Reducing environmental burdens of solid-state lighting through end-of-life design

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Abstract
With 20% of US electricity used for lighting, energy efficient solid-state lighting technology could have significant benefits. While energy efficiency in use is important, the life cycle cost, energy and environmental impacts of light-emitting diode (LED) solid-state lighting could be reduced by reusing, remanufacturing or recycling components of the end products. Design decisions at this time for the nascent technology can reduce material and manufacturing burdens by considering the ease of disassembly, potential for remanufacturing, and recovery of parts and materials for reuse and recycling. We use teardowns of three commercial solid-state lighting products designed to fit in conventional Edison light bulb sockets to analyze potential end-of-life reuse strategies for solid-state lighting and recommend strategies for the industry. Current lamp designs would benefit from standardization of part connections to facilitate disassembly and remanufacturing of components, and fewer material types in structural pieces to maximize homogeneous materials recovery. The lighting industry should also start now to develop an effective product take-back system for collecting future end-of-life products.

Keywords: green design, design for environment, solid-state lighting, light-emitting diode, end-of-life design, design for disassembly, recycling, teardown database

1. Introduction

Solid-state lighting (SSL) products with light-emitting diodes (LEDs) are of widespread interest to provide more flexible and energy efficient illumination than currently available technologies. Consumer SSLs are now available from providers such as Cree, Philips Lumileds and Osram. The US Department of Energy supports research and development for high performance, high efficiency SSL products. The current focus of SSL product development is use-phase performance—assuring the LED components perform well and efficiently throughout the lifetime of the product, and that luminaire performance conforms to manufacturer claims. However, the life cycle costs and environmental impacts of SSL products are also of concern. SSL products are currently 3–4 times more expensive to manufacture as other lighting technologies, so reducing product cost is essential to expanding market share. Also, the production of LEDs and other materials for SSL products is energy intensive (Matthews et al 2009), so reducing the embodied energy in an SSL is of interest. Even though SSL products are anticipated to be much more energy efficient during use than current lighting technologies, this energy savings may be smaller than anticipated when the energy consumption across the entire life cycle, including manufacturing and end-of-life, of the various technologies is considered. Likewise, as SSL products enter into widespread use, disposal of more and more end-of-life SSL products will become an increasingly important issue. Consumers and retailers want to be informed about the potential hazardous in technology purchases, and want to direct these products to the proper disposal path. Attention to end-of-life options in the design process can reduce life cycle cost, embodied energy.
and disposal issues, and promote more rapid and widespread adoption of SSL.

In this case study article, we examine how end-of-life green design principles can be applied to SSL products in order to reduce life cycle costs and environmental impact. First, we discuss SSL products and green design principles generally. Then, we apply the green design principles to SSL products, and discuss options for improving lamp and luminaire designs and supply chain systems to reduce life cycle cost and environmental impacts. This letter focuses on retrofit lamp products, i.e., products with traditional Edison screw-type bases that can be used in existing Edison socket fixtures. This market is a primary focus for conversion to LED lamps, and the potential demand is likely to lead to significant production volumes (DOE 2009a). We base our results on the teardown analysis of three LED retrofit lamps currently on the market and past experience of applying green design principles to other consumer products. To a lesser extent we discuss green design of LED luminaires.

2. Current state of design for LED SSL products

Table 1 describes the various components of an LED SSL product (full definitions are available from DOE (2009a)). An LED ‘lamp’ refers to an assembly with a standardized base designed to be connected to an LED ‘luminaire’ to form a complete lighting unit. In relation to conventional terminology for lighting, an LED lamp would correspond to a ‘light bulb’ (e.g., an incandescent bulb), while an LED luminaire would correspond to a lighting fixture (such as a table lamp or ceiling fixture). As noted, we focus on LED retrofit lamps (i.e., ‘bulbs’ with Edison screw bases) that could be used in existing luminaires or lighting fixtures. Other LED luminaires are complete systems where an LED module, electronic driver, and other components are designed into a single, consolidated lighting unit lacking a screw base (i.e., the luminaire is one piece rather than a fixture and separate bulb). Current popular LED luminaires are used for under cabinet lighting applications.

We should note that the SSL industry includes a diverse supply chain. Several companies are highly vertically integrated, notably Cree, Philips, and Osram, with research and development, and product design across all phases of SSL products from LED chips, packages, and arrays, LED drivers, and complete LED luminaires. The industry also includes numerous companies that specialize in one or two specific areas (e.g., manufacturing just LED dies and packaging, or just electronic LED drivers) that market products to other consumer products. To a lesser extent we discuss green design of LED luminaires.

Table 1. Components of light-emitting diode (LED) solid-state lighting (SSL) products.

| Components—no power source or driver |
|-------------------------------------|
| Die or chip | Basic LED on small piece of semiconductor material |
| Package | Assembly of one or more LED dies with associated electrical connections and thermal interfaces |
| Array | Assembly of one or more LED packages on a common wiring board |
| Module | LED package or array connected to a power source or driver, may have additional connections and interfaces |

Subassemblies and systems—including driver

| Driver | Power source with control circuitry to manage electrical loads to the LED |
| Lamp | Assembly of LED package, array or module on a standardized base for connection to an LED luminaire. Integrated lamps include drivers, non-integrated lamps do not include drivers (driver must be in the luminaire) |
| Luminaire | Complete lighting unit that can be connected to an electrical branch circuit |

housing (top structural components), LED module (packaged LEDs and initial structural components), main heat sink, base assembly (bottom structural components), driver (electronics), and Edison screw base. Although one lamp was much less material intensive overall (83 g versus 250 and 287 g), each lamp has a similar percentage of mass for the various component categories. For all lamps, the aluminum heat sink was the largest component by mass. The types of materials are also diverse within lamps. Each included a significant amount of aluminum in both the main heat sink and secondary heat sinks, and different plastics and glass for the housing and optics. The electronic components for the driver are considered a single component and not further disassembled.

Integrated SSL luminaires would have some corresponding components. The major difference would be the absence of the Edison screw or other standard base connection in exchange for a standard wall plug or electrical leads for direct connection to the electrical branch circuit. The heat sink for an integrated luminaire is most often designed to serve additional functions for the unit, such as structural support or aesthetic form. For example, current integrated luminaire products include track lighting systems for mounting under cabinets or in wall coves. The heat sink for these products also serves as the mounting track. A luminaire may include a replaceable lamp, or have the LED module and optics integrated into the luminaire that are not separable.

Another important factor in the current design of SSL products is the expected lifetime. One advantage of LED technology is the expected 10 000–25 000 h lifetime of the lighting source (with projections to 50 000 h). This is in comparison to 1000 h or 5000 h for existing incandescent and compact fluorescent products, respectively. A typical residential lighting fixture is only in use about 4 h daily, thus a 10 000 h product would last around 7 years, while a 25 000 h product would last upwards of 15 years. Although failure of
Figure 1. LED lamp 1 after teardown: (a) lens, (b) heat sink retention ring and plastic cone, (c) LED module, (d) heat sink, (e) driver, (f) base assembly, (g) Edison screw.

Table 2. Components of LED lamp 1 (source: author’s teardown).

| Part Type    | Name                                      | Material         | Mass (g) | Mass % |
|--------------|-------------------------------------------|------------------|----------|--------|
| Optics       | Lens                                      | Glass            | 21.8     | 8.8    |
| Housing      | Heat sink retention ring                  | Aluminum         | 9.0      | 3.6    |
|              | Plastic cone                              | Plastic          | 4.0      | 1.6    |
| LED module   | Array (9 LEDs in 1 array) sensor, substrate, thermal grease |                | 1.5      | 0.60   |
|              | Local heat sink                           | Copper           | 28.2     | 11.3   |
| Heat sink    | LED base, heat sink                       | Aluminum         | 147.4    | 59.2   |
| Base assembly| Insulating compound                       | Fiberglass       | 0.3      | 0.12   |
|              | Porcelain base (broken pieces)            | Porcelain        | 19.4     | 7.8    |
| Driver       | PCB (printed circuit board), resistors, transistors, inductors, capacitors, diodes, copper wire, Teflon tubing |            | 6.1      | 2.5    |
| Edison screw | Edison screw base                         | Tin plated steel | 9.1      | 3.7    |

Total = 246.8

the product may occur earlier, a high quality LED lamp or luminaire is expected to remain in service well beyond any existing normal decision time horizons for consumers.

3. Product life cycles and green design principles

Figure 4 illustrates a simplified product life cycle with several main stages—material extraction, material processing, manufacturing, use and various options for end-of-life. Across all life cycle stages, design decisions influence the resulting cost and environmental impact of a product. For example, the choice of material (e.g., metals versus plastics) determines the material extraction needed (e.g., mining ore versus drilling for oil), and the waste management options available (e.g., recycling versus incineration). Each of these activities incurs a cost and imposes environmental impacts. At end-of-life, products or portions of products may be reused, serviced, remanufactured, or recycled. These recovery strategies remove some burden from the life cycle cost and environmental impact by eliminating the need for new materials and components for future products.
Figure 2. LED lamp 2 after teardown: (a) lens, (b) housing, (c) LED module, (d) heat sink, (e) driver, (f) base assembly compound, (g) Edison screw.

Table 3. Components of LED lamp 2 (source: author’s teardown).

| Part type            | Name                                           | Material                  | Mass (g) | Mass % |
|---------------------|------------------------------------------------|---------------------------|----------|--------|
| Optics              | White border lens                              | Plastic                   | 22.6     | 8.0    |
| Housing             | Lexan stiffener                                 | Plastic                   | 11.4     | 4.0    |
|                     | 5 machine screws 440 × 3/8 PHP, 2 copper sheet metal screws, SMS No. 4 × 1/4 PHP | Metal (copper)            | 3.5      | 1.2    |
| Structural cone     | Plastic                                        |                           | 53.2     | 18.9   |
| O-ring              | Rubber                                         |                           | 0.5      | 0.2    |
| LED module          | Array (18 LEDs in 3 arrays)                    |                           | 3        | 1.1    |
| Heat sink           | Heat sink assembly, aluminum and copper         | Aluminum                  | 34       | 12.1   |
| Base assembly       | Edison base assembly                            | Aluminum, copper          | 120.9    | 42.9   |
|                     | Potting compound (black, silicon)              | Plastic                   | 10.8     | 3.8    |
|                     |                                                | Silicone                  | 6.8      | 2.4    |
| Driver              | PCB (printed circuit board), resistors, transistors, inductors, capacitors, diodes, copper wire, Teflon tubing |                                                | 6.7      | 2.4    |
| Edison screw        | Edison screw base                              | Tin plated steel          | 8.6      | 3.1    |
|                     | Total                                          |                           | 282.0    |        |

Fiksel (2009) and Graedel and Allenby (2003) offer textbook discussions on green design engineering approaches, and specifically ‘design for environment’ (DFE) principles that encompass consideration for end-of-life waste management. These include design for disassembly, recyclability, reusability, etc. Anastas and Zimmerman (2003) enumerated 12 principles for green engineering, three of which target end-of-life:

(6) Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition.

(9) Multi-component products should strive for material unification to promote disassembly and value retention (minimize material diversity).

(11) Performance metrics include designing for performance in commercial ‘after-life’.

Green design principles have been applied to numerous products, most notably in the automotive and electronics industries (Lund 1996, Kuehr and Williams 2003, Kim et al 2003, Kim et al 2006, see also the Proceedings of the IEEE International Symposium on Electronics and the Environment).
Figure 3. LED lamp 3 after teardown: (a) glass bulb, (b) LED module, (c) driver, (d) base assembly, (e) heat sink, (f) Edison screw.

Table 4. Components of LED lamp 3 (source: author’s teardown). Note that heat sink is in three parts (including local heat sink in LED module).

| Part Type   | Name                                  | Material              | Mass (g) | Mass % |
|-------------|---------------------------------------|-----------------------|----------|--------|
| Optics      | Glass bulb                            | Glass                 | 10.7     | 13     |
| LED module  | LED board connectors                   | Gold plated copper    | 0.5      | 0.6    |
|             | Array (9 LEDs in 1 array)              |                       | 1.5      | 1.8    |
|             | Local heat sink ring                   | Aluminum              | 5.7      | 6.9    |
| Heat sink   | Heat sink outer cone                  | Aluminum              | 18.1     | 22     |
|             | Heat sink inner cylinder              | Aluminum              | 13.1     | 15.8   |
| Base assembly | Edison base insulator               | Acrylic, polycarbonate| 4.2      | 5.1    |
|             | Inner insulator and adhesive connections | Acrylic, polycarbonate| 6.6      | 8      |
| Driver      | PCB (printed circuit board, capacitors, resistors, transistors, diodes) | | 10.1     | 12.2   |
| Edison screw | Edison base and leads                 | Gold plated steel     | 12.2     | 14.8   |
|             | Total                                  |                       | 82.7     |        |

As electronics, solid-state lighting products share similar characteristics to computers and related equipment that have been the focus of green design in recent years.

LED research and development is progressing at tremendous speed. In the rush to improve the performance of a new technology such as solid-state lighting, end-of-life considerations may seem secondary and may be overlooked.

The DOE has established research and development goals for SSL product operating performance and considers numerous performance criteria when evaluating SSL products during operation (DOE 2009a). However none of these goals or criteria considers the design of the lamp in relation to end-of-life waste management options. For example, packaging design of one commercial LED focused upon thermal
management to achieve safe junction operating temperature and minimize thermal stresses (Haque et al 2003). The authors note that ‘manufacturability’ is a key factor in LED design, but do not mention recovery after use. One factor that will determine the timing of SSL product replacement and entry into the end-of-life stream is the efficacy. Efficacy, or lumens per Watt, of the LEDs and associated lamps and luminaires is effectively a measure of efficiency. An improvement in efficacy leads to reduced energy consumption during the use phase and is a major goal for research. Incandescent lamps, with efficacies in the 10–20 lm W$^{-1}$ range, have high energy consumption. Replacement of incandescent lamps prior to failure by CFL or SSL lamps, with efficacies in the 50–70 lm W$^{-1}$ range, leads to significant energy savings for the consumer. A question then arises as to whether or not the pace of efficacy improvements within SSL products as technology progresses may lead to a scenario where past-year SSL products might be advantageously replaced prior to failure with future-generation SSL products in order to minimize energy consumption. Azevedo et al (2009) evaluated the annual cost of ownership of solid-state lighting, considering cost and consumption of electricity over the life of the product. While electricity consumption reduces dramatically with an improvement in efficacy at the lower ranges, savings in electricity consumption flattens out as efficacy passes $\sim$50 lm W$^{-1}$. Current technology has surpassed the 50 lm $W^{-1}$ level, so efficiency gains for replacement before failure are not likely to be a consideration. Also, the electricity consumption from a single lamp or luminaire is relatively small over its lifetime (e.g., a 60 lm $W^{-1}$, 300 lm, 25 000 h lamp consumes 125 kWh over approximately 15 years of typical use). Such low electricity consumption rates are likely to result in failure being the driving force for replacement.

4. Green design of LED lamps and luminaires

In this section, we discuss how green design principles can be applied to the design of LED products. Following the flow of product through life cycle stages as depicted in figure 4, we identify design improvements to minimize cost of production and recovery, and reduce environmental impacts.

4.1. Design for reuse and servicing

As with traditional ‘light bulbs,’ non-working LED lamps cannot be reused for lighting. Servicing non-working lamps may be an option, but given the long expected lifetime of the lamps, technological progress in LED lighting is anticipated to be a more efficient option so servicing is unlikely. Luminaires with replaceable lamps are a candidate for reuse with a new lamp. Assuming new lamps with the same base/connector are available, these would likely incorporate up-to-date LED technology allowing consumers to take advantage of increased lamp efficiencies while avoiding costs and burdens of new fixture manufacturing. But again, with the long expected lifetime of the lamps, full replacement of the luminaire may be more likely as consumer trends in lighting encourage upgrading to modern options. Thus, as with other emerging electronic products, end-of-life LED lamps and luminaires would enter an end-of-life take-back system, and design for remanufacturing and materials recovery is more important.

Two SSL product lighting applications that can benefit from consideration of design for servicing are street and traffic signal lighting applications. Municipalities are moving more toward replacement of existing street and traffic signal lighting with SSL products. In these cases, a single user (a municipality) is purchasing similar units in large quantities. If early failure occurs, workers can be trained to service products, replace components that have failed (such as the LED components), and reinstall the product.

4.2. Design for disassembly

A starting point for green design of LED lamps and luminaires is designing for efficient disassembly to permit access to the product components. Easy removal from architectural structures is an initial objective for design. Interestingly, the Edison screw (and other standard lamp base designs) is a classic example of easy disassembly from the structure. Options for luminaires include using a standard housing size over time to allow newer luminaires to be ‘inserted’ into existing wall or ceiling holes. This is similar, for example, to sizing large kitchen appliances (e.g., dishwashers) that are manufactured to standard outside dimensions to accommodate replacement of old units in existing cabinetry.

Figure 4. Life cycle of a typical consumer product including end-of-life options. (Adapted from Graedel and Allenby 2003).
Once removed from architectural systems, the individual lamps or luminaires would need to be disassembled for remanufacturing or materials recovery. The goal is to facilitate separation of components and individual materials. A remanufacturer would like disassembly into homogeneous materials to be relatively inexpensive and rapid. Resorting to destructive disassembly often means that the end-of-life disposal of the lamp would be landfiling or material recycling. The lamps in our teardown analysis exhibited design decisions that spanned from easy to difficult disassembly. Threaded screw connections and snap assemblies for some housing pieces permitted these parts to be separated by hand and kept intact, while adhesives and foams for one base assembly required simple tools but destruction of the piece (see lamp figures for examples). Only one lamp incorporated screws as connectors. These required only standard hand-held screwdrivers, but require additional time to remove.

Minimizing the number of materials and/or number of individual components is another consideration. This typically reduces the steps in the disassembly sequence and allows some pieces to remain connected for further processing. The number of materials/components for the three lamps in our analysis included 10–15 materials/components (the driver is considered one component). Each lamp had 2–4 different plastic materials in different colors, along with glass and metals. None of the lamps had any common parts, although this was expected since the lamps are manufactured by different manufacturers.

Solid-state lighting is only in the early stages of development and commercialization. The industry is only beginning to develop standards for lamp and luminaire designs to streamline production and installation, and in turn adoption rates, de-installation and disassembly. For example, standards for ballasts, controls, sockets, and other interconnects are under consideration (NEMA 2009) and will increase the modularity of lamp and luminaire designs. This modularly can improve disassembly characteristics, as products would have similar connections between modules simplifying disassembly. These standards allow for the technological progress of individual components (such as the LED components) alongside the consideration for component recovery.

4.3. Design for product and component remanufacturing

Given the extended lifetime of current and projected LED products (~10–15 years), technological changes in the LED chips and array configurations and in the electronic drivers, as well as trends in lighting design are likely to prevent remanufacturing of most products. Newer technology would be more energy efficient and reliable, and luminaire styles would reflect use of different designs and materials. Most of the product may be best used for materials recovery as discussed next.

However, product that fails prematurely is a candidate for remanufacturing, so design considerations to allow for this option remain essential to reducing the impact of the products. If LED lamps and luminaires are designed to facilitate inexpensive and non-destructive disassembly, product and component remanufacturing can be accomplished. The products or components would require inspection, some level of disassembly, cleaning, and re-assembly before reuse. The failed components can be removed, and replacement parts inserted, to create a remanufactured product. As such, the LED arrays and drivers, should be replaceable with components of similar function, allowing the bulk of structural materials to be reused as-is. Two of the case study lamps would allow for this remanufacturing option, as the LED array and driver were easily accessible and removed from the remaining lamp pieces without damage.

Other components, such as the heat sink and structural parts are not likely to fail in the same way that the electrical parts would. Design decisions for these parts could focus on remanufacturing potential over many products. For example, a company might design a heat sink to certain dimensions and heat dissipation capacity and use this same component in several lamp designs. If needed, a heat sink from a failed lamp would be ‘spare part’ option for remanufacturing for several lamp products.

4.4. Design for materials recovery

A more likely scenario for end-of-life LED lamps and luminaires is materials recovery. In this case, the products are disassembled, and then similar materials are gathered for recycling into the raw material for use in new products, while other materials or inseparable components are collected for proper disposal. Note that this option still requires products to be designed to facilitate inexpensive disassembly, but design for non-destructive disassembly to a lesser extent as components do not need to retain original functions.

Current heat sinks are a good candidate for materials recovery and recycling. In the case of the three lamps in our analysis, aluminum is the base material for this component and it comprises the greatest portion by weight of the lamp itself. Aluminum is also the most common heat sink material for integrated luminaires given its current costs, its density (relative to other metal conductors) and structural characteristics. Advances in LED design and costs will change how heat dissipation is treated in SSL product designs as the technology develops. Next-generation SSL products are lighter and more materials efficient than those used in our teardown analysis as heat sink design has been optimized for effectiveness and cost. Alternative designs using conductive liquids or mechanical fans are being investigated, however aluminum is expected to remain a common heat sink material choice. Thus, regardless of LED product design, aluminum is likely to be present in sufficient quantity to collect for recycling. Recycling aluminum is also a high-value recycling choice—the market for scrap aluminum is well-established and prices encourage recovery, and the energy savings in recycling scrap aluminum over producing virgin aluminum is high. Thus, materials recovery of the heat sink can reduce both the life cycle cost and environmental impact of the product.

Plastics for the housing and optics are another potential target for materials recovery. In our sample lamps, plastics comprised 1–4 of the approximately 10 parts of each lamp, and from 2% to 35% of the mass of the product. Each plastic
part within a single lamp, however, appeared to be a different type of plastic, and often were different colors. No plastic part was labeled or stamped to indicate the specific polymer blend. To facilitate recovery of larger volumes of plastics, designers should consider two criteria. First, designers should attempt to minimize use of multiple material types and multiple colors. The use of a single plastic (even if used on multiple pieces) would reduce the disassembly process and simplify collection. Second, all plastic parts should be labeled to indicate the material type. Labels clearly identify the type of polymer so different materials can be properly separated. This creates a high quality recycled material stream that commands a higher price in recycled materials markets.

Other lamp materials found in small quantities, or complex components such as the electronic driver or the LED chip itself, may be lower priorities for materials recovery and recycling. If the cost to separate and recover a single materials stream is higher than raw materials prices, the economics are not favorable. Future supplies and prices of precious metals, such as gallium, may lead recyclers to recover and process the LEDs, however. Gallium is the most prevalent metal for LED production, and is presumed to be a leading material in LED design for the next 5-10 based on current research portfolios (DOE 2009b). Gallium occurs in very small concentrations in ores of other metals; most gallium is a by-product of treating bauxite for alumina. Gallium (99.99% pure) prices range from $500–$600 kg$^{-1}$, while aluminum prices are around $4$ kg$^{-1}$. Recovery of gallium from end-of-life LEDs, especially if larger quantities are collected, may be profitable.

In the meantime, designing for materials recovery can encourage collection of used product, and then these components can be collected and disposed of properly. Current LED chips and drivers are considered benign from a materials perspective—existing products on the market meet requirements for the restriction of hazardous substances (RoHS), a European Union (EU) regulation requiring disclosure of certain hazardous materials prior to sales in the EU. But collection during product recycling can centralize collection and disposal of these parts, and, should issues relating to disposal arise, would allow quick diversion of the waste from the municipal waste stream.

4.5. Establishing product take-back

A critical element to any end-of-life product management is an effective product take-back scheme. Unless consumers can effortlessly return products, no recovery is achieved. Recent efforts to collect compact fluorescent lamps for recovery of the mercury and proper disposal of remaining materials are an indicator of the efforts needed for SSL product return. Direct return to the manufacturer is one option, but after the long expected life of the product, identifying the manufacturer and then returning the product may be difficult. Central collection at existing recycling facilities or at lamp vendors encourages consumers to return product, but the end-of-life product stream is a mix of products and a third-party agent would be required for materials recovery. Municipalities as consumers of SSL products in traffic lights and street lights create another take-back opportunity that can be more streamlined. These ‘consumers’ would have identical products in large quantities (e.g., thousands of units) that create better economics for recovery that encourage take-back systems to develop.

5. Conclusions

As solid-state lights enter more widespread use, disposal of more and more SSL products will become an increasingly important matter for consumers and retailers. Extended producer responsibility regulations, such as the EU Waste Electrical and Electronic Equipment Directive (WEEE) (Europa 2009), or corporate sustainability policies are likely to encourage the industry to consider waste management options. Valuable components and materials are incorporated into the products, and recovery and reuse of these parts can reduce the life cycle cost and environmental burdens of the product. Attention to end-of-life issues in the design process now can reduce these problems and promote more rapid and widespread adoption of SSL.

Manufacturers should pursue design strategies that incorporate options for end-of-life management such as:

- Designing lamps and luminaires for disassembly without destruction by employing screws or snap-fits rather than welds.
- Designing lamps and luminaires with replaceable parts, and standardized parts to ease remanufacturing, such as replaceable LEDs.
- Designing lamps and luminaires with minimal material types, with materials identifiable, to ease materials recovery.
- Supporting product take-back systems development in conjunction with product retailers and local waste management officials.

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References

Anastas P T and Zimmerman J B 2003 Design through the 12 principles of green engineering Environ. Sci. Technol. 37 94A–101A

Azevedo I L, Morgan M G and Morgan F 2009 The transition to solid-state lighting Proc. IEEE 97 481–510

European Commission 2009 Waste Electrical and Electronic Equipment http://ec.europa.eu/environment/waste/weee/index_en.htm (8 July 2009)

Fiksel J 2009 Design for Environment: A Guide to Sustainable Product Development 2nd edn (New York: McGraw-Hill)

Graedel T E and Allenby B R 2003 Industrial Ecology 2nd edn (New York: Prentice-Hall)
Haque S et al 2003 Packaging challenges of high-power LEDs for solid state lighting. 36th Int. Microelectronics and Packaging Society (IMAPS) Conf.
Kim H C, Keoleian G A, Grande D E and Bean J C 2003 Life cycle optimization of automobile replacement: model & application. Environ. Sci. Technol. 37 5407–13
Kim H C, Keoleian G A and Horie Y A 2006 Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. Energy Policy 34 2310–23
Kuehr R and Williams E (ed) 2003 Computers and the Environment: Understanding and Managing their Impacts (Dordrect: Kluwer Academic)
Lund R T 1996 The Remanufacturing Industry: Hidden Giant (Boston, MA: Boston University)
Matthews D H, Ashe M, Jaramillo P, Matthews H S, McMichael F C and Weber C 2009 DOE Solid-State Lighting Life Cycle Assessment. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/matthews_chicago09.pdf (accessed 18 August 2009)
National (NEMA) 2009 Solid-state lighting—the need for a new generation of sockets and interconnects. NEMA LSD–44–2009 www.nema.org/Std/sld44.cfm (accessed 10 December 2009)
US Department of Energy 2009a Multi-Year Program Plan FY’09–FY’15 Solid-State Lighting Research and Development. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf (accessed 10 December 2009)
US Department of Energy 2009b 2009 Project Portfolio: Solid-State Lighting. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2009ssl_projectportfolio.pdf (accessed 10 December 2009)
Yole Developpement 2008 LED Manufacturing Technologies 2008 edn www.yole.fr/pagesAn/products/ledm.asp (accessed 1 September 2009)