Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 40 (2016) 185 – 190

www.elsevier.com/locate/procedia

13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use

The Effect of Consumer Behaviour on the Life Cycle Assessment of Energy Efficient Lighting Technologies

Zhe Ying Yu[a], Vi Kie Soo[a], Matthew Doolan[a]*

[a]*Research School of Engineering, College of Engineering and Computer Science, The Australian National University, Canberra, ACT 2601, Australia*

* Corresponding author. Tel.: +6-126-125-2739; fax: +6-126-125-0506.*E-mail address:* matthew.doolan@anu.edu.au

---

Abstract

Energy efficient lamps offer significant energy savings throughout their life. However, there is a variety of energy saving lamps available and it is unclear which impacts the environment least throughout the lifecycle under different use patterns. Different use patterns have a significant impact on the lifetime of each light globe alternative and therefore affect the life cycle impact of each globe.

This paper undertakes a series of Life Cycle Assessments on two alternative lighting choices (Light Emitting Diodes and Compact Florescent Lamps) under a range of use conditions. It was found that the environmental impacts were comparable for CFLs and LEDs, though significantly less than traditional incandescent, for a range of different use cases. The sensitivity analysis carried out shows that the variation in lamp parameters has a far greater effect on the lifecycle impact rather than the use patterns.

Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing

Keywords: Life Cycle Assessment; energy efficiency; light globe; consumer behaviour; use case

---

1. Introduction

Approximately 20% of the world's electricity consumption [1] goes towards artificial lighting use. Of this, 50-70% of domestic lighting is supplied by traditional incandescent lamps (ICL) [2] that are 90-95% inefficient. Therefore the phasing out of ICLs can significantly reduce electricity consumption. In 2007, Australia was the first country to announce the phase out of ICLs [3] and promote alternative lighting sources.

The top alternatives include Light Emitting Diodes (LEDs) and Compact Fluorescent Lamps (CFLs). These alternative technologies reduce electricity consumption through energy-saving during the use phase in comparison to the low energy efficiency of incandescent lamps. Today, CFLs and LEDs are commonly used in homes due to the energy-saving benefit. It is important to understand which lighting technology results in the lowest environmental impact throughout the entire lifecycle to aid consumers in making an informed decision on the preferred choice of light.

Life Cycle Assessment has been used to understand the environmental impacts associated with each phase of the bulb's life. Where life cycle analyses have been conducted in the past, the long lifetimes of LED and CFL lamps are shown to offset the manufacturing and disposal impacts as fewer lamps are required [4-6]. However, lamp performance varies according to the operating environment and use patterns [7]. In particular, the lifetimes of lamps are generally rated as a point in time when it no longer produces sufficient lumens—rather than a complete black out of the lamp.

This study assesses sensitivity of the life cycle impact for both CFLs and LEDs under different operating conditions and different lamp parameters. The paper will identify the most appropriate technology for different use cases.

2. Background

Previous studies focus largely on the comparison between different lamp types and their relative environmental impacts. As the use phase is the largest contributor due to electricity usage, these studies favor the lamps with higher efficiency

Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing
doi:10.1016/j.procir.2016.01.097

and longer lifetimes [4-6]. However, due to the complex structure of these alternatives, they are harder to produce and dispose of in an environmentally friendly manner. A summary of percentages taken from past literature [4, 6, 8-14] of the impact of different phases in three impact areas are shown in Figure 1 below.

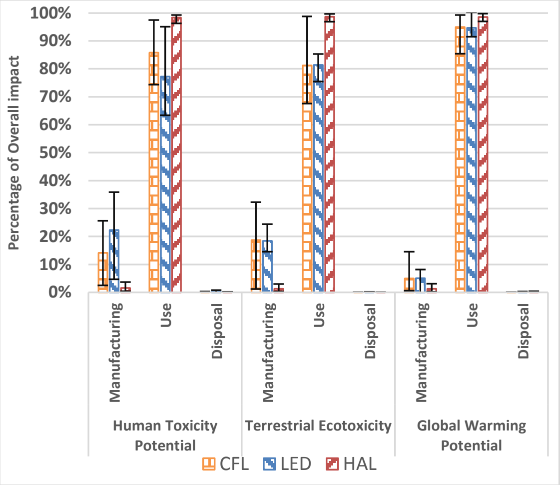

Figure 1: Ranges of Relative Percentages of Different Life Cycle Phases of Light bulbs on three Different Impact Areas in Past Literature

Although the results of past literature are not directly comparable to each other due to different lamp parameters and functional units chosen in LCA, there is a general consensus that the relative manufacturing impacts are higher for CFLs and LEDs than ICLs. However, such results are considered negligible due to the high impacts of electricity usage in the use phase and the relevant savings CFLs and LEDs make in this phase.

The wide range of values in Figure 1 also suggests a variety of lamps with varying performance are available on the market. In general, the lamp parameters of interest are the lumen efficiency, lifetime and wattage. However, such parameters can change over the lifetime of the lamp due to various external influences such as the use condition; this paper addresses this by modelling the impacts of lumen depreciation and reduced lifetime due to use conditions. Rapid on-off switches can also affect the performance of the lamp overtime and hence reduce its useful lifetime [15]. The limit on the number of switching cycles before failure is an often overlooked characteristic of lamps. The number of switching cycles is dependent on the specific start up mechanisms of lamps.

3. Methodology

3.1. Lamp Parameter Definition

This study will analyse the effects of use patterns on the environmental impacts of alternative lighting technologies. The lamp ratings for both technologies were taken from a sample of 70 LED bulbs, 105 compact fluorescents from OSRAM, GE Lighting and Philips lamp datasheets. The analysis is based on the medians of existing lamp data, and are summarised in Table 1.

Table 1: Rated Lamp Parameters Used in Analysis

	LED		**CFL**	
	Range	Median	Range	Median
Rated life time (hours)	15000-40000	25000	6000-12000	10000
Rated switching cycles	25000-100000	100000	7000-30000	10000
Lumen output (lm)	250-1650	806	270-5300	850
Wattage (W)	3.2-18	10	5-23	15
Efficiency (lm/W)	53.75-103.12	80.3	48.33-68.75	60
Lumen maintenance factor at end of life	-	0.7	-	0.65

3.2. Life Cycle Assessment (LCA)

As demonstrated in the past research [8-10, 16], LCA is a widely used tool to assess the environmental impacts of artificial lighting over its entire life span from cradle to grave. The LCA in this paper was conducted based on the Australian/New Zealand version of ISO 14040:1997 [17]. To standardise the lamps' performances, a functional unit of 200 million lumen hours of lighting service was used to ensure at least one lamp is replaced in the analysis. This functional unit is equivalent to approximately 23.5 CFLs and 9.92 LEDs.

The GaBi 6.0 Educational Database 2013 was used to model the processes involved in the life cycle of lamps from cradle to grave. A case study for Australia was made due to its pioneering move to phase out ICLs [18]. Transportation of the lamps was omitted from analysis due to the wide distribution of lamps and small environmental impact of transportation [4]. It was assumed lamps were manufactured in China and disposed of in landfills at the end-of-life (EOL). Inventory data was obtained from a previous comprehensive study by the United States Department of Energy [4]. The data inventories are representative of their respective types of lamps and are therefore suitable for analysis. Processes required to produce raw materials were taken from the GaBi database. The GaBi database does not contain electronic component data and for this, an external database—the CPM LCA Database from the Swedish Life Cycle Center [19] was used to model the production of resistors, transistors, capacitors and diodes. As suitable data was unavailable for individual LED units and the integrated circuit, they were modelled as diodes. The presence of phosphors for light emission and precious metals—gold, silver and mercury were also omitted from analysis due to lack of information in the databases.

As there is no large scale formal recycling scheme for energy efficient lamps in Australia, they were assumed to be disposed of to landfills. Data for Australian landfills was not available so four standard landfill models from the GaBi database for the European Union was used—landfill of metals, landfill of inert matter, landfill of plastics and landfill of municipal waste, all supporting leachate treatment and gas utilization. The materials present in the lamps were then broken down into these categories, with anything not fitting the other three categories being modelled as standard municipal waste.

3.3. Use Case Definition

Typical use patterns were then defined for a range of rooms using the number of switching cycles per day versus the number of hours lights are switched "on" for. This data is based on likely use patterns for the different rooms. The use cases are defined to identify extremes of operation. The use conditions are defined for a typical household of 4 in Australia and lighting is switched on only when natural lighting is low.

- The Bedroom is a private space assumed for the occupiers to return to at the end of the day. It is assumed the room is occupied from late at night until the next morning.
- The Bathroom is assumed to be occupied randomly during the day but lighting is only required for late at night.
- The Hallway is assumed to be a common space where light is left on overnight to allow for ease of movement.
- Common spaces encompass the kitchen, dining and living room areas where the room is occupied by multiple people during the morning, evening and late at night.
- The Office is a workspace for which light remains on during business hours over the course of the day.

Given these assumptions, the following table summarizes lamp use under the given conditions.

Table 2: Defined Use Case Parameters

	Number of switching cycles/day	Number of "on" hours/day	Average on-time (hours)
Bedroom: ($9m^2$)	2	4	2.0
Bathroom: ($4.5m^2$)	4	1	0.25
Hallway: ($3m^2$)	1	12	12.0
Common space: ($20m^2$ living room)	2	7	3.5
Office: (~$9m^2$)	1	12	12.0

Other factors defining the use environments such as temperature and required lighting levels were assumed constant and hence not factored in as differences. The number of switching cycles and "on" hours were then used to determine the cause of failure in the lamp and through this, the overall lifetime of the lamp was determined under the given use condition. As expected there was an increase in relative impact of lamp replacement, the altered lifetime would then affect the overall environmental impact of using a lamp in the given scenario.

3.4. Impact Assessment

The CML2001 (April 2013) method in the GaBi Database provides 12 midpoint indicators which were used to assess the environmental impacts. Of these, three indicators were chosen to understand the environmental impacts of the lamps. Global Warming Potential (excluding biogenic carbon) (GWP), was chosen to reflect the impact of the use phase on the environment. Human toxicity (HTP) and terrestrial ecotoxicity (TET) were then used as comparative indicators to understand the impacts of manufacturing phases. The midpoint indicators were measured in world person equivalents.

4. Results

The cause of failure in the lamps for various use cases is shown in Table 3. Of the given use environments, the only lamp whose lifetime was limited by switching cycle was the CFL when used in the bathroom.

Table 3: Life times of bulbs under different use patterns (the lower value indicates the reason for failure for the given use pattern)

	CFL		LED	
	Lifetime based on switching cycles (days)	Lifetime based on rated hours (days)	Lifetime based on switching cycles (days)	Lifetime based on rated hours (days)
Bedroom	5000	2500	50000	6250
Bathroom	**2500**	10000	25000	25000
Hallway	10000	833.3	100000	2083.33
Common space	5000	1428.6	50000	3571.4
Office	10000	833.3	100000	2083.3

The high number of switching cycles for both lamps means they are likely to fail before the rated hour life time for the majority of use cases. However, the critical times (t_c) for which lamps are required to be switched on to ensure failure is not caused by switching cycles can be found using the following equation:

$$t_C = \frac{rated\ hour\ life\ time}{rated\ maximum\ number\ of\ switching\ cycles} \quad (1)$$

If the "on" time per switching cycle is less than the critical time, the life of the lamp is limited by the number of switching cycles. For the given lamps, the LED has a critical "on" time of 15 minutes and the CFL has a critical "on" time of 60 minutes. As the equation is a direct ratio, the critical time is inversely proportional to the number of switching cycles. If the rated switching cycles decrease by 50%, critical time increases by 50% but under most use cases this has little effect on the overall life cycle analysis due to the low frequency of switching. However, with the Bathroom scenario where switching is more frequent, switching cycles limitation plays a much stronger role. The limitations in switching cycle reduces overall lifetime by 75% for the CFL and if nominal switching cycles is halved for the LED, the overall lifetime of the lamp is reduced by 50%.

LCA was carried out for each of the use cases identified above with the functional unit of 200 million lumen hours. The lumen output of each lamp was assumed to be the average rated output as indicated in Table 1. As the failure mechanism is limited by the rated hours in all cases, (other than the bathroom for CFL), the LCA provides the same results. The results as shown in Figure 2 are presented for the LED, the CFL and the CFL in the bathroom.

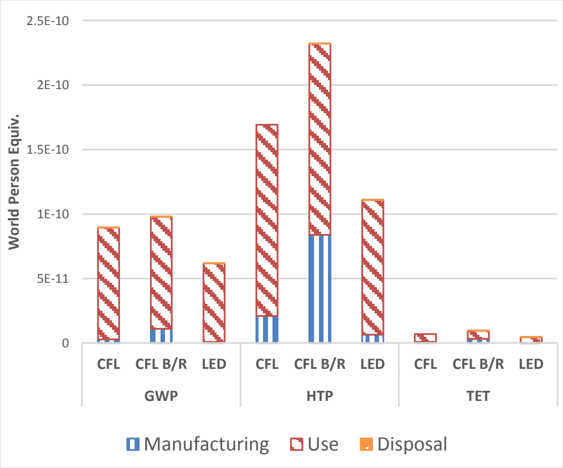

Figure 2: Impact Assessments for LED, CFL standard ratings and CFLs used in the bathroom (B/R)

As can be seen in Figure 2 the high switching cycles of the bathroom use case reduces the lifetime of the CFL by 75% resulting in a high CFL disposal impact. This increases the impact of CFL in the bathroom manufacturing and disposal cases by a factor of 4 for the same amount of lighting service. Both the human toxicity and terrestrial ecotoxicity indicators reflect the manufacturing impacts of the different lamp choices. Therefore both of these indicators are impacted by the increase in lamp replacement, and in use cases where switching frequency is high, the human toxicity and terrestrial ecotoxicity impact becomes much higher. The climate change indicator is not significantly affected by the change in failure mode for the lamps as most of the impact is generated during the use phase of the lamp.

However, this assessment has been undertaken for a single median lamp. The following analysis is undertaken to understand the impact of variability in lamp parameters and their impacts on the life cycle assessment.

5. Sensitivity Analysis

As a range of lamps exist in the market, the sensitivity of the results to varying initial lamp parameters and use impacts were tested independently. The test was conducted by altering the parameters listed in Table 1 using the scenarios listed in Table 4.

Table 4: Defined Scenarios for Sensitivity Analysis

Scenario	Description
A	Baseline Case with Median Values
B	50% Decrease in Lifespan
C	25% Decrease in Lumen Efficiency
D	25% Increase in Lumen Efficiency
E	Lumen Depreciation
F	Bathroom case (CFL has 75% reduction in life)
G	Switching time of 5 Minutes

Scenario D simulates the performance of lamps depreciating over time through a decrease in lumen output. Actual lumen depreciation is dependent on a range of factors including ambient temperature, heat extraction, voltage, driver and component factors [20] but the modelling of these aspects are outside the scope of this paper. For LEDs, only a lumen maintenance factor of 0.7 at the EOL was provided from datasheets. Therefore, depreciation over time was modelled as a linear curve given that the lumen depreciation occurs at varying rates for different lamps when comparing the lumen depreciation charts. Lumen depreciation for CFLs was modelled using a polynomial function for given data values [21-24]. The overall effects of lumen depreciation were then found by averaging lumen output over the course of the lamps' lifetimes as depicted in Figure 3.

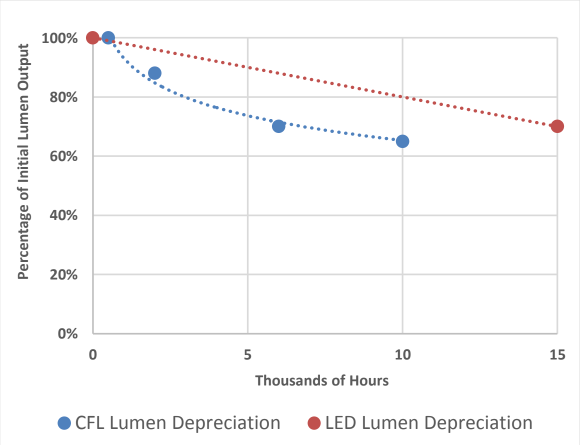

Figure 3: Assumed Lumen Depreciation Graphs for CFLs and LEDs

The impact of each scenario on climate change is shown in Figure 4. The most significant impact is seen for scenarios D, E and F. Each of these relate to the lumen efficiency of the lamp.

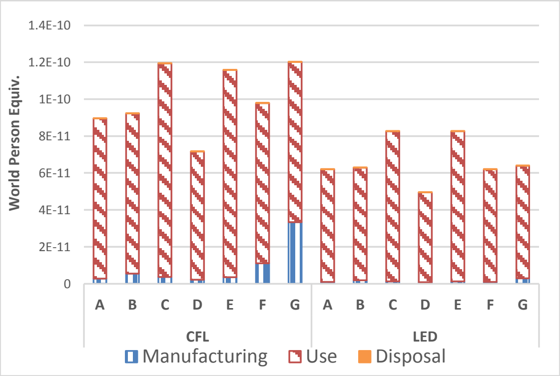

Figure 4: CML2001 Global Warming Potential Midpoint indicator excluding Biogenic Carbon for varying LED and CFL ratings

The CFL appears to have a higher overall impact on climate change due to lower efficiency. The manufacturing phases have similar but relatively small impacts on climate change. In general, the total climate change impacts of lamps are not affected by lifespan variations due to the high impact of use phase. The high electricity consumption during use causes a significant decrease (Scenario D) or increase (Scenario C) in use phase impact but no changes to disposal or manufacturing impacts when lumen efficiency is tested by adjusting lumen output.

Similarly, when efficiency decreases over time due to lumen depreciation (Scenario E), the lamps have significantly higher impacts simply due to reduction in output over time. The reduction in output increases the number of lamps required to fulfil the functional unit of given lighting service and thus increases the number of lamps required. However, due to higher manufacturing impacts of the CFL in GWP, the overall increase in CFL impact is higher. LED disposal impact also increases slightly due to the requirement of more lamps to account for this decrease in output.

The other two indicators: terrestrial ecotoxicity and human toxicity, are influenced significantly by the manufacturing impact of the lamps and hence the need for replacement of lamps. The impact of the different scenarios on these two indicators are shown in Figures 5 and 6.

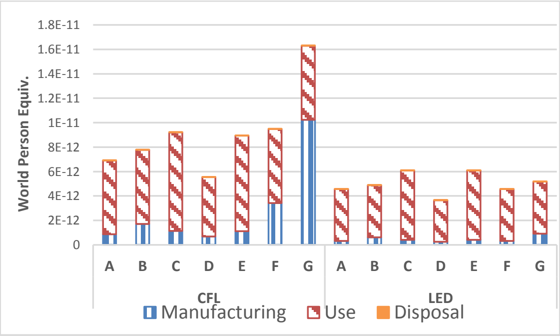

Figure 5: CML2001 Terrestrial Ecotoxicity midpoint indicator for varying LED and CFL ratings

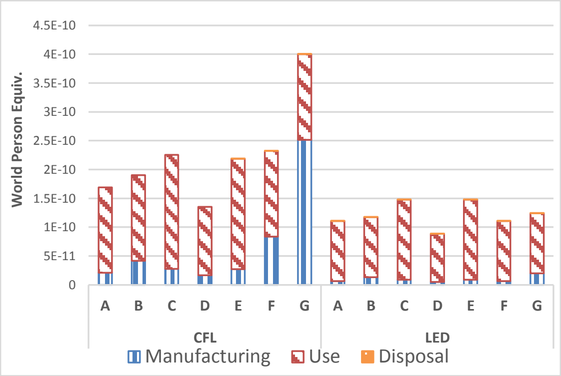

Figure 6: CML2001 Human Toxicity midpoint indicator for varying LED and CFL

Both Figures 5 and 6 highlight the significant toxicity impacts of disposal and LED manufacturing as a result of landfill disposal. The relative impacts of each life cycle stage on terrestrial ecotoxicity and human toxicity are very similar and carry a significant portion in the manufacturing phase due to the large number of electronic components present in the CFL system. In all cases, the disposal phase appears to have minimal impact across all categories.

6. Discussion/Conclusion

The climate change impacts for LEDs and CFLs are similar due to the similar efficiencies. However, although the lamps have similar climate change impacts, their different component structures and operating principles result in significant differences in toxicity impacts. As a result, the older CFL's manufacturing phase accounts for 12.4% of the human toxicity impact while an LED only has 5.9% impact in the manufacturing phase. There is also more dependence of toxicity impacts on lamp parameters as lamp replacement has a direct influence on the magnitude of disposal impacts. By accounting for lumen depreciation (Scenario D), human toxicity impacts are increased by 33.3% and 29.3% for LEDs and CFLs respectively. This indicates CFL impacts are more susceptible to lumen loss from operation over time.

The use case modelling carried out shows that both CFLs and LEDs are not affected significantly by most use cases. However, the critical time for a lamp's average use cycle is significantly higher for the CFL making it more sensitive to frequency switching under the defined use cases. The LED is less susceptible though not immune to frequent switching as shown by a test for a standard five-minute switching period (Scenario G). This demonstrates that the life of the LED can also be significantly decreased by switching but the relative increase in impact remains smaller due to the low manufacturing impact of LED production. Therefore in situations where lamps are regularly switched on and off, LEDs are the most appropriate lighting choice.

This study shows that variation in lamp parameters has a far greater effect on the lifecycle impact compared to most use patterns. The variation in these parameters present on the market was represented in a sensitivity analysis. This showed that lamp efficiency (lumens per watt) still remains the largest influence on the environmental impact of the lamps but use patterns have little effect on these two parameters.

Overall, current LEDs and CFLs available on the market have similar total impacts in the use phase and are both suitable replacements for household incandescent lamps if electricity savings are desired. However, the CFL has greater manufacturing impacts and also significant limitations in switching cycles. Therefore, where there is very frequent switching, lifespan becomes limited by switching cycles and results in significant increases in the CFL's manufacturing impacts. In such situations, the LED is recommended to reduce the overall impact of lighting on the environment.

However, as shown by Table 1, LED technology is still under development and has a much wider range of parameters—some of which are not better than the CFL. Therefore future research and legislation should not only focus on the improvement but also standardization of lamp performance through features such as minimum efficiency and lifetime regulations. Ensuring a consistent standard of lamps on the market would also allow for a more representative analysis between the different lamp types and hence reduce current areas of bias due to a range of lamps being available on the market.

References

1. IEA. *Energy Efficiency: Lighting*. 2006 [cited 2014 22 September]; Available from: http://www.iea.org/topics/energyefficiency/lighting/.
2. UNEP, *Multi billion dollar benefits of global switch to energy-efficient lighting*. 2010, UNEP Environment for Development: Cancun.
3. Howarth, N.A.A. and J. Rosenow, *Banning the bulb: Institutional evolution and the phased ban of incandescent lighting in Germany.* Energy Policy, 2014. **67**: p. 737-746.
4. Scholand, M.D., Heather E;, *Life Cycle Assessment of Energy and Environmental Impacts of LED lighting products: Part 2: LED Manufacturing and Performance*, U.S.D.o. Energy, Editor. 2012, U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy.
5. Aman, M.M., et al., *Analysis of the performance of domestic lighting lamps.* Energy Policy, 2013. **52**(0): p. 482-500.
6. Welz, T., R. Hischier, and L.M. Hilty, *Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis.* Environmental Impact Assessment Review, 2011. **31**(3): p. 334-343.
7. Khan, N. and N. Abas, *Comparative study of energy saving light sources.* Renewable and Sustainable Energy Reviews, 2011. **15**(1): p. 296-309.
8. Ramroth, L., *Comparison of life-cycle analyses of compact fluorescent and incandescent lamps based on rated life of compact fluorescent lamp.* Rocky Mountain Institute, 2008: p. 11-12.
9. Navigant Consulting Group Europe Ltd, *Life Cycle Assessment of Ultra Efficient Lamps*, F.a.R.A. Department of Environment, Editor. 2009, Queen's Printer and Controller: London.
10. Sangwan, K.S., et al., *Life Cycle Assessment of Incandescent, Fluorescent, Compact Fluorescent and Light Emitting Diode Lamps in an Indian Scenario.* Procedia CIRP, 2014. **15**(0): p. 467-472.
11. Quirk;, I., *Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies* 2009, Berkley Institute of Environment.
12. Elijošiutė, E., J. Balciukevičiūtė, and G. Denafas, *Life cycle assessment of compact fluorescent and incandescent lamps: comparative analysis.* Environmental Research, Engineering and Management, 2012. **61**(3): p. 65-72.
13. Principi, P. and R. Fioretti, *A comparative life cycle assessment of luminaires for general lighting for the office - compact fluorescent vs Light Emitting Diode - a case study.* Journal of Cleaner Production, 2014. **83**: p. 96.
14. Technology;, O.O.S.G.S.C., *Life Cycle Assessment of Illuminants: A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps*. 2009.
15. Ji, Y., R. Davis, and W. Chen, *An investigation of the effect of operating cycles on the life of compact fluorescent lamps.* Journal of the Illuminating Engineering Society, 1999. **28**(2): p. 57-62.
16. Lim, S.-R., et al., *Potential environmental impacts from the metals in incandescent, compact fluorescent lamp (CFL), and light-emitting diode (LED) bulbs.* Environmental science & technology, 2013. **47**(2): p. 1040.
17. International Organisation for Standardization, *AS/NZS ISO 14040:1998: Environmental management-Life cycle assessment-Principles and framework*, in *Australian/New Zealand Standard*. 1998, Standards Australia/Standards New Zealand: Australia/New Zealand.
18. Hong Kong Productivity Council, *Final Report for Comprehensive Study on International Practice on Phasing out Energy Inefficient Incandescent Lamps*. 2009, Environment Bureau: Hong Kong.
19. Systems;, C.f.E.A.o.P.a.M., C.U.o. Technology, Editor. 2000: Sweden.
20. Beckwith, D., *Solid-State Street Lighting: Calculating Light Loss Factors*, D.o. Energy, Editor. 2011, Municipal Solid State Street Lighting Consortium: Oregon, USA.
21. *Tornado T2 Family FactSheet*, in *Philips Lighting*, K.P.N.V.R. Philips), Editor. 2014.
22. *Tornado High Lumen Family Factsheet*, in *Philips Lighting*, K.P.N.V.R. Philips), Editor. 2014.
23. *Tornado Dimmable Family Factsheet*, in *Philips Lighting*, K.P.N.V.R. Philips), Editor. 2014.
24. *OSRAM Dulux Pro Micro Twist Product Family Datasheet*, in *OSRAM Lighting*, O. GmbH., Editor. 2014.