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Considering optimal lifetimes for LED lamps: a mixed approach and policy implications

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Abstract
Ecodesign policy for energy-using products so far has tended to focus on the energy efficiency requirements, but there is increasing interest in durability requirements as well. This exploratory study analyses whether and when long lifetimes are preferable when considering the trade-offs between durability and other important parameters such as costs and environmental impacts, examining the case of LED lamps. This is an interesting product group to examine because of the improving lumen efficiency of the technology as well as the increasing emphasis on lifetimes by both producers and policymakers. This research integrates both economic and environmental approaches to examine optimal lifetimes in the case of LED lamps. The first part of the research utilised an optimised least lifecycle cost (LCC) model of LED household lamps for sale in a Swedish online market, finding that optimal lifetimes were in the range of 25000-30000 hours for these lamps. However, this modelling did not consider dynamic factors such as changing prices and efficiencies. This study took the case of 800 lumen lamps to consider these factors, utilising both LCC scenarios, varying lifetime, purchase prices, energy cost and efficiency as well as LCA scenarios, varying electricity mix and lifetimes. The mixed approach demonstrates that different conclusions can be reached depending on the approach and the assumptions used. The merits and possible future improvements of these approaches for approximating optimal lifetimes of LED lamps are discussed based on preliminary findings. Lastly, the implications of the findings for further development of durability requirements and other policies are briefly discussed.

Introduction

Durability refers to the "ability of a product to perform its function at the anticipated performance level over a given period (number of cycles/uses/hours), under the expected conditions of use and under foreseeable actions" (Boulos et al., 2015). Mandatory eco-design durability requirements have been set for lighting products through EU Ecodesign regulation and it is expected that more product groups will follow in the future (Maitre-Ekern & Dalhammar, 2016). EU Regulation 1194/2012 prescribes standard testing for light-emitting diodes (LEDs) for 6000 hours, requiring that at least 90% of the samples have survived (i.e. survival factor) and maintained at least 80% of their average initial light output (i.e. lumen maintenance).

Several manufacturers are promoting the long life of LED lamps as a valuable attribute to consumers, with some claiming lifetimes exceeding 50000 hours. However, a key question is whether long lifetimes are optimal for these products. This question can be considered both from an economic approach (i.e. lifecycle cost (LCC)) and from an environmental approach (i.e. life cycle assessment (LCA)). These approaches have been used in past research on the question of optimal lifetimes for electronics and appliances (see e.g. Bakker, et al., 2014; EU Commission, 2015; Prakash, et al., 2015; VHK, 2014); however, often research has taken either an LCC or an LCA approach, but it is important to consider both in considering sustainability of the products (Tähkämö, 2013).

This exploratory research integrates both economic and environmental approaches to examine optimal lifetimes in the case of LED lamps. LED lamps for sale online in Sweden were examined in the first part of the research to model the optimal durability of these lamps, assuming factors such as energy use and price were also optimised. More dynamic LCC scenarios were developed for a subset of the market (~800 lumen lamps) in which the LCC was calculated for different case scenarios assuming different improvements in efficiency, price, and the price of electricity, similar to the case study approach used by Boulos et al. (2015). Lastly, an LCA approach developed scenarios for an 800 lumen LED lamp modelled in previous research (Scholand & Dillon, 2012), considering different lifetimes, improving efficiency and different electricity mixes. It should be noted that results presented here are preliminary as ongoing research aims to integrate more current data and refine the modelling approaches.

Lifetimes on the market

LED lamps on the market in Sweden in December 2016 were examined in the first part of the research using web-scraped data from online market webpages (e.g. Pricerunner.se for household replacement lamps). Table 1 below outlines the range of key characteristics for LED lamps in this market.

Life cycle cost approach

The starting point for calculating LCC, aligned with the Ecodesign performance standards, is the following formula:

$$LCC = P_P + PWF \cdot P_E \cdot UEC \qquad (S1)$$

Where PP is the purchase price (€/lamp), PWF is the present worth factor, PE is the price of electricity (€/kWh), and UEC is the annual unit energy use (kWh). End of life costs are often excluded from LCC calculations, particularly if the cost of end of life management is part of the purchase price, as in extended producer responsibility schemes (i.e. the case in the EU) (Siderius, 2013).

Optimal durability the market

The first part of this research explored optimal lifetimes for the LED lamp dataset through theoretical modelling (see Richter, Van Buskirk, & Dalhammar, 2017). In the LCC equation introduced above, lifetime is related to PWF, which can be defined as:

$$PWF = \frac{1-(1+i)^{-L}}{i} \qquad (S2)$$

Where i is the interest or discount rate and L is the product lifetime (in hours) (Van Buskirk, et al., 2014). The relationship between LCC and PWF can be expressed in the following manner in which the PWF is singled out from the rest of the equation:

$$\frac{LCC}{PWF} = \frac{P_P}{PWF} + P_E \cdot UEC \qquad (S3)$$

The optimum relationship between LCC, price and PWF can then be explored by calculating the price regression coefficients, which were used to calculate price as a function of lifetime. The results of the Richter et al. (2017) study (Figure 1) indicated that, considering the relationship between purchase price and lifetimes,

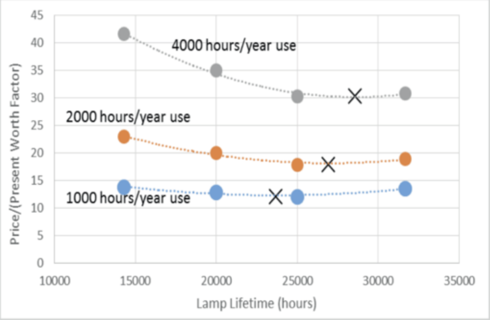

Figure 1. Model approximating optimum lifetimes (marked with x), assuming 6% DR. Source: (Richter et al., 2017)

Lifetime (h)	AVG: 21000 Range: 10000-50000
Price (€/piece)	AVG: 14.4 € Range: 0.9-99 €
Luminous flux (lm)	AVG: 498 Range: 8-2200
Luminous efficacy (lm/W)	AVG: 75 Range: 16-128
Correlated colour temperature (K)*	AVG: 2800 Range: 1800-6500

Table 1. Characteristics of LED lamp Swedish online market data

**Correlated colour temperature (CCT) illustrates the colour of the light, so that CCT around 3000K is perceived as warm white, 3500-5000K as neutral white, and >5000K as cool white light.*

optimal lifetimes are generally around 25000 hours - longer than the range of lifetimes available on the market and certainly longer than the minimum lifetimes required in the Ecodesign standards for lighting (i.e. 6000 hours). Factors such as intensity of use and discount rates (DR) can be influential, but the main finding remains intact (even with a higher DR of 9%, optimal durability was still over 20000 hours for all intensity of use scenarios).

Optimal durability: ~800 lm case scenarios

The method above can be useful for assessing durability in the entire market and assessing LCC in a real time market. However, it focusses only on durability and price, and does not consider dynamic factors such as improving efficiency of replacement lamps. To illustrate this, we examined a subset of data for 800 lumen LED lamps (±25 lm) with a CCT of 2700-3000K. The choice of 800 lumen lamps also aligns with the LCA presented in the next section.

The LCC was calculated with a simplified method in which the discount rate was equal to the rise of electricity prices (a method used by Siderius, 2013), and thus the PWF simplifies in the equation S1 above to the lifetime. This simplification allowed for exploration of the variables of increasing efficiency of LED technology, decreasing purchase price, and high or low electricity prices. The LCC for the 10000 hour, 20000 hour and 30000 hour lamps are compared (normalized to the 30000 hours, i.e. 3 x 10000h lamps, and 1.5 x 20000h lamps are needed for 30000 hours).

In this simplified LCC calculation, the intensity of use does not affect the LCC but would affect the length of the

Lifetime (h)	10000 (n=3)	20000 (n=10)	30000 (n=3)
Price (€)	AVG: 14.97 Range: 11-19.3	AVG: 18.94 Range: 8.2-34.5	AVG: 19.02 Range: 12.5-25.6
Efficiency (lm/W)	AVG: 105.1 Range: 84.8-115.1	AVG: 81.1 Range: 80.6-82.5	AVG: 84.2 Range: 80.6-90

Table 2. Characteristics of ~800 lumen LED lamp Swedish online market data.

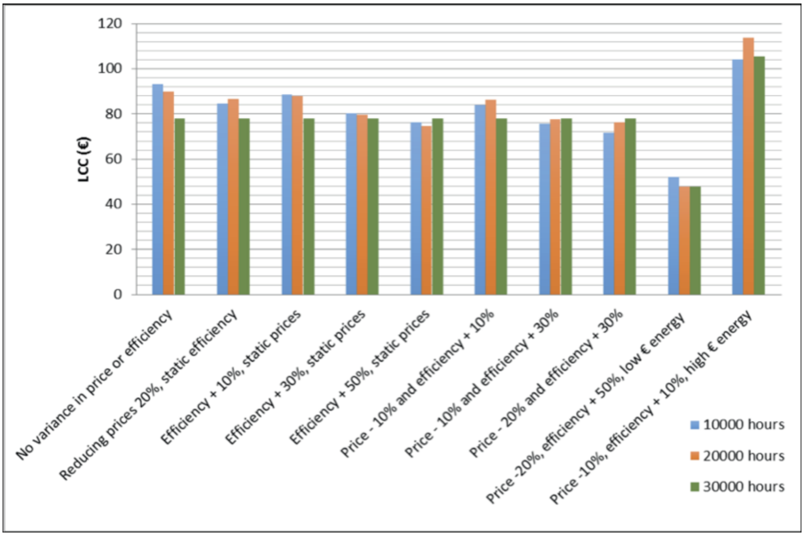

Figure 2. LCC case scenarios for ~800 lumen LED lamps on Swedish market

replacement cycles. The scenarios presented in Figure 2 assume a replacement every 10 years for a 10000 hour lamp operating at 1000 hours per year (approximately 2.7 hours/day). In reality, some lamps in a household could be used much more intensely than this. More intense use, e.g. 4000 hours, would result in shorter replacement cycles, e.g. 2.5 years for 10000 hour lamps. Shorter replacement cycles, would have implications for how much improvement in price or efficiency is realized in that time.

In scenarios where there are either significant efficiency improvements (i.e. efficiency doubled) or both price decreases and efficiency improvements, shorter life LED lamps that can take advantage of the learning curves and efficiency improvements in the replacement lamps, are preferred for least life cycle costs (LLCC).

The LCC scenarios were also sensitive to the price of electricity. The EU average (0.205€/kWh for 2016 according to Eurostat data) was the default assumption; however, in low cost energy contexts (e.g. Bulgaria at 0.09€/kWh), longer lifetimes would be preferable for LLCC, even with lower purchase prices and improving efficiency of replacements. High energy prices (e.g. 0.3€ in Denmark) also had implications in which the gains of spreading the purchase price over a longer lifetime were a trade off with the gains of saving costs of electricity, yielding the 20000h lamps as the LLCC option.

Life cycle assessment approach

Tähkämö (2013) found that for downlight LED luminaire, extending the lifetime of the luminaire lowered the overall environmental impacts (particularly for impact categories related to waste and resources, but also to a lesser extent in energy impact categories). In that study, shorter lifetimes also raised the relative significance of the manufacturing stage compared to the use stage (about 45% in a 15000h lifetime compared to just above 20% of a 50000h lifetime). However, previous LCAs for lighting focused more on comparison between lighting technologies (i.e. incandescent, fluorescent, LED) than between characteristics of the same technology, and as such, have not explicitly compared the environmental impacts considering varying lifetimes and improving efficiencies between lamps with the same technology.

Optimal durability: ~800 lm case scenarios

The LCA in this study constructs scenario cases for short (12500h) and long (25000h) lifetimes of LED lamps, considering a range of key environmental impact indicators, similar to the approach by previous studies of other product groups (Ardente & Mathieux, 2014; Boulos et al., 2015). The base case data is from the Department of Energy 2012 LCA (Scholand & Dillon, 2012 - "DOE 2012 LCA"), which considered an 806-lumen lamp and functional unit of 20 million lumen-hours. The LCA was modelled in SimaPro using Ecoinvent database and the 2012 DOE LCA report data.

While the DOE report also used Ecoinvent, it used an earlier version so direct comparisons should not be made as some unit processes have been updated. In addition, the LED market data from the LCC study indicates there is already efficiency improvements from the lamp considered in the DOE report. It is also known that components such as aluminium heat sinks have developed (e.g. decreased in mass) significantly since that study. Therefore, the LCA study presented here should only be considered exploratory while the approach is further developed with more current data. The choice to model the same LED lamp type as the DOE 2012 LCA was made because the report is currently the most comprehensive data publically available for household replacement LED lamps.

The DOE 2012 LCA considered a lamp with a relatively long (25000h) lifetime, so the comparison was made with a scenario in which the lifetime was assumed to be half this (12500h), thus requiring two lamps for the same functional unit. The replacement lamp for the 12500 lamp was assumed to be twice as efficient as the original 12.5w lamp (i.e. 6.25w). The material composition was assumed to be the same, but in reality, the replacement lamp would also have material changes. The scenarios were modelled with the EU energy mix (with approximately half of production from thermal sources) and the Norwegian mix (with primarily hydroelectricity).

Figure 3 shows that, with the EU average electricity mix, the longer life LED lamp (blue) has more significant impacts in energy related categories while the shorter life lamp (red) has relatively higher impacts in the toxicity and metal depletion environmental impact categories – highlighting possible trade-offs between different types of environmental impacts. The scenarios with the less carbon intensive Norwegian electricity mix (green and purple) do not show the same trade-offs, with the longer life LED lamp having relatively less impact compared to the more efficient short life scenario in all environmental impact categories, with the exception of water depletion due to hydroelectricity generation.

Discussion and conclusions

These initial findings indicate that in certain contexts, longer life LEDs can have both cost and environmental benefits, but this is not true in all cases. From the LCC perspective, if prices continue to fall and efficiency continues to improve rapidly, least life cycle costs may be found through shorter life LED lamps, particularly in the context of average-high contexts (0.205-0.3€/kWh). Interestingly, in the subset of data used for the cases (the 800 lumen lamps), the more efficient products tended to have a lower lifetime than the durable products (this was influenced by the low number of lamps in the data). This was observed on the dataset as whole, but less pronounced. Testing the LCC approach on another subset or developing a generalized case from the market dataset could also strengthen the findings.

It is worth noting in the 800 lumen subset, as well as the entire dataset, that there is a range of prices and efficiencies, which means that the actual LCC for consumers can be quite different, depending on their purchase choices. This highlights the importance of information and that policy requirements for durability may already appropriate in certain scenarios.

In further developing the LCC scenarios, the projected outlook of the LED lamp market could be more thoroughly researched to match the theoretical scenarios to likely projections. For example, the U.S. Energy Information Administration projects LED lamp prices to continue decrease in price and increase in efficiency, close to the improving price and efficiency scenarios in the cases, though this trend is projected to slow as soon as 2020 and the market is projected to reach maturity by 2030 (U.S. EIA, 2014). This would mean that longer lifetimes could be motivated from an LCC perspective in the near future. Already there are lamps currently on the market starting to approach the limit projected for the market in the U.S. EIA's projection (200 lumens/watt – see (Philips Lighting, 2017). However, other projections were not researched in this study and may show different scenarios, including the possibility of new LED laser technology (Maloney, 2016).

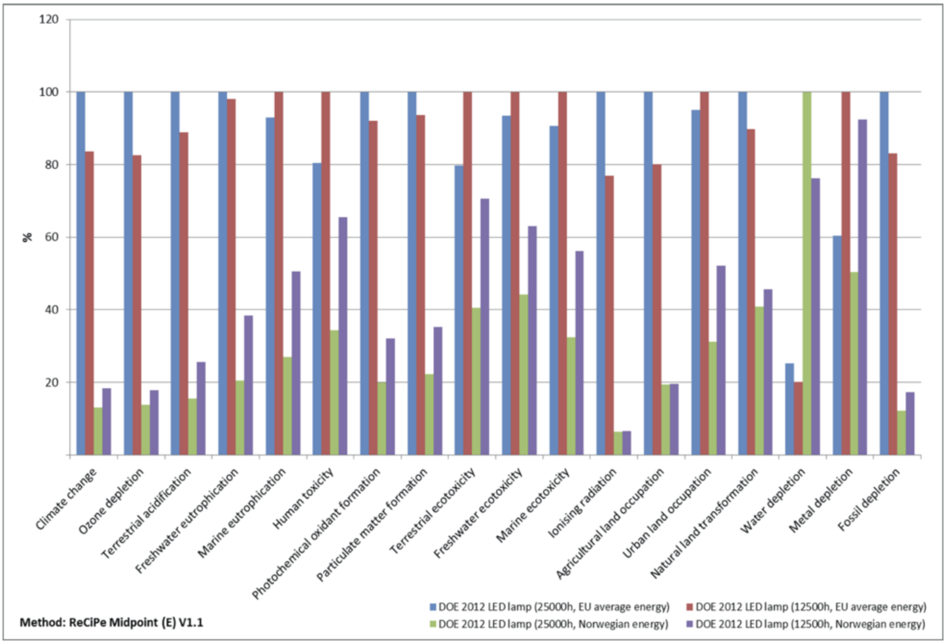

Figure 3. Comparative environmental impacts of LCA scenarios.

The LCA approach indicated that with an average EU electricity mix, there may be trade-offs between energy and material environmental impacts. Development of the approach and scenarios with more current product data and sensitivity analysis of using different impact indicator methods could further elaborate the scenarios. There is also a need to further explore scenarios with different electricity mixes, as the findings suggest that more durable LED products are preferable in contexts with less thermally sourced electricity generation. Lastly, whether decreasing mass and material changes to LED lamps in the replacement scenarios could influence the results also needs to be investigated.

Policy options for LED lamp durability

Producers are already promoting durability as an attribute of LEDs, so some consumer protection may already exist in consumer law if LED products fall short of lifetime claims (Stone, 2015). While use of the term "energy –efficient" is defined by Ecodesign regulations for lighting, it remains to be seen whether the term "long life" will also be included. Mandatory warranties could be another policy approach to increase consumer confidence and ensure stated claims about lifetime, but may be more complicated for the consumer than mandatory requirements. There are also questions about whether and how lifetime information could be integrated into labelling requirements to highlight durability to consumers.

While current Ecodesign requirements are based on 6000 hours, this study revealed that in some contexts and scenarios it may already be, or soon will be, relevant to consider policies to ensure longer lifetimes for LEDs. Testing lamp durability involves several parameters and accelerated tests are currently being developed (see Narendran, et al., 2016) that could make lifetime and durability tests more feasible. Improved testing procedures could in turn enable mandatory requirements on durability. The question would be the timing, design, and stringency of such requirements to coincide with the maturing of the LED lamp market.

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