Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp

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Image: Compact Fluorescent Lamp. From Mark Stozier on istockphoto.

Abstract
This paper addresses the debate over compact fluorescent lamps (CFLs) and incandescents through life-cycle analyses (LCA) conducted in the SimaPro[1] life-cycle analysis program. It compares the environmental impacts of providing a given amount of light (approximately 1,600 lumens) from incandescents and CFLs for 10,000 hours. Special attention has been paid to recently raised concerns regarding CFLs—specifically that their complex manufacturing process uses so much energy that it outweighs the benefits of using CFLs, that turning CFLs on and off frequently eliminates their energy-efficiency benefits, and that they contain a large amount of mercury. The research shows that the efficiency benefits compensate for the added complexity in manufacturing, that while rapid on-off cycling of the lamp does reduce the environmental (and payback) benefits of CFLs they remain a net "win," and that the mercury emitted over a CFL's life—by power plants to power the CFL and by leakage on disposal—is still less than the mercury that can be attributed to powering the incandescent.

Introduction

This document provides an evaluation of the environmental impact of lighting a room for 10,000 hours with CFLs, and, alternatively, with incandescents over the products entire life. Several claims have been made recently challenging the "green" credentials of CFLs—specifically that their complex manufacturing process uses so much energy that it outweighs the benefits, that turning CFLs on and off frequently eliminates their energy-efficiency benefits, and that they contain a large amount of mercury.

The processes modeled using SimaPro for the two scenarios are thought to represent industry averages. However, the life cycle of each bulb is unique, and this paper cannot include absolute judgements on all CFLs and incandescents. The author's goal is to educate the reader on the differences between these two lighting options' life cycles, and to explore the claims described above.

Background

The CFL Versus Incandescent Debate

CFLs were invented by a GE engineer in response to the 1973 oil crisis.[2] They have been on the market since the early 1980s, but they have only recently been touted as a key component in the fight against global warming. The unmistakable CFL image has become an icon of energy awareness and environmental concern as it represents an easily implemented and financially smart tool to reduce greenhouse-gas emissions. The rise of CFLs' importance as the avant-garde of a climate change-conscious society was cemented in December 2007 when the President signed a law requiring the gradual phasing out of incandescents.[3,4] The benefits of CFLs have prompted the phasing out of incandescents in several countries. Australia has led the way with a plan to phase out incandescents by 2010. Great Britain and Canada have similar plans in place. In America, the President recently passed the Energy Independence and Security Act of 2007; this includes a measure for phasing out incandescents.[5,6] The bill includes efficiency requirements for manufacturers as well as the phasing out of 100 W to 40 W bulbs as part of an ongoing program that begins in 2012 and ends in 2014. Performance requirements for manufacturers of incandescents include a 25–30 percent reduction in energy use compared to today's most common incandescent bulbs by 2014 and a 70 percent reduction by 2020.

Despite their rising popularity, concerns have been raised that CFLs might actually be worse for the environment due to their mercury content, the impact of short "on" times on the life of the lamps, and the energy used during their complex manufacturing process.

In order to address these three concerns, this study compares the greenhouse-gas emissions and toxic releases that can be attributed to lighting a room for 10,000 hours with 1,600 lumens of light from a CFL and the toxic releases that can be attributed to lighting a room for 10,000 hours with 1,600 lumens of light from an incandescent. To calculate these emissions, we did life-cycle analyses (explained below) using the software tool SimaPro.

Benefits and Detriments of CFLs and Incandescents

CFLs and incandescents produce light through fluorescence and incandescence, respectively—two processes that are further explained in the "Operation of a CFL" and "Operation of an Incandescent" sections of Appendix A. Incandescent lighting is dramatically less efficient because 90–95 percent of the energy that goes into an incandescent becomes heat. This is much more than the amount of energy "lost" as heat by a CFL. In fact, the typical CFL is four times as energy efficient as a typical incandescent. The efficiency comes with a price: CFLs currently cost three to ten times more. Furthermore, the 5 mg of mercury necessary for fluorescence in a CFL has caused consumers to be cautious of their wide-scale use, which would be necessary in an incandescent phase out. The characteristics of CFLs and incandescents are compared in Table 1.

Table 1: Comparison of Incandescents and CFLs[7,8,9,10]

	Incandescent	**CFL**
Cost	An incandescent is 1/3 to 1/10 the cost of a CFL.	
Life	1:10 (incandescent:CFL)	
Power Factor: low-power factor loads increase losses in a power distribution system and result in increased energy costs.	1	0.5–0.6
Power: the rate at which electrical energy is transferred by an electrical circuit.	4:1(incandescent:CFL)	
Application Requirements (i.e., operating cycle and temperature)	None	• Lifetime decreases with shorter operating cycles. • Illuminance decreases at cold temperatures.
Complex and Energy-Intensive Manufacturing Process	Less complex	More complex (electronic ballast)
Contains Mercury *Refer to Mercury Discussion for further information	No	5 mg
Appearance	Pleasing	Not as pleasing aesthetically

This study focuses on exploring the implications of several of the positive and negative characteristics of CFLs—specifically mercury content, life span, and manufacturing process.

Life-Cycle Analysis

Life-cycle analysis (LCA) is a methodology for assessing the environmental impacts associated with a product over the course of its life.[11] This LCA was conducted using SimaPro in accordance with the relevant ISO standards for LCA.[12]

It is important to note that in this LCA the *service* provided by each lamp is compared (10,000 hours at 1,600 lumens)—not the actual lamps themselves.

The authors' intention was to give the general public insight into the environmental impacts associated with CFLs and incandescent lamps. Our LCA is a tool that can help characterize the influence of different factors on the life cycle of a lighting product or system, and it can also show the role that consumer behavior plays. It is not a comparison between two specific products.

This study describes the procedures, choices, and data gaps required by ISO 14040 series standards. The calculation of the impacts of various processes was based on mass. In general, if a material component had a mass less than the scale sensitivity of 0.1 g it wasn't included . The 5 mg mercury figure is an average provided by the EPA; we assumed that those 5 mg of mercury were within the electrode assembly.[13] The tungsten filament of the incandescent was placed on a postal scale, and it was found to be 0.02 grams in mass.

All the data we used were thought to adequately represent the processes involved in the life cycle of the lamps. Contemporary industry averages (when possible) and country-specific data for major processes are both included in the life cycle. This is a second-order LCA, meaning that while all processes during the life cycle are included (for example, transport from factory to retail outlet), the capital goods associated with these processes are excluded (for example, the manufacture of the truck that transports the lamps).

Lamp Data Collection

Industry manufacturers contacted were unwilling to share mass breakdown information. Therefore, a triple beam balance scale was used to determine the mass of various components (see Table 2 and Table 3). The lamps selected were a 23 W Philips Marathon Mini CFL and a 100 W (soft white) incandescent made by General Electric. The lamps were selected based on their widespread availability. The incandescent and CFL wattage were specifically chosen because the EPA deems them to be of equivalent minimum light output (see Appendix A).[14]

Table 2: Mass Breakdown of A CFL

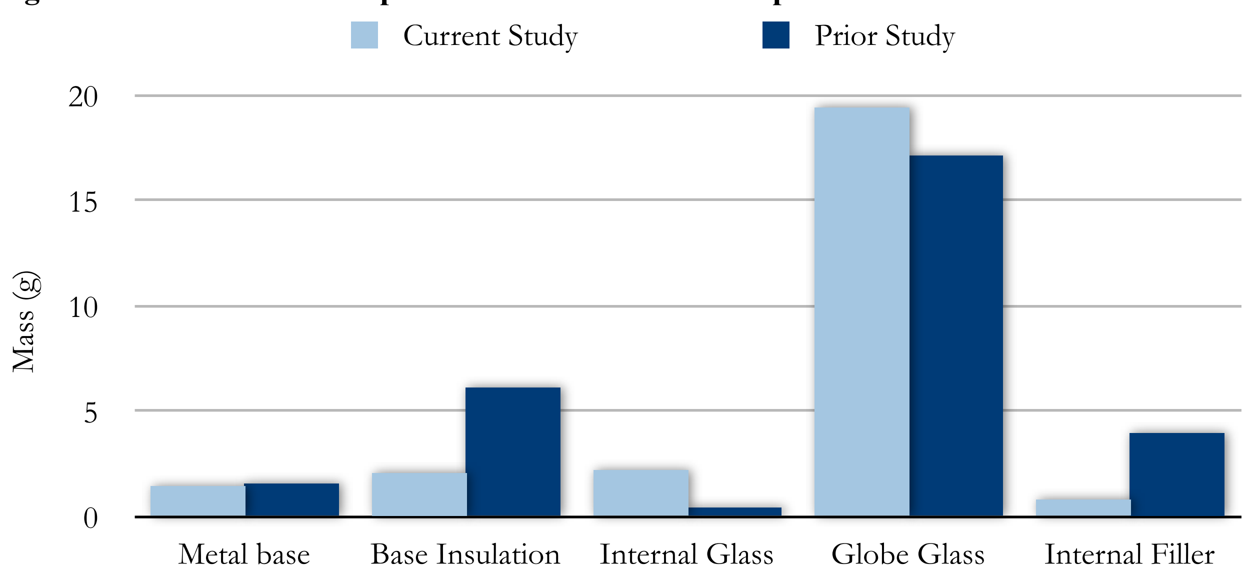
Philips Marathon 23 W CFL	
Component	**Mass (g)**
Assembled lamp	93.60
Metal base (tin plate)	4.80
Base pins (copper)	1.90
Base insulation (black glass)	4.90
Tube glass	33.70
Plastic base (PVC)	16.80
Printed board	4.00
Printed board assembly	24.70
Foam	3.00
Electrode assembly (includes mercury)	1.60
Total =	95.40
Error =	1.89%

Table 3: Mass Breakdown of an Incandescent

General Electric 100 W Incandescent	
Component	**Mass (g)**
Assembled lamp	27.30
Metal base (tin plate)	1.50
Filament (tungsten)	0.02
Base insulation (black glass)	2.15
Internal glass	2.30
Globe (glass)	19.50
Internal filler	0.90
Total =	26.37
Error =	3.41%

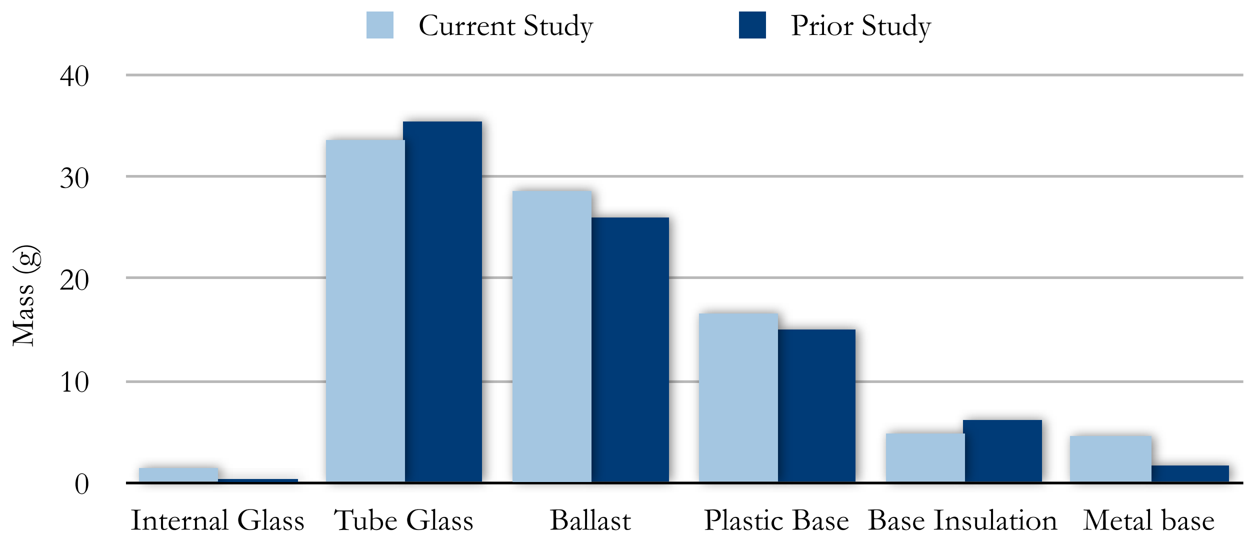
For verification purposes it is necessary to evaluate this data against other sources. These materials were compared to those in the Parsons 2006 Australian study.[15] In the Parsons study a 100 W incandescent was compared to an 18 W CFL. The bar chart in Figure 1 illustrates the discrepancies between major components in the two studies.

Figure 1: Incandescent Lamp 100 W Material Mass Comparison



The total mass of the incandescent lamp analyzed by RMI came to 26.37 g while Parsons reported a mass of 31.5 g. A possible source of discrepancy is the lamps being produced by different manufacturers. This could be producing the variance observed in the masses of the base insulation black glass and the internal filler.

Figure 2: 23 W and 18 W (Current and Prior Study Respectively) CFL Material Mass Comparison

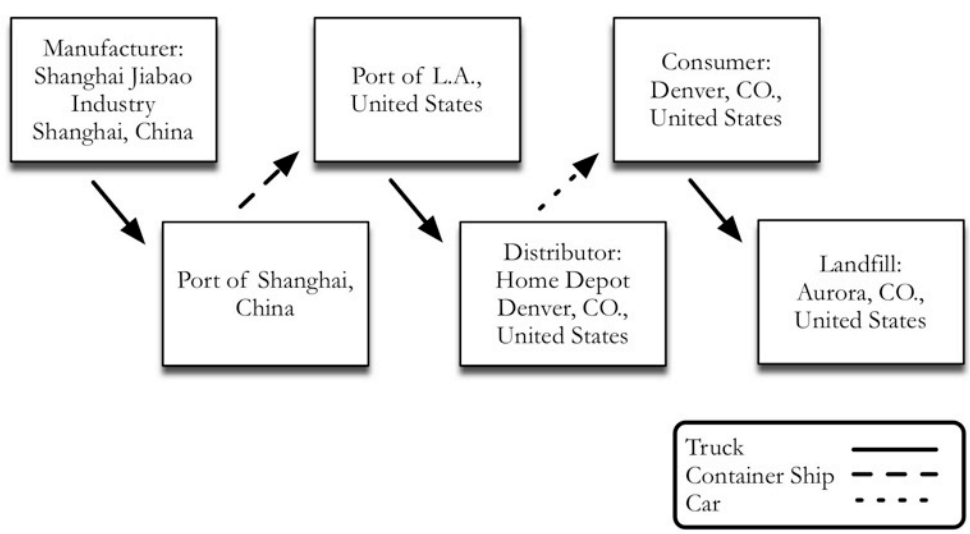


The total mass of the 23 W CFL was 95.4 g while that of the 18 W was 90.6 g. Possible sources of deviation include the different wattages of lamp and different manufacturers. The biggest deviations in mass were between the masses of the metal bases and the ballasts.

Assumptions

An LCA includes research into three phases of the life cycle of each product. These phases include the manufacturing and assembly phase, the operation/use phase, and the disposal phase. The geographic path that the lamps take from assembly to disposal must be included in order to accurately represent the life cycle of a product (see Appendix A for distance details). It is assumed both lamps were made for General Electric (GE) in Shanghai, China and then shipped to the United States, where they ultimately ended up with consumers in Denver, Colorado (Figure 3).[16]

Figure 3: Life-Cycle Path of Bulbs



In this example, a container ship at the Port of Shanghai carries the lamps to the Port of Los Angeles. From Los Angeles, they are transported by truck to a distributor in Denver, Colorado, where they are purchased, taken home, and used by a consumer. Upon failure, the lamps are taken by truck to a landfill in Aurora, Colorado.[17]

Life-Cycle Phases: Assembly, Use (Operation), and Disposal.

To complete these analyses, assumptions were made in all three phases of the LCA as follows:

Assembly

The assembly phase includes the period covering the life of the product from "cradle to gate," or from the manufacture of the product to the point where it leaves the factory. The main assumption for this phase is that the material components inside the electric circuit are as detailed in Appendix A. We used a mass correction factor of one-third for the printed board that holds the circuit, as was done in Parsons.[18] We used this correction factor because we assumed the printed board to be simpler than the industry standard. This correction factor had a negligible effect on the results of the analysis. Finally, we assumed the electricity used in assembly to be from a standard Chinese generation mix.[19]

Operation

The operation phase includes everything between leaving the plant and disposal. Processes and resources used in this phase include transportation from Shanghai to Denver and the energy used during the operation of the lamp. Assumptions made in this phase included the rated life of the lamps and the amount of energy used from well to pump (in extraction and refining the oil) for transportation. When calculating the environmental impacts of using energy (electricity, transport fuel, etc.), the environmental impacts of creating and delivering that energy (for example, pumping and refining oil into gasoline and then delivering gasoline to the filling station) are included. The electricity mix used in the operation phase is assumed to be the average of all U.S. generation.[20] Our most important assumption in this phase is that a CFL has a life span ten times longer than that of an incandescent.[21] The effect of reduced lamp life resulting from variation in operating cycle will be explored in a sensitivity analysis to follow.

Disposal

The final phase of the life cycle is disposal. For the purposes of this LCA, the end of each lamp's life is evaluated under the assumption that disposal takes place at a landfill.

It is helpful to analyze energy use associated with these phases, both together and individually, to determine in which phase environmental impacts occur, and to isolate the processes that have the biggest impact.

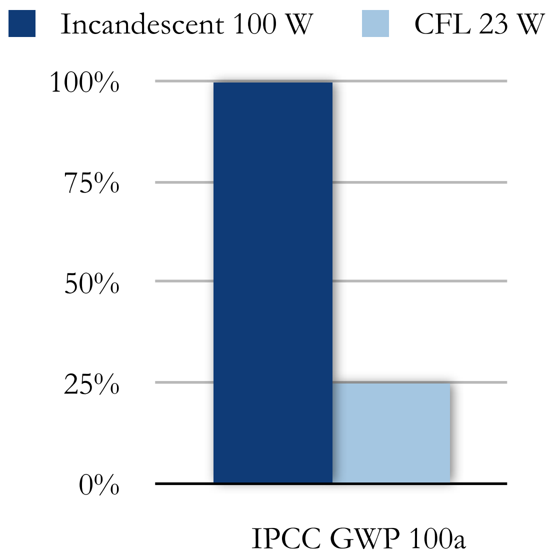
Data Analysis

Through the LCA we determined greenhouse-gas emissions related to the creation, use, and disposal of both a CFL and an incandescent. The Intergovernmental Panel on Climate Change (IPCC) 2001 Global Warming Potential (GWP) 100a method was used to convert several greenhouse-gas emission estimates into a common, comparable unit. A multiplier is assigned to each greenhouse gas based on the impact it has on global warming over the course of 100 years on a scale normalized to the impact one atom of carbon dioxide (CO_2) has over 100 years. These units are called carbon dioxide-equivalents, or CO_2e. This report also includes LCA information on mercury and arsenic pollution resulting from each lighting scenario.

Qualitative Discussion of Carbon Dioxide Emissions: Greenhouse-Gas Pollutants

Producing visible light via fluorescence—instead of incandescence—offers dramatic energy-efficiency benefits over the entire life cycle. During the 10,000 hour period (the rated life of a CFL lamp), the CFL would produce 25 percent (184 kg CO_2e) of the greenhouse gases that would be emitted by ten incandescent bulbs over the same period (734 kg CO_2e).

Figure 4: CO_2e Characterization of 100 W Incandescent and 23 W CFL Life Cycle



It is helpful to assign CO_2e emissions to various processes in order to determine which are the major polluters.

Table 4: Top 5 Contributors of kg CO_2e to Incandescent 100 W Life Cycle

Process	kg CO_2e
1. Electricity used by the consumer in USA	730
2. Personal vehicle travel from store to home	2.42
3. Production of gasoline used in personal vehicle	0.447
4. Electricity used during assembly in China	0.355
5. Container ship	0.303

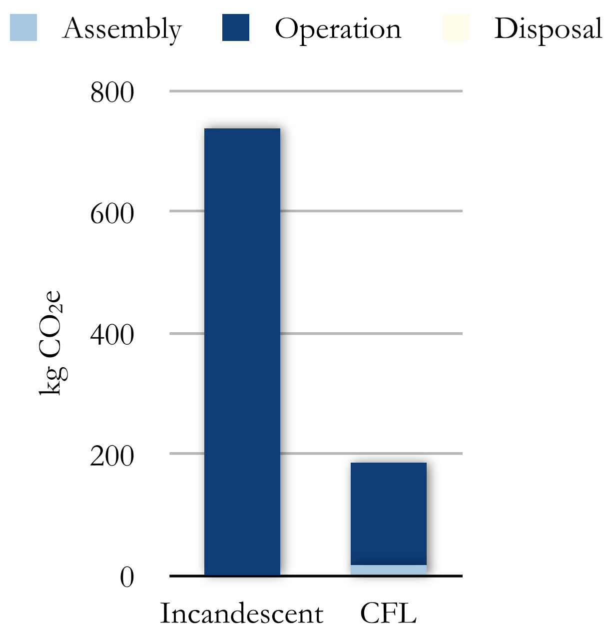
Table 5: Top 5 Contributors of kg CO_2e to Compact Fluorescent 23 W Life Cycle

Process	kg CO_2e
1. Electricity used at the consumer in USA	168
2. Integrated circuit	13
3. Personal vehicle travel from store to home	2.42

Process	kg CO_2e
4. Production of gasoline used in personal vehicle	0.447
5. Printed board	0.194

For an incandescent lamp, almost all of the greenhouse-gas emissions attributable to the lamp occur during the operation phase. Ninety-nine percent, in fact, come from generating the electricity required to power the lamp at users' sites, while most of the other 1 percent is attributable to consumer transportation. Ninety-three percent of the CO_2e emissions from a CFL lamp occur during the operation phase, while approximately 7 percent occur during assembly.

Figure 5: kg CO_2e Characterization of 100 W Incandescent and 23 W CFL Life Cycle



Over the assumed 10,000 hour CFL lifetime using a CFL instead of an incandescent saves 191 lbs of coal (See Appendix A for details), and, if everyone in America replaced one 100 W incandescent with a 23 W CFL, 29,000,000 short tons of coal could be saved.[22,23,24] This accounts for 2.6 percent of total 2006 U.S. coal consumption. These claims are validated by Wal-Mart's research, which can be found in Appendix A.

Qualitative Discussion of Other Non-Carbon Dioxide Pollutants

Mercury Discussion

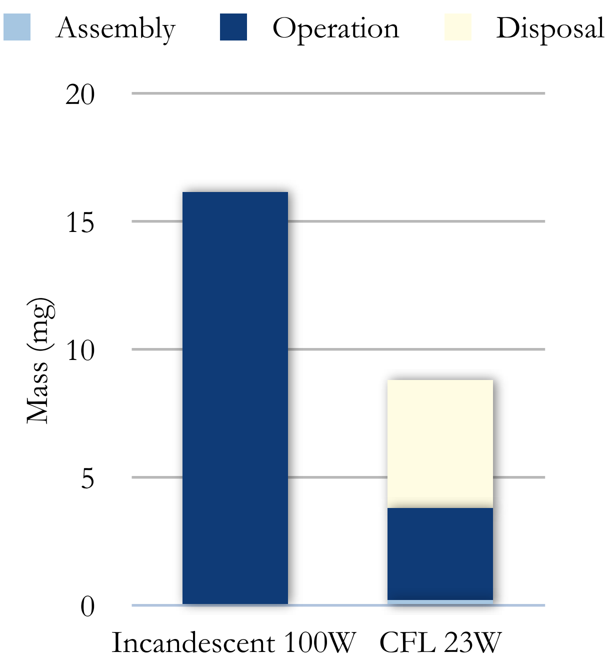
The greatest concern of many consumers is the mercury emissions that can occur during the disposal of CFLs. When the gas mixture in a CFL is ionized, mercury is used to produce ultraviolet light. The average CFL contains 5 mg of mercury (an amount roughly equivalent to the volume of the tip of a ball point pen).[25] In order to fully understand the environmental impact of mercury from CFLs compared to the impact of mercury from incandescents, one must analyze the product over all three phases of its life cycle.

Incandescent lamps are responsible for four times the mercury emissions of CFLs during the operation phase. The mercury emissions produced in the operation phase come from the generation of electricity in coal-fired plants. Coal-fired plants account for 50 percent of the U.S. electricity mix, and for every kWh they generate, 0.016 mg of mercury is emitted.[26]

Quantifying this in the LCA for the required lumen-hours (1,600 lumens for 10,000 hours), incandescents emit 16 mg into the air during operation while CFLs only emit 4.6 mg.

Another 5 mg of mercury is added to the CFL's total if it ends up in a landfill (the worst case scenario), which brings the total mercury emissions for the CFL to 9.6 mg. This is still 6.4 mg less than what would be released when using an incandescent.

Figure 6: Hg Emissions Over Life Cycle



The efficiency of a CFL means it saves a significant amount of electricity during the operation phase. Where coal-fired plants play a major role in producing electricity for a given region, the benefits of using CFLs are therefore increased proportionately.

Lead and Other Toxins Discussion

In addition to greenhouse-gas emissions and mercury pollution, lead and arsenic are also of concern. A greater amount of arsenic and lead are released during the life of a CFL than during the life of an incandescent.

Table 6: Life Cycle Arsenic and Lead Emissions

	Arsenic Emissions (mg)			Lead Emissions (mg)		
	Airborne	*Waterborne*	*Soil*	*Airborne*	*Waterborne*	*Soil*
Incandescent 100 W	0.639	1.002	0.011	0.79	1.091	0.073
CFL 23 W	0.507	7.19	0.002	1.434	34.6	0.012

For a CFL the production of the integrated circuit and the electricity used in China have the highest environmental impact with regards to arsenic and lead. There have been many concerns raised about electronics with regard to arsenic and lead in general. This is evident in the Restriction of Hazardous Substances Directive (RoHS) that was adopted by the European Union and took effect in 2006. It limits the amounts of six types of materials used in the manufacture of electronics, including lead.

For the incandescent lamp, the production of electricity used in China during the manufacture of the lamp is the biggest contributor to lead and arsenic emissions.

Sensitivity Analysis

Several assumptions were made in this LCA. A sensitivity analysis was done on the electronic ballast factor as well as on the life span of the CFL to measure the influence of these parameters on the LCA results.

Electronic Ballast Factor

The electronic ballast is the most critical part to model correctly (see Appendix A for modeling details) since it has the largest environmental impact.

Due to the relative simplicity of the printed board in our CFL compared to industry norms, we multiplied the published life-cycle inventory data for a printed board by a factor of one-third. In order to ascertain the impact of this assumption on our final report, a sensitivity analysis was performed. After adjusting the factor by increments of one-third, the greenhouse gas impact only changed by a tenth of a percentage point.

Operating Cycle (On/Off Cycle of Lamp)

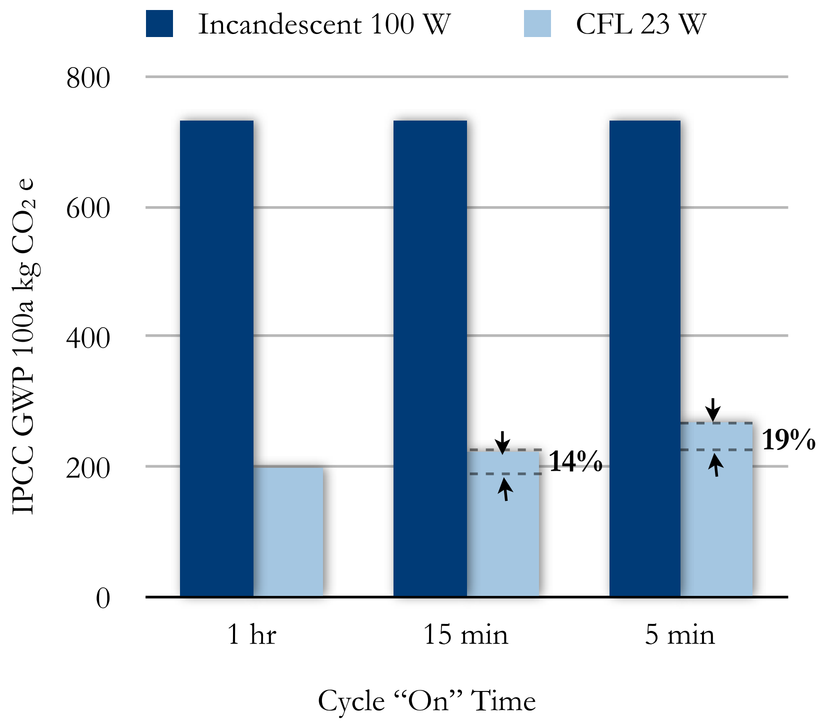
The length of a lamp's rated life depends on factors specific to lamp type. An incandescent lamp's life largely depends on operating voltage while a CFL's life depends on operating cycle.[27] An incandescent lamp fails when its tungsten filament has evaporated to the point where it breaks, and thus cannot carry a current. A CFL fails due to a loss of electron-emissive coating on the electrode, which prevents the lamp from creating and maintaining an electrical arc. This loss of coating occurs during operation, but is accelerated when the lamp is turned on, and the electrode is bombarded with mercury ions. The short CFL life that comes from using them with short operating cycles is a concern to many consumers who don't want to give up the environmental and economical benefits of using CFLs.

A study published in 1998 examined CFL performance for five different operating cycles. It found that when the length of time the lamps were on was reduced from 3 hours to 1 hour, the lamp lasted for 80 percent of its rated life. When reduced to 15 min and 5 min, the lamp lasted for 30 percent and 15 percent, respectively, of its rated life.[28]

Long life is an important consideration for consumers when buying CFLs because of their relatively high cost. For this LCA, we assumed that the life of the CFL was ten times that of the incandescent.

The balance between use-phase CO_2e emissions and assembly phase CO_2e emissions is different for CFLs and incandescents. CFLs are responsible for a larger portion of CO_2e emissions during assembly than incandescents. Incandescents, however, are responsible for a much greater amount of CO_2e during the operation phase than CFLs. When the life of the CFL is reduced through rapid cycling, the emissions associated with assembly for each additional lamp required increase the CFL 's CO_2e emissions over the entire 10,000 hour study period.

Figure 7: Characterization of 23 W CFL Life Cycle

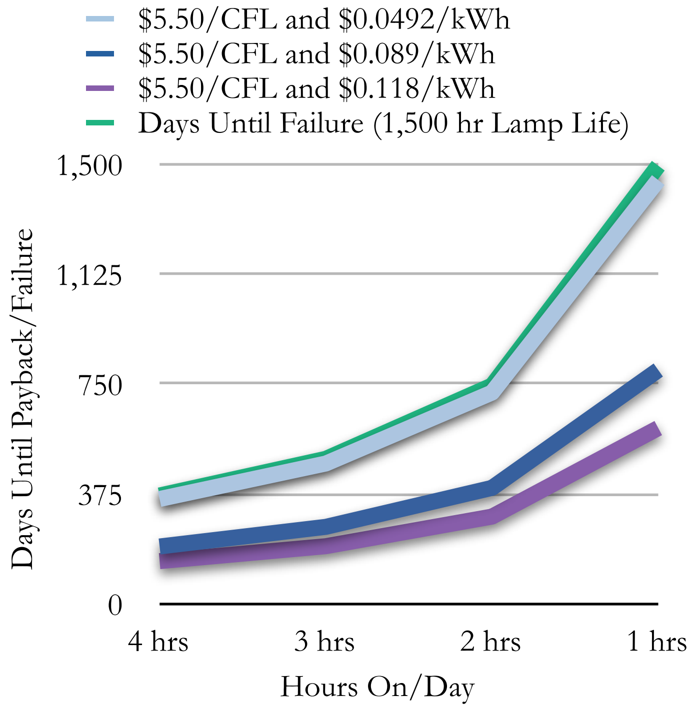


If the cycle time of the light in question is reduced from 1 hour to 15 minutes, then the relative CO_2e savings are reduced 14 percent. If the cycling time is further reduced from 15 minutes to 5 minutes, the relative CO_2e savings are reduced by 19 percent. Even with a cycle time of 5 minutes, CFLs still save 63.4 percent of of the CO_2e emitted from incandescents. The environmental impact from CFLs is dramatically smaller than incandescents for all operating cycles.

Though CFLs with reduced cycle times are clearly net winners in terms of the CO_2e impact the reduced cycle time will have a more significant impact on the economic savings associated with CFLs. An incandescent lamp comparable to the one used in this study currently costs $0.55.[29] Applying the three-to-ten cost factor described in Table 1, a comparable CFL (similar to the one used in this study) costs in the range of $1.65–$5.50. Assuming an on-time of 4 hours/day and a cost of electricity in the range of $0.0492–0.118/kWh (average $0.089/kWh), the lamp will always pay for itself in energy savings.[30]

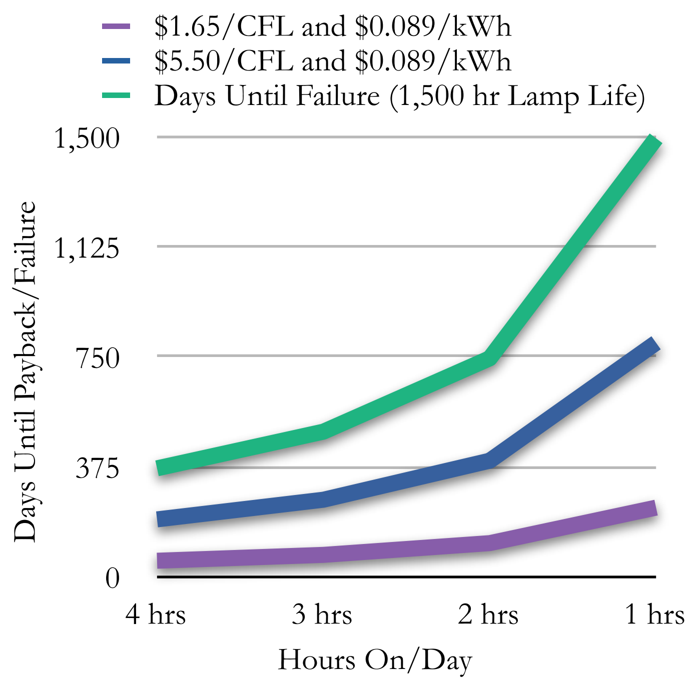
As the cost per kWh of electricity changes, so does the payback period for the CFL. The following graph shows the relationship between payback and cost per kWh. As the cost of electricity decreases, the payback period gets longer. In the worst case scenario—at 1,500 hours of lamp life (assuming 5-minute on-cycles that result in 15 percent of the 10,000 hour rated lamp life) and the cheapest electricity cost—the lamp still pays for itself, but by the smallest of margins.

Figure 8: Dependency of Payback on Cost of Electricity and Failure



There is also a relationship between payback time and the capital cost of the CFL—more expensive lamps, clearly, have longer payback periods. In all scenarios the CFL pays for itself prior to lamp failure.

Figure 9: Dependency of Payback on Cost of CFL and Failure



The ability of a CFL to pay for itself through energy savings decreases as lamp life gets shorter, with low electricity costs, and with high lamp costs. Wal-Mart and Philips are working on initiatives to expand production and bring lamp costs down, which would shorten consumers' payback periods.

It is important to consider operating cycles when installing CFLs. The use of CFLs in appropriate locations, where lights are typically left on more than five minutes, will allow the lamp to reach its rated life and to achieve maximum savings for the consumer.

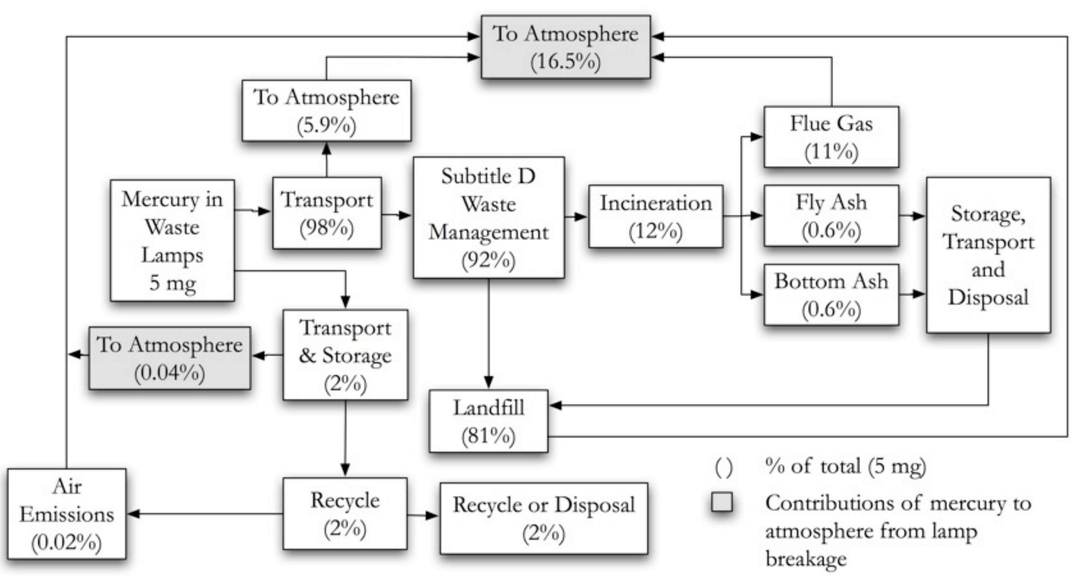
Disposal Options and Recycling

The disposal of a CFL is particularly important when analyzing mercury emissions. Recycling is the best option because it decreases the amount of raw material extracted for new lamps, and it keeps the mercury from getting into the natural environment. However, despite the recent growth in CFL sales, the current options for recycling are limited. One website (www.lamprecycle.org) has regulation and recycling information by state. Sales are expected to increase even further as a wave of programs are initiated around the globe to phase out incandescents. A large increase in CFL sales will mean greater numbers of CFLs will be disposed of. It is therefore vital that consumers dispose of CFLs by methods that have the least environmental impact.

The average amount of mercury contained in a CFL is 5 mg. On a per-lamp basis, this is a very small amount. But the widespread use of CFLs will mean greater amounts of mercury are emitted into the atmosphere and leached into our groundwater. The EPA estimates that CFLs account for 0.01 percent of anthropogenic emissions of mercury. Once incandescents are phased out, assuming a lamp life of ten years and sales per year of 400 million, the amount of mercury disposed of every ten years will be 2.2 short tons (see Appendix A for further details). This amounts to 0.14 percent of anthropogenic mercury emissions.[31,32] It is important to work on solutions to mercury pollution problems that will occur as a result of the conversion to CFLs.

There are three disposal scenarios for a CFL—recycling, incineration, and landfilling. The following schematic is adapted from a mercury end-of-life study on tubular fluorescent lamps, and it illustrates the end-of-life paths for CFLs.

Figure 10: End-of-Life Paths of Mercury from Used Mercury-Containing Lamps[33]



In 2004, The Association of Lighting and Mercury Recyclers estimated that 2 percent of lamps used in homes are recycled.[34] The worst-case scenario for disposal is that the lamp breaks before it is put in a landfill. In that case the mercury goes directly into the atmosphere, groundwater, and/or soil. In a landfill, the mercury is kept in a designated area that is tested regularly for leaching, and, if an unacceptable level is reached, remediation is generally undertaken.

The best scenario for disposal is recycling of the CFL as this results in less mercury going into the natural environment. Additionally, less energy is required for processing new lamps (due to the reuse of materials). Despite these benefits, the recycling of CFLs is expensive. The EPA estimates the cost of proper recycling to be $0.50–$2.00 per lamp.[35] This high cost makes recycling hard to implement. Widespread recycling that captures at least 80 percent of CFLs could reduce the potential mercury load on the environment by 1.8 short tons every ten years.

Conclusion

These analyses of CFL and incandescent lighting's life cycles show that the operation phase dominates both options' CO_2e impact. Therefore, the example CFL use produces fewer emissions than the incandescent. The energy benefits of CFLs have made them a realistic solution in the lighting sector.

Consumers should be aware of disposal methods for CFLs in their areas. There are numerous websites that list recyclers as well as hazardous waste facilities in each state. In addition, some retailers such as IKEA offer a free take-back program in which they provide recycling bins in their stores for spent CFL disposal. Recycling one CFL prevents 5 mg of mercury from entering the environment and reduces the amount of virgin material extracted for a new lamp. In the event that a CFL breaks, cleanup information can be found at (www.epa.gov/mercury/spills/index.htm).

Although CFLs can pay for themselves in almost all applications, to get the most out of their efficiency benefits and reduce their impact on the environment, they should be used in situations where they are left on for long periods. Consumers should be cognizant that lamp life depends on operating cycle. Conscious efforts can be made by the consumer that will result in longer lamp life, quicker payback, and fewer greenhouse-gas emissions as society transitions from incandescents to more efficient forms of lighting.

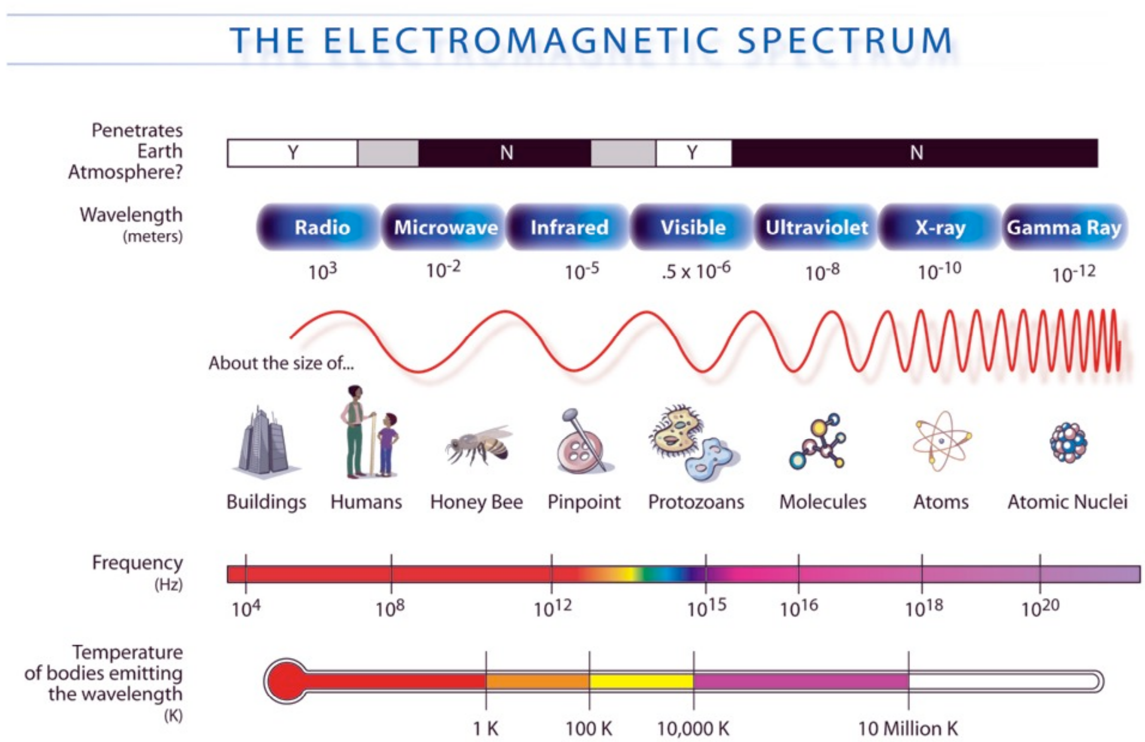
Appendix A

Operation of a CFL

A CFL operates on the principal of fluorescence. It is composed of two main components: a glass tube and an electronic ballast.

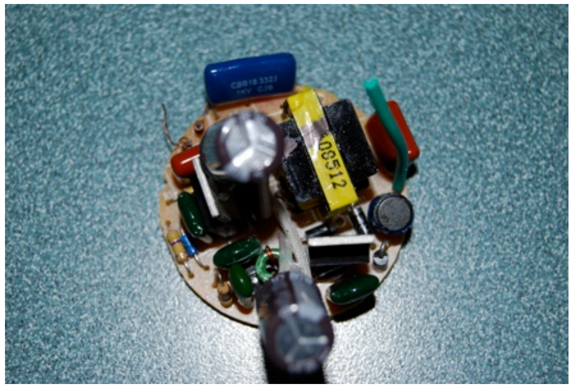
The glass tube encloses a noble gas, typically argon or xenon. When the lamp is turned on, mercury vaporizes in the noble gas forming an ionized cloud which current can flow through. This produces ultraviolet light. This ultraviolet light excites the phosphor coating in the glass tube, producing visible light. Fluorescence occurs when the molecular absorption of a photon triggers the emission of another photon with a longer wavelength (ultraviolet waves become visible light when they are induced by the phosphor). A diagram of the electromagnetic spectrum explains this in greater detail.[36]

Figure 11: The Electromagnetic Spectrum



The electronic ballast provides the lamp's starting power and limits the amount of current flowing through the electrical circuit. It accomplishes this using a relatively simple integrated circuit, as shown in Figure 12.

Figure 12: Electronic Ballast



Operation of an Incandescent Lamp

Incandescent lamps operate on the principal of incandescence.

Incandescence occurs as the result of an object being heated. In an incandescent lamp, the current experiences resistance within the filament, which causes it to heat up producing electromagnetic radiation.

These two types of lamps create visible radiation through different processes. When comparing these processes, producing a given quantity of light via fluorescence is more energy efficient than producing that same quantity of light via incandescence. Despite the energy-efficiency benefits of CFLs, much controversy exists regarding their environmental impact when compared to incandescents.

Establishing Light Equivalency

Table 7: Light Output Equivalency Table:[37] Bulb equivalence was established using the EPA equivalency table.

LIGHT OUTPUT EQUIVALENCY

To determine which ENERGY STAR qualified light bulbs will provide the same amount of light as your current incandescent light bulbs, consult the following chart:

INCANDESCENT LIGHT BULBS	MINIMUM LIGHT OUTPUT	COMMON ENERGY STAR QUALIFIED LIGHT BULBS
WATTS	LUMENS	WATTS
40	450	9-13
60	800	13-15
75	1,100	18-25
100	1,600	23-30
150	2,600	30-52

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Life-Cycle Path Assumptions

Distance Sources
Port of Shanghai to Port of Los Angeles: 5,810 nautical miles = 6,686 miles
Source: www.cn.ca/specialized/ports_docks/prince_rupert/transit/en_KFPortsPrinceRupert_transit.shtml
Verified with Google Earth

Port of LA to distributor in Denver: 1,032 miles
Source: Google Maps, http://maps.google.com

Consumer in Denver to landfill in Aurora: 12 miles
Distributor:
Home Depot
Santa Fe, 500 S Santa Fe Dr, Denver, Colo., 80223

Landfill:
Denver Arapahoe Disposal Site, 3500 S. Gun Club Road, Aurora, Colo., 80046
Source: Google Maps, http://maps.google.com

Modeling of CFL Ballast in SimaPro

Table 8: Modeling of CFL Ballast in SimaPro

Component	Material(s)	Mass (g)
Electrolytic Cap	Aluminum	4.25
	General Plastic	~0
Other Caps	Polypropolene Film	4.25
Inductor	Iron	5.67
	Copper Wire	4.25
	Plastic	~0
Transistors	Plastic (ABS)	1.42
	Aluminum	2.84
Resistors	Integrated Circuit	1.42
Diodes		
High Voltage Capacitor		
Torus Magnet	Iron	0.60
	Total =	24.70

Note: Components and materials were estimated from inspection of a CFL ballast, general electrical engineering knowledge, and www.wikipedia.com.

Calculations

Coal Savings

Coal savings resulting from replacing incandescents with compact fluorescent lamps.

$$734\,kgCO_2e - 184\,kgCO_2e = 550\,kgCO_2e\ savings$$

$$550\,kgCO_2e \times \frac{2.205\,lb}{1\,kg} = 1212.75\ lbCO_2\ saved$$

$$\frac{1212.75\,lbCO_2\ saved}{2.095\,\frac{lbCO_2}{kWh}} = 578.88\,kWh$$

$$578.88\,kWh \times \frac{3{,}412\,Btu}{1\,kWh} \times \frac{1\,short\ ton\ of\ coal}{20{,}681{,}000\,Btu} = .0955\,short\ tons\ of\ coal$$

$$.0955\,short\ tons\ of\ coal \times \frac{2{,}000\,lbs}{1\,short\ ton} = 191\,lbs\ coal\ saved$$

$$191\,\frac{lbs\ coal\ saved}{CFL\ lamp\ substitution} \times \frac{.0005\,short\ tons}{1\,lb} \times 301{,}139{,}947\ people = 29{,}000{,}000\,short\ tons$$

$$\frac{29{,}000{,}000\,short\ tons}{1{,}112{,}292{,}000\,\frac{short\ tons\ consumed}{year}} = 2.61\%$$

Predicted Mercury Emissions

Predicted mercury emissions from CFLs and their contribution to anthropogenic mercury emissions after stringent regulations are placed on incandescents.

$$200{,}000{,}000\,\frac{CFLs\ sold}{year} \times 2 \times 5\,\frac{mg\,Hg}{lamp} = 2{,}000{,}000{,}000\,mg\,Hg = 2\,\frac{Mg\,Hg\ disposed}{10\,yrs}$$

$$144\,\frac{Mg\,Hg\ emitted\ from\ anthropogenic\ sources}{year} - .0001\left(144\,\frac{Mg}{yr}\right) + \frac{1}{5}\,\frac{Mg}{year} = 144.19\,\frac{Mg\,Hg}{year}$$

$$\frac{.2\,\frac{Hg\ disposed\ from\ CFLs}{year}}{144.19\,\frac{Mg\,Hg\ emitted\ from\ anthropogenic\ sources}{year}} = .14\%\ total\ anthropogenic\ emissions$$

Validation By Comparison With Wal-Mart Claims[38]

Wal-Mart claims:

1. One Compact Fluorescent light bulb keeps half a ton of greenhouse gases (CO_2e) out of our air.

In comparison to Wal-Mart's claims, the savings achieved in this scenario is .606 short tons CO_2e per lamp.

$$\left(734\,kgCO_2e - 184\,kgCO_2e\right) \times \frac{2.205\,lbs}{1\,kg} \times \frac{1\,short\ ton}{2{,}000\,lbs} = .606\,short\ tons$$

2. If its 100,000,000 customers bought just one compact fluorescent light bulb, they would keep 22 billion lbs of coal from burning at power plants.

When the coal savings are applied to 100,000,000 customers instead of the population (as done in the coal savings calculation), 19.26 billion lbs of coal are saved (compared to Wal-Mart's 22 billion).

$$29{,}000{,}000\,\textit{short tons} \times \frac{2{,}000\,\textit{lbs}}{1\,\textit{short ton}} \times \frac{100{,}000{,}000\,\textit{customers}}{301{,}139{,}947\,\textit{people}} = 19.26\,\textit{billion lbs of coal saved}$$

Appendix B

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