Accounting for durability in least life cycle cost methods

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Keywords
Directive on Eco-design (EuP/ErP), life cycle cost (LCC), minimum energy performance standards (MEPS), LED, lighting, durability, product lifetime

Abstract
In the European Union (EU), mandatory durability ecodesign requirements have recently been set for vacuum cleaners and lighting products. Durability standards for additional product groups are expected in the future and it is also envisioned that durability issues will be integrated in the EU energy labelling scheme. Durability standards can bring environmental benefits, but there are several methodological challenges, not least regarding the trade-offs between different product attributes. In this paper, we review previous literature and studies examining durability and increased lifetimes for products, with a focus on the case of LEDs. We analyse the methods suggested and assumptions used and compare these to an innovative method for calculating an attribute-adjusted least life cycle cost (LLCC) when durability is included. Then we analyse the case of LEDs available in an online market in 2016 and model optimal lifetimes in relation to life cycle costs. The model identifies factors influencing optimal lifetimes. The statistical error of the regressions does not allow for calculation of the optima with precision, but the calculation is illustrative that the LLCC optima for the range of LED bulbs considered is close to 25,000 hours. The model also indicates that greater durability is important for cases with smaller discount rates and more intensive use of the product. We discuss the usefulness of the method and its application and development in context of policy development of durability standards, as well as future research that can complement this approach. The initial results indicate that, at least from an LLCC perspective, longer lifetimes than currently required by standards may be desirable, so we also discuss the advantages and disadvantages of using three different policy instruments to stimulate increased durability.

Introduction
One of the substantial policy developments related to the Circular Economy is the interest for incentivizing more durable products (European Commission, 2016). 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, p. 4). This interest has been manifested in several policies and initiatives already, including national schemes to promote product repairs. Public procurers in some countries have started to purchase remanufactured furniture and remanufactured IT products, and there is a general interest in promoting product durability in public procurement (Montalvo, Peck, & Rietveld, 2016). France has banned planned obsolescence and set up incentives for manufacturers to provide spare parts (Maitre-Ekern & Dalhammar, 2016). Mandatory eco-design durability requirements (mainly pertaining to lifetimes) have recently been set for vacuum cleaners and lighting products through EU regulations, and it is expected that more product groups will follow in the future. More and more actors in the EU are also arguing that durability information should be included in the mandatory EU energy labelling scheme (Bur-

Table 1. Ecodesign requirements for lamps related to durability and quality.

Requirements of EU Ecodesign regulations	Directional and LEDs	Non-directional lamps *(italics for lamps excluding CFL and LEDs)*
lamp survival factor at 6,000 hours	≥70 % except LEDs ≥90 % LEDs	≥70 % *≥ 85 % at 75 % of rated average lifetime and 2,000 hour minimum rated lifetime for lamps*
lumen maintenance' at 6,000 hours	≥70 CFLs ≥80 LEDs	≥ 85 % at 75 % of rated average lifetime
number of switching cycles before failure	≥15,000 if rated lamp life ≥ 30,000 hours, otherwise ≥ half the rated lamp life expressed in hours	≥ lamp lifetime expressed in hours ≥ 30,000 if lamp starting time > 0.3 s *≥ four times the rated lamp life expressed in hours*
premature failure rate (maximum number of failure products in %)	≤5 % at 1,000 h	≤2 % at 400 h *≤5 % at 200 h*
'colour rendering' requirements for various applications	≥80	≥80

rows, 2016). In general, the various initiatives reflect a lack of belief that the markets alone will deliver more durable products without governmental interventions.

There is a large potential to set mandatory standards for durability under the Ecodesign Directive for several product groups. It is generally acknowledged, however, that there is great variance among different product categories regarding the suitability of setting durability eco-design requirements (Boulos et al., 2015; European Commission, 2015; VHK, 2014). In this paper, we examine the case of durability of lighting products, which are one of the first product groups to have mandatory minimum durability requirements under the Ecodesign Directive. In this case, the durability requirements have focussed primarily on the minimum lifetime of lamps, defined in EC Regulation 244/2009 as "the period of operation time after which the fraction of the total number of lamps which continue to operate corresponds to the lamp survival factor of the lamp, under defined conditions and switching frequency". We examine how the lifetime aspect of durability can be considered with life cycle costs (LCC) through modelling this attribute in relation to LEDs currently on the market. By modelling the relationship between LCC and durability we approximate optimal lifetimes for the LED products considered. We then discuss the implications of this approach for informing durability standards for LEDs, and three policy options for increased durability standards in context of the findings. Finally, we also discuss areas for future research.

Durability for lighting products

The EU Ecodesign regulations on lighting products[1] have set functionality requirements relating to domestic lighting and directional lamps. In the case of lighting products, durability/lifetime has several dimensions and the requirements on directional lamps include those parameters outlined in Table 1.

The transition of the lighting market towards LEDs has also meant a rapid improvement in durability of lighting products, with an increasing number of models in the market lasting longer periods and with good quality lighting output (Bennich, Soenen, Scholand, & Borg, 2015). Manufacturers now promote the long life of LEDs as a valuable attribute. However, it is important to consider what these claims mean. The lighting industry typically defines the lifetime of LEDs as the time it takes for LED packages, arrays, and modules (as opposed to the LED system – i.e. lamp or luminaire) to reach 70 % of initial light output (Narendran, Liu, Mou, Thotagamuwa, & Eshwarage, 2016). The standards for testing lumen maintenance and lifetime[2] require testing a set of LED lamps for a minimum of 6,000 hours and measuring the lumen maintenance. A lamp's rated life also considers a statistically-determined estimate of *median* failure measurement. According to the EU Commission Regulation No 1194/2012 for LEDs, lifetime values should be obtained by extrapolation from the lamp survival factor and from the average lumen maintenance of the lamps in the test batch at 6,000 hours. The survival factor and lumen maintenance requirements at 6,000 hours have been increased for LEDs in the 2012 EU Ecodesign regulations (see table above).

One EU preparatory study identified the 6,000 hours (250 days) test to verify lamp survivors and lumen maintenance factor test currently required by regulation 1194/2012 to be problematic because of the dynamic LED market and the challenges for timely market surveillance (VITO & VHK, 2015). Shorter testing times are preferred, but this can be a trade-off with reliable testing methods for durability (Narendran et al., 2016). This being said, there are also positive developments in accelerated testing methods that may help to address these issues (Narendran et al., 2016 and Narendran, personal communication, 3 March 2017).

When it comes to LEDs, the controversies surrounding the banning of traditional light bulbs and the mistrust of lighting regulations (cf. Sachs, 2012), means that it is paramount to set stringent quality standards for new lighting technologies. Therefore, certain durability/lifetime standards should be set

1. Commission Regulation (EU) No 1194/2012 of 12 December 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment; and Commission Regulation (EC) No 244/2009 of 18 March 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non-directional household lamps.

2. Illuminating Engineering Society (IES) Standard LM80-08: Approved lumen maintenance testing of LED light sources and IES Standard TM-21-11: Projecting long-term lumen maintenance of LED light sources.

as a means to guarantee product quality and increase consumer confidence that LEDs are worth investing in. Another question is whether longer lifetimes are actually preferable. Two approaches can be taken to consider this. It can be approached from life cycle cost (LCC) to model the costs associated with the products through their life cycle and whether durability is preferable. This is the approach of Boulos et al. (2015) in their investigation of refrigerators and ovens comparing two cases of a durable versus standard product and calculating LCC. While this approach can determine whether durability is preferred, it does not give an indication of optimal durability without including many more cases. In this paper, we propose an approach using market data that estimates the optimal durability of a given product, in this case for domestic retrofit LEDs.

For examining whether durability is preferable from an environmental perspective, a life cycle assessment (LCA) approach can be used. Studies considering optimal product lifetimes from an environmental perspective (looking at full range of impacts, or in some cases only energy demand) have demonstrated that longer product lifetimes can be preferred for some product groups, particularly when the environmental impacts in the extraction, production and waste phases are the most significant; this generally applies for ICT products (Bakker et al., 2012; Cooper & Gutowski, 2015). For these products, extension of lifetime may be positive even if the technology is becoming more energy efficient (Bakker, Wang, Huisman, & den Hollander, 2014; EU Commission, 2015; Prakash, Dehoust, Gsell, Schleicher, & Stamminger, 2015; VHK, 2014). However, for energy-using products for which the majority of life cycle impacts occur in the use phase, studies have generally found that increased durability may not be preferred to replacement with more efficient products (Boulos et al., 2015; Cooper & Gutowski, 2015; Gutowski et al., 2011); however, some of these studies only consider energy use and related emissions, and not a full life cycle assessment (LCA) which also includes categories such as waste, material extraction, and resource use for the materials and manufacturing of the product.[3] Following explanation of the LCC method, we review recent LCA studies for lighting products to highlight possible trade-offs and conditions where increased durability might be preferable for the case of LEDs.

LCC and Durability

In the preparatory studies for the lighting product Ecodesign standards (VITO & VHK, 2015a), least life cycle costs for base cases were calculated as:

$$LCC = PP + PWF \cdot OE + EoL \quad \text{(S1)}$$

where LCC is Life Cycle Costs, PP is the purchase price, OE is the operating expense, PWF is present worth factor, which is a factor of the product life and the discount rate minus the growth rate of running cost components e.g. energy, water rates (equation defining PWF is below), and EoL are the end-of-life costs. The calculation shows a relationship between lifetimes (N), present worth factor (PWF) and life cycle costs (LCC), which we explore further by examining LCC in relation to PWF in particular.

Similar to the EU calculations, this paper defines LCC as:

$$LCC = P_A + PWF \cdot P_E \cdot UEC + EoL \quad \text{(S2)}$$

where P_A is the appliance price, PWF is the present worth factor, P_E is the price of electricity, and UEC is the annual unit energy use and EoL is end of life costs.

The durability of a product determines the lifetime, which in turn determines the present worth factor. The Present Worth Factor can be defined as:

$$\text{PWF} = \frac{1-(1+i)^{-L}}{i} \quad \text{(S3)}$$

Where i is the interest or discount rate and L is the product lifetime. Under optimal market conditions both PWF and UEC are optimized. Under UEC optimization, UEC decreases with increasing PWF, which in turn increases with durability and lifetime. If the model is optimized to minimize LCC (applying an LCC optimization regression method from Van Buskirk et al., (2014)[4]).

Dividing by the present worth factor (which takes into account the influence of inflation and discount rates) gives an annualized LCC:

$$\frac{LCC}{PWF} = \frac{P_A}{PWF} + P_E \cdot UEC + EoL \quad \text{(S4)}$$

Annualized LCC measure the costs of the lamps that may occur every year (taking into account that these are not regular). We focus on the change in price with respect to the hours of durability. To do this, the LED models in the data were binned into four categories: <15 K hours, 20 K hours, 25 K hours and >30 K hours and the price regression coefficients for each bin were calculated for a selected subset of LED bulbs.

The regression results were then used to calculate Price as a function of lifetime. As PWF depends on the number of years of operation, PWFs for three different scenarios of years, based on hours of operation per year – 1,000, 2,000 and 4,000 – were considered in relation to the product lifetime hours. Then price/PWF was calculated for each of the cases, yielding three curves for the 1,000, 2,000, and 4,000 hours per year as well as the minima (i.e. optimal cost points) for the 1,000 hours/year, 2,000 hours/year, and 4,000 hours/year use scenarios respectively. While the effect of energy use (UEC) is not modelled, we discuss the implications of the model in relation for optimised LCC and the UEC.

DATA

The data used for the regression analysis were 299 LED products on the online market in Sweden and Denmark (i.e. web-scraped data) in December 2016. These were binned in three lifetime groups for analysis. Other characteristics of the models are shown in Table 2.

3. The LCA studies referenced consider the following categories: Primary energy, Renewable energy, Non-renewable energy, Abiotic depletion potential, Water consumption, Hazardous waste, Non-hazardous waste, Inert waste, Radioactive waste, Global warming potential, Acidification potential, Air pollution, Water pollution, Ozone depletion potential, Photochemical ozone creation potential, and Eutrophication potential.

4. LCC optimization method is only briefly presented here, for a full explanation please refer to supplementary data ("Supporting Information") which can be accessed online in (Van Buskirk, Kantner, Gerke, & Chu, 2014).

Table 2. Data characteristics for LEDs in each lifetime category.

Lifetime	≤15,000 h (n = 30)	25,000 h (n = 139)	≥30,000 (n = 30)
Price	AVG: €13 Range: 28–959 SEK	AVG: €14.4 Range: 19–720 SEK	AVG: €15.2 Range: 19–390 SEK
Lumens (lm)	AVG: 475 Range: 8–1,800	AVG: 573 Range: 136–1522	AVG: 455 Range: 82-1,500
Efficiency (lm/W)	AVG: 83 Range: 16–128	AVG: 79 Range: 46–125	AVG: 68 Range: 27–120
Temperature (K)	AVG: 2,700 Range: 1,900–6,500	AVG: 2,700 Range: 2,100–6,500	AVG: 3,000 Range: 2,700–6,000

The dataset showed a correlation between price and lumen output and CRI, respectively, but not with efficiency or lifetime. Other studies of LEDs have also found that brands names and experience curves play a role in the price of LEDs (see e.g. Gerke, 2014). Previous studies have indicated that a lack of relationship between price and efficiency can be problematic in using LCC to set MEPS (see Siderius, 2013). The main objective of this study is not to develop base cases for LCC, but to track the role of durability (and its relationship with energy use) in assuming optimization of LCC based on a snapshot of a current LED market in real-time.

Analysis

The results of the modelling for optimal durability in the three cases are shown in Figure 1 below. This modelling focusses on the optimization of the present worth factor in optimization of LCC and shows lifetime related to the price/present worth factor. The "x" marks the minimum of the curves, or the lowest value for price/present worth factor, which then corresponds to the optimized lifetime for each scenario of yearly use. The statistical error of the regressions does not allow for calculation of the optima with precision, but the calculation is illustrative that the LLCC optima for this range of LED bulbs is close to 25000 hours, with slightly longer lifetimes optimal the more intensely they are used. For comparison, the average lifetime for the data modelled in the sample is approximately 21500 hours.

In this analysis, we used a discount rate of 6 % in the calculation. Different assumptions about the interest or discount rates shift the price/PWF slightly, favouring slightly longer lifetimes with a smaller discount rate and shorter lifetimes with a high discount rate (as shown in Figure 2), in relation to the base case with 6 % (as shown in Figure 1).

Discussion

The approach described above for estimating the optimized lifetime for LEDs can be used for gauging optimized policy parameters (like economically optimum durability) in "real-time" using automated Internet-based market surveys. Such methods have been applied to price-monitoring of LEDs (see Gerke, Ngo, & Fisseha, 2015), and have been suggested as a more generalized method for monitoring LLCC optimization of energy efficiency policies in real-time (Van Buskirk, 2015a, 2015b).

In theory, least life-cycle cost (LLCC) policies should move markets to an optimum where there are specific relationships between price, energy use, cost of energy, and present worth factor (and by implication durability). Returning to the original equation for LCC below shows that in an optimised LCC, there is a direct synergy between smaller energy use and increased durability under LCC optimization through the relationship between PWF (with lifetime implicit) and UEC.

$$LCC = P_A + PWF * P_E * UEC + EoL$$

If minimum standards on durability increase product lifetimes relative to an unregulated market, the increase in product lifetime increases PWF. In calculating optimum LCC with respect to energy use, higher values of PWF imply lower values of UEC at LCC-optimum. In other words, solving market imperfections for durability can increase durability, which in turn leads to increased product efficiency for LCC-optimized MEPS. End of life costs per LED are very low, for example approximately €0.04 per LED in the Danish EPR system.[5]

Our findings are in line with previous product studies conducted with LCC methods by Boulos et al. (2015) who found that generally more durable products yield a lower life cycle cost compared to a standard product scenario, primarily due to the avoided cost of the replacement product. The advantage of this approach is that optimal lifetime is solved for rather than a comparison of cases (which determine if the durable option is preferable but whether it is optimal). However, the model assumes LCC optimization for other factors (e.g. energy use) which is not the reality. The comparative cases can often be good for illustrating how the different factors influence LCC. Comparative cases for lighting (particularly LED street lighting as opposed to domestic lighting) have also been illustrative for identifying how different factors such as price, lifetime, efficiency, and technology development interact in LCC for LED lighting (see Ochs, Miller, Thal, & Ritschel, 2014; Tähkämö, Räsänen, & Halonen, 2016). These studies also showed that even with increased efficacy and falling prices of lighting products, delaying purchase of replacements could still be advantageous from an LCC perspective. This is attributed to the large role of the purchase price in the LCC for LEDs.

The Regulation stipulating functionality requirements stated that their aim is "to ensure consumer satisfaction with energy-saving lamps, in particular LEDs …".[6] The issue of durability for

5. Using the fees charged by a Lighting Producer Responsibility Organization as indicative, see www.lwf.nu.

6. Commission Regulation (EU) No 1194/2012 of 12 December 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment, at (15).

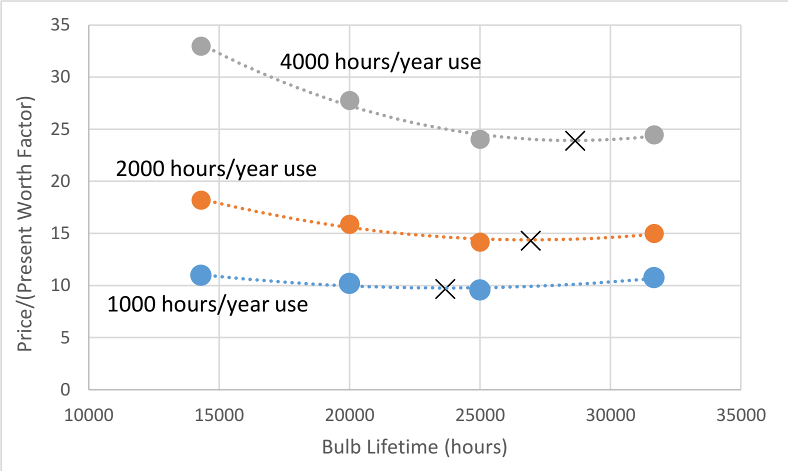

Figure 1. Model approximating optimum lifetimes (marked with x) for different scenarios of use.

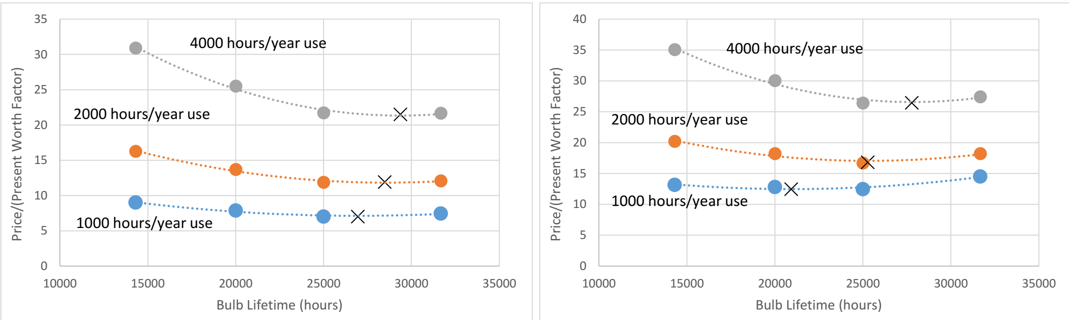

Figure 2. Model with discount rates of 3 % (left) and 9 % (right). The "x" corresponds to the minimum of the quadratic trend line fit for each curve.

LEDs has been pushed by consumer groups and quality and functional requirements are crucial for the market acceptance of LEDs (this was also the case in the U.S. – see e.g. Sandahl et al., 2014). In a review of EU Ecodesign lighting regulations finalized at the end of 2015, as preparation for new regulations, the consultants also stress the importance of functionality requirements as consumers can be suspicious about "enforced" lighting solutions (VITO & VHK, 2015b). Research has found that consumers value durability as an attribute for lighting, with a stated willingness to pay more (between = USD 0.52 and 0.66 for every 1,000 h in a U.S. study – see Min, Azevedo, Michalek, & de Bruin, 2014).

It has already been noted that the minimum functionality requirements on durability are lower than consumer expectations of the claimed lifetimes. The modelling of optimal lifetimes has illustrated that the optimal lifetime to yield the least life cycle cost is approximately 25000 for products on the market now, which further indicates a disparity between the LLCC optimum and the minimum durability standards as they are set now. The modelling also indicates that the LCC-optimum durability is slightly higher than the current market average, which says that there is likely to be a role for durability MEPS to help move the market closer to its apparent optimum, but the question of feasibility remains and is discussed further below. The model also indicates that greater durability is important for cases where there are smaller discount rates and more intensive use of a product. Lastly, improved durability also leads to lower energy use for products that have LCC-optimized MEPS. This implies that durability standards can indirectly have an effect on climate change mitigation by allowing for LCC-optimized efficiency standards become a little more stringent.

Increasing the stringency and ambition of the minimum requirements would involve development of more feasible and accurate testing methods, as current methods would make it very difficult to test durability if it implies using the products for a very long time in order to test it. Standard testing methods consider the lifetime of the LED components rather than the whole system and often focus on lumen depreciation over catastrophic failure (i.e. complete non-functioning) though both are of concern (Narendran et al., 2016). Practical methods that can reliably predict the important sources of failure are a necessary first step in setting minimum standards. Such methods that stress test important parameters (e.g. switch cycles, change in temperature) and consider all important components in the lighting system (not only the LED but also e.g. drivers, solder between the LED and PCB, etc.) (Narendran et al., 2016).

ALTERNATIVE APPROACHES FOR DETERMINING OPTIMAL DURABILITY

Life cycle costs are not the only approach for determining optimal lifetimes and this question can also be considered from an environmental perspective. LCAs of lamps, including LEDs, generally find that the use phase dominates the total life cycle environmental impacts, with an average of 85% of the overall impacts. Tähkämö et al. (2013) look at the role of lifetime in in-

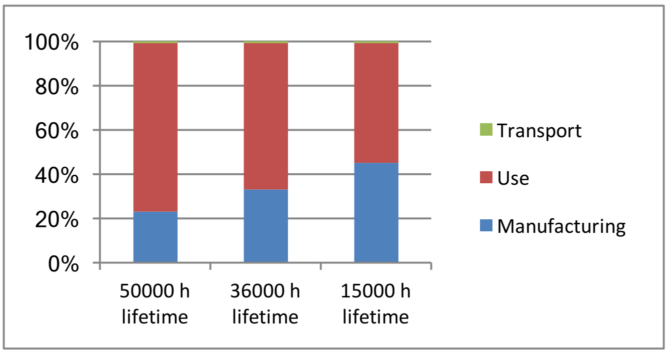

Figure 3. Overall life cycle impact by life cycle phase. Source: based on (Tähkämö et al., 2013).

fluencing the overall environmental impact of LED for the case of an LED downlight luminaire. The authors found that the average environmental impact of a luminaire with a 50,000 hours useful life was 34 % (with a range of 2–70 % amongst different impact categories) lower compared to a 15,000 hours useful life, while a 36,000 hours useful life resulted in 23 % (1–47 %) lower average impacts compared to the 15,000 hours case. The difference impacts varied depending on what impacts were being considered, with the largest differences in the waste categories (both hazardous and non-hazardous) and the smallest in the primary energy, but with significant differences in most impact categories considered.[7]

The authors also found the lower the LED lifetime, the larger the share of manufacturing in the total life cycle impacts (due to the need for manufacturing additional replacement lamps), as shown in Figure 3. This highlights again the need to consider carefully the different life-cycle phases and their associated impacts.

The relative importance of these phases will also vary depending on the assumptions about the energy mix during the use phase. An energy mix composed of higher renewable energy sources changes the dynamic of the impact, with increased renewable energy resulting in a decreased impact of the use phase and increasing the relative impact of the manufacturing stage, relative to the overall life cycle impact (Tähkämö, 2013).

The role of improving technology should also be considered. Scholand and Dillon's study for the U.S. Department of Energy found that 5-year improvements (2012 and projected 2017) in efficacy and production yield could results in 50 % average reduction in the considered environmental impacts. The authors project the improved efficacy from 65 lm/W to 134 lm/W (Scholand & Dillon, 2012), while another DOE study projected the maximum LED package efficacy to increase up to 250 lm/W by 2025 (U.S. Department of Energy, 2013. There are large ranges of efficacy within existing LED products on the market (for example, the DOE study finds a range between 10 lm/W to approximately 120 lm/W) and efficacy also changes when considering the LED package, the lamp system, or the lighting system (U.S. Department of Energy, 2013). As the efficacy as LED technology develops will also decrease the relative impact of the use stage compared to the raw material and manufacturing stage, as less energy will be required when LEDs are more energy efficient.

Lastly, there are also strategic materials (e.g. rare earth elements, indium, gallium) used in LEDs that need consideration in the context of critical material strategies (e.g. as the EU develops its raw materials policies). While the overall amounts of critical materials in LEDs are very low, criticality of materials is noted even if it is yet unclear how such an index should be used (VITO & VHK, 2015a).

The LCA studies of lamps have mainly been focussed on comparing technologies (e.g. halogen, fluorescent, LED). While some have highlighted important parameters, including lifetimes (Tähkämö et al., 2013) and technology development (e.g. Scholand & Dillon, 2012), they have not yet sought to investigate the question of optimal lifetimes. Using an LCA, or a fast track LCA as outlined in (Bakker et al., 2014), could be complementary approach for determining optimal LED product lifetime and the results could then be compared to the findings of the LCC approach we have suggested in this paper.

Options for additional durability requirements

One of the key success factors explaining the widespread adoption of MEPS in different jurisdictions is that regulations implementing MEPS also include mandatory functionality standards, covering the most important quality and functionality parameters for the users. While mandatory standards should only ensure the minimum quality level, and thus a minimum for acceptable lifetime, there are at least three potential policies that may be used to go even further and encourage 'beyond basic' longevity: more progressive mandatory requirements, customer warranties, and mandatory labelling. Each approach has its merits and limitations, which are also outlined in Table 3 at the end of this section.

MORE AMBITIOUS MANDATORY REQUIREMENTS

Generally, mandatory durability standards have some benefits compared to the other policy options presented below. Firstly, it allows policymakers to make the appropriate trade-offs between different functions (e.g. energy use, technological developments, and durability), based on not only LLCC but also technology assessments and LCAs. Secondly, the high complexity of establishing 'durability' for lighting, and the problems for consumers to understand information about durability implies that mandatory requirements can be a good idea cf. to labelling and warranties.

Our findings have motivated the case that, at the very least, minimum lifetime should be ensured through mandatory requirements. The analysis of a current LED market from an optimised LCC perspective also suggested the optimal lifetime for lamps is around 25,000 hours. The analysis also found there is a relationship between optimised durability and optimised energy savings. This implies a benefit to optimising durability for both consumers and society.

It has been argued that domestic consumers are not usually interested in very durable products; whereas professional buyers can make use of warranties when they want durable LEDs (cf. Next Generation Lighting Industry Alliance, 2014). However, research in the U.S. has found that consumers do value durability as an attribute for lighting products, with stated

7. It should be noted that the differences are far less in considering energy impacts than considering other impacts related to waste, water pollution, resource efficiency, etc.

willingness to pay more between USD 0.52 and 0.66 for every 1,000 h increase in lifetime (Min, Azevedo, Michalek, & de Bruin, 2014). Manufacturers are already selling LEDs highlighting the long life to consumers as a valuable attribute, and this could in itself push the market towards increased durability without more ambitious standards. However, our analysis of a current market indicated the current average lifetimes on the market were below the optimal lifetimes from the LCC perspective, suggesting a role for more stringent durability standards to push the market towards its optimum in this regard. In order to enforce such standards there would need to be practical testing procedures (also for labelling). While there are promising developments in accelerated testing procedures, (Narendran et al., 2016 and Narendran, personal communication 3 March 2017), there may still be issues with practical enforcement by member states.

There is also a need to assess optimal durability from an LCA approach to assess possible trade-offs and disadvantages of durability from an environmental perspective. Additional research would be beneficial to approach this question to identify parameters with which durability is desirable and further inform how progressive standards could be made for durability. LEDs are still under rapid technological development and prices are currently decreasing by 18 % with each doubling of cumulative production (i.e. learning rate)(Gerke et al. 2015), which is lower than learning rates estimated for consumer electronics, but higher than most appliances (Siderius, 2013). This introduces several uncertainties into projections for setting progressive standards for durability and such dynamics would need to be more thoroughly considered.

The increasing importance of resource efficiency is likely to raise the relevance of more ambitious durability standards in the near future. While our analysis indicates a role for more ambitious standards, additional research is needed to examine optimal durability from an LCA perspective. In addition, practical methods for lifetime testing are required to implement and enforce any mandatory standards.

MANDATORY LABELLING

Lifetime information is already required on lamp packaging, but not for specification in a label (i.e. the energy label). There is growing momentum in the EU to include durability requirements in mandatory energy labels, and this is an option that allows consumers to differentiate products not only in relation to energy efficiency but also durability. In the EU debate there has been proposals that most products should be labelled with an 'average expected product lifetime', calculated through standardised methodologies, to allow better consumer decision-making (RREUSE, 2015). Already today, energy labelling in the EU includes some non-energy related information. One example is the label for vacuum cleaners, as it is a multi-dimensional label, where mandatory information includes: energy rating; annual energy use; emission (dust in exhaust air); noise level; pick-up performance for carpets, and pick-up performance for hard floors.

However, there is some general concern regarding the design of energy labelling and how consumers interpret the energy efficiency information (ECOFYS, 2014; Waechter et al., 2015) that implies it can be difficult to also include information on expected lifetime. The first question is whether the producer should account for minimum lifetime, or expected lifetime of the product, and how the choice of parameter can be communicated in an easy-to-understand fashion to consumers. Further, as discussed previously, lifetime entails many dimensions in the case of lighting. It is not realistic to expect consumers to understand all of them, nor to have information about all of them on the product (i.e. expected lifetime in terms of acceptable luminous flux, expected lifetime for acceptable colour rendering etc.). One potential way forward is that the labelling law stipulates a minimum for all these categories and that the expected lifetime indicated by the producer implies that all these dimensions are fulfilled to satisfactory level during the indicated lifetime. For most LED applications, it is primarily lumen output that matters, so lumen depreciation could be a potential first category to include in labelling.

The main advantage of using labelling to communicate lifetime is that it allows consumers to choose products according to preferences, and provides for competition in the market. The main disadvantage is that there may be incentives to cheat for producers as there are challenges related to market monitoring and product testing. Further, the wide range of products and applications may imply that it is hard to put a meaningful number for the expected lifetime in all cases, as LED are often integrated into various systems (Next Generation Lighting Industry Alliance, 2014).

WARRANTIES AND GUARANTEES

Another possible option for ensuring the durability of LEDs is extended guarantees or warranties. A warranty is a term of a contract, breach of which gives rise to a claim for damages, but (usually) not the repudiation of the whole contract. Such warranties can be pursued either through *mandated* warranty periods, or through *voluntary* warranties. As a baseline, consumers in most jurisdictions have a legally mandated warranty for a certain period of time, often ranging from one to three years. Both in the EU and the US, there are different rules in different jurisdictions related to warranties for consumers. Some jurisdictions such as Iceland and Norway also provide consumer rights for non-conforming products for a longer period of 5 years when the products are meant to last for a considerably longer time (Tonner & Malcolm, 2017). It should be noted that it is not only the general warranty that is of importance; in some jurisdictions, producers' claims about lifetime could lead to a consumer claim if the product falls short of its indicated lifetime, as this can constitute a breach of satisfactory quality (Stone, 2015).

It is not only the length of the warranty per se that is of importance, but also other factors, most notably when the burden of proof for showing that a product defect was present at the time of purchase is transferred from seller to buyer, as this can be difficult to prove. In most EU countries this burden of proof is moved from the seller to the buyer after six months. The EU NGO RREUSE has proposed that products can be more durable and repairable if the burden of proof is extended to two years manufacturers, and that this can be enforced through higher "Mean Time Between Failure (MTBF)" requirements for critical subassemblies such as those with electro mechanical parts/components (RREUSE, 2015).

EU law on consumer protection is a mix of both acts that aim at minimum harmonization and acts that aim at total harmoni-

Table 3. Summary of options for durability requirements.

Policy choice	Advantages	Disadvantages
Mandatory requirements	Allows policymakers to make the appropriate trade-offs between different functions (e.g. energy use, technological developments, and durability). The complexity of establishing 'durability' for lighting, and the problems of consumers to understand information about durability implies that mandatory requirements can be a good idea cf. to labelling and warranties.	By setting durability standards that goes further than a mere 'baseline', policymakers may interfere with decisions that are best taken by designers, based on customer needs. May be better to let customers use labelling to differentiate product lifetime according to their preferences.
Mandatory labelling	Allows consumers to choose products according to preferences, and provides for competition in the market. Less intrusive for producers than mandatory lifetime requirements.	Difficult for consumers to understand/ interpret the information. Risk of cheating. The broad range of LED products and applications can lead to quite varying lifetimes in practice.
Voluntary extended warranties	Useful in B2B applications where buyers can interpret technical information and enter into relevant contracts that are suitable for the purpose where the LED products are used.	Less useful for private buyers as the information is complex and the limited price of many LED products may mean that buyers are not very interested.
Mandatory extended warranties	Could be useful for consumers and increase confidence in LED products.	Not so useful in B2B relations.

zation. The main benefits of minimum harmonization are that it secures minimum rights for the consumer while allowing Member States to strengthen consumer protection. The main drawback is that practices in EU Member States differ, which forces producers to adopt different business practices throughout the EU (Mańko, 2015).

Whether warranties actually provide incentives for durability depends on the circumstances. When it comes to LEDs, the rather limited cost of the product and its longevity, may mean that consumers do not pursue a warranty claim, e.g. because the reward is limited compared to the effort. And consumers may be suspicious towards warranty claims from firms that may be on the market only temporarily (Price & Dawar, 2002).

Industry associations seem to view the use of warranties, reliability claims etc. as good source of information for customers (Next Generation Lighting Industry Alliance, 2014), but in reality, this mainly applies to professional users as private consumers cannot be expected to understand this information and assess its validity.

Generally, for most products groups there are indications that EU companies prefer eco-design requirements setting mandated minimum lifetime in hours, to mandated extended warranties in years; the likely reasons are that 1) guaranteeing lifetime in hours rather than years protects the producers from intensive product use by consumers and 2) mandated long warranty times undermines the lucrative business of selling longer warranties to consumers (Dalhammar, 2016). Also for LEDs, providing warranties in hours (in use) rather than years appears most suitable (Next Generation Lighting Industry Alliance, 2014).

For professional users, there is the option for producers to voluntarily offer extended warranties that include both replacements of faulty products and other services such as maintenance. The buyers can then chose a contract that suits their risk preferences and the technical installation. It is doubtful if a mandated warranty should be legislated for B2B relations, as the LEDs can be used for many different purposes. Regarding mandatory warranties for consumers, it is also doubtful if LED guarantees going beyond what is provided through general consumer protection legislation should be implemented, although such warranties could further improve consumer confidence in LED products.

Conclusions and recommendations

This paper has demonstrated how modelling the relationship between LCC and durability can approximate optimal lifetimes for the product market being considered. The LCC optimum durability for the LED market considered was found to be higher than the market average durability, indicating there is likely a role for durability MEPS to move the market closer to its LCC optimum. The analysis also indicated that greater durability is important when smaller discount rates and more intensive use of a product are factors. For products not used so intensely, durability is not as important as those products will last long without stringent standards. We also find a relationship in an optimized LCC between improved durability and lower energy use

The findings motivate further investigation into the feasibility of setting more stringent minimum durability requirements for LEDs. In order to further develop standards for durability, it is recommended that the LCC approach adopted in this study is complemented by an LCA approach that also seeks to find optimum durability for LEDs, while considering the context of continued development of LED technology and markets. In addition, increasing stringency of durability requirements in MEPS also requires implementation of accelerated testing methods (currently in development) to ensure such standards can be practically enforced. While we recommend that durability continues to be addressed first and foremost by MEPS, there is also a role for development of better labelling and warranties for these products in terms of durability.

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