What We Know and Don't Know about Embodied Energy and Greenhouse Gases for Electronics, Appliances, and Light Bulbs

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ABSTRACT

Over the past two decades, great strides have been made to improve the energy efficiency of electronics, appliances, and lighting and thereby reduce their energy use and the greenhouse gas (GHG) emissions caused by their use, largely through technological innovation and oversight in codes and standards initiatives and voluntary programs. However, relatively little focus has been given to the upstream energy and GHG impacts from the manufacturing and materials acquisition phases, for which there may be significant opportunities to reduce energy consumption. Based on expert interviews and an extensive literature review, we summarize current life cycle assessment (LCA) tools and practices and identify industry "hotspots" for the electronics, appliances, and lighting sectors. "Hotspots" refer to areas for which improved material choice and/or manufacturing practices could reduce energy consumption and negate unnecessary harmful environmental impacts. To the extent possible, for various products we estimate and compare the amount of energy required to manufacture and use the product, and suggest practices that could reduce embodied energy and GHG impact.

Using life cycle analysis for accurate model specific comparisons is near impossible given current outstanding barriers; however, it can be highly useful for identifying industry hotspots. White goods, including refrigerators, clothes washers, and dishwashers, currently utilize a significant amount of energy in the upstream phase, although this is dwarfed by an even larger energy expenditure in the use phase. Electronics generally have a higher proportion of their life cycle energy use tied to their production. Upstream phases for light bulbs account for less than 2 percent of their life cycle energy use, and have a much smaller total impact relative to white goods and consumer electronics. We expand on these trends and outline recommendations for how improvements to LCA tools and approaches can lead to increased energy savings and GHG reductions.[1]

Introduction

Over the past two decades technological innovation, spurred both by market forces and codes and standards and voluntary specification programs, have yielded significant improvement in energy efficiency of electronics, appliances, and lighting and thereby reduce their energy use and the greenhouse gas (GHG) emissions caused by their use. Traditionally, much more attention has been placed on the amount of energy used by product than the amount of energy it took to produce it. For instance, in consumer electronics, improved power conversion and management systems, and the evolution of the integrated circuit have in many cases drastically reduced

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[1] For a more extensive discussion on these topics, refer to NRDC's upcoming report, *Upstream Energy and GHG Emissions Impact Evaluation and Industry Hotspot Identification for Consumer Electronics, Appliances, & Lighting*". Currently in draft—contact authors for additional details.

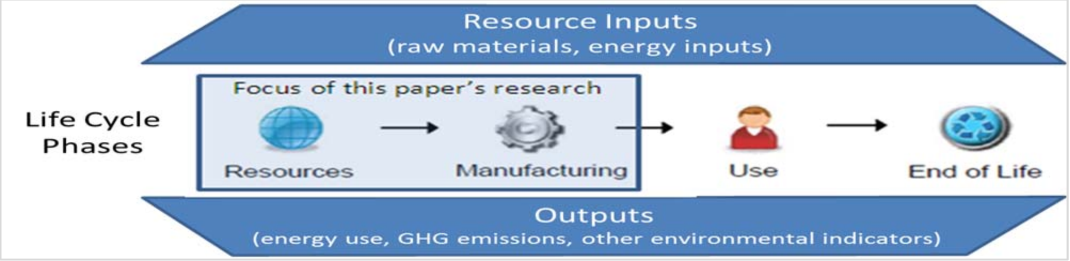
energy consumption. Likewise, design considerations and material choices within the major appliances sector have yielded up to 80 percent reductions in the use phase for some appliances (NRDC 2010). These have been achieved through a combination of policies including energy use disclosures, labeling programs such as ENERGY STAR®, financial incentives provided by utilities, and/or minimum energy efficiency standards set at the state or national level. Within the lighting industry, some new technologies have led to five-fold improvements in efficiency and a twenty-five fold increase in the product's rated life (OSRAM 2009).

While the focus has largely been on downstream energy and environmental impact, there may be opportunities upstream in the manufacturing and materials acquisition phases of the product's life cycle for which modification of industry practices could yield reduced energy and environmental impact. Key drivers, such as increasing consumer demand for "green products" and concerns about global warming, a growing trend in holistic design, and better life cycle analysis (LCA) tools are now beginning to shift this focus upstream. Given this upstream opportunity, this paper summarizes LCA opportunities and barriers, and identifies hotspots for "upstream" (materials acquisition/choice and manufacturing practices) improvements within the consumer electronics, appliances, and lighting sectors. These product categories were selected for review because: (1) they are consumer products for which upstream voluntary specifications could conceivably be created, (2) they represent different points for comparison on the spectrums of total and relative upstream energy use, and (3) credible data was more readily available. For each product category, we looked at a variety of products' energy use throughout their life cycles. We also considered their associated point source GHG emissions, and also where possible assessed GHG emissions from manufacturing and production.

Life Cycle Assessment Basics

Life Cycle Assessment (LCA) attempts to provide a holistic approach to the evaluation of a system, business, or product in which the impact during the system's creation, use, and retirement are taken into consideration. Figure 1 below illustrates the stages of the life cycle through which a product will flow, as well as the inputs and outputs generally required of each phase to evaluate life cycle impact; transportation of the product and its materials, occurs between each phase of the life cycle, but was not considered within the scope of this report. Additionally, while use and end-of-life are phases of the life cycle, this paper primarily explores only the upstream impact, using the use-phase in some instances as a proxy to understand the upstream impact. For example, key upstream impacts for an electronic device could include the energy required to extract and process copper used in components of the device, and the energy and GHG emissions associated with manufacturing its integrated circuits or encasing.

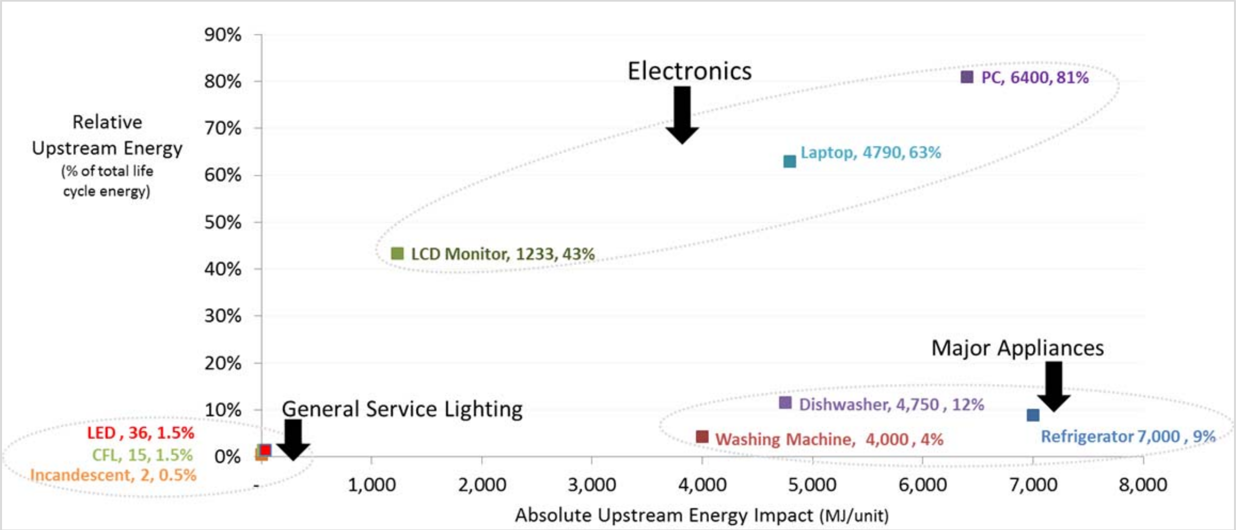
Figure 1. Life Cycle Stages and Concepts



Source: Adapted from OSRAM 2009

To simplify the nomenclature associated with life cycle analysis, we define two phases: upstream embedded energy and use phase energy. We can think about upstream impact on an absolute basis (measured in either megajoules per unit or kg-CO_2e/unit), or on a relative percentage basis in which it is compared to its total life cycle impact. Figure 2 provides a comparison of the three categories of consumer products using these two metrics. The established research is very limited to date and thus the individual data points are from single studies. Caution should be used not to interpret the single points as representative of their entire respective product classes. Furthermore, these data points come from different studies and thus a truly uniform basis of comparison cannot be applied since LCA methodologies and data assumptions vary widely. Total life cycle energy refers to the sum of all energy required to make the product (raw materials extraction, processing, & unit assembly), transport the product, use the product, and retire or recycle it. For each category we show the energy impact in MJ/unit and the upstream energy use as % of total life cycle energy use.

Figure 2. Upstream Impacts by Category (Based on Limited Available Studies)



NOTE: The individual data points are from single studies and should not be interpreted as representative of their entire respective product classes. The dotted circles serve to highlight the three categories of consumer products for ease of comparison; they do not represent a range of expected values within each category, and should not be interpreted as such.

Source: Energy Solutions analysis adapted from Deng, Babbit, & Williams (2011); Kirchain et. al (2011); Boustani, Sahni, & Gutowski (2010); OSRAM (2009).

White goods, including refrigerators, clothes washers, and dishwashers, require a significant amount of energy to produce, although this is dwarfed by its even larger expenditure in the use phase. As an example, consider a refrigerator with a useful life of 14 years; the energy consumed over 14 years far exceeds the initial energy expended to make the product (71,000 kWh vs. 7,000 kWh). Another common trend observed is that products with shorter useful lives as well as those with semiconductor manufacturing (e.g., electronics) tend to have much higher relative embedded energy and GHG emissions contribution compared to products with motors, pumps, and compressors, etc. (e.g, appliances) (Weber 2011). In general, electronics have a higher proportion of their overall energy use tied to their production. Nevertheless, the amount of energy required to produce a white good is roughly equivalent, if not larger than the amount to produce a consumer electronic product. The upstream phases for general service light bulbs account for a very small percentage of total life cycle energy use (OSRAM 2009 estimates 2 percent) and have much smaller total relative impact than white goods and consumer electronics.

Opportunities & Barriers to Using LCA

LCAs can yield widely diverging results for similar products; this tends to happen when there is a complex product supply chain, variation in the LCA approach, a variation in the boundaries used for the evaluation, and other various unexplained or only partially explained assumptions (Duque, Gutowski & Garetti 2010; Draucker 2011). For instance, a computer company has direct relationships with only some companies in its products' supply chains, but more likely than not, has far more indirect relationships, making it difficult for it to demand and obtain robust, reliable, and detailed data about their product's impacts. When data cannot be accounted for, evaluators modeling the product's life cycle are forced to make assumptions about those inputs, and in some cases that material or process may altogether be disregarded (Olivetti 2011 & Williams 2011). Current and in-development databases such as Ecoinvent[2] and NREL's Life Cycle Inventory,[3] among others, are used to fill in the information/data gaps (Draucker 2011). Still, these databases tend to be incomplete and are not always reflective of industry practices, especially when those practices are proprietary (Mars 2011).

These variations currently create challenges for policymakers to address embedded energy and GHGs in voluntary specifications. It is one of the most significant barriers to utilizing LCA for the purpose of product comparison. Nonetheless, considerable effort and progress have been made by industry-backed organizations to build more realistic and reliable models and methodologies for LCA for product comparison purposes. While LCA may not yet be ready to cross compare very similar products, it can be highly useful in identifying industry hotspots for which improved material selection or manufacturing design could yield lower impact on upstream product development. The remainder of this paper describes a compilation of results from various studies on the upstream impact of consumer electronics, large appliances, and lighting.

Consumer Electronics Life Cycle Analysis

Consumer electronics, such as laptops, desktops, televisions, and tablets, have the highest upstream impact on a percentage basis, as illustrated in Figure 2. Put differently, over the course of the product's life cycle, the majority of its energy use is tied to the production of the unit, and not due to their usage. This is largely due to shorter useful lives (1 to 5 years typically for a product, compared to 10 to 15 years for most major home appliances such as refrigerators and clothes washers), and the energy intensive manufacturing processes associated with semiconductor, heat sink, and LCD fabrication. The following section serves to assess the differences amongst various consumer electronics and highlight industry hotspots and best practices for widely used electronic components. Analyzing the entire consumer electronics industry is beyond the scope of this study; thus, we limited our analysis to desktop computers, laptops, tablets, and TVs. These are commonly owned electronics for which upstream impact is

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[2] Ecoinvent version v2.2 is one of the world's leading database with consistent and transparent, up-to-date Life Cycle Inventory (LCI) data. For more information visit: http://www.ecoinvent.org/database/.

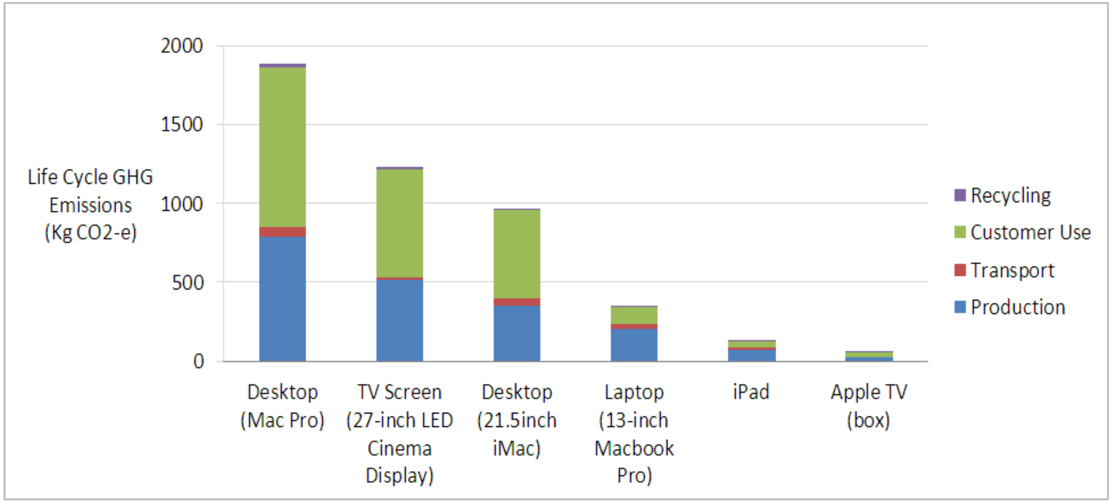
[3] NREL and its partners created the U.S. Life Cycle Inventory (LCI) Database to help life cycle assessment (LCA) practitioners answer questions about environmental impact. For more information visit: http://www.nrel.gov/lci/.

generally larger than downstream impact, and for which innovative LCA research is being conducted.

Discussion of Apple's Product LCA Results

To highlight the differences among various consumer electronics, we use the publicly available Apple Environmental Product reports that are posted on its website.[4] While we do not assert that Apple comprehensively represents the market of consumer electronic products, to our knowledge, it is the only company that publically provides LCA data for its products. Furthermore, Apple use a consistent LCA framework (ISO 14040) for all its products, thus providing useful data to highlight trends across different product types (see Figure 3).

Figure 3. Life Cycle Impact of Selected Apple Products



Sources: Adapted from Apple (2010a); Apple (2010c); Apple (2010b); Apple (2010f); Apple (2010e); Apple (2010d)

One of the most striking observations from Figure 3 is the difference in total life cycle emissions associated with desktops, laptops, and the iPads. While assumptions about the useful lives of these devices were not disclosed in the reports, current trends suggest that desktop computers last longer than laptops, which last longer than tablets. Nonetheless, even factoring in this consideration, the difference in life cycle emissions between technology types is significant. From an overall energy usage perspective one desktop is equal to more than two laptops, while one laptop is roughly equal to two iPads in emissions impact. In addition to assumptions about useful life, material requirements also affect relative and total upstream impact, which likely explains why desktops have higher total embodied energy, but lower relative embodied energy compared to results for laptops. And while some consumers may be replacing a desktop with a laptop, many are adding more devices like these per home. For example, one consumer may own a desktop, laptop, and iPad—seeing each device as complimentary instead of as substitutes for one another. While device replacement suggests potentially lower overall energy consumption for the sector, the trend towards owning complimentary devices could significantly increase overall energy consumption.

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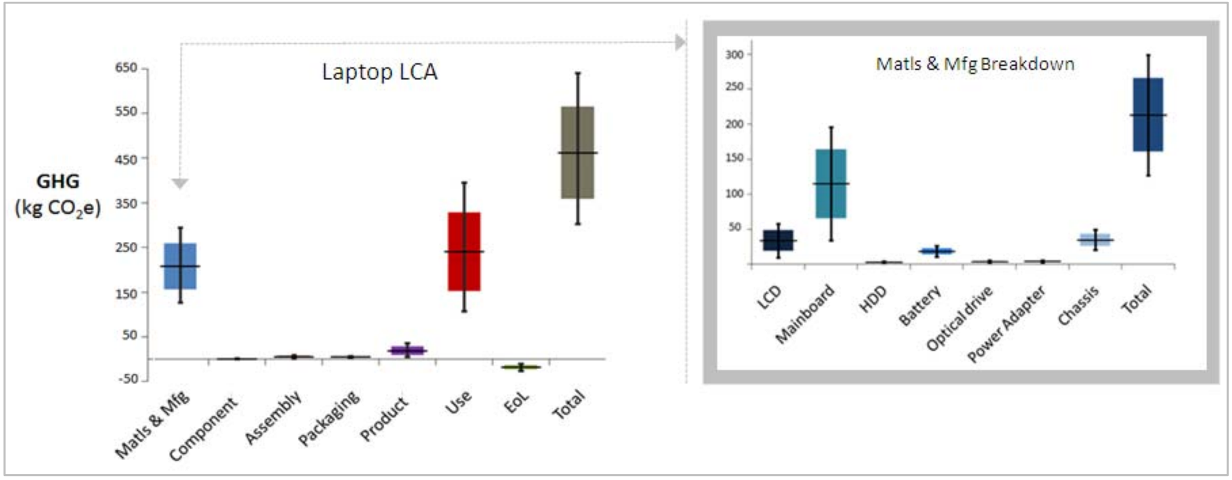
[4] http://www.apple.com/environment/reports/

Laptop LCA Model – Product Attribute to Impact Algorithm

The Product Attribute to Impact Algorithm (PAIA) tool is a model being co-developed by staff at Massachusetts Institute of Technology; Carnegie Mellon University; University of California, Berkeley; and Arizona State University; with considerable industry support. The PAIA Project has modeled the life cycle phases of laptop computers with a level of specificity that allows impact comparisons among laptops of different size, hardware configurations, and performance specifications. The current modeling tool is highly useful for investigators who wish to understand the relative impact of the aforementioned considerations as well as to identify industry hotspots. It enables modelers to better understand the life cycle energy and GHG impacts, for instance, of moving from a plastic to aluminum enclosure for a laptop, or transitioning from CFL to LED backlights.

Figure 4 shows the impact by life cycle phase and then specifically the component impacts within the materials acquisition and manufacturing stage. The usage and materials & manufacturing phases are by far the largest contributors of GHGs. Within materials and manufacturing phase, the production of the mainboard, LCD panel, and the Chassis comprise the large majority of GHG impact (approximately 75 percent).

Figure 4. Laptop LCA Results from PAIA Model



NOTES: The figure is a typical box and whisker plot with the ends of the error bars representing the maximum and minimum data points from model results, and the horizontal bar in the middle representing the median. The shaded region comprises 50% of results, with the upper and lower bounds representing the lower and upper quartiles, respectively. Products labeled with an asterisk (*) indicate the transportation phase.

Source: Kirchain et al. 2011

While PAIA follows a rigorous methodology and enables insight into the uncertainty of results, there is still considerable variance in results, as indicated by the box and whisker plots above in Figure 4. Total life cycle emissions ranged from approximately 275 kg CO_2e to 650 kgCO_2e for a range of laptops. Materials & manufacturing and end-use had the largest variance in results. Within materials and manufacturing there was a significant range in results from the mainboard, which generally contains the circuitry for the central processing unit. The range in results is dependent upon a variety of factors, including assumptions about manufacturing processes, the laptop-class assessed (e.g., 15’’ screen vs. 13’’ screen), the product’s useful life, and whether or not power management is enabled. Given the number of these confounding variable inputs to the model, it will be difficult to pinpoint the most significant factors affecting variance until full publication of results are released later in 2012. Nonetheless, even with these large variances it seems clear that the main hotspots are within material acquisition and production of the mainboard and LCD screen; manufacturers should evaluate design changes in material selection or modification to manufacturing practices to reduce associated energy consumption and GHG from these upstream hotspots.

PFC Abatement in Semiconductor Manufacturing and the Fabrication of LCD Screens

There is significant concern regarding the uncertainty around GHG emissions abatement for integrated circuit and LCD screen fabrication—particularly for perfluorinated compounds (PFC). PFCs range between 7,000 and 17,000 times more potent than Carbon Dioxide (CO_2) based on 100-year Global Warming Potential GWP[5]. And while CO_2 has atmospheric lifetimes between 30 and 95 years, PFCs can last 740 to 50,000 years (Pew Climate 2010). In 1999 the World Semiconductor Council (WSC), which includes the semiconductor industry associations of Japan, Europe, Korea, Taiwan, and the U.S, committed to PFC emissions reductions of 10 percent from 1995 or 1999 baseline levels by the end of 2010 (Boyd, Horvath & Dornfeld 2009). Based on EPA data, the industry has already achieved this: between 2000 and 2009 in the U.S., there was a 40 percent decrease in PFCs from semiconductor manufacture, from 13.5 CO_2e in 2000 to 5.6 Tg CO_2-e in 2009 (EPA 2011a). While the semiconductor industry appears to be further ahead in PFC abatement, industry abatement of PFCs during LCD fabrication (particularly for TVs and computer monitors) remains less clear. The PAIA project is currently studying the impacts of PFC abatement for LCD production and published results are expected later in 2012. ENERGY STAR® previously identified PFC abatement for LCD production as an important consideration since current models do not typically require factory considerations on whether or not the PFCs are directly emitted into the atmosphere. However, EPA likely will not incorporate any kind of partner commitment specification into the next round of Television specifications. Nonetheless, emissions reduction could be achieved by installing effective local scrubbers, gas substitution, and process optimization (ITRI 2005) at manufacturing sites.

Large Consumer Appliances: Refrigerators, Dishwashers & Clothes Washers

For major appliances including refrigerators, dishwashers, and clothes washers, otherwise known as “white-goods”, great strides have been made through standards to increase the end-use efficiency of these appliances, as evidenced by Figure 5 below.

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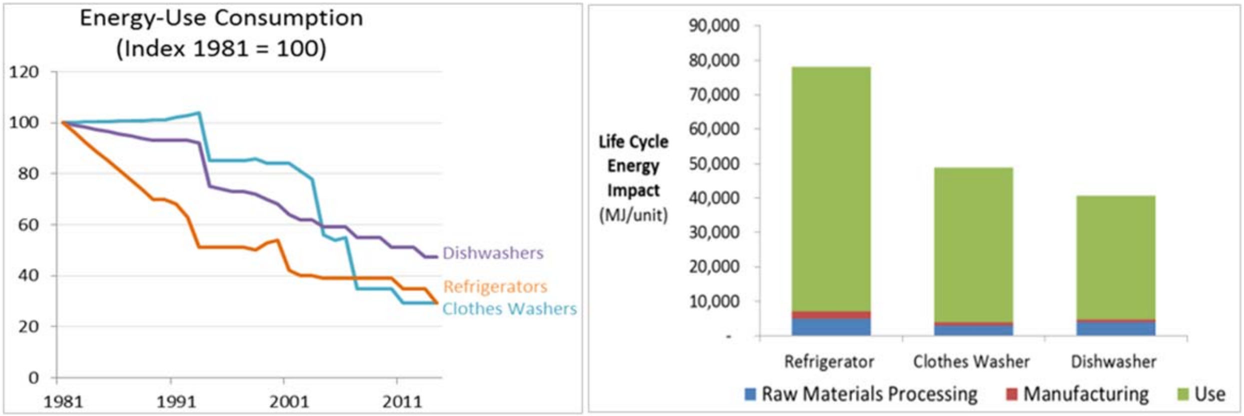
[5] Global Warming Potentials (GWPs) are a simplified index based upon radiative properties that can be used to estimate the potential future impacts of emissions of different gases upon the climate system in a relative sense. It compares the amount of heat trapped by a certain mass of the gas in question to the amount heat trapped by a similar mass of carbon dioxide, over a defined time horizon. GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1).

Figure 5. End-Use Energy Improvements and LCA Impacts for White Goods[6]



Sources: End-use energy consumption adapted from Boustani et al. 2010; Life cycle energy impact adapted from Boustani, Graves & Gutowski 2010

These trends have been in large part driven by the combination of state and federal appliance standards, ENERGY STAR® specifications, and utility incentives programs. For instance, before we had energy efficiency policies in the U.S., a top-freezer refrigerator used 2,127 kWh per year. After the newly proposed DOE refrigerator standard goes into effect in 2014, the highest energy permitted by new fridges with top mounted freezers on the market will be approximately 450 kWh per year[7] (NRDC 2010). If we assume that ENERGY STAR® and other programs can save 10 percent beyond that on average, we will exceed an 83 percent reduction in energy over 4 decades (NRDC 2010).

The Environmentally-Benign Manufacturing Lab at MIT has done considerable research on life cycle analysis of white goods. Their high-level results suggest that even though white goods expend the large majority of their energy during the use phase, the amount expended during production to make the appliance is still significant (e.g., roughly on order with what a desktop expends upstream). Figure 5 above shows the LCA results for these appliances; 88 to 92 percent of total life cycle energy is consumed in the use phase. The MIT group also found that the upstream energy contribution since the 1980's appears to either remain level or possibly be increasing due to increasing size of the units and more material expenditure to make them. Moreover, this is supported by the fact that raw materials processing accounts for the lion's share of the upstream impact. Manufacturers should consider alternative materials or practices for processing materials used in the production of white goods to reduce the energy consumption and associated GHG of this hotspot.

LED, CFL, and Incandescent A-lamp Lighting Technologies

One of the biggest pushes within lighting is to provide more energy efficient alternatives to the 125 year old inefficient, incandescent bulb. LEDs are currently receiving considerable

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[6] For the LCA graph, the base model year is 2008. The clothes washer data was adapted for a 2008 model by using the manufacturing and raw materials processing numbers from the 2003 Model Unit that *Boustani, Graves & Gutowski* studied, and updating the use phase to reflect the federal standard efficiency levels in 2008. Over the course of their lifetime these units consume 78,000 MJ, 48,778 MJ, and 40,750 MJ per unit refrigerator, clothes washer, and dishwasher, respectively. Approximately 91%, 92%, and 88% of total life cycle energy is expended in the end-use phase for refrigerators, clothes washers, and dishwashers, respectively.

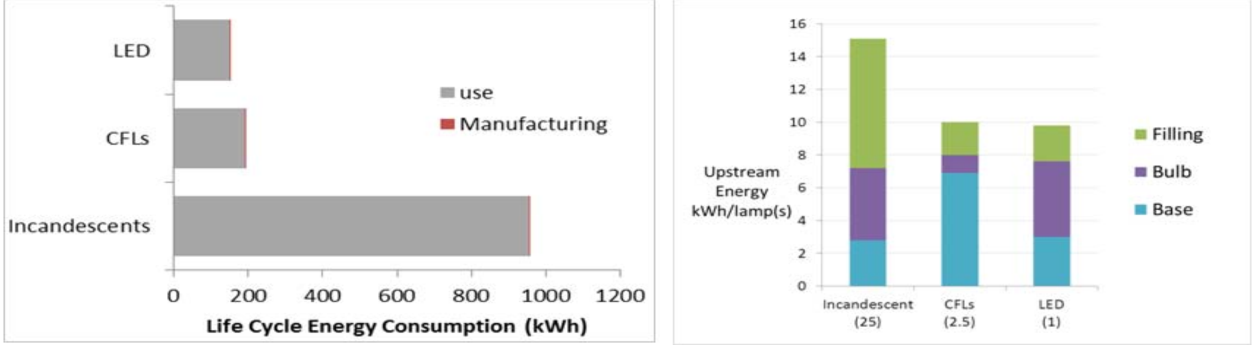
[7] 450 kWh/yr is an approximation of the standard, since the standard changes based on the volume on the fridge.

attention as a potential game changing technology for lighting; they are approximately five times more energy efficient than today's incandescent, are mercury free, turn on instantly, and last up to 25,000 hours (NRDC 2011; OSRAM 2009). CFLs also remain highly efficient, have rated lifetimes of 6,000-10,000 lumen hours, and serve as a very cost effective alternative to the incandescent bulb (NRDC 2011; OSRAM 2009).

While it is very promising that significant investment is going into improving the performance and efficiency of these technologies during the use phase, more research is still needed to fully understand their life cycle implications from an embodied energy and material toxicity perspective. This section highlights results from a lighting study conducted by OSRAM Opto Semiconductors and Seimens Corporate Technology[8] (OSRAM 2009), in which incandescents (GSILs), CFLs, and LEDs were compared.

To provide a uniform basis of comparison, the studied lamps ranged between 345-420 lumens[9], a correlated color temperature between 2700-3000K, and a color rendering index (CRI) of at least 80. Efficacies for the LED, CFLs, and GSILs for use phase energy calculations were modeled at 70, 55, and 11 lumens per watt, respectively. Results were modeled for 25,000 useful hours, equivalent to some LED lamp claims. This is roughly equivalent to 2.5 CFLs lamps and 25 GSILs. Results for this comparison are displayed below in Figure 6.

Figure 6. LCA and Manufacturing Impacts Comparison Lighting[10]



Source: Adapted from OSRAM 2009

As one can see, the use phase trumps the impact from manufacturing for each of the technologies; manufacturing accounts for less than 3 percent of the total life cycle impact for each of the technologies according to OSRAM (2009). In comparing these technologies on a one-for-one lamp basis (as opposed to normalizing the comparison over the useful lifetime of the LED), incandescent lamps have both smaller manufacturing and end-use impact, due to their shorter lifetimes, than both CFLs and LEDs. While LEDs require slightly more energy during their production on a one-for-one bulb comparison, evidence from this study suggests that their

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[8] There are currently very few published LCA lighting studies that looks at all three technologies. Siemens study appeared to be the most comprehensive and up to date study within the industry. While this industry study was conducted internally within OSRAM, they did follow ISO LCA guidelines which require external review. Nonetheless, no underlying documentation of the study was made publicly available and caution should be used when using the results. For other LCA lighting information, see: Deanna Matthews, Peter Alstone, and Arne, http://pubs.acs.org/doi/pdf/10.1021/es101052q.

[9] 345-420 lumen output is roughly equivalent to a 40W incandescent light

[10] The "bulb" category on in the left figure consists of the encasings and the heat sink for the LED. The "base" category includes the ballast and chip for the CFL and LED, respectively.

upstream impact is nearly negligible when compared to the gains in efficiency over their much longer useful lifetimes.

Figure 6 also shows upstream energy impact from three lamp components: the filing, base, and bulb. The upstream impact of the incandescent is primarily associated with the processing of aluminum in the base and filling. For CFLs, the most significant factor was the printed circuit board within the ballast at the base. For LEDs, the main contributor was the production of the aluminum heat sink and chip.

LED fabrication yield also has a large impact upstream energy impact. The difference between the base case (100 percent) yield and worst case (~60 percent) yield is about 2.7 kWh per lamp, which is significant in comparison to the study's results for total LED upstream impact (2.4 kWh per lamp). In reality, front-end and back-end[11] fabrication yield can range from 60 percent to 90 percent, depending on chip design, material defects, and fabrication process variations (CS 2010). To this end, a process known as automated inline inspection within the front-end manufacturing process can reduce the number of defective wafers, prevent minor excursion defects from becoming major excursions, and ultimately increase yield (CS 2010).[12] Researchers are also developing an advanced layering technique that is supposed to cut manufacturing costs and increase "quantum efficiency" – the process by which LEDs convert electricity to light (CEC 2012). The new process, known as hydride vapor phase epitaxy, should minimize the number of defects in semiconductor layers – resulting in increased yield, reduced use of chemicals for fabrication, improved product wavelength uniformity and output power, and decreased manufacturing waste (CEC 2012).

Recommendations

Due to the complexity of many product supply chains, limited availability and access to data, and divergence in modeling methodologies, accurate product-model level LCA comparison is near impossible. However, tools can be employed to identify industry hotspots across and within categories of products, and should be used for this purpose. We recommend more resources be devoted to defining methods for evaluating and collecting data (as is done in the use phase through test methods) across all aspects of the supply chain. Data sharing should be encouraged and the use of repositories for this information, like the NREL Life Cycle Inventory Database, should be supported. Moreover, the development of product-class specific tools like PAIA backed by academia and industry will become increasingly valuable as the market shifts us toward this upstream evaluation.

Across categories we found that electronics, with shorter useful lives and manufacturing intensive processes, tended to have greater upstream impact compared to the use phase than did large appliances. However, large appliances had roughly equal or slightly more total upstream impact. Upstream impact from lighting was almost negligible. Within electronics manufacturing of integrated circuitry, LCD screens, and the chassis appeared to be the most energy and GHG intensive hotspots. To this end, we recommend supporting future ENERGY STAR® specifications that would require suppliers to purchase their screens from PFC abating facilities. Within appliances we recommend that incentive programs and innovative policies be developed to

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[11] Front-end describes fabrication of the chip which involves the use of substrates in lithography and wafer bonding while back-end describes plasma cleaning and fastening the wires and lens.

[12] For more information about these processes, visit this site: http://compoundsemiconductor.net/csc/features-details.php?id=19731921

address the market inefficiencies associated with owning a white good for as long as possible (to reduce cost) versus retiring the product when a much more efficient option is made available. Within lighting, we identified LED fabrication yield as a hotspot for which the use and development of process-management software, as well as research into more innovative techniques could help in this respect.

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