Life Cycle Energy Comparison of Compact Fluorescent and Incandescent Light Bulbs

Hitesh Soneji

Sustainability Science Paper
LUMES, Lund University, Sweden

January 11, 2008

1 Introduction

There is presently a widespread trend towards wholesale replacement of incandescent bulbs with compact fluorescent light(CFL) bulbs. Certain nations and regions (Australia, the EU, and Ontario, Canada) have or are considering bans on incandescent lighting.[12] With such a significant shift looming, especially in a ubiquitous device, this study intends to shed some clarity on the life-cycle energy impact. While it is clear that during use, CFLs consume less electricity than traditional incandescent bulbs, it is not so evident to what extent the increased manufacturing burden offsets the energy savings during use. Of primary concern is to determine whether energy burdens are simply being migrated from household to manufacturing sectors and in practice, to facilities in Southeast Asia. This analysis is especially pertinent due to growing global concerns over green house gasses, for which migration of CO2 emissions from one region to another is of no environmental benefit.

The incandescent light bulb was invented by Swan in England and Thomas Edison in the US, both in 1879, well before the age of electronics.[2, 4] Besides developments in filament materials, the incandescent has remained true to its original, simple design. Today's incandescent: a tungsten alloy filament rests inside of a glass bulb filled with argon and nitrogen. When excited by electricity, the filament glows.[5] Although the incandescent produces a rather warm full spectrum light, it wastes most of its energy, lost to heat. As little as 10% of the electricity consumed is transformed into visible light.[12]

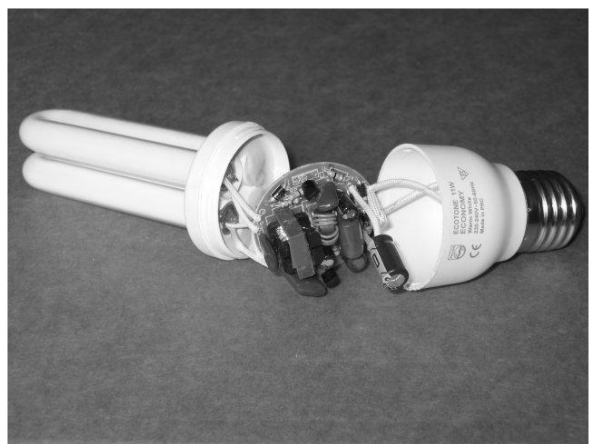

Figure 1: CFL tube, electronics, and base (left to right). Photo from www.pavouk.org/hw/lamp/

Fluorescent lamps were developed in 1938. The compact fluorescent variety have existed in various formats since the 1970s.[4]. The CFL is a more complex device than the incandescent. As shown in figure 1, a typical CFL consists of an electronic starter circuit and a phosphor lined tube, filled with argon and a small amount(5-

10mg) of mercury vapor.[5] High voltage electricity is used to excite(ionize) the mercury vapor which then radiates ultra violet light. The UV light is converted to the visible spectrum by a fluorescent coating inside the tube.[13] Recent advances have brought CFL's closer to a broad spectrum light, but the light is typically considered to be of a less quality than that of an incandescent.[12] The greatest advantage of CFLs is found in its energy efficiency during use, with much less energy lost to heat. CFLs typically convert about 45% of the electricity to visible light.[12]

Since CFL's take advantage of both passive and semiconducting electronic components, they involve complex manufacturing flows and induce greater energy demand. This study intends to quantify the manufacturing induced energy demand, and compare this increase with the energy savings of a CFL over an incandescent. In this way, a life-cycle energy comparison is formulated. Additionally, a life-cycle mercury comparison is included. This study does not account for the energy impacts from CFL disposal.

(Note: Throughout this document, decimal point [.] denotes fraction, while comma [,] denotes thousands.)

2 Methodology

As with most life-cycle analysis, the greatest hurdle is lack of appropriate data and information regarding the manufacturing process. The source data for this study comes primarily as proxy information for materials and technologies similar to those used in CFLs. The proxy data was found in studies relating to life-cycle analysis of computers, computer monitors, and industrial economic flows. Estimation techniques then translate the proxy data to equivalent data for CFLs. These assumptions and estimates are laid out in section 3.

Two approaches have been used to quantify the energy demand of CFL manufacture. The first is the Process-Sum method. In this method, the various manufacturing processes are translated into energy / unit of material and then normalized per bulb. The second method involves the economic input-output method. In this method, industry wide monetary movements are the basis for determining energy consumption within various industrial sectors. With careful estimation, the industry wide values can then be normalized to a per unit basis.[14]

When appropriate, separate values are maintained for thermal energy and electrical energy. Only during the final comparison are the two types of energy merged. The electrical energy is translated by reverse calculating the thermal energy required for electricity generation based on a global average as presented in section 3.

2.1 Process - Sum

CFL	Incandescent
electronic starter	tungsten filament
phosphor coating +	dispersal coating +
gases +	gases +
glass tube*	glass bulb*
plastic casing	
metal base*	metal base*

Table 1: Bulb Components. [*] indicates similar segments. [+] indicates segments that lack data

The Process - Sum method begins by identifying the physical construction of each bulb. In table 1, the physical segments of each bulb type are listed. In order to simplify the analysis, similar and identical components were identified and not included in the computations. These include the metal base and glass tube or bulb (indicated with an *). Additionally, no process energy data was available for the various bulb coatings and gases used to fill the tube or bulb (indicated with a +). It is estimated that these elements of the bulbs do not vary significantly between the two types of lights. The remaining components differ in complexity and purity and thus have different manufacturing energy demands. The derivation

Component	EIOLCA Industrial Sector[6]	Fraction of 1 Mil 1997 US $
electronic starter	semiconductors and related device mfr.	65%
phosphor coating	electric lamp bulb and part mfr.	total = 12.5%
argon, mercury vapor	electric lamp bulb and part mfr.	see total above
glass tube	glass and glass products	17.5%
plastic casing	... all other plastic products	5%
metal base	electric lamp bulb and part mfr.	see total above

Table 2: Industrial sectors involved in CFL manufacture.

of their energy demands will be discussed in section 3.

If similar components are assumed to demand similar amounts of energy, the following equation can be used to compute the additional manufacturing energy demand of a CFL bulb, where units should be in terms of energy / bulb.

$$E_{TotalDiff} = E_{electronics} + E_{plastic} \quad (1)$$

The total difference is then compared against the typical electricity savings over the lifetime of the bulb.

2.2 Economic Input - Output

This method involves extracting data from an existing economic input - output (IO) energy analysis. Carnegie Mellon University's Green Design Institute[6] has compiled a concise and useable IO energy database (EIOLCA) for some 500 economic activities. The EIOLCA tool also provides a hybrid option where various sectors can be combined in the appropriate proportions to represent the specific product for which analysis is being performed. The base unit in EIOLCA is in terms of 1 million US dollars of *producer price* economic activity *in 1997*.

Using the EIOLCA base unit, the various industrial sectors which contribute to the manufacture of the CFL have been estimated as shown in table 2 on page 3. The core industrial sector: *electric lamp bulb and parts manufacture* represents the entire industry, including incandescent bulbs, fluorescent tubes, and CFLs. Therefore, I have included this sector as a fraction of the overall CFL contribution, while increasing the semiconductor and glass contributions to more accurately reflect the different CFL design. For comparison, the *electric lamp bulb and parts manufacture* sector is used directly to represent the production energy impact of the incandescent lamp bulb. Although this is a gross approximation, it serves for the rudimentary nature of the precision of this study.

3 Analysis

Analysis begins by determining the energy savings during use of a typical CFL. CFLs have lifetimes ranging from 5000-10,000 hours, depending on quality of construction and usage patterns. Meanwhile, an incandescent lifetime is only 1,000 hours. The same CFL will use 15 watts, while the incandescent will use 60 watts.[12] Using these time frames, normalized to one average-life CFL, the electricity savings during use is given by the equations:

$$E_{savings} = E_{incandescent} - E_{CFL} \quad (2)$$

$$\begin{aligned} E_{savings} &= (7.5\text{bulbs} * 1,000\text{hours} * 60\text{watts}) \\ &\quad - (1\text{bulb} * 7,500\text{hours} * 15\text{watts}) \\ &= 337,500\text{Wh} = 337.5\text{kWh} \quad (3) \end{aligned}$$

Electrical energy is not equivalent to thermal energy. Therefore, in order to use the value above in comparisons with manufacturing flow energy, it must be translated into fossil fuel energy equivalent. The global average of electricity generation technologies requires 320 g fossil fuels to generate 1 kWh.[14] Furthermore, the average energy content of fossil fuels, as estimated by the International Energy Agency World Energy Statistics database is 39 MJ / kg.[7] Combining equation 3 with these two data points, the energy savings in terms of fossil fuels can be computed:

$$E_{Fossil} = \frac{337.5kWh}{\text{bulb}} * \frac{320g \text{ f.f.}}{kWh} * \frac{39kJ}{1g \text{ f.f.}} = \frac{4,212MJ}{\text{bulb}} \quad (4)$$

Thus, 4,212 MJ is the base energy savings to be compared against. Ideally, CFL manufacture should demand no more than this amount of energy, and preferably significantly less to have a positive environmental impact. As stated earlier, two methods of analyzing the manufacturing energy demand of CFLs are compiled here. The Process-Sum details are presented first, the IO analysis follows, and the analysis is concluded with a summary of the results as compared with the life-time energy use.

3.1 Process - Sum Analysis

Continuing from the methodology of the process-sum approach, equation 1 can be further broken down to the electronic components. Based on schematics for typical CFL electronic starter circuits, the contents of each CFL's electronics payload can be estimated as in the following table.[13]

Qty	Item	Proxy Process	Norm
1	PCB	circuit board	12.56 cm^2
9	diodes	semiconductor	2 mm^2
2	transistor	semiconductor	4 mm^2
9	passives	semiconductor	1 mm^2
1	assembly	1/300 of 1 PC	
1	plastic	bulk materials	50 grams

Table 3: Electronic starter components per bulb.

For each component, the proxy process and norm is provided to correlate with available data. Process data is leveraged from LCA studies of the personal computer industry by Williams[14]. Williams' data is specific to production processes for electronic materials and is an average of several global sources. This data acts as a proxy for specific CFL manufacturing processes as was shown in table 3. The table below shows Williams' pertinent data, normalized to units applicable to a CFL. (See section 7.1 for normalizing calculations.)

Process	norm	Elec Wh /norm	Fossil Fuels kJ /norm
circuit board	cm^2	3.4	11.6
semi-conductor	mm^2	15.4	27
assembly	per CFL	170	386
plastic	per CFL	n/a	3,400

Table 4: Normalized computer industry data from Williams[14].

Combining the two tables, multiplying factors, and summing each process, the thermal and electrical energy values are computed. These values represent the additional manufacturing energy required over and beyond that required for traditional incandescent bulbs. (See section 7.2 for summation details.)

$$E_{elec} = 751 \text{ Wh/CFL} \quad (5)$$

$$E_{thermal} = 4.88 \text{ MJ/CFL} \quad (6)$$

Summing the above and translating to thermal equivalents provides:

$$E_{thermal} = 14.257 \text{ MJ/CFL} \quad (7)$$

3.2 I-O Analysis

The economic I-O analysis is carried out in a completely different manner. Using the hybrid sector fractions presented in table 2 on page 3, EIOLCA returns information on energy use in the many sectors contributing to CFL lamp manufacture. Then using only the *electric lamp bulb* *manufacturing sector*, EIOCLA returns a different set of results is used to represent the traditional incandescent bulb. As the details of the EIOLCA methodology are readily available at their website[6], only the totals are reported here in table 5.

Sector	Total TJ/1M US$
Hybrid CFL sector[6]	6.96
Elec lamp bulb sector[6]	7.79

Table 5: EIOLCA results for 1 million 1997 US dollars of producer price activity.

Table 6 shows casual estimates for consumer and producer pricing of lamps in 1997 US dollars. A 40% retail markup is assumed. More precise data regarding lamp pricing was not available for this study. Combining the EIOLCA results with producer prices shown in table 6, we can compute energy contribution per bulb. The result of this normalization as well as the delta between CFL and incandescent can be seen in table 7. The diff. column indicates the increased demand of a single CFL over a single incandescent.

Price Type	CFL	Incandescent
Consumer	$8.00	$0.50
Producer	$4.80	$0.30

Table 6: Bulb Pricing in 1997, US dollars.

Energy Demand	CFL	Incand.	Diff.
Total MJ	33.41	2.34	31.07

Table 7: Manufacturing energy demand per bulb based on EIOCLA data.

3.3 Life-Time Energy Summary

Comparing the data for manufacturing energy against the energy savings, it becomes clear that there is little question regarding the life-time energy savings. Using the more pessimistic of the two methods, the energy savings during CFL use is more than 135X greater than the increased energy demand during manufacture. The following table summarizes the results:

Analysis Method	Energy savings during use	CFL induced manufacturing energy
Process-Sum	4,212 MJ	14 MJ
Economic I-O	4,212 MJ	31 MJ
Averaged	4,212 MJ	22.5 MJ

Table 8: Savings during use vs. manufacturing burden

4 Uncertainties

The data computed by EIOLCA in table 5 seems non-intuitive upon further analysis, where 1 million dollars of activity results in a greater energy burden for incandescent bulbs than for CFL bulbs. Even after normalizing to the producer prices for each bulb, the difference is smaller than one might expect. This uneasiness with the EIOLCA data hints that some of the assumptions made when using the EIOLCA database may be incorrect. Alternatively, the data is correct and intuition is off-track. Further analysis of the EIOLCA assumptions would be fruitful in resolving this uncertainty.

The different results from the process-sum method and EIOLCA are not surprising. The methods are inherently afield and the assumptions involved with each are significant. The many assumptions have been noted in the methodology and analysis. These were necessary in order to complete the study. Ideally, the estimates and approximations would be resolved to more accurate values. In light of the magnitude of difference in the result (between the manufacturing energy cost versus the energy-savings during use), this study finds that the precision used for this study is sufficient to support the conclusion that CFLs have a net energy savings despite their increased manufacturing complexity.

5 The question of mercury

This analysis would not be complete without addressing the question of mercury content in CFLs. As noted in section 1, mercury is a key operating component of the fluorescent bulb. Although alternative ionizing materials may exist, they have not been deployed. Mercury has been identified as a key human health toxicity risk.[3] Per the European Union Restriction of Hazardous Substances (ROHS) directive, mercury content in CFLs has been capped at 5 milligrams.[10] The National Electrical Manufacturers Association (NEMA) has followed suit with a voluntary declaration in the US to limit similar wattage CFLs to 5 milligrams of mercury.[10] Many well known lamp manufacturers have signed on to the voluntary declaration.[9]

Using the calculated CFL energy savings computed above, the electricity generation mercury emissions can be compared with the mercury (Hg) content of a CFL. The most significant contributor to mercury during power generation is coal-fired power plants.[1] According to the International Energy Agency, the global fraction of power generated by coal in 2005 was 40.3%.[8] This value is then combined with actual power plant emissions. The *Hitch Hiker's Guide to LCA* calculates that for each TJ of electricity generated by coal, 0.0325 kg of mercury (or .0325 mg Hg / MJ) are released.[1]

Assuming that 40.3% of the energy savings comes from coal, then the total savings of mercury due to reduced energy demand equates to:

$$\mathrm{Hg}_{\mathrm{reductions}} = \frac{337.5kWh}{\mathrm{bulb}} * \frac{3.6MJ}{1kWh} * \frac{40.3}{100} * \frac{.0325mg\ \mathrm{Hg}}{MJ} = 15.9mg\ \mathrm{Hg} \quad (8)$$

Thus, despite a very poor CFL recycling rate of 2% (in the US), as reported by NEMA and the Association of Lighting and Mercury Recyclers[11], the typical environmental release of mercury per bulb is reduced from 15.9 mg to 5 mg, a net environmental benefit.

6 Implications for wide adoption of CFL as replacement for incandescent.

6.1 To switch or not to switch

From the perspective of a cradle to grave life cycle analysis, this paper finds wholesale incandescent replacement to be of environmental, energy, and economic benefit, especially in a global CO2 concern. Section 3.3 has shown that CFL energy savings during use are more than 150X the energy demand induced during manufacture. In addition, section 5 has shown that overall mercury release is reduced from 15.9 mg to 5 mg with CFLs. While questions regarding waste and chemical use will be left to future studies to analyze, their impact is estimated to be less significant then the benefits observed in this study. Thus this study concludes on a rather positive note for the switch from incandescent to compact fluorescent bulbs.

6.2 Potential strategies to further improve the environmental benefits of CFLs

CFLs designed with modular electronic ballast and tube could further reduce manufacturing energy demand. Thus, only tubes would need to be replaced, while the ballast and base could be reused.

During the analysis, it was observed, that in general, the larger wattage the CFL, the greater the amortization of manufacturing energy, and thus life-time energy savings when compared with an equivalent incandescent light bulb.

CFL recycling/refurbishing/buyback programs could help to further minimize environmental release of Hg and could also be of economic benefit to CFL manufacturers.

7 Appendix of Calculations and Notes

7.1 Normalizing Willaims' PC data[14]

Circuit board process normalizing from m^2 to cm^2:

$$\frac{34kWh}{m^2} * \frac{m^2}{10,000cm^2} * \frac{1000}{1k} = \frac{3.4Wh}{cm^2} \quad (9)$$

$$\frac{116MJ}{m^2} * \frac{m^2}{10,000cm^2} * \frac{1000k}{1M} = \frac{11.6kJ}{cm^2} \quad (10)$$

Semiconductor process normalzing from cm^2 to mm^2:

$$\frac{1.54kWh}{cm^2} * \frac{cm^2}{100mm^2} * \frac{1000}{1k} = \frac{15.4Wh}{mm^2} \quad (11)$$

$$\frac{2.7MJ}{cm^2} * \frac{cm^2}{100mm^2} * \frac{1000k}{1M} = \frac{27kJ}{mm^2} \quad (12)$$

Assembly process normalization from per PC to per CFL bulb:

$$\frac{51kWh}{\text{PC}} * \frac{1 \text{ PC}}{300 \text{ CFL bulbs}} = \frac{170Wh}{\text{CFL bulb}} \quad (13)$$

$$\frac{116MJ}{\text{PC}} * \frac{1 \text{ PC}}{300 \text{ CFLbulbs}} * \frac{1000k}{1M} = \frac{386kJ}{\text{CFL bulb}} \quad (14)$$

Normalization of plastic in CFL base (average of CRT and control unit elements):

$$\frac{68MJ}{kg} * \frac{1kg}{1000g} * \frac{50g}{\text{CFL bulb}} = \frac{3.4MJ}{\text{CFL bulb}} \quad (15)$$

7.2 Computing product-sum energy demand[14]

Printed Circuit Board:

$$\frac{3.4Wh}{cm^2} * \frac{12.56cm^2}{\text{CFL}} = \frac{42.7Wh}{\text{CFL}} \quad (16)$$

$$\frac{11.6kJ}{cm^2} * \frac{12.56cm^2}{\text{CFL}} = \frac{145.7kJ}{\text{CFL}} \quad (17)$$

Semiconductor Devices:

$$\frac{15.4Wh}{mm^2} * \frac{(18+8+9)mm^2}{\text{CFL}} = \frac{539Wh}{\text{CFL}} \quad (18)$$

$$\frac{27kJ}{mm^2} * \frac{(18+8+9)mm^2}{\text{CFL}} = \frac{945kJ}{\text{CFL}} \quad (19)$$

Electricty Sum:

$$42.7Wh + 539Wh + 170Wh = 751Wh \quad (20)$$

Thermal Sum:

$$145.7kJ + 945kJ + 386kJ + 3,400kJ = 4,876kJ \quad (21)$$

References

[1] Henrikke Baumann and Anne-Marie Tillman. *The Hitch Hiker's Guide to LCA*, chapter Appendix I: General Inventory Data, pages 487–490. Studentlitteratur, 2004.

[2] Bernard Finn. A Brilliant Achievement. *Electric Perspectives*, 29(5):20–28, 2004.

[3] G. Tyler Miller Jr. *Living in the Environment*, chapter 24, pages 556–558. Brooks/Cole, 14th edition, 2005.

[4] J. B. Harris. Electric lamps past and present. *Engineering Science and Education Journal*, August:161–170, 1993.

[5] James A. Hunt. Automated Lamp Manufacture. *Assembly Automation*, 27(3):190–197, 2007.

[6] Carnegie Mellon University Green Design Institute. Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet]. Available from: http://www.eiolca.net/ [Accessed 4 Jan, 2008]. Energy Data Last Updated Dec 10 2006.

[7] International Energy Agency, Vienna. *World Energy Statistics and Balances: Basic Energy Statistics - Non OECD Member Countries, Release 1*, 2002.

[8] International Energy Agency, France. *Key World Energy Statistics: 2007*, 2007.

[9] National Electrical Manufacturers Association (NEMA). NEMA Voluntary Commitment on Mercury in Compact Fluorescent Lights [Internet]. Available from: http://www.nema.org/gov/ehs [Accessed 4 Jan, 2008]. Site Last Updated Nov 25 2007.

[10] National Electrical Manufacturers Association (NEMA). Voluntary Industry Commitment to Limit Mercury Content in Self-Ballasted CFLs Sold in the U.S. Press Release, March 2007.

[11] Association of Lighting and Mercury Recyclers. NATIONAL MERCURY-LAMP RECYCLING RATE and Availability of Lamp Recycling Services in the U.S. Available from NEMA Website: http://www.nema.org/lamprecycle/, November 2004.

[12] Steve Tosenstock. anotherperspective. *Electric Perspectives*, 32(5):100, 2007.

[13] A. Vitanza, R. Scollo, and A. Hayes. *Electronic Fluorescent Lamp Ballast*. STMicroelectronics, 1999. Application Note.

[14] Eric Williams. Energy Intensity of Computer Manufacturing: Hybrid Assessment Combining Process and Economic Input-Output Methods. *Environmental Science and Technology*, 38(22):6166–6174, 2004.