evaluating the phase use of medium screw-base lamps, it is important to consider the impacts of the Energy Independence and Security Act of 2007 (EISA 2007). EISA 2007 prescribed maximum wattage requirements for medium screw-base general service incandescent lamps, which take effect between 2012 and 2014. It is unlikely that covered non-halogen incandescent products, such as the 60 Watt incandescent lamp considered for this report, will meet these energy conservation standards. Thus, EISA 2009 is expected to cause a market transition toward more efficient lamps, such as standards-compliant halogen lamps, CFLs, and LED lamps. Despite the important role halogen lamps are likely to play in the future lighting market, the overall life-cycle energy impacts of these products are not considered in this report due to lack of available manufacturing energy data. However, halogen lamp use-phase energy consumption estimates are provided for comparison to other technologies.

Figure ES.1 indicates that the average life-cycle energy consumption of LED lamps and CFLs are similar, at approximately 3,900 MJ per 20 million lumen-hours. This is about one quarter of the incandescent lamp energy consumption—15,100 MJ per functional unit. By 2015, if LED lamps meet their performance targets, their life-cycle energy is expected to decrease by approximately one half. In addition, based on this analysis, the “use” phase of incandescent, compact fluorescent and LED lamps is the most energy intensive phase, on accounting for approximately 90 percent of total life-cycle energy. This is followed by the manufacturing and transport phases, respectively with transport representing less than one percent of life-cycle energy for all lamp types.

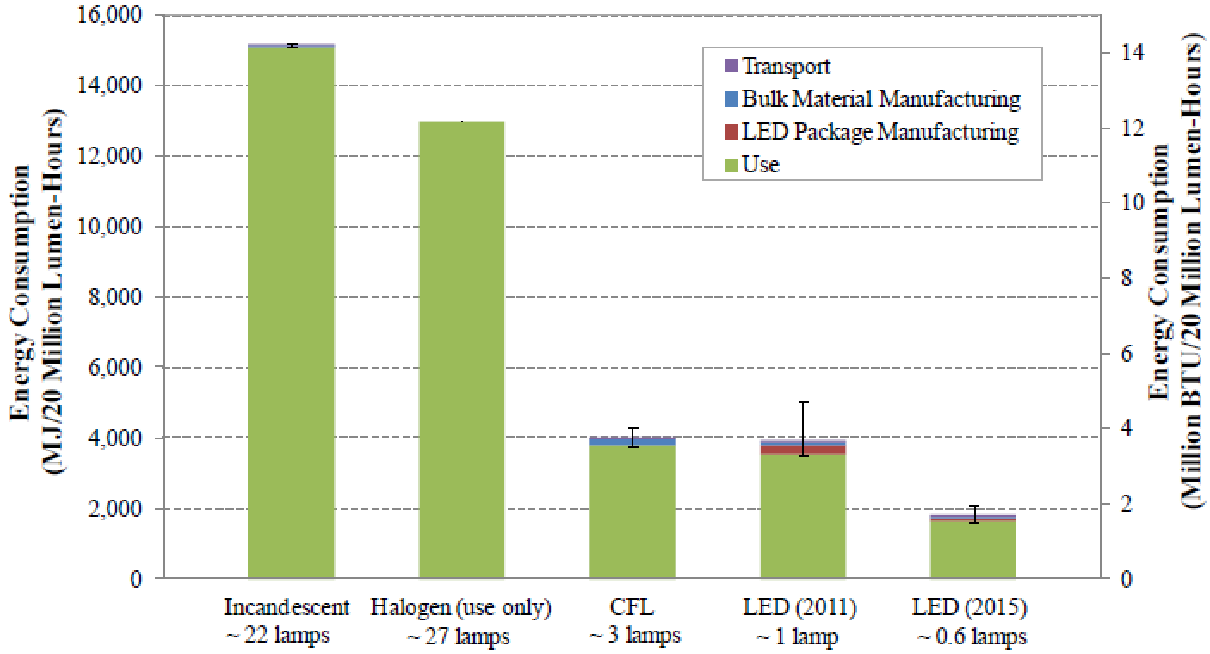

Figure ES. 1 Life-Cycle Energy of Incandescent Lamps, CFLs, and LED Lamps

1 Introduction

Light-emitting diode (LED) lighting has the potential to surpass many conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality. It is forecasted that LED lighting will represent 46 percent of general illumination lumen-hour sales by 2030, resulting in an annual primary energy savings of 3.4 quads (Navigant Consulting, Inc., 2012a).

Increasing the efficiency of installed lighting products through the adoption of LED technology is an effective method to reduce the electricity consumed on site; however, to truly gauge the full energy (and environmental) impact of a lighting technology, the materials and energy resources used must be traced over the entire life cycle of the lamp. In other words, even though the energy consumed during the use of LED lamps is less than that consumed by compact fluorescent lamps (CFLs) and incandescent lamps, the question arises whether the energy and environmental benefits achieved during use of the product are outweighed by energy and/or environmental impacts during earlier phases in the life-cycle process. The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program recognizes the importance of understanding life-cycle impacts, and that this evaluation is crucial prior to the mass adoption of LED lighting products. Early identification of potential energy and environmental benefits or concerns during manufacture, use, and disposal will allow for LED lighting technology to evolve in a responsible manner.

This report is the first installment of a larger DOE project to assess the life-cycle environmental and resource costs in the manufacture, use, and disposal of LED lighting products compared to traditional technologies. The assessment consists of three elements:

- Comparison of the total life-cycle energy consumed by LED and other lamp types based on existing life-cycle assessment (LCA) literature;
- An LCA study of an LED lamp considering both the direct and indirect material and process inputs to fabricate, ship, operate and dispose of the lamp; and
- The purchase, disassembly and chemical testing of LED and conventional lighting products to study whether potentially hazardous materials are present in concentrations that exceed hazardous waste regulatory thresholds.

This report provides the findings for the first element of the total assessment. The subsequent two elements will be covered in separate reports and will evaluate an array of LED lighting products both lamps and luminaires comparing multiple incumbent lighting technologies across several applications. Combined, the results of the three elements will form a basis for comparing the full environmental trade-off between LED and traditional lighting sources.

The purpose of this report is to use existing life-cycle assessment (LCA) data to determine what conclusions can be made on the life-cycle energy consumption of current LED lamp products as compared to incandescent and CFL technologies. This report analyzes several existing life-cycle assessment studies, which include academic publications, as well as manufacturer and other independent research reports. Data was extracted and combined from these LCA studies to calculate a mean and range of life-cycle energy consumption estimates. Each study's approach, sources, methods, assumptions, and uncertainties were also documented. The data from the previous studies allow for both a quantitative and qualitative analysis enabling the development of a comprehensive LED lighting LCA literature review. The specific goals of the report are highlighted below:

1. How much energy is consumed during each life-cycle phase of LED lamps (manufacture, transport, use, etc.)?
2. How does the life-cycle energy consumption of LED lamps compare to that of incandescent and CFL lamp products?
3. How might the life-cycle energy consumption of LED lamp products change in the future?

Although LED lamps are commercially-available in a variety of lamp form factors, this meta-analysis assesses the life-cycle energy consumption of only general lighting service (GLS) lamps.[1] This is largely because the majority of existing LCA literature on lighting products has focused on evaluating the life-cycle impacts of these lamps. In addition, GLS lamps have the largest installed base of any lighting type within the U.S. with over three billion installations in 2010 (Navigant Consulting, Inc., 2012b). This report evaluated the three main technologies that comprise these installations: incandescent lamps, CFLs, and LED lamps. Currently, 72 percent of installed GLS lamps are non-halogen incandescent lamps, followed by CFLs which constitute 27 percent of the installed base. Halogen and LED lamps currently comprise only 1 percent and 0.01 percent, respectively, of the installed GLS lamp base (Navigant Consulting, Inc., 2012b). However, this is projected to change with the Energy Independence and Security Act of 2007 (EISA 2007) which prescribed maximum wattage requirements for these lamps, taking effect between 2012 and 2014. This is predicted to cause a market transition toward more efficient standard-compliant halogen lamps. Despite the important role halogen lamps are likely to play in the future lighting market, the overall life-cycle energy impacts of these products are not considered in this report due to lack of available manufacturing energy data. However, halogen lamp use-phase energy consumption estimates are provided for comparison to other technologies.

Furthermore, it is important to note that this report only considers LED replacement lamp products, while the upcoming sequences of the larger DOE LCA effort intend to evaluate the life-cycle impacts across a variety of LED luminaire products and applications. LED luminaire products with optimized form factors are able to better utilize the inherent benefits of LED technology, and can produce efficacies beyond that of best-in-class LED replacement products. The performance improvements associated with LED luminaires, have the potential to further reduce the relative life-cycle impacts of LED lighting compared to incumbent technologies. Finally, because this report aggregates the life-cycle data from a variety of sources, this report does not aim to characterize the energy impacts of any specific incandescent, compact fluorescent, or LED product on the market. Instead, this report evaluates the energy impact of different technologies assuming a typical product performance found on the market. It is important to note, however, that large variations in efficacy and lifetime do exist on the market.

For example, as discussed in section 4.1, this report analyzes an LED lamp product with an

[1] For the purposes of this report, a "general lighting service lamp" is defined as a medium screw-base lamp meant to serve as a direct lamp replacement for the traditional A-shape incandescent lamp.

efficacy of 64 lumens per watt (lm/W). In contrast, best-in-class LED lighting products, such as the Philips 60 Watt replacement lamp for the DOE L-Prize competition, achieve efficacies greater than 90 lm/W, demonstrating the tremendous potential for LED lamps. This is over six times the efficiency of traditional incandescent lamps and one-and-a-half times the efficiency of CFLs. These variations in efficacy of products on the market will have a large impact on the overall life-cycle energy use of LED lamps. Although the best-in-class lighting products are not directly analyzed in this report, an estimate for future 2015 LED replacement is included to represent the life-cycle benefits of continued performance improvement.

2 Life-Cycle Assessment Background

Energy consumption is an important component of any LCA study, and the majority of data collected for this energy assessment of incandescent lamps, CFLs, and LED lamps was gathered from information provided in existing LCA reports. Although this report is not an LCA study itself, a brief overview of the basic LCA process is provided for context when interpreting the findings.

An LCA is a tool used to evaluate energy and raw material consumption, emissions, and other wastes related to a product or system's entire life cycle. It characterizes and quantifies the inputs, outputs, and environmental impacts of a specific product or system at each life-cycle stage (ISO, 2006). The general procedure for conducting a life-cycle analysis is defined by the International Organization for Standards (ISO) 14000 series. The main phases of an LCA according to ISO guidelines, as shown in Figure 2.1, are goal, scope, and boundary definition; life-cycle inventory (LCI) analysis; life-cycle impact assessment; and interpretation.

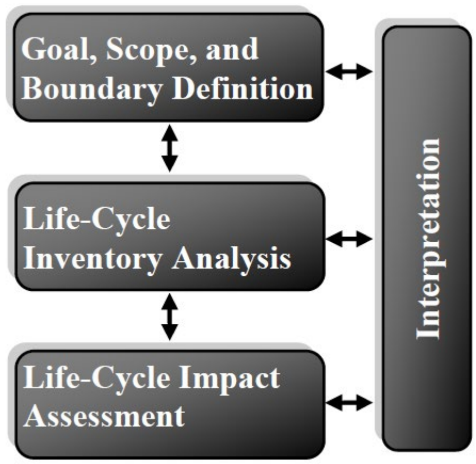

Figure 2.1 LCA Framework Schematic Based on ISO Standards

2.1 Goal, Scope, and Boundary Definition

Defining the goal of the study involves establishing the purpose and audience and describing the intended use of the results. Potential goals may include determining the environmental impacts in the product or process life-cycle, identifying opportunities for improving the existing system, or comparing different systems and their potential impacts (e.g., incandescent, CFL, and LED lighting technologies). As discussed earlier, the goal of this analysis is to conduct a comparison of existing studies to determine whether conclusions can be drawn about the life-cycle energy consumption of current GLS LED lamp products as compared to incandescent lamp and CFL technologies.

The scope determines which product system or process will be analyzed, the unit processes evaluated, functional unit, system boundaries, allocation procedures, impact categories, data requirements, and limitations. Definitions for these terms are provided in the ISO guidelines, some of which are summarized below (ISO, 2006).

A *unit process* describes a stage within a product system's life cycle and serves as the basic element of analysis in the LCA. The identification of unit processes facilitates the quantification of the inputs and outputs (which include consumed resources and waste emissions to air, water, and land), or "flows," at each phase of the life cycle. Examples of unit processes include the mining of copper to produce electrical connections and machining of tin-plated steel to produce the Edison screw base. These flows are then grouped into common phases such as primary resource acquisition, raw material processing, manufacturing and assembly, transportation, use, and finally, the end-of-life.

A *product system* is the complete set of steps that are involved in the production, use, and disposal of a product or service throughout its life cycle. The LCA of a product system evaluates the resource consumption and byproduct or waste emissions incurred by each process or phase of the life cycle. The product systems evaluated in this analysis are those of a medium screw-base incandescent lamp, CFL and LED lamp.

System boundaries are a set of criteria which define the scope of the analysis. These boundaries specify the unit processes to be included in the LCA. Accurate description of the system and its boundaries has strong implications for the results of the assessment and must be clearly stated. Because the results presented in this document are based on several LCA studies (some of which provide limited documentation on their own system boundaries), defining clear system boundaries for this analysis is difficult. Generally, this analysis considers the energy consumption associated with primary resource acquisition, raw material processing, manufacturing and assembly, transportation from the manufacturing facility to a retail outlet, and the usage of each lighting product. However, the unit processes included within primary resource acquisition, raw material processing, and manufacturing and assembly vary significantly.

The *functional unit* is a quantified measure of performance that serves as the basis for comparison when considering the environmental impacts of multiple product systems. For example, the environmental impacts of lighting technologies can be quantified per lamp, per lamp lifetime hour(s), or per lamp lumen-hour(s). The functional unit used in this analysis to compare lighting product systems is 20 million lumen-hours. Further discussion of the functional unit utilized in this report can be found in section 4.1.

Allocation procedures are methods used to apportion the environmental load of a process between the product system under study and other product systems. This is often necessary because many industrial processes perform more than one function or yield more than one type of product; therefore, the input and output data of each unit process must be appropriately partitioned from other product systems. For instance, a manufacturing facility is often designed to produce more than one type of product at the same time; hence, the impacts of the facility need to be apportioned between each of these products. However, this is very difficult to do and has remained an unsolved problem when determining the life-cycle impacts of LED as well as incumbent lighting products.

Impact categories are the types of environmental impacts to be considered. Many LCA studies cover several categories that include resource use, global warming potential, acidification, toxicity, and many others. The selection of impact categories will determine the types of data that will need to be collected. This analysis does not provide quantification for any impact category and only considers the elemental flow of primary energy consumption.

Data requirements depend on the level of detail of the study and the need for site-specific or generic data. This report aims to provide the life-cycle energy consumption for a generic incandescent lamp, CFL, and LED lamp product.

2.1.1 Life-Cycle Inventory Analysis

Life-cycle inventory (LCI) analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system(s) (i.e., the incandescent lamps, CFLs, and LED lamps). Data collection is the identification and quantification of relevant inputs and outputs for each unit process of a specific product system. Data for each unit process within the systems boundary often include energy, raw material, products, co-products, and waste and emissions to air, water, and soil. In the context of this analysis, an example unit process for the manufacturing of a lamp product is the machining of tin-plated steel to produce the Edison screw base. The LCI then involves determining the energy consumption required to complete this unit process. Typically, data for each unit process in a product system is either provided directly from industry or using an LCI database, such as Ecoinvent. Databases such as these provide industrial data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services for a variety of generic unit processes that allow for the development of more complex product systems (Ecoinvent Centre, 2012). This report uses the Ecoinvent 2.2 database to develop manufacturing energy use estimates for each lamp type.

Typically, a product's unit processes are simplified and grouped into five main phases, as depicted in Figure 2.2. These include primary resource acquisition, raw material processing, manufacturing and assembly, use, and the end-of-life phase. Transportation is often included between each phase. The first three life-cycle phases are grouped together and discussed in section 4.2 Manufacturing Phase, while the use and transport are discussed in sections 4.3 Transportation Phase and 4.4 Use Phase, respectively. It is important to note that the end-of-life phase is not considered in this report due to the lack of available data, as well as the great variability in how a lamp can be processed for disposal. The following section describes each of these five general life-cycle phases:

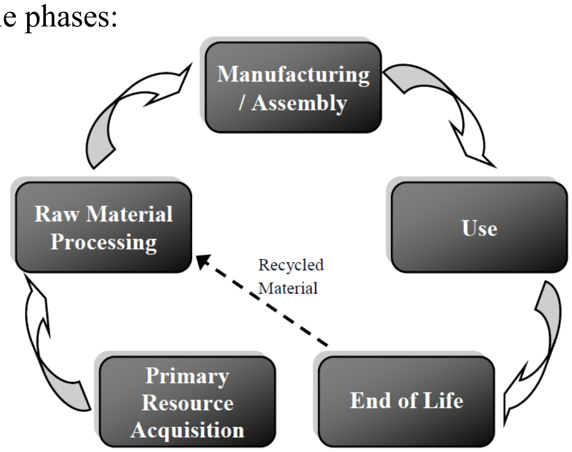

Figure 2.2 General Life-Cycle Phases of a Product or System

Raw Materials Acquisition describes the extraction of raw materials from the earth. Within this report, raw material acquisition includes the mining of non-renewable materials, such as aluminum for the heat sink of an LED lamp, mercury for the fluorescent tube of a CFL, or tungsten for the filament of an incandescent lamp. Transportation of these materials from the point of acquisition to the point of processing is also included in this phase.

Raw Material Processing involves the activities that convert raw materials into a form that can be used to fabricate a finished product.

Manufacturing and Assembly takes the manufactured material and processes it into a product that is ready to be packaged. Packaged products are transported via truck, train, plane, or cargo ship to distribution facilities where they are then transported to retail outlets or directly to the consumer.

Use describes the phase where the consumer actually uses the product. Once the product is distributed to the consumer, all activities associated with the useful life of the product are included in this phase. This includes energy demands and environmental wastes from both product storage and consumption.

End-of-Life is the phase at which the consumer no longer needs the product. It includes the energy requirements and environmental wastes associated with disposing and/or recycling of the product or material. The end-of-life phase also offers the opportunity for lamp products to receive an energy "credit" if they are recycled allowing for materials to be harvested and reused. For example, standardized recycling procedures have been implemented within the U.S. for CFLs. In addition, due to the significant amount of aluminum often used for the heat sink component of an LED lamp, the life-cycle environmental impacts of LED products could be significantly reduced by reusing, remanufacturing or recycling this material. However, currently no standardized recycling procedures exist for LED lamp products (Hendrickson, 2010).
The energy consumption, emissions, and other waste products at each life-cycle phase are the results from the LCI analysis. Using these results, a life-cycle impact assessment (LCIA) can be conducted.

2.1.2 Life-Cycle Impact Assessment

Although a life-cycle impact assessment (LCIA) is not conducted for this analysis, it will be included in the upcoming phases of the larger DOE life-cycle assessment effort. The impact assessment stage of an LCA uses the LCI results to evaluate the significance of potential environmental impacts. LCI results focus on quantifying the different "flows" of the product system such as emissions, waste generation, etc. The impacts are the downstream effects of these flows, such as the health effects caused by the inhalation of emissions. It is very difficult quantify and assess these impacts; therefore, several studies stop at the LCI phase.

In general, an LCIA will consider impact categories including global warming potential (GWP), natural resource depletion, ozone depletion, eutrophication, acidification, human toxicity, and aquatic toxicity. These categories aim to simplify the complexity of potentially hundreds of flows into a few environmental areas of interest. LCAs include that a large number of flows often utilize software, such as SimaPro[2] or Gabi[3], due to the complexity of developing an LCIA. These software programs have features that organize inventory flow data into standardized impact categories.

2.1.3 Life-Cycle Interpretation

The final step in the life-cycle assessment is interpretation of results. This includes drawing conclusions and making recommendations from the inventory analysis and/or impact assessment. It is in this stage that areas for improvement are identified or shortcomings are noted. Within the ISO standard, the following steps for completing the life-cycle interpretation are identified and discussed:

1. Identification of the Significant Issues – This first step of the life-cycle interpretation stage involves reviewing information from the prior three stages; Goals, Scope and Boundary Definition, Life-Cycle Inventory, and Life-Cycle Impact Assessment. These phases are reviewed in order to identify the data that contribute most to the results of both the LCI and LCIA for each product system evaluated, otherwise known as "significant issues." For instance, these significant issues can be identified by assessing the relative contributions of each life-cycle phase (manufacturing and assembly, use, end-of-life, etc.) to determine which consume the greatest amount of energy.
2. Evaluate the Completeness, Sensitivity, and Consistency of the Data – The second step establishes the confidence level and reliability of the LCA results. This involves checking to ensure that all relevant data needed for the interpretation are available, complete and consistent with the stated goals and scope of the LCA study. As well as, measuring the uncertainty and sensitivity of the significant issues identified in Step 1 to determining whether this will affect the decision-makers' ability to confidently draw conclusions from the LCA results.
3. Draw Conclusions and Recommendations – Lastly, this step interprets the results of the LCIA (not the LCI) to determine which product system and/or unit processes have the overall least impact concerning the specific environmental and/or human health interest areas defined by the goals and scope of the LCA.

As in the case of this report, many life-cycle analyses only include inventory results and choose not to complete an LCIA – therefore a thorough interpretation and comparison of multiple product life cycles is often not possible. However, the results are still valuable and can be used to help inform decision-makers as long as the underlying uncertainties and limitations are concretely stated.

3 Literature Review

As previously indicated this report aggregates existing data from academic publications as well as manufacturer and independent research reports to assess the life-cycle energy consumption of incandescent lamp, CFL and LED lamp products. A total of twenty-six publications investigating the environmental and energy impacts of these three lamp types were reviewed (see Appendix A for complete list of studies considered). Some followed the rigorous ISO protocols described in section 2, while others followed only parts or specific phases. From this list it was determined that ten provided the data and level of disaggregation necessary to develop a comprehensive analysis of the life-cycle energy of LED lamp products as compared to incumbent incandescent lamps and CFLs. The years of these studies ranged from 1991 to 2010 with the majority of reports published in 2009. Each of the LCA studies evaluates the impacts of one or a combination of the three different lighting technologies specified for this report. The ten selected studies include either estimates of manufacturing impacts or detailed descriptions of lamp components and their associated masses. Studies that provide a detailed list of component materials allowed for manufacturing energy use to be estimated using the LCI database Ecoinvent 2.2. This database, discussed later in section 4.2.1 provides life-cycle energy estimates for the manufacture and processing of a variety of different materials. Table 3.1 lists the ten studies and the lamp products considered within each. See Appendix B for more details on these LCA studies.

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2 Information on the SimaPro software can be found at: http://www.pre-sustainability.com/content/simapro-lca- software
3 Information on the Gabi software can be found at http://www.gabi-software.com/america/index/

Table 3.1 List of Studies Utilized for Life-cycle Energy Consumption Comparison

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

1. The Carnegie Mellon (2009) study only provides energy estimates for an LED package.
2. The Carnegie Mellon (2010) study only provides data on the bulk lamp materials of an LED lamp.
3. Data from this publication was presented at the 2011 DOE SSL R&D Workshop.[4]

The following section provides brief descriptions of each aforementioned study, including purpose, method, life-cycle process phases, lamp types considered, results, and resources used to estimate life-cycle energy (list corresponds to ordering in Table 3.1).

1. *Life Cycle Analyses of Integral Compact Fluorescent Lamps Versus Incandescent Lamps,* One of the first LCA comparisons of a 15 Watt CFL versus a 60 Watt incandescent lamp, in 1991, analyzes the various environmental effects associated with the production, use and disposal of each lamp type. The publication provides a list of primary component materials and the embodied manufacturing energy consumptions associated with each lamp type. The specific components of each lamp analyzed are the glass, plastic, electronics and brass. The results, provided on the functional unit basis of one million lumen-hours, emphasizes how the energy needed to produce an incandescent or CFL is

4 Information on the 2011 DOE SSL R&D Workshop can be found at: http://www1.eere.energy.gov/buildings/ssl/sandiego2011_materials.html

equivalent to only about one percent of the total energy consumption during its lifetime, and therefore, CFLs offer significant energy savings. (Gydesen, 1991)

2. *Comparison Between Filament Lamps and Compact Fluorescent Lamps,* Using product line analysis (PLA) and LCA, this 1996 report provides a comparison between an 11 Watt CFL and a 60 Watt incandescent lamp. The functional unit of this study is one million lumen- hours. This study considers both the manufacturing and use life-cycle phases concluding that manufacturing only represents one to five percent of total lifetime energy. Considering the entire life-cycle energy consumption, a 60 Watt incandescent lamp uses five to eight times more primary energy compared to equivalent CFL product. (Pfeifer, 1996)

3. *The Environmental Impact of Compact Fluorescent Lamps and Incandescent Lamps for Australian Conditions*, This 2006 analysis investigates the life-cycle impacts of a 100 Watt incandescent and 18 Watt CFL A-type lamp design considering Australian conditions. An inventory of materials was developed for each lamp type and is provided within the report. The Australian version of SimaPro, an LCA software tool, was then used to determine the life-cycle impacts of each components and processes involved in manufacturing, transporting, use and disposal of each lamp type. These results were reported on the functional unit basis of 8000 hours, the lifetime of an 18 Watt CFL. (Parsons, 2006)

4. *Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp,* This study, completed in 2008, provides an evaluation of the environmental impacts of a 60 Watt incandescent and an equivalent 13 Watt CFL. The analysis provides a detailed bill of materials and corresponding masses for each lamp type, and uses SimaPro software to model the environmental impacts associated with the manufacture, use and disposal. The functional unit in this study is 10,000 hours. The report does not provide life-cycle energy consumption results and rather focus on emissions and toxicity, and indicates that the use phases for both lamp types have the largest CO_2 equivalent impacts. (Ramroth, 2008)

5. *Energy Consumption in the Production of High-Brightness Light-Emitting Diodes,* Due to the significant potential for LED-based lighting to reduce electricity consumption, this 2009 study examines the energy consumption necessary to produce a single LED chip. Using data provided by an MOCVD manufacturer, two university LED processing facilities and data from the manufacture of semiconductor logic chips, an estimate of LED chip production energy consumption is developed. Secondary electricity consumption estimates are presented in the form of per LED wafer and chip (Matthews, 2009). Between 2009 and 2010, the Carnegie Mellon LCA effort was ongoing and updated results were presented at the 2009 DOE SSL R&D Workshop in Chicago, IL.[5] The presentation indicates a similar range of energy consumption for LED chip fabrication that is likely between 20 kWh and 80 kWh per LED wafer.

6. *Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies,* Published in 2009, this study evaluates the full life-cycle costs and benefits

of using a 13 Watt CFL and 6 Watt LED-based lighting products as compared to a less efficient 60 W incandescent lamp. The study employs the use of the LCA software Gabi 4.2 to determine the necessary energy consumption for all lamp type components during the life-cycle phases manufacturing, transport, use and disposal on a per lamp basis. Due to the unavailability of LED semiconductor data within the Gabi 4.2 software, the energy needed to manufacture this component was taken from *Energy Consumption in the Production of High-Brightness Light- Emitting Diodes* analysis (see above for description of this study). The study concludes that CFL and LED lamp products are roughly four times more efficient than incandescent lamps. (Quirk, 2009)

7. *Life-cycle Assessment of Illuminants - A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps,* The 2009 OSRAM study analyzes the environmental impacts of a 40 Watt incandescent, 8 Watt CFL and 8 W LED-based lamp. This LCA considers the manufacturing, transport, use and disposal life-cycle phases using 25,000 hours as the functional unit. Data for the LED lamp were collected at OSRAM, while the incandescent and CFL data were extracted from two existing studies and combined with data sheets provided by OSRAM. The study concludes that current LED lamp products, as of 2009, are comparable to CFLs in terms of life-cycle energy, and therefore, both provide significant energy savings compared to incandescent lamps. It is also indicated that future improvements of LED lamps will further increase energy savings as compared to both CFL and incandescent lamps. (Osram, 2009)

8. *Life-cycle Assessment of Ultra-Efficient Lamps,* In 2009 Navigant released an LCA comparing a variety of LED and incumbent lighting products, including a 12 Watt LED-based lamp, 23 Watt CFL and 100 Watt incandescent lamp. This report does not include estimates for life-cycle energy consumption, but uses the Ecoinvent 2.1 software to determine the environmental impacts to resources, soil, air and water for the manufacture, transport, use and disposal of each lighting product. The study does provide a detailed bill of materials and their associated masses for each lamp type using a functional unit of one

9. *Reducing Environmental Burdens of Solid-State Lighting through End-of-Life Design,* This study, published in 2010, focuses on how the environmental impacts of LED products could be significantly reduced by reusing, remanufacturing or recycling components of the end products. To investigate this point, teardowns detailing the material components of three LED replacement bulbs were conducted to analyze potential reuse strategies. The major component categories analyzed were optics, housing, the LED module, heat sink, base assembly, driver and screw base. These potential strategies include standardization of part connection to facilitate disassembly and fewer material types in structural pieces to maximize homogeneous materials recovery. (Hendrickson, 2010)

10. *Life-cycle Energy Consumption of Solid-State Lighting,* The information from this study was extracted from a poster presented at the 2011 DOE SSL R&D Workshop. The study analyzes the life-cycle manufacturing and use phase energy impacts for a 2011 LED lamp as compared to a standard equivalent 15 Watt CFL and 60W incandescent product.

5 The Carnegie Mellon presentation at the 2009 DOE SSL R&D Workshop can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/matthews_chicago09.pdf
million lumen-hours and including a bill-of-processes as well. (Navigant Consulting Europe, Ltd., 2009)

The poster also presents detailed energy consumption estimates of substrate production and LED die fabrication, while also considering the energy consumption from material extraction and processing. However, this study does not consider the energy required to "package" an LED. The estimates for LED manufacturing are built from the Carnegie Mellon (2009) study, however, no further detail the additional analysis is provided in the poster. It is important to note that this study presents a large range for LED manufacturing energy. The high estimate from this study represents an outlier compared to estimates from other studies evaluated.

As seen above, the scope of the ten different studies incorporated in this report varies significantly, and great effort was taken to incorporate all relevant data in order to develop comprehensive life-cycle energy estimates.

4 Life-Cycle Energy Analysis

As described in section 2, the flexibility of the LCA framework allows for a broad range of possible outcomes. While many of the ten LCA studies consider similar products, there is much variation in the definition of the goals, scope, and boundaries. Therefore, the energy results presented throughout the report are based on a wide variety of assumptions. In light of these significant variations, the following general procedure was utilized in order to standardize the life-cycle data provided within the previous LCA studies:

1. Determine typical product performances and define the functional unit to be used as a metric for equal comparison of energy impacts across the three lamp types.
2. Identify the life-cycle phases for which conclusions on energy consumption can be made. Extract all relevant LCA data from existing studies.
3. Aggregate results and develop minimum, maximum, and average energy characteristics.

As described above, prior to quantifying energy impacts it was first necessary to determine the 2011 incandescent lamp, CFL and LED lamp performance and define the functional unit across which these lamps will be compared. Performance characteristics are developed for the incandescent lamp and CFL based on the products analyzed in the cited studies, while for the LED lamp they are determined using the 2011 DOE Solid State Lighting Multi Year Program Plan (MYPP) (DOE, 2011a). Considering the performance for each lamp type, the functional unit chosen for this analysis is 20 million lumen-hours, or the lighting service provided by the 2011 LED lamp product. Details on these procedures are provided in section 4.1.

The second step involves extracting all data from the ten LCA studies to determine the life-cycle phases for which energy consumption can be quantified. From the studies it was found that some of the most difficult and important life-cycle phases to characterize are primary resource acquisition, raw material processing, and manufacturing and assembly. These phases can be energy and/or emissions intensive and without the cooperation of manufacturers it is difficult to estimate energy and environmental impacts. Each of the ten studies discussed in the previous section are selected because it provides data that can be used to estimate energy impacts from these three life-cycle phases. The manufacturing energy values provided in this report are determined solely using the existing data. Significant variations exist in how each of the studies presented data for primary resource acquisition, raw material processing, and manufacturing and assembly making it difficult to determine common boundaries. In light of these data gaps the manufacturing phase is presented as a lump sum of these three phases. The manufacturing phase is described in section 4.2 of this report.

Although all studies used for this analysis enable the development of estimates for manufacturing phase impacts, only a few provided data on transportation impacts, and those that did give minimal insight into their calculation assumptions. Hence, the energy consumption from transportation presented in section 4.3 of this report was determined by separate analysis. The results provided by each study for the use phase represents that of the specific products chosen. In order to best represent current incandescent, CFL, and LED lamp products, performance characteristics were derived using both inputs from the previous LCAs and independent data. The use phase life-cycle results are discussed in section 4.4. Lastly, the end-of-life phase often includes some type of recycling which results in a positive energy "credit" lowering overall life-cycle energy impacts for a product. However, end-of-life impacts are not considered in this report due to the lack of available data, as well as the great variability in how a lamp can be processed for disposal.

The final step taken was to aggregate all the relevant energy data in order to develop conclusions on the life-cycle energy consumption for incandescent lamps, CFLs and LED lamps. The energy consumption estimates for the manufacturing and transportation unit processes are presented in the form of minimum, average and maximum values. Inputs from each of the LCA studies enable the development of a range or point estimate for the energy consumption of an incandescent, CFL and/or LED lamp product. For this analysis, the minimum value presented represents the lowest estimate derived from the studies, the maximum represents the greatest estimate and the average is determined using equal weighting of all estimates. The use phase unit process assumes 2011 lamp performance specifications for each lighting technology, and is presented as a point estimate.

4.1 Lamp Performance and Functional Unit

Incandescent lamp, CFL and LED lamp products represent different lighting technologies each having varying performance characteristics. When conducting an assessment of life-cycle energy consumption it is important that products be compared on an equivalent basis. Each of the previous LCA studies considers an array of lamp products each having different specifications. Therefore, several steps were taken in order to compare the results between studies.

For incandescent lamps and CFLs manufacturing estimates were derived from the studies on a per lamp basis (see section 4.2.1 for how this data is standardized). It is then assumed that the energy imbedded within this life-cycle phase for a single technology would not vary greatly with lamp lumen output, wattage, or lifetime. Thus, the energy estimates provided within this report represent the life-cycle energy consumption for incandescent lamp and CFL products with a lumen output, wattage, and lifetime equivalent to the average characteristics of the lamps analyzed within the LCA studies.

Determining the 2011 LED lamp performance is more difficult because the majority of lamps evaluated within the previous studies are representative of products prior to 2009. This is less of an issue for incandescent and CFL lamps since performance improvements are relatively stagnant, however, LED lighting technology has been improving significantly from year-to-year. Furthermore, the LED lamps considered in the previous studies are not adequate replacements. The average light output of all of these products is only 400 lumens, far below the average 900 lumen output provided by the incandescent and CFL lamps. Therefore, efforts are made to develop an energy consumption profile for that of an equivalent 2011 LED lamp product. The LED lamp specifications provided in Table 4.1 represent that of current product performance and are provided by the 2011 MYPP (DOE, 2011a).

Table 4.1 Performance of Conventional and LED Lighting Technologies

Lamp Type	Watts	Lumens	Operating Lifetime (hrs)
Incandescent	60	900	1,000
CFL	15	900	8,500
LED (2011)	12.5	800	25,000
LED - future (2015)	5.8	800	40,000

As discussed in the introduction, best-in-class LED products such as the Philips L-Prize winning entry whose efficacy exceeds 90 lm/W are not considered since this report aims to evaluate 2011 lamp performance. However, in order demonstrate energy saving potential for LED lighting technology, as well as the importance in continued improvements to efficacy and lifetime, life-cycle energy estimates are provided for future LED lamp products. The future (2015) LED lamp specifications are determined using efficacy projections provided by the 2011 MYPP. According to the 2011 MYPP, LED package efficacy is expected to increase to 202 lm/W by 2015 (DOE, 2011a). Using this assumption, as well as predicted improvements to luminaire and thermal efficiency, the wattage of the lamp is projected to decrease to 5.8 Watts. Consistent with lifetime targets in the 2011 MYPP, the 2015 LED lamp is assumed to have a lifetime of about 40,000 hours (DOE, 2011a). The MYPP improvement performance for the 2015 LED lamp provide a good standard for comparison and show the potential and importance of continued improvements to LED efficacy and operating lifetime.

Considering the lumen output and lifetime for each lamp shown in Table 4.1 it is apparent that these products are not perfectly equivalent. To provide a common basis necessary to conduct a life-cycle energy analysis, a functional unit is utilized. As described in section 2.1, the functional unit is defined as a quantified measure of performance that serves as the basis for comparison when considering the environmental impacts of multiple product systems. The functional units employed varied among the studies examined, however, the three most common were lifetime hours, lamp and lumen-hours. For this report the functional unit selected is lumen- hours. This metric is chosen because the main function of a light bulb is to provide lighting, and the metric of lumen-hours is commonly used to describe this service. In addition, the present- day 12.5 Watt LED lamp, due to its long operating lifetime, provides the greatest amount of lighting service over its product life cycle. Therefore, 20 million lumen-hours is used as the functional unit for all products. Since an incandescent lamp and CFL each provide lighting service that is less than the functional unit value, the life-cycle energy estimates will need to be multiplied by the number of lamps needed to reach this equivalence.

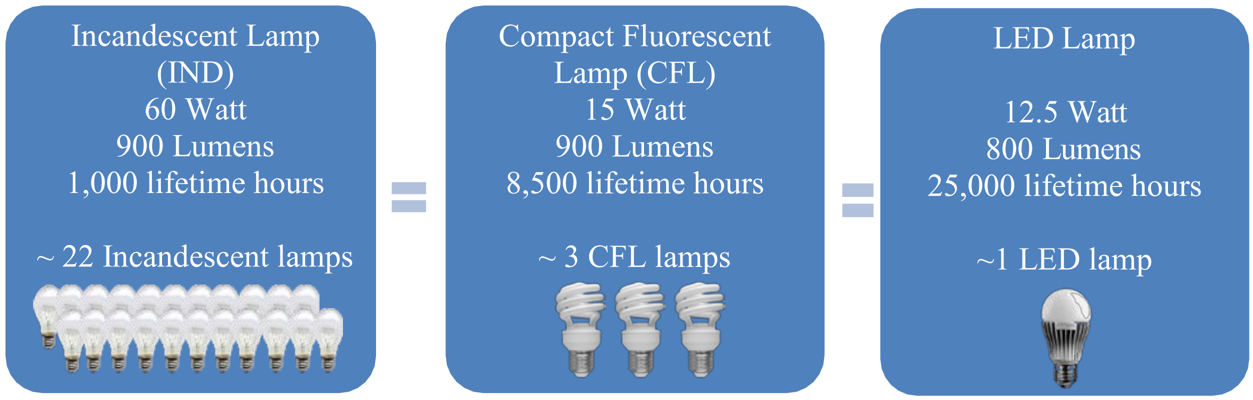

Figure 4.1 Number of Lamps Needed to Supply 20 Million Lumen-Hours[6]

As shown in Figure 4.1, since the incandescent lamp has a lumen output of 900 lumens and an operating lifetime of 1,000 hours one would need twenty-two lamps to provide 20 million lumen-hours of lighting service. Similarly for a CFL with an output of 900 lumens and an operating lifetime of 8,500 hours one would need three lamps. All energy consumptions values presented within this report are in terms of the energy needed to supply 20 million lumen-hours of lighting service.

4.2 Manufacturing Phase

In this report the manufacturing phase encompasses three of the five life-cycle phases: primary resource acquisition, raw material processing, as well as manufacturing and assembly. The manufacturing phase is presented as a lump sum due to variations in how the studies presented data for these different phases and the difficultly in determining the boundaries between material processing and manufacturing.

4.2.1 Method

In order to characterize the manufacturing energy use of incandescent, CFL and LED lighting technologies, the first step was to assemble all pertinent data from the ten life-cycle reports into a database. The data recorded included lamp type, performance characteristics, component masses, functional unit, and energy consumption. Each study provided differing levels of disaggregation for their manufacturing analysis. Many provided direct estimates of manufacturing phase energy use reporting either in terms of primary or secondary energy. However, not all studies focused on life-cycle energy impacts. Several investigated other environmental impacts such as global warming potential, water quality, toxicity and air pollution. It was determined that secondary and primary energy, global warming potential (measured in carbon dioxide equivalents or CO_2-eq), and lamp component masses estimates provided within the previous studies can all be converted into a standardized form for energy comparison within this report. All estimates are converted to megajoules (MJ) of primary energy consumption. In addition, all functional unit assumptions used within each of the studies were removed to return all manufacturing energy estimates to per lamp product. Once in this form the selected functional unit for this report of 20 million lumen-hours is then applied using the product specification described in section 4.1. The process for these conversions is shown in

6 The lifetime hours listed in Figure 4.1 refers to the useful life of the lighting product and does not include any shelf life assumptions.

Figure 4.2:

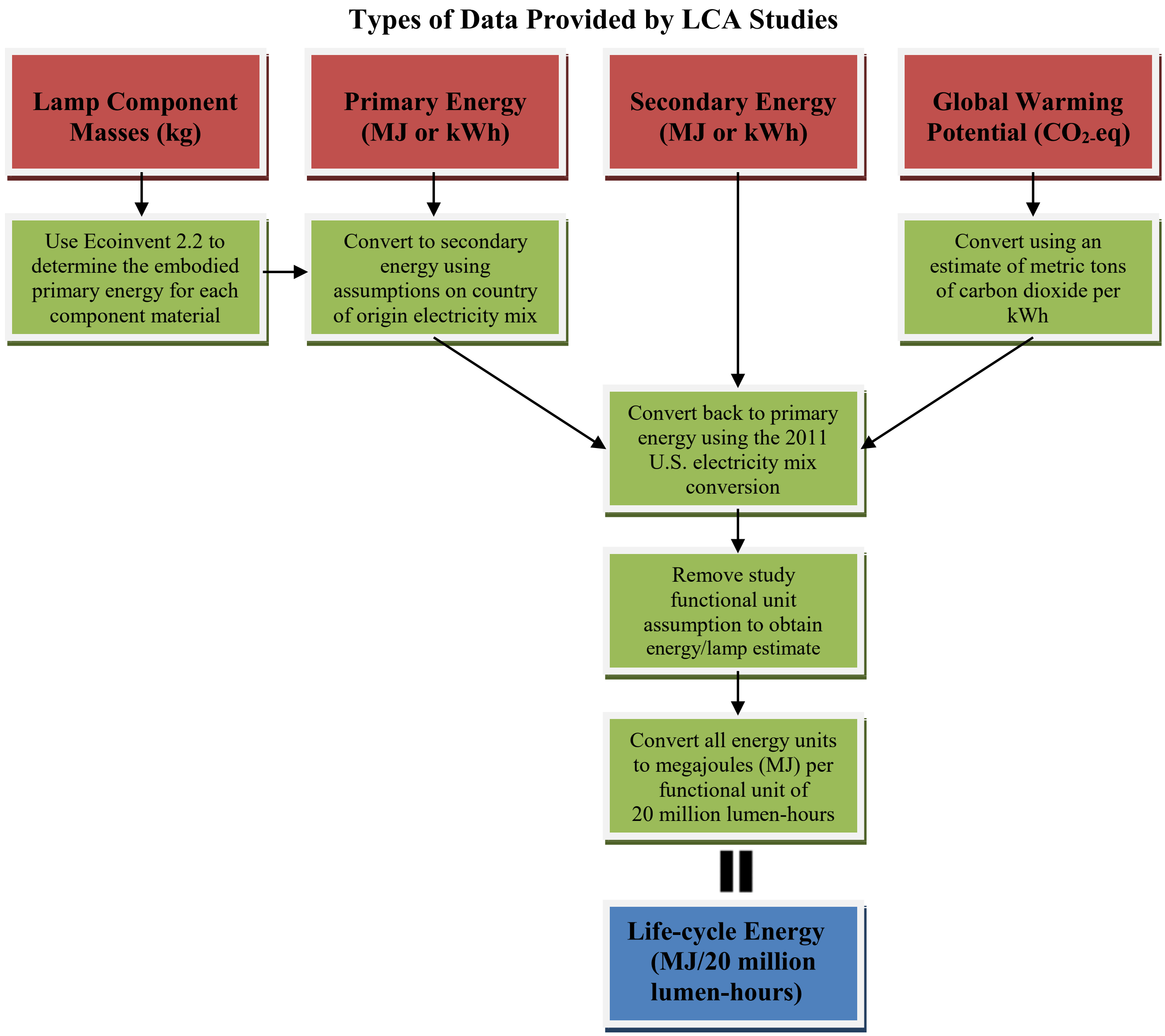

Figure 4.2 Method for Standardizing LCA Manufacturing Data

Those studies that provide primary energy consumption estimates each include different assumptions on manufacturing origins. Therefore, all primary energy values are first converted to secondary energy using electricity mix values that correspond to the country where manufacturing is conducted. All energy estimates are then converted to primary energy using secondary electricity to primary energy conversion factors[7] based on the assumed manufacturing origins discussed in section 4.3.1.

The LCA studies that considered impacts other than energy consumption either provided data on global warming potential or disassembled lamp components and their associated masses. Assuming that global warming potential is entirely the result of carbon dioxide (CO_2) emissions, these CO_2 emissions are converted to energy consumption using assumptions on the metric tons of carbon dioxide per unit of electrical energy production (see Appendix C for this conversion). Whereas, details on the lamp component masses allowed for the development of manufacturing energy use estimates using the LCI database Ecoinvent 2.2. The Ecoinvent 2.2 database includes estimates for the life-cycle environmental and energy impacts of various materials and processes. For example, if it is known that a specific product contains one kilogram of aluminum the Ecoinvent 2.2 database can then provide an approximation of the energy needed to extract and process it. Table 4.2 shows an example of LED lamp component descriptions and masses provided in the 2010 Carnegie Mellon article, *Reducing Environmental Burdens of Solid-State Lighting through End-of-Life Design* (Hendrickson, 2010).

Table 4.2 Example of LED Lamp Components

Name	Material	Mass (g)	Mass %
Glass bulb	Glass	10.7	13.0%
LED board connectors	Gold plated copper	0.5	0.60%
Array (9 LEDs in 1 array)		1.5	1.80%
Local heat sink ring	Aluminum	5.7	6.90%
Heat sink outer cone	Aluminum	18.1	22.0%
Heat sink inner cylinder	Aluminum	13.1	15.8%
Edison base insulator	Acrylic, polycarbonate	4.2	5.10%
Inner insulator and adhesive connections	Acrylic, polycarbonate	6.6	8.00%
Printed circuit board, capacitors, resistors, transistors, diodes		10.1	12.2%
Edison base and leads	Tin plated steel	12.2	14.8%
	Total =	82.7	100%

Source: (Hendrickson, 2010)

Each component listed in the bill-of-materials extracted from the reports has an assigned mass, while assumptions have to be made for the production-related processes of these materials. The material and process inputs are then matched to those provided within the Ecoinvent 2.2 database. Data for the embodied energy per unit mass (MJ/kg) for each material can then be retrieved from the Ecoinvent 2.2 database.

Ecoinvent is an important and useful tool for obtaining LCI data; however, it has significant limitations. While the database has a plethora of material entries, such as the energy needed to produce one kilogram of copper, it provides severely limited data on the energy needed to process it into a useful product component. Best estimates of material processing are used where possible; however, it is likely that the energy consumption values determined using the Ecoinvent 2.2 database under-represent the true values.

7 See Appendix C for a list of secondary electricity to primary energy conversion factors utilized for this analysis.

Since several reports included lamp component and mass data, Table 4.3 shows a list of common components, materials and the range in total mass for incandescent, CFL, and LED-based lamps.

Table 4.3 General Components and Associated Materials by Lamp Type

Component	Lamp Materials		
	Incandescent	CFL	LED
Edison screw	Tinplate steel	Tinplate steel	Tinplate steel
Base assembly	Copper, solder, insulate	Copper, solder, insulate	Copper, solder, insulate, porcelain
Ballast/Driver	N/A	Printed circuit board, resistors, transistors, inductors, capacitors, diodes, copper wire	Printed circuit board, resistors, transistors, inductors, capacitors, diodes, copper wire, Teflon® tubing
Heat sink	N/A	N/A	Aluminum, copper, plastic
LED module	N/A	N/A	LED die, aluminum, plastics, copper wire
Housing	N/A	Plastic, glass, copper wire	Plastic, glass, copper wire
Filament	Tungsten	Electrodes	N/A
Gas	N/A	Mercury	N/A
Optics	Glass	Glass tubing	Glass, Plastics
Total mass range (g)	30-32	91-110	83-290

* N/A indicates that no component materials were identified for that lamp type within any of the LCA studies

Determining the manufacturing energy consumption for the incandescent and CFL lamp is fairly straight-forward since the majority of previously conducted LCA research focuses on these lamp types. However, several studies do not clearly specify which unit processes are included within their manufacturing analysis. It is likely that some estimates are incomplete and only represent energy consumption from material extraction and processing or manufacturing and assembly. In particular, this is apparent with the manufacturing energy estimates for the LED package.

4.2.2 LED Manufacturing Data Sources

Due to the complexity and relative early stage of development of LED lighting technology, publicly-available data of LED manufacturing processes and materials is limited. The next two elements in the DOE three part life-cycle assessment of LED lighting products aim to improve upon the current LED life-cycle databank by providing a comprehensive assessment of the full environmental trade-offs between LED and traditional lighting sources. However, these existing resources still have significant value and provide general bounds for possible LED life-cycle energy consumption. Data provided from a total of six studies is used to estimate the life-cycle energy consumption of an LED lamp. Table 4.4 provides details on the products evaluated within each of these studies and type of data provided.

Table 4.4 Summary of the Types of Data Provided Within the LED Focused Studies

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

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

The majority of these studies have focused on the manufacturing of the LED package due to concern that the energy consumption during this process may out-weigh the energy savings during the use phase.

4.2.3 LED Package Manufacturing and Process Steps

The manufacture of an LED package is an extremely technical and complex process. However, in an effort to simplify, the manufacturing of an LED package is broken down into three segments:

1. Substrate production
2. LED die fabrication
3. Packaged LED assembly

The substrate production stage includes preparing wafers composed of either silicon carbide or sapphire to use in a metal organic chemical vapor deposition (MOCVD) reactor for LED die fabrication. The main processing steps involved in the production of the wafer include starting with the growth, processing and then ending with a cleaned and polished wafer.

The LED die fabrication process is subdivided into epitaxial growth and other front-end processes. In the epitaxial growth phase, the substrate wafer is mounted in a MOCVD reactor and goes through a complex series of deposition and etching stages to become what is referred to as an LED epi-wafer. Following the epitaxial growth, the LED epi-wafer undergoes a series of steps to make the LED device and prepare it for packaging. These include lithography, further etching and the application of electrical connections. Lastly, the substrate is removed, and the wafer is cut into LED dies. These completed LED dies are tested and binned according to their performance. They are then ready to be manufactured into LED packages.

The final phase of LED manufacturing is referred to as the "packaging" of the device, and involves mounting the LED chip in housing, providing electrical connections, coating with phosphor (for pc-LED packages), and applying the encapsulant and optics. Lastly the finished LED packages are tested and binned into product classes according to their performance.

The manufacturing process for the LED lamp is more complex compared to both the incandescent lamp and CFL. LED lamp and package designs vary significantly and there is little consistency among products. When considering the LED package some designs utilize phosphor converted LEDs (either coated or remote phosphor), while others use hybrid techniques which incorporate both phosphor coated and colored LEDs to create white light. The size of the package can also differ; with some containing a single LED die while others have several. In addition, lamp design (shape, size, and light distribution) can vary significantly from product to product. Each of these LED package and lamp design options likely requires different manufacturing procedures and materials, and hence has different manufacturing energy requirements. The overall manufacturing energy consumption range, provided in the following section includes data points based on several different LED lamp products, but by no means represents the full range of possible LED package and lamp designs.

4.2.4 LED Package Energy Estimates

Five studies included an evaluation of the manufacturing energy of an LED package. Figure 4.3 depicts the ranges from each study of manufacturing energy per package (after standardizing the data as described in Figure 4.2). The Quirk (2009) study bases its estimate for an LED package from the results provided in the Carnegie Mellon (2009) study, while the Navigant (2009) study uses the manufacturing of an LED indicator light as a proxy for an LED package. Only Carnegie Mellon (2009), Osram (2009) and Carnegie Mellon/Booz Allen (2010) provide details on the manufacturing processes included in their life-cycle analysis, and the results and methods presented within these three studies vary significantly.

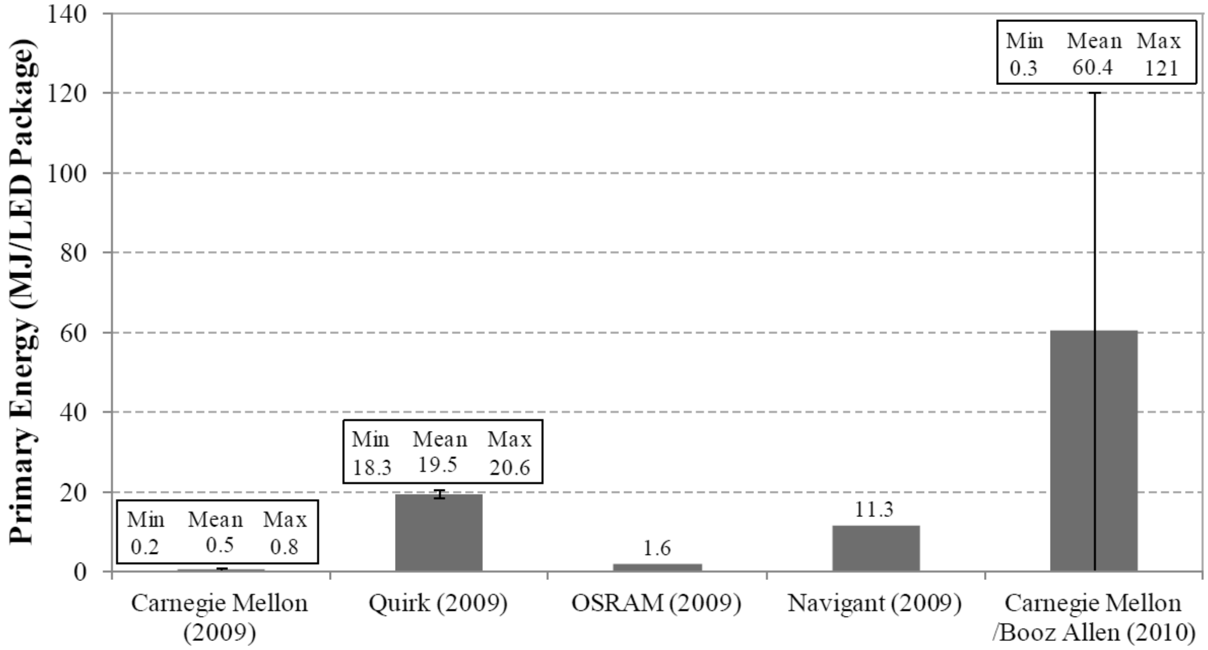

Figure 4.3 Comparison of Manufacturing Energy per LED Package from LCA Studies

The Carnegie Mellon (2009) analysis uses metered data from an LED equipment manufacturer and university laboratories to estimate the energy consumption for the LED die fabrication process. This estimate neglects the substrate production and LED package assembly, as well as the embodied energy of the materials needed for this manufacturing. By excluding these processes it is likely that the Carnegie Mellon (2009) study underestimates the energy contribution from the LED package. Osram (2009) provides energy consumption data for the LED die fabrication and LED packaging phases of LED package manufacturing, and according to correspondence with Osram their life-cycle energy estimate also includes substrate production and considers upstream material extraction and processing (Makarand, 2012).

In contrast, the Carnegie Mellon/Booz Allen (2010) analysis attempts to define best case and worst case scenarios. As seen in Figure 4.3, this study presents a large range for the energy consumption from LED package manufacturing and represents an outlier compared to other LED package estimates. The Carnegie Mellon/Booz Allen (2010) analysis uses the results from the Carnegie Mellon (2009) report as a foundation to develop a more comprehensive estimate that quantifies the energy consumption from substrate production and LED die fabrication while also considering the energy consumption from material extraction and processing. This study does not consider the energy required to "package" an LED. Despite the significant differences among these three studies, each indicates that LED die fabrication is likely the most energy intensive manufacturing process. Consuming up to half of all the energy required to manufacture an LED package.

4.2.5 Manufacturing Phase Energy Consumption

Using the methodology described in the previous sections, aggregate life-cycle energy values for the manufacturing of bulk lamp materials, as well as the LED package were determined. To calculate the aggregate LED lamp manufacturing energy, three main assumptions were made. These assumptions are discussed below.

First, the manufacturing energy consumption for an LED lamp is assumed to be the sum of the energy associated with manufacturing the bulk lamp materials plus the energy associated with the manufacture of a single LED package multiplied by the number of packages. Thus, assuming that the packages have incorporate equivalent die areas, an LED lamp that uses five packages has a lower embodied energy consumption compared to an LED lamp that uses sixteen packages.

In order to determine the average number packages (each of one mm^2 of total die area) incorporated into an 800 lumen output LED lamp, a survey of die and package configurations of current 2011 LED lamp products was conducted. Data was found for ten separate products and indicate that each one mm^2 of die accounts for approximately 40 to 80 lumens of lamp light output lumens.[8] Therefore, it is assumed that 50 lumens per one mm^2 of LED die (the mean of the range) is representative of a 2011 LED lamp product. Furthermore, since many of the surveyed LED lamp products utilized one mm^2 of LED die per package, it is then inferred that this lumen output per LED die is transferable to the package level. Assuming 50 lumens of lighting service per package, an LED lamp would require sixteen packages to produce a light output of 800 lumens. However, there is great uncertainty in the number of packages needed to provide the desired light output, and difference in the assumed number of packages has implications for manufacturing energy use.

The second assumption utilized was that the manufacturing energy consumption of a single LED package is not correlated to efficacy, as long as total die area remain constant. For example, an LED package of 50 lm/W has the same embodied energy consumption as an LED package of 60 lm/W. This assumption allows for the package manufacturing energy estimates from the existing LCA studies to be utilized in characterizing 2011 LED packages, which may have higher efficacies. Also, based on the first two assumptions and expected increases in lamp and package efficacies, it is projected that the average number of LED packages required to produce an 800 lumen output lamp will decrease from sixteen in 2011 to five in 2015 (DOE, 2011a).

The third assumption used was that manufacturing energy consumption of the LED bulk lamp materials remains constant if wattage does not change. However, changes in wattage may affect the thermal management for the lamp causing a change in product design and material use. The previous LCA studies that were used to calculate the embodied energy of the LED bulk lamp materials evaluated LED lamp product that have an average wattage of about 12 Watts. Using assumptions discussed above, as long as LED lamp wattage remains constant, the efficacy or lumen output can be increased. It is then possible to describe the life-cycle energy consumption of an LED lamp with higher lumen output performance than those analyzed in the existing LCA studies. Although 2015 LED lamp efficacy improvements will likely decrease the wattage of LED lamps, and thus potentially decrease the manufacturing energy consumption of the bulk lamp materials, due to the high uncertainty, no attempt was made to quantify these manufacturing energy impacts.

The energy consumption range for the manufacturing phase of an incandescent, CFL and LED

8 See Appendix B for more details on the lamp products analyzed.

lamp is presented below in Table 4.5. The minimum manufacturing energy estimate represents the lowest derived from the previous LCA studies, while maximum represents the greatest. The average or mean manufacturing energy estimate is an average of all derived values. The energy consumption values are all normalized to the functional unit of 20 million lumen-hours, thus the different lifetimes of the 2011 LED and 2015 LED lamp products cause their energy consumption to differ.

Table 4.5 Manufacturing Phase Primary Energy (MJ/20 million lumen-hours)

Manufacturing Process	Incandescent			CFL			2011 LED (16 LED Packages)			Future 2015 LED (5 LED Packages)		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
Bulk Lamp Material	10.1	42.2	106	11.3	170	521	38	87.3	154	25.4	58.5	103
1 LED Package[1]	N/A	N/A	N/A	N/A	N/A	N/A	0.12	16	83.5	0.11	14.6	76.2
Total LED Packages contribution	N/A	N/A	N/A	N/A	N/A	N/A	1.9	256	1,336	0.54	73	381
Total	10.1	42.2	106	11.3	170	521	39.9	343	1,490	25.9	132	484

1. This value is not included in the total sum, but is presented to show the manufacturing energy contribution from one LED package.

The mean values for total manufacturing energy of incandescent, CFL and LED lamps are 42.9 MJ, 183 MJ, and 343 MJ per functional unit respectively. Therefore, on average CFL manufacturing is over four times and LED manufacturing is eight times more energy intensive than incandescent lamp manufacturing. Interestingly, the mean estimate for the LED lamp indicates that the LED bulk lamp materials represent about 25 percent of the total LED lamp manufacturing; with the remaining 75 percent from manufacturing the LED package. This indicates the importance of the LED package, both the energy needed to produce one and the number of LED packages needed to reach the desired luminance.

LED lighting technology is rapid changing technology and currently there is a lack of publicly available data on private industry manufacturing processes. Figure 4.4, illustrates the large range in possible manufacturing energy of an LED lamp. This uncertainty is mainly surrounding the energy needed to produce a single LED package. However, it is important to note that the maximum energy estimate within this range represents an outlier. The Carnegie Mellon/Booz Allen (2010) study presents an extremely broad range for manufacturing energy, and their estimates produce a far upper limit. When the estimates from this study are removed from the analysis the maximum value for the manufacturing of LED lamps decreases from 1,490 MJ/functional unit to only 484 MJ/functional unit. This decrease is illustrated in Figure 4.4.

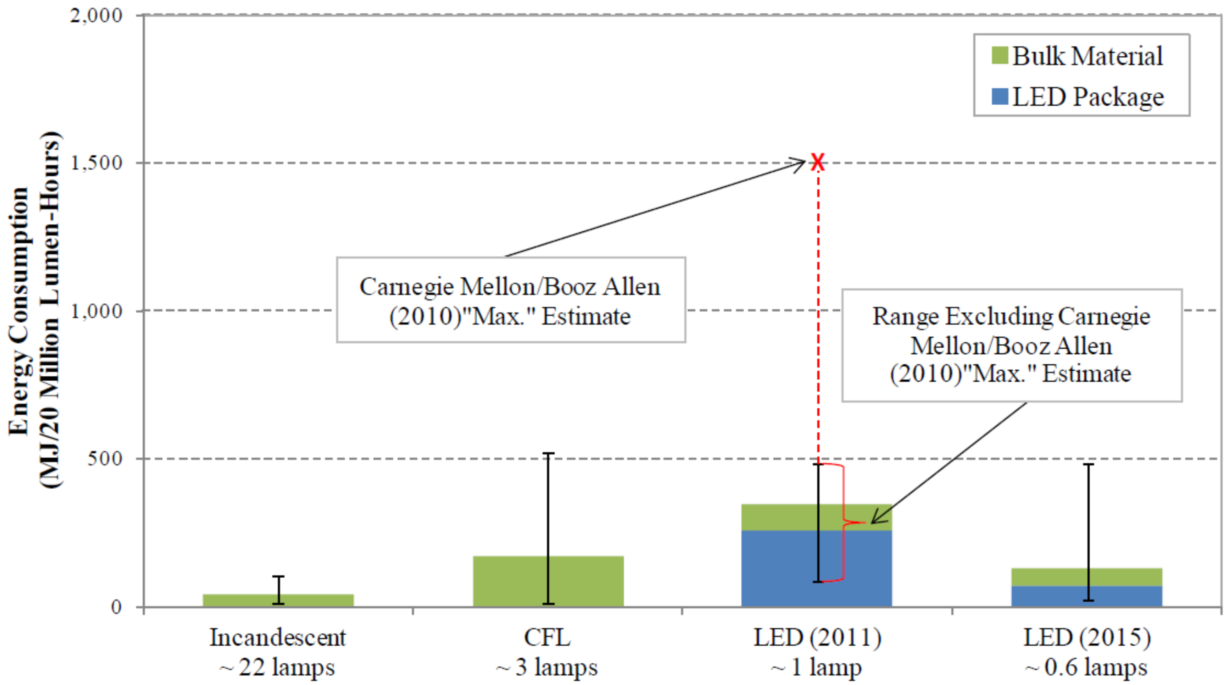

Figure 4.4 Life-Cycle Manufacturing Primary Energy (MJ/20 million lumen-hours)

Despite this drastic difference, the Carnegie Mellon/Booz Allen (2010) estimate is included within this report as the purpose is to present life-cycle energy conclusions using all available LCA data. Including this high estimate, Figure 4.4 indicates that currently the average manufacturing energy use to produce a complete LED lamp product is about three times that of a comparable CFL.

In addition to the uncertainty in the energy needed to manufacture a single LED package, there is also uncertainty in the number needed to reach the desired luminance. This report assumes that a 2011 LED lamp product would requires about sixteen packages (each with 1 mm^2 of die area) to provide 800 lumens. However, due to the variety of LED lamp and package designs, there is great variability in the number of packages needed to provide 800 lumens of light output. While this report assumes sixteen LED packages, this count could be more or less, resulting in an even smaller or larger manufacturing energy range.

As previously discussed, it is predicted that the number of LED packages required to produce 800 lumens will decrease as efficacy increases. Therefore, by 2015 the same LED lamp product is projected to only need five packages (DOE, 2011a). Due to these projected increases in performance specifications, the life-cycle manufacturing energy for the 2015 future LED lamp is significantly less. In addition, the future LED lamp estimates do not assume any improvements to current manufacturing methods and procedures. It is likely that projected increases in yield, wafer size and automation will also reduce the life-cycle contribution from LED manufacturing.

Regardless, it is important to note that the manufacturing phase on average only represents about 8.8 percent of total life-cycle energy for current LED lighting products and is far outweighed by the use phase discussed in section 4.4.

4.3 Transportation Phase

For this report the transportation life-cycle phase is defined as the energy impacts associated with transporting a packaged lighting product from the manufacturing facility to the retail outlet. To increase simplicity, the transport to and storage in distribution centers before being shipped to retail outlets and/or consumers is not considered, as these patterns are similar across all lighting technologies the energy impacts are likely negligible. In addition, traditionally transportation is considered between each life-cycle phase. However, since the impacts of primary resource acquisition, raw material processing and manufacturing and assembly are all combined into a single phase, transportation is only considered between the manufacturing and use phase. Some of the studies analyzed include energy estimates for this value; all indicate that the contribution from transport is relatively insignificant representing less than one percent of total life-cycle consumption. However, these studies offered limited data describing how these transportation energy use estimates are derived, and hence provide no way to standardize these estimates for use in this report. Therefore, an independent transportation profile is developed for each of the three lamp types.

4.3.1 Method

To calculate the energy use due to the transportation, first the manufacturing origin for each lighting technology is characterized. Then, based on the distance of transport, and type of transportation vehicle, and the estimated capacity of that vehicle (in terms of number of lamps able to be transported), the total transportation energy use, on a per lamp basis, is calculated.[9] Lastly, the transportation energy is then converted using the functional unit assumptions discussed in section 4.1.

Although incandescent lamps are produced in facilities across the world, only two manufacturing origins are considered for this analysis. It is assumed that an incandescent lamp is either manufactured in the northeastern U.S. or Shanghai, China. Therefore, the transportation energy consumption profile for an incandescent lamp represents a combination of these two. For the northeastern location, the packaged incandescent lamps are transported via truck from the factory location to a retail outlet location in Washington DC. While for China, it is assumed that lamps are transported via container ship from the Port of Shanghai to the Port of Los Angeles (the largest U.S. industrial port). From Los Angeles, the CFLs are transported by truck to the same retail distributor in Washington DC.

China is currently the largest CFL manufacturer in the world (USAID, 2008). Thus, it is assumed that CFLs are produced in Shanghai, China and then transported via container ship from the Port of Shanghai to the Port of Los Angeles. From Los Angeles, the CFLs are then transported by truck to a retail store in Washington DC.

LED lighting market is highly fragmented with several firms focusing on a specific part within the LED supply chain. This fragmentation could result in the LED chip being manufactured in one location, packaged in another, and then lamp or luminaire assembly occurring in a third.

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9 The number of lamps capable of being transported was based on the cargo weight capacity of the vehicle. While volume capacity may be a better criterion on which to base these estimates, limited information was available on the volume capacity of container ships and commercial trucks. The assumptions used for the transportation energy calculations are presented in Appendix C.

However, the manufacture of LED packages is largely concentrated in Asia (Young, 2011); therefore, to increase simplicity it is assumed that the complete LED package is produced in Taiwan and then is assembled into the finished LED lamp product in Taiwan or the U.S. Therefore, similar to the incandescent lamp, the transportation energy consumption profile for an LED lamp represents a combination of these two. In the first scenario LED packages and complete lamp products are manufactured in the same location in Taiwan and transported via container ship to the Port of Los Angeles. The complete LED lamp product then travels via commercial truck to the same retail outlet as the CFL and incandescent lamp in Washington DC. In the second scenario, LED packages are produced in Taiwan and then shipped to the southeast region of the U.S. where they are assembled into complete LED lamp products. The finished LED lamp product is then shipped via commercial truck to Washington DC. In order to calculate energy consumption, data was collected on typical container ship and commercial truck cargo weight capacity, efficiency and fuel embodied energy. Appendix C summarizes these values.

4.3.2 Transportation Phase Energy Consumption

Table 4.6 presents the transportation phase energy consumption of each lighting technology on a per kilogram and per functional unit basis. Furthermore, the range of possible energy values represents the lamp mass variations across the LCA studies utilized.[10]

Table 4.6 Transportation Phase Primary Energy (MJ/20 million lumen-hours)

Lamp Type	Energy Use (MJ/kg)	Energy Use (MJ/20 million lumen-hours)		
		Min.	Avg.	Max.
Incandescent	7.63	0.26	0.27	0.27
CFL	15.1	1.42	1.57	1.71
LED (2011)	14.8	1.23	2.71	4.19
LED – future (2015)	14.8	0.77	1.69	2.62

Based on the analysis described above and the average results presented in Table 4.6, incandescent lamps are estimated to have the lowest transportation energy at approximately 0.27 MJ per 20 million lumen hours, followed by CFLs at 1.57 MJ per 20 million lumen hours, and current LED products at 2.71 MJ per 20 million lumen hours. As the lifetime of LED lamps are projected to increase, fewer lamps are necessary to service the 20 million lumen hours functional unit, as indicated by the decrease in transportation energy for the 2015 LED lamp, In general, the differences in energy consumption between the lamp technologies have a minor impact on the total life-cycle energy use for all three lamp types, with the transportation phase energy consumption representing less than one percent. Further discussion of how each of the life-cycle phases compare can be found in section 4.5.

4.4 Use Phase Energy Consumption

The use phase of a lamp product's life cycle is associated with the consumption of electricity to produce light. Nearly all of the LCA studies utilized for this analysis include estimates for the

10 The lamp mass ranges for the incandescent, CFL and LED lamp were determined using the mass values provided in the ten LCA studies utilized for this analysis. Based on estimates provided by these studies, product packaging for each lighting type is assumed to be 13 percent of total product mass for incandescent lamps, 4 percent for CFLs and 1 percent for LED lamps.

energy consumption from the lamp(s) they considered. Section 4.1 describes the typical lamp characteristics applied for the use phase energy analysis in this report. Using the performance characteristics the primary energy consumption for each lamp type is calculated per functional unit of 20 million lumen-hours.

The calculation for life-cycle use phase energy represents the energy required for a lamp to provide 20 million lumen-hours, which is equal to the lighting service provided by one LED lamp over its operating lifetime. Therefore, in the case of an incandescent lamp the use phase is the energy consumed during the operational lifetime of 22 lamps (assuming a lifetime of 1,000 per lamp). While for CFLs the use phase is the energy consumed over the operational lifetime of about three lamps (assuming a lifetime of 8,500 per lamp). Using the performance specifications shown in Table 4.7, the following equation shows this calculation of life-cycle use phase energy for the incandescent.

$$Incandescent\ lamp\ equivalent = \frac{20\ million\ lumens - hrs}{1{,}000\ hrs * 900\ lumens} = 22.2\ lamps$$

$$Life - cycle\ use\ phase\ energy = \frac{60W * 1{,}000\ hrs}{\frac{1000W}{kW}} * 3.6\ \frac{MJ}{kWh} * 3.15 * 22.2\ lamps$$

$$= 15{,}100MJ$$

Note: In order to convert to primary electricity consumption the EIA U.S. electricity mix conversion factor of 3.15 is used (U.S. EIA, 2011).

Due to the low efficacy of incandescent lighting, the results indicate that its use phase energy consumption is by far the greatest compared to both the CFL and LED lamp. In addition, the projected 2015 efficacy improvements of LED replacement lamps has the potential to result in even greater life-cycle energy use savings.

When evaluating the use phase of medium screw-base incandescent lamps, CFLs and LED lamps, it is important to consider the impacts of EISA 2007. This regulation prescribes maximum wattage standards for medium screw-base general service incandescent lamps, which take effect between 2012 and 2014. It is unlikely that covered non-halogen incandescent products, such as the 60 Watt incandescent lamp considered for this report, will meet these maximum wattage standards. This is expected to causes a market transition toward more efficient lamps, such as standard-compliant halogen lamps, CFLs and LED lamps.[11] Due to the lack of available manufacturing energy data EISA 2007 complaint halogen lamps are not considered in this report, however, they have a smaller use phase impact compared to traditional non-halogen incandescent lamps in use today. Standard-compliant halogen lamps only require 43 Watts to provide 750 lumens of light-output compared to 60 Watts, effectively lowering use phase energy consumption by almost 15 percent.

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11 The Energy and Water Development and Related Agencies Appropriations Act, 2012, passed by the U.S. Congress on December 16, 2011, contains a provision that prohibits DOE from enforcing the GSIL, candelabra-base incandescent lamp, and intermediate- base incandescent lamp standards contained in Section 321 of EISA 2007 in fiscal year 2012. The standards, however, have not been repealed and remain in effect.

Despite this potential reduction in use phase energy, CFLs and LED lamps still consume far less than both traditional and EISA 2007 compliant halogen incandescent lamps.

Table 4.7 Use Phase Primary Energy (MJ/20 million lumen-hours)

Lamp Type	Watts	Lumens	LED Packages per Lamp	Lifetime	Energy Use (MJ/20 million lumen-hrs)
Incandescent	60	900	N/A	1,000	15,100
Halogen	43	750	N/A	1,000	13,000
CFL	15	900	N/A	8,500	3,780
LED	12.5	800	16	25,000	3,540
LED - future (2015)	5.8	800	5	40,000	1,630

4.5 Total Life-Cycle Energy Consumption Results

When analyzing the resulting total life-cycle energy consumption it becomes clear that the use phase is by far the most energy intensive for incandescent lamp, CFL and LED lamp products. The importance of manufacturing varies; however, energy consumption due to transportation represents less than one percent of the life cycle across all three lighting types.

For an incandescent lamp the use phase represents over 99 percent of total life-cycle energy with the remaining percent allotted between manufacturing and transport. Although, the use phase dominates life-cycle energy consumption of CFL and LED lamps, since these lighting technologies are more complex, manufacturing energy consumption becomes more significant. For a CFL it was found that manufacturing energy use ranges between 0.3 and 12 percent averaging at about 4.3 percent.

LED lighting technology is rapid changing technology and currently there is a lack of publicly available data on private industry manufacturing processes. Therefore, as previously discussed in section 4.2.5, the contribution from LED manufacturing is highly uncertain, the majority of which is centered on the manufacturing of the LED package rather than the bulk lamp materials (all material components of the lamp product other than the LED package). The high upper bound of potential LED package manufacturing energy is largely due the estimates provided by the Carnegie Mellon/Booz Allen (2010) study which produce an outlier compared to the other available LED package manufacturing estimates. . However, the Carnegie Mellon/Booz Allen (2010) estimate is still included within this report as the purpose is to present life-cycle energy conclusions using all available LCA data.

As seen in Figure 4.5, the lowest reported estimate indicates the manufacturing of the LED packages represents 0.1 percent of total life-cycle energy use, while the greatest estimate indicates that it contributes as much as 27 percent. The average of all estimates derived from the previous studies indicates that the contribution from LED package manufacturing is likely about 6.6 percent while the bulk lamp materials are only around 2.2 percent of total life-cycle energy.

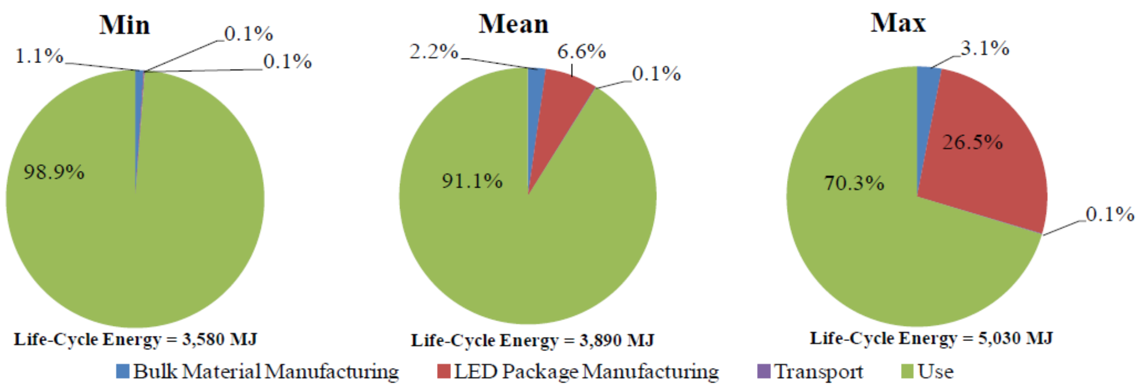

Figure 4.5 LED Lamp Life-Cycle Energy Use Range (MJ/20 million lumen-hours)

In addition, the previous LCA studies indicate that while the energy contribution from lamp bulk materials does not increase significantly with lumen output, the energy contribution from LED packages does. This is because the greater the lumen output of a product, the greater the number of LED packages required to produce it. Therefore, as the performance of LED packages improves there will be a large impact on the life-cycle energy consumption of LED lighting products. Using assumptions provided in the 2011 MYPP, an 800 lumen output LED lamp required sixteen packages in 2011, but only five by 2015. As shown in Figure 4.6, this reduces the possible range of life-cycle energy significantly.

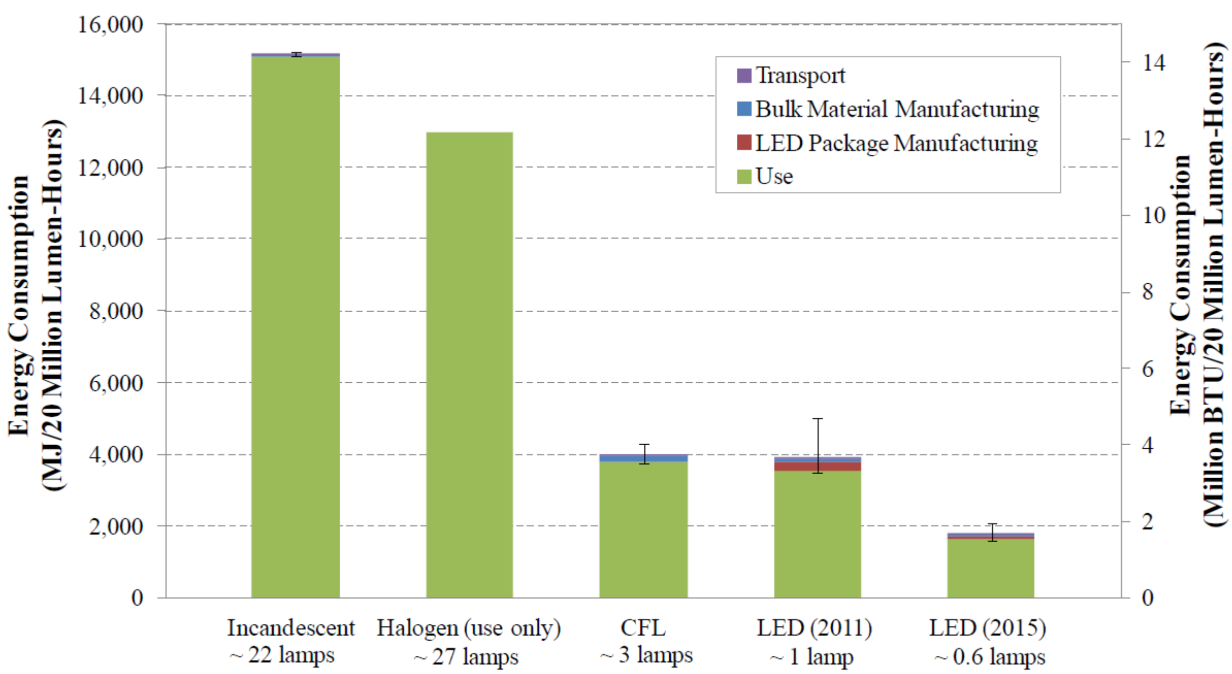

Figure 4.6 Life-Cycle Energy of Incandescent Lamps, CFLs, and LED Lamps

As discussed in section 4.1, the functional unit used in this report is 20 million lumen-hours and is based on the performance of the 2011 LED lamp. Since the incandescent lamp and CFL have lower performance compared to the LED, the functional unit can be used to show how many incandescent lamps and CFLs are needed to reach equivalence. Shown in Figure 4.6, the life-cycle impacts of twenty-two incandescent lamps, three CFLs, one 2011 LED lamp, and a fraction of one 2015 lamp must be compared to establish equivalent among the products.

Despite the great uncertainty in the energy required to manufacture LED lamps, the average life-cycle energy consumption of LED lamps and CFLs are similar, at approximately 3,900 MJ per functional unit (20 million lumen-hours). This is about one quarter of the incandescent lamp energy consumption—15,100 MJ per functional unit. However, due to the EISA 2007 maximum wattage standards for medium screw-base general service incandescent lamps, there is expected to be a transition toward more efficient standard-compliant halogen lamps. Standard-compliant halogen lamps effectively lower use phase energy consumption by 15 percent. Currently there is no available life-cycle data on the manufacturing impacts of these halogen lamps; however, it is likely due to the significant reduction in use phase energy consumption that overall life-cycle energy is less than traditional non-compliant incandescent bulbs.

Despite this potential increase in efficiency of baseline lighting products, by 2015, if LED lamps meet their performance targets, their life-cycle energy is expected to decrease by approximately one half. Table 4.8 below shows the life-cycle energy consumption ranges in numerical form.

Table 4.8 Total Life-Cycle Primary Energy (MJ/20 million lumen-hours)

Life-Cycle Phase	Incandescent			CFL			LED (2011)			LED - future (2015)		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Bulk Lamp Material Manufacturing	10.1	42.2	106	11.3	170	521	38.0	87.3	154	25.4	58.5	103
LED Package Manufacturing	N/A	N/A	N/A	N/A	N/A	N/A	1.88	256	1,340	0.54	73.0	381
Total Manufacturing	10.1	42.2	106	11.3	170	521	39.9	343	1,490	26.0	131	484
Transport	0.26	0.27	0.27	1.42	1.57	1.71	1.23	2.71	4.19	0.77	1.69	2.62
Use	15,100	15,100	15,100	3,780	3,780	3,780	3,540	3,540	3,540	1,630	1,630	1,630
Total	15,100	15,100	15,200	3,790	3,950	4,300	3,580	3,890	5,030	1,660	1,760	2,120

5 Conclusion

LED lighting has the potential to save energy and improve lighting quality and performance beyond that of many conventional lighting technologies. However, in order to develop an energy use comparison for LED, CFL and incandescent lamps, it is necessary to estimate the life-cycle energy consumption of these three light technologies. The results of this report are based on an analysis of ten existing life-cycle assessment studies, which include academic publications, manufacturing documents, and independent research reports. Using the existing literature, data was leveraged from these LCAs to calculate a middle ground estimate of life cycle energy consumption. The data from the previous studies allow for both a quantitative and qualitative analysis enabling the development of a comprehensive LED-based lighting LCA literature review. While many of the ten LCA studies consider similar products, the goals, scope and boundaries defined for each vary. The greatest variance in assumptions was seen in life cycle phases included, as well as the level of disaggregation provided within each study. In light of these data gaps, this report only considers three major life cycle phases: manufacturing, transportation and use.

The key results of this analysis indicate that the average life-cycle energy consumption of LED lamps and CFLs are similar, at approximately 3,900 MJ per functional unit (20 million lumen-hours). This is about one quarter of the incandescent lamp energy consumption—15,100 MJ per functional unit—however the life-cycle energy savings from CFLs and LED lamps compared to EISA 2007 compliant halogen lamp is likely less. In addition, by 2015, if LED lamps meet their performance targets, their life-cycle energy use is expected to decrease by approximately one half. It was also found that the "use" phase of incandescent, compact fluorescent, and LED lamps represents the most energy intensive life-cycle phase, accounting for 90 percent of total life-cycle energy on average. This is followed by the manufacturing and transport phases, respectively with transport representing less than one percent of life-cycle energy use for all lamp types. Lastly, it is important to note that most of the uncertainty in life-cycle energy consumption of an LED lamp centers on the manufacturing of the LED package. The low estimate indicates the LED package contributes to 0.10 percent of life-cycle energy use, while the high estimate shows it could be as much as 27 percent. The average indicates that LED package manufacturing is likely at about 6.6 percent of total life-cycle energy use.

The purpose of the report is not to develop a unique estimate for the life cycle energy use of incandescent, CFL and LED lamp products, but to provide general conclusions based on previous LCA data. This report is the first installment of a larger DOE project to assess the life-cycle environmental and resource costs in the manufacture, use and disposal of LED lighting products in relation to comparable traditional technologies. The life cycle energy use findings presented in this report are aimed to provide context for the second and third components of DOE's life cycle analysis of LED lighting technology.

Appendix A Complete List of LCA Studies Considered

#	Publication Title	Organization/Author
1	Life-cycle Analyses of Integral Compact Fluorescent Lamps Versus Incandescent Lamps	Technical University of Denmark
2	Comparison Between Filament Lamps and Compact Fluorescent Lamps	Rolf P. Pfeifer
3	Life-cycle Assessment of an Intelligent Lighting System Using a Distributed Wireless Mote Network	University of California, Berkeley
4	A Technology Assessment of Light Emitting Diode (LED) Solid-State Lighting for General Illumination	U.S. Environmental Protection Agency, National Center for Environmental Economics
5	Solid State Lighting for the Developing World - The Only Solution	University of Calgary
6	Barriers To Technology Diffusion: The Case Of Compact Fluorescent Lamps	Organization for Economic Co-operation and Development; International Energy Agency
7	The Environmental Impact of Compact Fluorescent Lamps and Incandescent Lamps for Australian Conditions	University of Southern Queensland
8	Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp	Rocky Mountain Institute
9	LCAs of spent fluorescent lamps in Thailand at various rates of recycling	Chulalongkorn University; New Jersey Institute of Technology; King Mongkut's University of Technology Thonburi
10	LED Lighting: Applying Lessons Learned from the CFL Experience	Pacific Northwest National Laboratory
11	LED/Solar/NiMh Vs. Kerosene Vs. Candles	University of California, Davis
12	Life-cycle Assessment of Streetlight Technologies	University of Pittsburgh
13	Energy-Efficient Lighting Lifecycle – White Paper	Cree, Inc.
14	Life-cycle Assessment for Evaluating Green Products and Materials	University of Pittsburgh
15	Hybrid Life-cycle Energy Assessment of Commercial LED Lamps	Matthew J. Eckelman
16	Life-cycle Assessment of an emergency lamp manufactured by the firm Beghelli	Florence University; Bologna University; Beghelli; Italian National Agency for New Technologies, Energy and Environment
17	Energy Consumption in the Production of High-Brightness Light-Emitting Diodes	Carnegie Mellon University
18	Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies	Ian Quirk
19	Life-cycle Assessment of Illuminants - A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps	OSRAM, Siemens Corporate Technology
20	Life-cycle Assessment of Ultra-Efficient Lamps	Navigant Consulting Europe, Ltd.
21	Reducing Environmental Burdens of Solid-State Lighting through End-of-Life Design	Carnegie Mellon University
22	Life-cycle Energy Consumption of Solid-State Lighting	Carnegie Mellon University, Booz Allen Hamilton
23	Assessing the Economic and Environmental Impacts Associated with Currently Available Street Lighting Technology	Air Force Institute of Technology
24	200mm GaN-on-Si for LEDs (presentation)	Bridgelux
25	Environmental impacts of lighting technologies — Life-cycle assessment and sensitivity analysis	Swiss Federal Laboratories for Materials Testing and Research
26	Potential Environmental Impacts of Light-Emitting Diodes (LEDs): Metallic Resources, Toxicity, and Hazardous Waste Classification	University of California, Davis; University of California, Irvine

Appendix B List of Studies Utilized for Life-Cycle Energy Consumption Comparison

Publication Title	Organization/ Author	Year	Product(s)	LCA Phases: Mfg.	LCA Phases: Transport	LCA Phases: Use	LCA Phases: EOL	Data Provided
Life-cycle Analyses of Integral Compact Fluorescent Lamps Versus Incandescent Lamps	Technical University of Denmark	1991	OSRAM 15W CFL 60W Incandescent	X		X		Lamp componen Secondary Elect Emissions
Comparison Between Filament Lamps and Compact Fluorescent Lamps	Rolf P. Pfeifer	1996	11W CFL 60W Incandescent	X		X		Primary energy, Emissions, Cost
The Environmental Impact of Compact Fluorescent Lamps and Incandescent Lamps for Australian Conditions	University of Southern Queensland	2006	18W CFL 100W Incandescent	X		X	X	Lamp componen Secondary Elect multiple impact categories
Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp	Rocky Mountain Institute	2008	23W CFL 100W Incandescent	X		X		Lamp componen GWP/GHG emi (kg CO2e), Cost Emissions
Energy Consumption in the Production of High-Brightness Light-Emitting Diodes	Carnegie Mellon University	2009	LED package	X				Secondary Elect
Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies	Ian Quirk	2009	6W EarthLed LED 13W Philips CFL 60W GE Incandescent	X*	X	X		Primary energy, GWP/GHG emi (kg CO2e)
Life-cycle Assessment of Illuminants - A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps	OSRAM, Siemens Corporate Technology	2009	8W Parathom LED 8W DULUX Superstar CFL 40W Incandescent	X		X	X	Primary energy, Impact Categori
Life-cycle Assessment of Ultra-Efficient Lamps	Navigant Consulting Europe, Ltd.	2009	LED CFL Incandescent	X	X	X	X	Lamp componen Secondary Elect 15 Impact Categ
Reducing Environmental Burdens of Solid-State Lighting through End-of-Life Design	Carnegie Mellon University	2010	10W LED Spotlight 11W LED Floodlight 4W A19 LED lamp	N/A				Lamp componen
Life-cycle Energy Consumption of Solid-State Lighting	Carnegie Mellon University, Booz Allen Hamilton	2010	LED package	X				Primary energy, electricity

Appendix C Calculation Assumptions and Conversion Factors

Energy Consumption by Fuel Type for Electricity Generation (% of total)

Energy Type	Coal	Oil/Liquids	Natural Gas	Nuclear	Hydro	Other	Renewable	Conversion Factor (Secondary to Primary)
U.S. 2011[1]	48%	0.9%	20%	21%	6.2%	0.4%	4.2%	3.14
EU 2010	24%	2.0%	27%	23%	10%	-	14%	2.45
California 2009	1.0%	1.0%	47%	19%	16%	-	15%	2.19
UK 2009[2]	27%	-	46%	18%	-	2%	7.0%	3.02
China 2009	79%	-	1.0%	2.0%	17%	-	1.0%	2.76
Malaysia 2009	31%	2.0%	61%	-	6.0%	-	-	2.97
Germany 2009	44%	2.0%	13%	23%	3.0%	2.0%	13%	2.80
Germany 1994	57%	2.0%	8.0%	29%	4.0%	-	1.0%	3.34
All coal[3]	100%							3.72

[1] U.S. 2011 data can be found at http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0804b

[2] UK 2009 data can be found at: http://www.decc.gov.uk/assets/decc/11/stats/publications/dukes/2307-dukes-2011-chapter-5-electricity.pdf 3 Assumptions presented in the Quirk (2009) LCA study

Note: Data for all other countries can be found at: http://databank.worldbank.org/ddp/home.do?Step=12&id=4&CNO=2

Conversion Factors to Energy Units

Initial Unit	Conversion Factor	Final Unit
Metric tons of CO_2	6.9×10^{-4} Metric tons of CO_2 / kWh	kWh

Source: EPA; data can be found at: http://www.epa.gov/cleanenergy/energy-resources/refs.html

Vessel Characteristics for a Container Ship and Commercial Truck

Vessel Type	Cargo Weight Capacity (tons)	Efficiency (gal/hr)	Fuel Type	Embodied Fuel Energy[3] (Btu/gal)
Container ship[1]	19,200	1,876	Bunker fuel	149,700
Commercial truck[2]	25	2.75	Diesel	138,700

1. The U.S. Department of Transportation (DOT) provides estimates for cargo weight capacity (DOT, 2008). Vessel efficiency is estimated to be 1,876 gal/hr (Talberth, 2006).
2. The U.S. Environmental Protection Agency (EPA) indicates the average payload size for commercial vehicles.
3. The Bureau of Transportation Statistics (BTS) provides embodied fuel estimates for petro-diesel and bunker fuel (U.S. BTS, 2009).

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