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Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts

Jessika Luth Richter [a,*], Leena Tähkämö [b], Carl Dalhammar [a]

[a] International Institute for Industrial Environmental Economics, Lund University, Sweden
[b] Lighting Unit, Department of Electrical Engineering and Automation, Aalto University, Espoo, Finland

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ABSTRACT:

Longer product lifetimes are promoted by the EU's Circular Economy Action Plan, but incentivising longer lifetimes could also result in trade-offs between different environmental impacts for some product categories. LED lamps are still experiencing improvements in efficacy and material design, which raises questions about whether longer lifetimes are desirable from an overall environmental perspective. Applying a comprehensive life cycle assessment using actual product cases from 2012 to 2017, the research builds on previous product lifetime studies and lighting product research to determine the scenarios in which longer lifetimes are desirable from an overall environmental perspective. The factors explored in the scenarios included improving products in terms of efficiency and dematerialisation as well as decarbonised electricity contexts. The results indicate that product replacement with improved products resulted in environmental benefits compared to keeping longer life products in use, but there are some trade-offs between environmental impacts. However, these trade-offs are minimised in the context of decarbonised electricity mixes and will further decrease as LED lamp technology matures and product development slows. The policy implications of the findings are also discussed.

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1. Introduction

In the transition to a Circular Economy, there is a need for more efficient use of resources and reconsideration of how products are designed. Promoting longer product lifetimes is a key component of Circular Economy policies for both the EU (EU Commission, 2015; Montalvo et al., 2016) and the member state level (Montalvo et al., 2016). At the same time, research notes that trends in lifetimes are getting shorter for some products; for example consumer electronics (Bakker, Wang, Huisman, & den Hollander, 2014; Prakash et al., 2016). This, in turn, has implications for resource efficiency and waste produced from higher volumes of product consumption (Rivera and Lallmahomed, 2016). Countries like France have responded with legislation targeting planned obsolescence specifically and there is increasing interest in further incorporating durability standards into the EU Ecodesign Directive and associated regulations (Maitre-Ekern & Dalhammar, 2016).

Lighting products are one of the first product categories for which there are durability standards in the Ecodesign Directive (2009/125/EC). The requirements of regulations 244/2009 and 1194/2012 mostly focus on different dimensions of lifetime and set a minimum lifetime of 6000 h (Richter et al., 2019). Lifetimes of lamps may vary depending on environmental conditions and user behaviour (e.g., intensity of use, switching, etc.). Rated lifetimes, as used in declarations by manufacturers, are a combination of lumen depreciation and survival factor:

> ‘lamp lifetime’ means the period of operating 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. For LED lamps, lamp lifetime means the operating time between the start of their use and the moment when only 50% of the total number of lamps survive or when the average lumen maintenance of the batch falls below 70%, whichever occurs first.[1]

* Corresponding author.
E-mail address: jessika.luth.richter@iiiee.lu.se (J.L. Richter).

[1] See Annex II in 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. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012R1194.

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Several manufacturers have promoted the long life of LED lamps, with some lamps introduced to the market claiming lifetimes exceeding 50000 h (Hixon, 2012). However, more recent trends in household LED lighting indicate that the costs for manufacturing LED lamps have decreased dramatically, which puts less pressure on manufacturers to make longer lifetime claims (Katona et al., 2016). There are also some actors who believe that manufacturers might intentionally produce LED lamps with shorter lifetime to increase sales (MacKinnon, 2016).

Research has examined optimal lifetimes for LED lamps from a life cycle cost (LCC) perspective, where the main parameters include the upfront purchase price of the product as well as the costs of use during its lifetime (e.g. electricity costs). The study found that the optimal lifetimes for lamps on the market in Sweden in 2016 was approximately 25000 h (Richter et al., 2019), higher than the current 6000 h minimum lifetime in EU legislation. The findings indicate that from an LCC (economic) perspective, a much longer lifetime than the legal minimum of 6000 h would be optimal. Longer product lifetimes have also been motivated by studies citing potential economic, social and environmental benefits (Montalvo et al., 2016).

However, long lifetimes are not always associated with lower environmental impacts for all products; in fact, there can be trade-offs between different environmental impacts in promoting longer lifetimes. An example is electrical and electronic equipment with improving energy efficiency. Shorter lifetimes are often preferable for these products since there are environmental benefits derived from the efficiency improvements in replacing the old products which outweigh the environmental benefits of longer lifetimes (Bakker et al., 2014; Boulos et al., 2015; Cooper and Gutowski, 2015). Thus, Circular Economy policies promoting longer lifetimes for such products could result in trade-offs that could undermine the environmental benefits.

Life cycle assessment (LCA) is a method to assess the environmental impacts of products and can be used to explore the question of optimal lifetimes. In their study exploring longer product lifetimes, Bakker et al. (2014) apply a "fast track" LCA of the optimal durability for refrigerators and televisions. While the study gives an indication of optimal lifetimes, the authors also mention the "fast track" LCA as a limitation and suggest a more comprehensive LCA would be interesting for future research. Previous research has also addressed whether extended lifetimes for vacuum cleaners (Bobba et al., 2016) and washing machines (Ardente and Mathieux, 2014) result in reduced environmental impacts. The studies constructed baseline (i.e. product "A" replaced with new product "B" versus *durable* product "A" replaced at a later time with new product "B") and used environmental assessments based on LCA to test varying assumptions about lifetime extension and energy efficiency improvements. The studies note that the focus was not to present a comprehensive LCA of the product, but rather provide an indication of whether durability made sense for the product cases considered. To simplify the method, the studies restricted the detailed analysis of environmental impacts to a few impact categories: global warming potential (GWP), abiotic depletion, and human toxicity (Bobba et al., 2016) or terrestrial ecotoxicity (Ardente and Mathieux, 2014). The studies found that some extension of the lifetime could reduce the GWP even if the replacement product was more energy efficient while the other impact categories showed lower impacts with lifetime extension. Ardente and Mathieux (2014) also noted the challenges in making assumptions about product development (particularly when product "A" is still in an early development stage) and recommended conducting sensitivity analyses of key parameters; for example, the energy efficiency of replacement products. Bobba et al. (2016) conduct such a sensitively analysis considering decreased energy consumption of the replacement vacuum cleaner (i.e. product "B"). The study found that replacement resulted in less global warming potential impact if the product replacement was 25% more efficient, but did not result in less impact in the other categories examined (abiotic depletion and human toxicity).

Boulos et al. (2015) applied a combined LCC and LCA approach considering durable versus energy efficient models of fridge-freezers and ovens. The study used the International Reference Life Cycle Data System (ILCD) 2011 method (Wolf et al., 2012) to characterise 15 environmental impact categories and identify trade-offs between the impacts. They found replacing an oven or refrigerator with a 10% more energy efficient new model was preferable to the durable model for most environmental impacts considered, with the exception of impacts stemming from the production or end-of-life phase (e.g. ozone depletion, human toxicity, freshwater ecotoxicity, and mineral, fossil and renewable resource depletion for the refrigerator), which were always less with the durable model. While the research identified the trade-offs between different kinds of impacts, there was no further investigation of the relative significance of these different impacts. The research demonstrated the importance of the assumptions about product development (particularly energy efficiency improvements) when considering the role of lifetimes, as these have large implications for the outcomes. Further, it was evident that the actual trade-offs between impacts are product specific.

Previous LCA research for lighting products has found that longer lifetimes decrease overall environmental impacts from LED lighting products (Casamayor et al., 2017; Casamayor et al., 2015; Tähkämö, 2013), and there has been some research promoting design for longevity for lighting products (Casamayor et al., 2015; Dzombak et al., 2017; Hendrickson et al., 2010). However, previous LCA research did not consider the improving efficacy of LED lighting products, which has been substantial (see e.g. Bennich et al., 2015; Gerke et al., 2015), when considering lifetimes. Some research has indicated that there are potential trade-offs between different lifecycle phases (Nissen et al., 2012). The question remains whether longer lifetimes for LED lighting products produce less environmental impact in the long term, and what trade-offs there may be in promoting longer lifetimes for such products.

The aim of this research was to build on previous LCA-based durability studies and lighting product research to explore possible trade-offs with promoting longer lifetimes for LED lamps and determine the contexts in which longer lifetimes are desirable from an environmental perspective. The research applied LCA methodology similar to previous research (Ardente and Mathieux, 2014; Bobba et al., 2016; Boulos et al., 2015; Richter et al., 2017) considering lifetimes in relation to other dynamic factors, including improved efficacy of the LED products and design changes (including dematerialisation). While previous research has focussed on prospective assumptions about product development, this research considered a retrospective case with more specific data from products available in 2012 and 2017 to construct scenarios. 2012–2017 was a period of rapid development of LED lamps, allowing for more empirical consideration of a situation explored hypothetically in other studies. In addition to scenarios considering product development factors, the scenarios in this research also considered different electricity mixes, as this parameter can have a strong influence on the results of LCAs for lighting products (Franz and Wenzl, 2017; Tähkämö, 2013; Welz et al., 2011). This implies that whether longer lifetimes for LED lamps are preferable from an overall environmental perspective is also specific to the electricity context considered. The electricity mix is also important considering the fact that electricity mixes are expected to change, albeit slowly, in response to climate and energy policies in the near future.

The article first describes the methodology of the study and details of the scenarios are presented, followed by the results of the different modelled scenarios. Possible approaches for how to handle trade-offs are further explored through alternative characterisation and normalisation methods. Lastly, the remaining challenges of the research approach and implications of the results for Circular Economy policies promoting longer product lifetimes are discussed.

2. Methodology

The LCA method in this study followed the ISO 14040 (ISO, 2006a, b) and 14044 standards (ISO, 2006a, b), and analysis was conducted using SimaPro (V.8.5.0) software with the Ecoinvent (V3.3) database; these have been used in several studies about LCA of LED lamps and LED lighting products (Boulos et al., 2015; Casamayor et al., 2017; Tähkämö et al., 2013). The life cycle inventory (LCI) included the processes and materials for the LED lamps (the full LCI can be found in the Appendix and is summarised in section 2.4). The inventory was constructed with the bill of materials (BOM) from an LED lamp from 2012 and three LED lamps from 2017 (data from Scholand and Dillon, 2012 and Dillon et al., 2019). The BOM was then matched with Ecoinvent data with the SimaPro software.

2.1. Goal and scope of LCA

The goal of the LCA is to explore factors of product development and electricity mix in relation to the LED lamp product lifetimes to assess in which cases longer product lifetimes result in lower overall environmental impacts. The results of the study can be used to inform policies such as lifetime standards for lighting products. This research considers four approximately 800 lumen retrofit LED lamps (A-19 shape with E-27 base), building on previous LCAs of such products from 2012 (Scholand and Dillon, 2012) and three lamps from 2017 (Dillon et al., 2019).

2.2. Functional unit

The choice of an appropriate functional unit is fundamental to LCA. Lumen-hours, the functional unit used by the two studies on which this research is based, is one of the most common functional units for lighting products, incorporating important functional parameters of luminous flux and operating hours (Tähkämö and Dillon, 2017). Casamayor et al. (2017) noted that quality parameters such as correlated colour temperature (CCT) and colour rendering index (CRI) can also influence energy efficiency (e.g. high CCTs tend to be more slightly more efficient and higher CRIs less

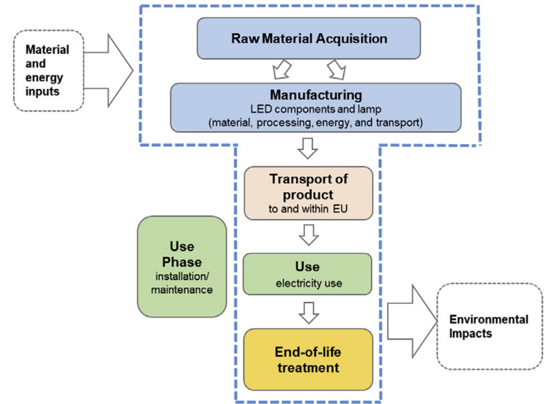

Fig. 1. System boundaries.

efficient). However, in this study the lamps compared are for the same 60 W equivalent retrofit household application and the CCT, CRI and conditions of use (e.g. room temperature and intensity of use) are assumed to be the same.

The choice of lumen-hours as a functional unit is appropriate for enabling comparisons between lamps (this unit is easily used for comparison between lighting products) as well as with previous LED lamp LCA studies upon which this study builds (Dillon et al., 2019; Scholand and Dillon, 2012). Thus, the functional unit used in this research was 20.3 million lumen hours (Mlmh) – equivalent to the function of the base case product (2012 LED lamp from Scholand and Dillon, 2012).

2.3. System boundaries

The product system considered in all scenarios was cradle to grave, i.e., raw materials acquisition, manufacturing, transport, use, and end-of-life. Fig. 1 shows the main life cycle stages considered.

2.4. Life cycle inventory

Table 1 indicates important attributes and materials for the LED lamps considered in the 2012 LCA by Scholand and Dillon (2012) and the updated study by Dillon et al. (2019). Only a summarised inventory of major material groups is presented here. The inventory data used as the long life base case in all scenarios was obtained from the 2012 United States (U.S.) Department of Energy's (DOE) comprehensive LCA of an 800lm 12.5W E-27 LED lamp in 2012 with a lifetime of 25000 h, CCT of 2700 K and CRI of 80 (Scholand and Dillon, 2012). The updated comparison of the 2017 LED lamps to the 2012 LED lamp concluded that the performance of LED lamps in

Table 1
Overview of case products.

Product (source)	2012 LED lamp (Scholand and Dillon, 2012)	2017 LED lamp replacement 1 (Dillon et al., 2019)	2017 LED lamp replacement 2 (Dillon et al., 2019)	2017 LED lamp replacement 3 (Dillon et al., 2019)
Luminous flux (lm)	812	800	800	815
Power (W)	12.5	8.5	9.5	11
Lifetime (h)	25000	10950	25000	25000
Aluminium (g)	68.20	11.03	20.69	–
Other metals (g)	10.65	1.92	2.19	1.90
Electronics (g)	80.25	13.14	21.72	17.38
Plastic (g)	11.10	19.26	35.71	27.55
LEDs (pieces)	12	11	20	8
Product mass (g)	176.00	45.66	81.96	47.09
Packaging (g)	37.00	17.99	30.68	26.72

Table 2
Overview of use stage for static scenario.

Lamp in scenario	2012 LED lamp	2012 LED lamp	2012 LED lamp
Lifetime (h)	25000	12500	5000
Number of products needed for 20.3Mlmh	1	2	5
Electricity use for 20.3Mlmh (kWh)	312.5 kWh	312.5 kWh	312.5 kWh

Table 3
Overview of use stage for improved lamp replacement scenario.

Lamps in scenarios	2012 LED lamp no replacement	2012 LED lamp 2017 replacement 1	2012 LED lamp, 2017 replacement 2	2012 LED lamp 2017 replacement 3
Additional number of products needed for 20.3Mlmh	0	1.83	0.8	0.8
Electricity use for 20.3Mlmh (kWh)	312.5	232.5	252.5	282.5

terms of environmental impacts had improved from 2012 (Dillon et al., 2019). The study confirmed the dominance of the use phase, making greater efficacy of the newer lamps advantageous even if the lifetime was shorter. While improved compared to 2012, it is clear that the luminous efficacy (lm/W) still varied between the lamps, as did the range of materials. Aluminium heatsinks were noted as large contributors to environmental impacts from the manufacturing phase (Dillon et al., 2019; Scholand and Dillon, 2012). As can be seen from Table 1, the aluminium content decreased in some newer products and was even designed out in product 3. The total lamp weight has also reduced from 2012 to 2017, indicating improving material efficiency as well.

Four changes were made to the overall inventory from the original research cited: 1) the electricity mix in the use stage was changed to the European context (from a U.S. mix in the original model); 2) as wafer sizes used in LED manufacturing have increased in size (and therefore efficiency) in recent years (Dillon and Ross, 2015; Roos, 2017), the yield of the LED die component for the 2017 lamps compared to the 2012 lamps was increased from 2438 to 3500 (using the projections in the Scholand & Dillon LCA study (2012)); 3) the 11g plastic phosphor host was modelled as polycarbonate plastic rather than rare earth mix indicated in the original inventory, though the 1g phosphor coating itself is still modelled as per the original inventory (see Scholand and Dillon, 2012 p. 35 p. 35)[2]; 4) an end-of-life waste treatment scenario in the European context was developed considering a 30% collection and recycling rate, which aligns with the European average recycling rate for gas discharge lamps (which are in most current cases recycled together with LED lamps, so assumed to be indicative - see Richter and Koppejan, 2016). Recycling of 50% of the aluminium (from the lamps collected as well as some discarded into other waste streams), 30% of glass was assumed treated as part of the collected lamp waste stream, while plastic was assumed to be incinerated based on waste material routes from literature and practice (e.g. Richter and Koppejan, 2016, Nordic Recycling, 2016). More detailed inventories can be found in the Appendix and the dataset in supplementary materials.

2.5. Life cycle impact assessment (LCIA) method

The environmental impacts were assessed using the life cycle impact assessment (LCIA) method ReCiPe (see Huijbregts et al., 2016). The midpoint level was used to give a more detailed indication of what impact categories are affected by the assumptions of the scenarios midpoint. The midpoint level assesses environmental impacts categorised into 18 different impact categories (as opposed to the ReCiPe endpoint level which further aggregates impacts into 3 categories and even a single score). The ReCiPe method harmonises the CML (Centrum Milieukunde Leiden) methodology and Eco-indicator 99 methodology and is one of the most recently updated impact assessment methods. The hierarchist perspective is based on a consensus model (between the shorter term individualist perspective and the longer term egalitarian perspective (see Goedkoop et al., 2009) and can be considered the default approach (PRé Sustainability, 2018).

2.6. Scenarios

Three scenario sets for general lighting service household LED lamps were considered in this LCA.

2.6.1. Static scenario

The approach in this scenario set considers shorter and longer lifetimes as a sensitivity analysis. It is the same approach used in previous LED lamp LCA studies (Casamayor et al., 2017; Tähkämö et al., 2013), in which the lifetime is varied with the assumption that the product is replaced by an identical product to fulfil the functional unit (i.e., 2 products are needed to fulfil the functional unit if the lifetime is changed to 12500 h and 5 products if 5000 h). All other variables are held constant (i.e. the inventories in Table 1 and the end-of-life assumptions). The reference flow and electricity use for this scenario set is shown in Table 2.

2.6.2. Improved product scenario: EU electricity context

This scenario set used the same 2012 DOE LED lamp data as the static scenario, but assumes that the original 2012 lamp is replaced at 5000 h by an improved lamp (considering both efficacy and material design from real 2017 lamps) rather than using the lamp for its full lifetime. As such, this scenario set represents replacing a lamp on the market in 2011–2012 with a lamp on the market in 2016–2017. A reference use of 1000 h per year (approximately 3 h a day) is assumed in this scenario. Three possible replacement products are compared with LCA data for three 800–815 lumen LED lamps on the market in 2017 (Table 1) and the reference flows and electricity use are shown in Table 3. Several products for comparison demonstrate real variation between energy efficiency and material design improvements. The scenarios are considered in the context of a European average electricity mix.

[2] The reason for changing the material from REE to plastic is that we could not find any evidence in literature about REE content in LEDs that the amount would be higher than 1g and certainly not as high as 11g (c.f. Andre, Soderman, & Tillman, 2016; Buchert et al., 2012; Franz and Wenzl, 2017; Machacek et al., 2015; Rollat et al., 2016; Tunsu et al., 2015). Also, as the description of the material in the original inventory is *plastic* host, we believe this was an error in the original inventory.

Table 4
Composition of electricity supply mix (EU,NO, SE) (Itten et al., 2012).

Source	European Electricity Mix[a]	Electricity supply mix Norway	Electricity supply mix Sweden
Renewable	5.8%	0.9%	6.8%
Hydro	17.6%	96.2%	43.3%
Nuclear	26.6%	0%	38.1%
Fossil Fuels	49.6%	0.4%	2.3%
Waste	1.2%	0.1%	1.3%
Imported	0.1%	2.4%	8.1%

[a] Ecoinvent uses the aggregation of country electricity mixes within the specified region (Europe- RER) in 2012.

Table 5
Overview of scenarios in this study.

	Product assumptions	Electricity mix assumptions
Static Scenario	2012 product replaced at 12500 h or 5000 h by identical product	EU electricity mix
Improved product scenario: EU electricity mix	2012 product replaced at 5000 h by 1 of 3 potential 2017 products	EU electricity mix
Improved product scenario: decarbonised electricity mix	2012 product replaced at 5000 h by 1 of 3 potential 2017 products	Norway and Sweden electricity mixes

2.6.3. Improved product scenario: decarbonised electricity mix

While the improved product scenario set considered an average EU electricity mix for the use stage, this scenario set considers the same products and replacement assumptions but in the context of decarbonised electricity. The Norwegian electricity supply mix average and the Swedish electricity supply mix average are examined (low voltage for households). The compositions of these mixes in Ecoinvent are shown in Table 4.

Prior LCAs conducted by Tähkämö et al. found that considering the LED product lifetime in the context of a Norwegian electricity mix, with very low fossil fuel sources, can have significantly lower overall environmental impacts (Tähkämö, 2013; Tähkämö et al., 2013; Tähkämö et al., 2014). Moreover, these previous LCAs found that in the Norwegian mix context, the manufacturing stage was responsible for most of the overall environmental impacts, rather than use stage (which normally dominates). This would then imply that durability would be desirable in this context, even with improved energy efficiency of the replacement products. However, the Norwegian mix can also be considered a very special case, with its high share of hydroelectricity, so the Swedish context is also considered, which has a higher share of nuclear and non-hydro renewable electricity. While still an extreme case, consideration of both contexts can shed light on the influence of lifetimes and improving lamp technologies in a decarbonised context versus the average EU context.

3. Results

3.1. Static scenario

Based on the scenario detailed in Table 2, Fig. 2 shows the results of comparative impacts of the DOE 2012 LED lamp (y axis – 100%) with various lifetimes, assuming that the replacement technologies for the shorter lifetime products are identical. It is clear that the longer life product has lower environmental impacts in all impact categories than a product with a fifth and half the lifetime. The

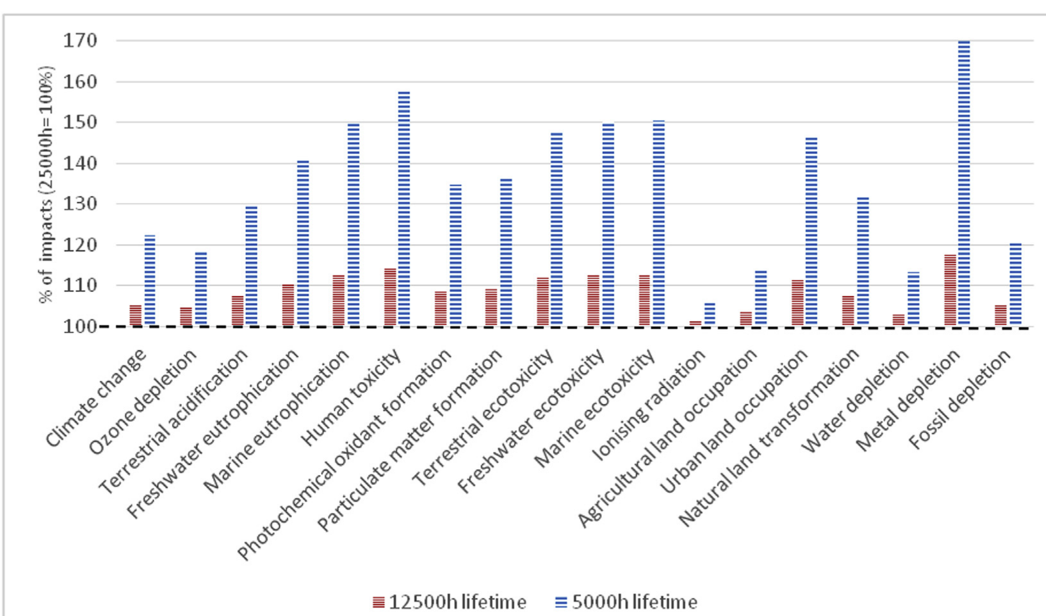

Fig. 2. Comparison of environmental impacts of identical 2012 LED lamps, varying the lifetime (12500 h, 5000 h) compared to the 25000 h base case LED lamp (100% on y axis – dotted line).

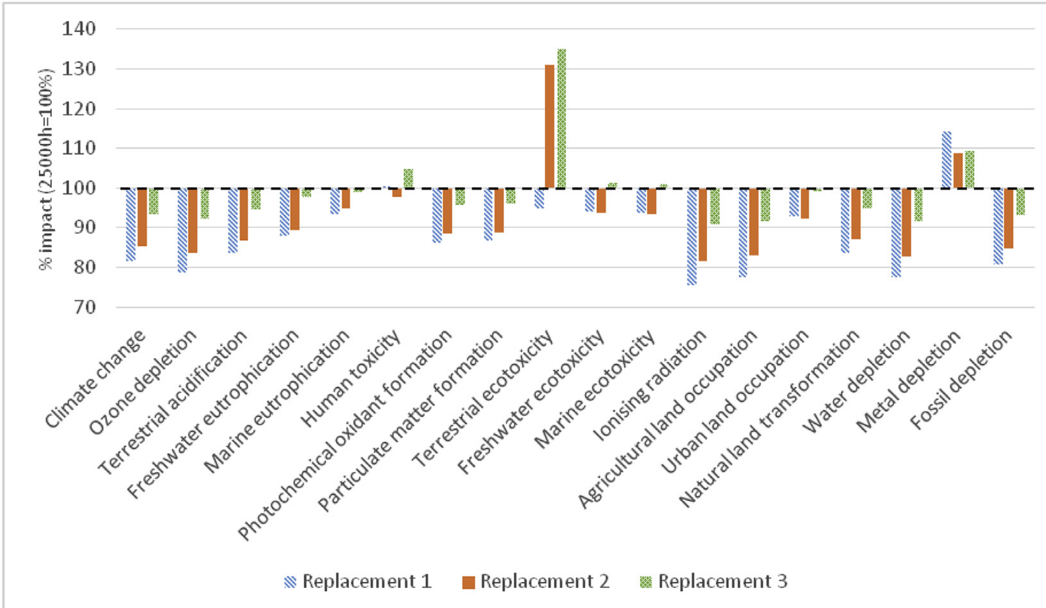

Fig. 3. Comparison of environmental impacts of 3 replacement options (original lamp replaced after 5000 h of use) relative to no replacement (i.e. base case – dotted line) in the context of EU average electricity mix. Replacement 1 represented the most efficient replacement and replacement 3 the least efficient. Replacement 1 has a lifetime of 10950 h, while all other product lifetimes are 25000 h. More specific details of products are found in Table 1.

largest differences are seen in material resource depletion and toxicity tied to the resources and processing needed for manufacturing the additional products to satisfy the 20.3 Mlmh functional unit. The fact that in many energy-related impact categories the difference is minimal also indicates the dominance of the use stage (and associated energy consumption) in driving impacts throughout the LED life cycle in this scenario.

3.2. Improved product scenario: EU electricity context

The picture changes when comparing longer and shorter lifetimes considering improvements in energy efficiency and material design of the replacement lamps (from the scenario in Table 3). In Fig. 2 it can be seen that the no replacement (i.e. longer lifetime) scenario has greater relative impacts in energy-related categories compared to the replacement scenarios. This makes sense given that the improved efficiency of the replacement products in the shorter life scenario result in decreased energy consumption in the use phase, but also requires manufacture and disposal of an additional product, which incur increased environmental impacts. There are also material improvements in the replacements that result in lower impacts for the shorter lifetime scenarios even in many of the toxicity categories. Compared to all of the replacement scenarios, the no replacement scenario only has relative benefits in the category of metal depletion; however, the no replacement scenario has less impact than at least one replacement lamp for each of the toxicity impacts, underscoring the importance of the assumptions about the replacements in scenarios. The most important assumption was the energy efficiency of the replacement lamp (which drives the lower impacts of replacement lamp 1 in many of the impact categories).

3.3. Improved product scenario: decarbonised electricity context

The results confirm that assumptions about the electricity mix can change the results of the comparison, as considered by this scenario outlined in Table 4. Fig. 4 compares the no replacement scenario with the replacement products in context of the decarbonised Norwegian electricity mix. The results here do not indicate the same trade-offs as in the context of the EU energy mix, with the longer lifetime LED lamp having relatively less impacts compared to the more efficient replacement scenario in the majority of the environmental impact categories.

In contrast to the Norwegian mix, the use of nuclear and some fossil fuel sources of electricity in the Swedish mix (Fig. 5) results in larger magnitude in the trade-offs, as well as additional trade-offs between impact categories, compared to the Norwegian mix (Fig. 4).

3.4. Sensitivity analysis

Aside from the static scenario set, all the scenarios involving improving the material/energy efficiency of replacement lamps resulted in some trade-offs between impacts. It was tested whether similar trade-offs were observed if using another LCIA method. The impacts were characterised with the ILCD recommendations for LCIA in the European context. (ILCD method, see Wolf et al., 2012). While Fig. 6 indicates that using different characterisation methods can result in slightly different results (c.f. Owsianiak et al., 2014), the trade-offs remain similar to those with the ReCiPe method illustrated in Fig. 3.

Another possible method of further interpreting impacts and possible trade-offs is to use normalisation to identify the magnitude of the impacts *relative to reference information*; for example the impacts in each category relative to the per capita impacts globally in 2010. Fig. 7 shows the comparison of the no replacement and replacement scenarios in the context of the EU and Swedish electricity mix, this time with the ReCiPe global per capita normalisation applied.[3]

[3] Global normalisation is applied because the processes within the system boundary extend beyond the European context (see Pizzol et al., 2017). ILCD normalisation was also applied, with similar results that can be viewed in the supplementary materials dataset.

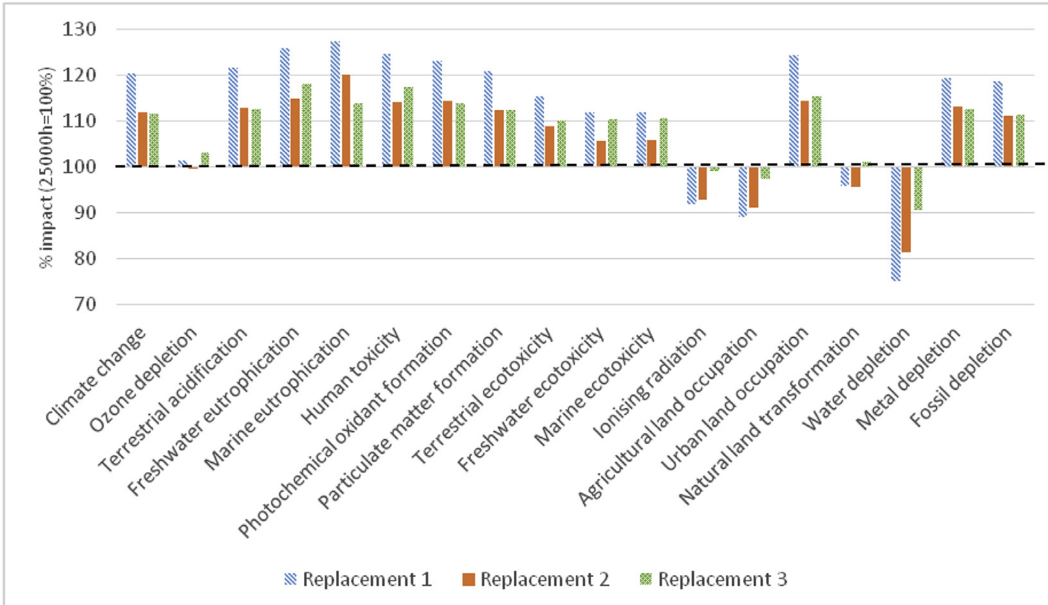

Fig. 4. Comparison of environmental impacts of 3 replacement options (original lamp replaced after 5000 h of use) relative to no replacement (i.e. base case – dotted line) in the context of Norwegian average electricity mix.

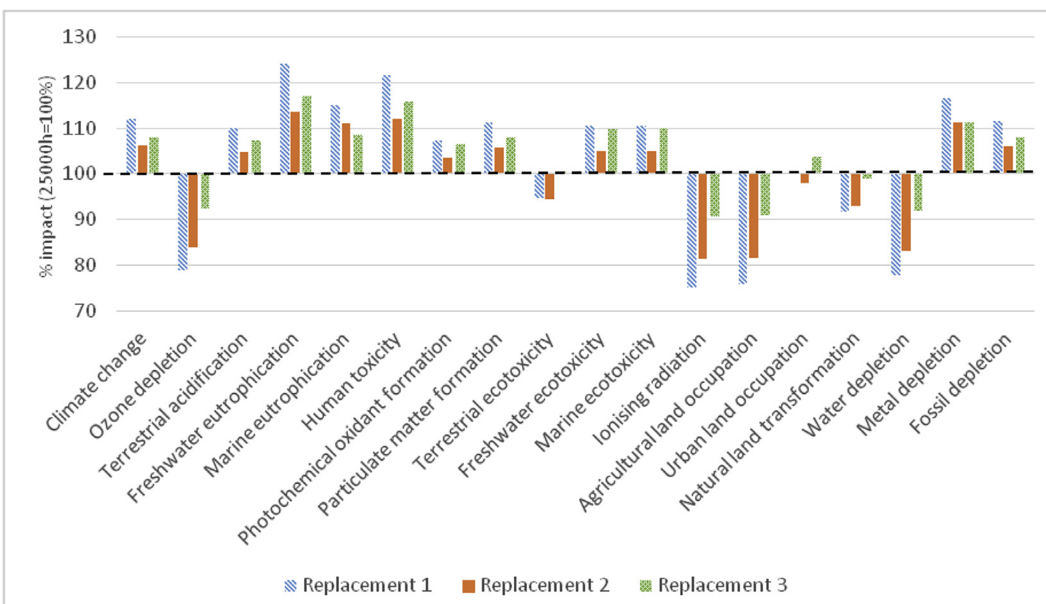

Fig. 5. Comparison of environmental impacts of 3 replacement options (original lamp replaced after 5000 h of use) relative to no replacement (i.e. base case – dotted line) in the context of Swedish average electricity mix.

It can be seen that normalisation identifies the impacts with the largest magnitude as the human and multiple ecotoxicity categories as well as the freshwater eutrophication impact categories. Within the impact categories with the highest magnitude, the no replacement scenario generally has the highest impacts in the EU average electricity context (except compared to replacement 3) while the no replacement scenario has the lowest impacts in these categories in the Swedish electricity context.

Normalising impacts into common units, i.e. Points in ILCD,[4] and aggregating results can produce a single score for the environmental impact. Fig. 8 shows the single aggregated scores for the different scenarios in this study. The method also highlights that the differences between scenarios within a given context are small, further underlining the importance of the choice of electricity source during use.

3.4.1. Lumen depreciation

LED lamps are distinctive from other light sources when considering lifetime. Lifetime includes not just failure to produce

[4] The normalisation factors for ILCD that support the conversion to Points can be found on the JRC website (http://eplca.jrc.ec.europa.eu/uploads/Table_ILCD_NFs_08-03-2016.xlsx) and in the underlying studies (see Sala et al., 2015).

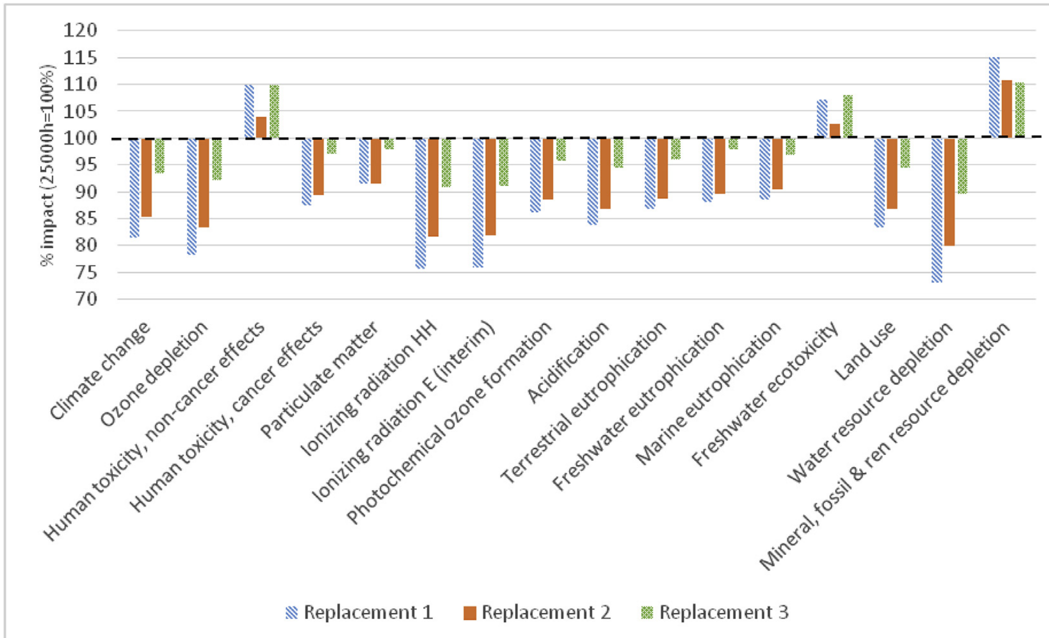

Fig. 6. Comparison of environmental impacts of 3 replacement options (original lamp replaced after 5000 h of use) relative to no replacement (i.e. base case – dotted line) in the context of EU electricity mix using ILCD.

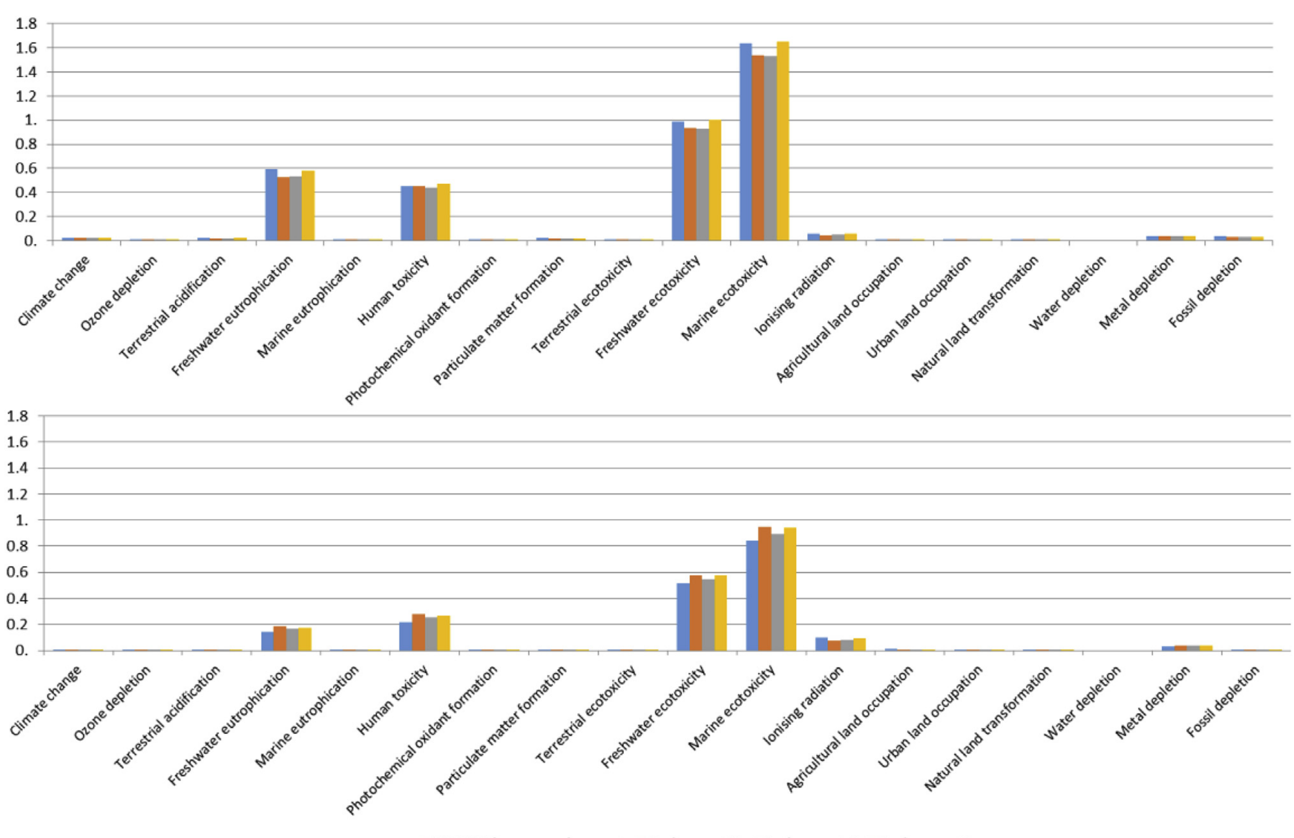

Fig. 7. Normalised environmental impacts of no replacement (i.e. base case – blue column) compared to 3 replacement options (original lamp replaced after 5000 h of use) in the context of EU (top) and Swedish electricity mix (bottom) using the ReCiPe midpoint hierarchist, normalised method (i.e. divided by the average impact in that category globally per capita in 2010, so a score of 1 is average impact in this category). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

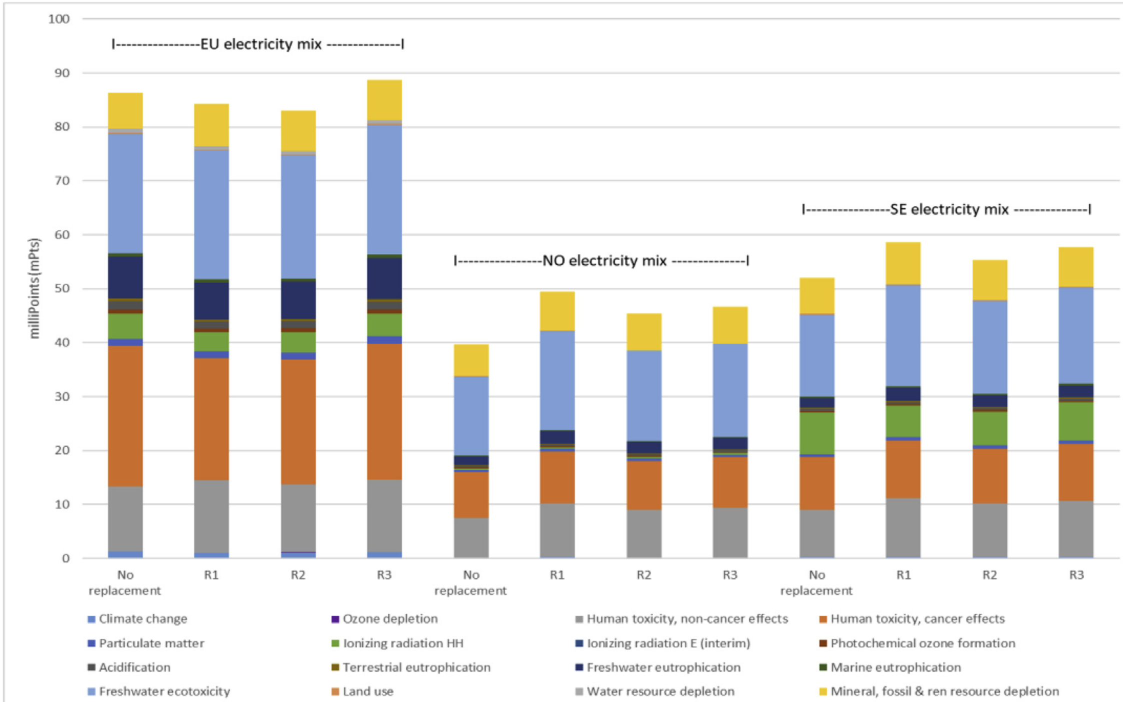

Fig. 8. Comparison of relative environmental impacts of the no replacement baseline scenario compared to 3 replacement options at 5000 h, in the context of an EU, NO, and SE electricity mix using ILCD single score method (normalising midpoint impacts by 2010 EU 27 normalisation factors to convert to Points and aggregating results).

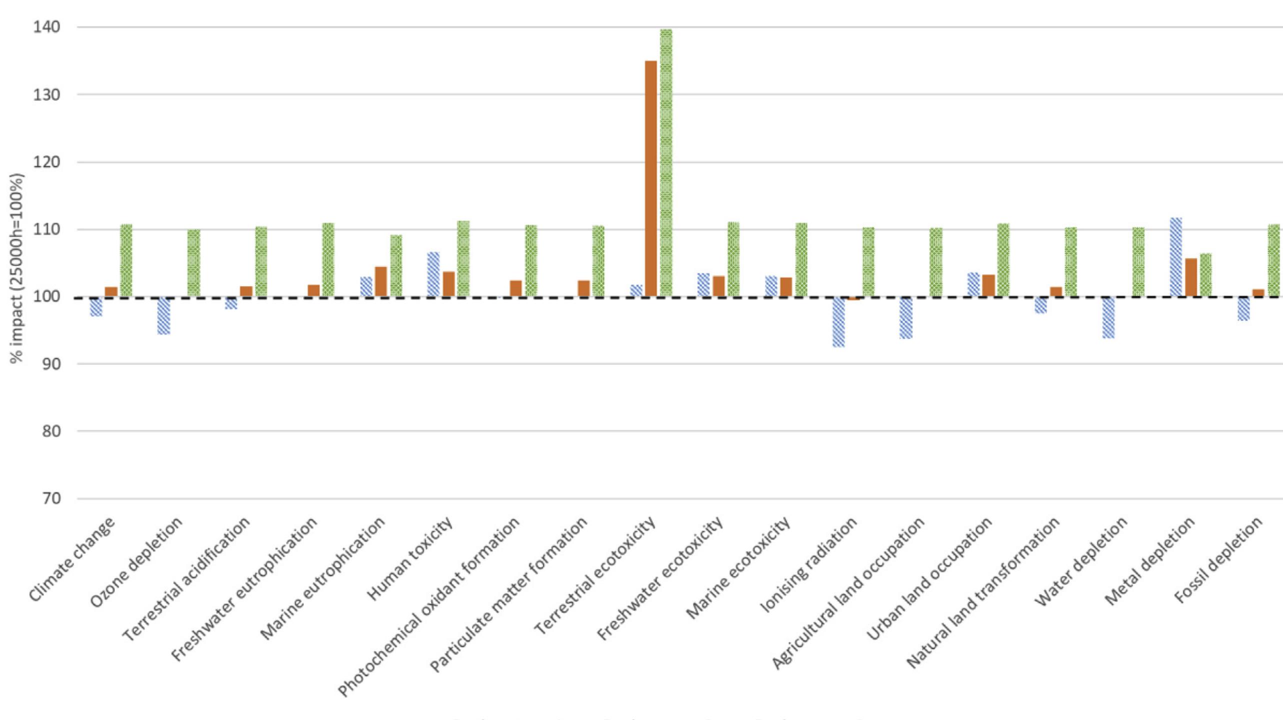

Fig. 9. Comparison of environmental impacts of 3 replacement options (original lamp replaced after 5000 h of use) relative to no replacement (i.e. base case – dotted line) in the context of EU average electricity mix and considering 30% lumen depreciation throughout the lamp lifetime (ReCiPe midpoint).

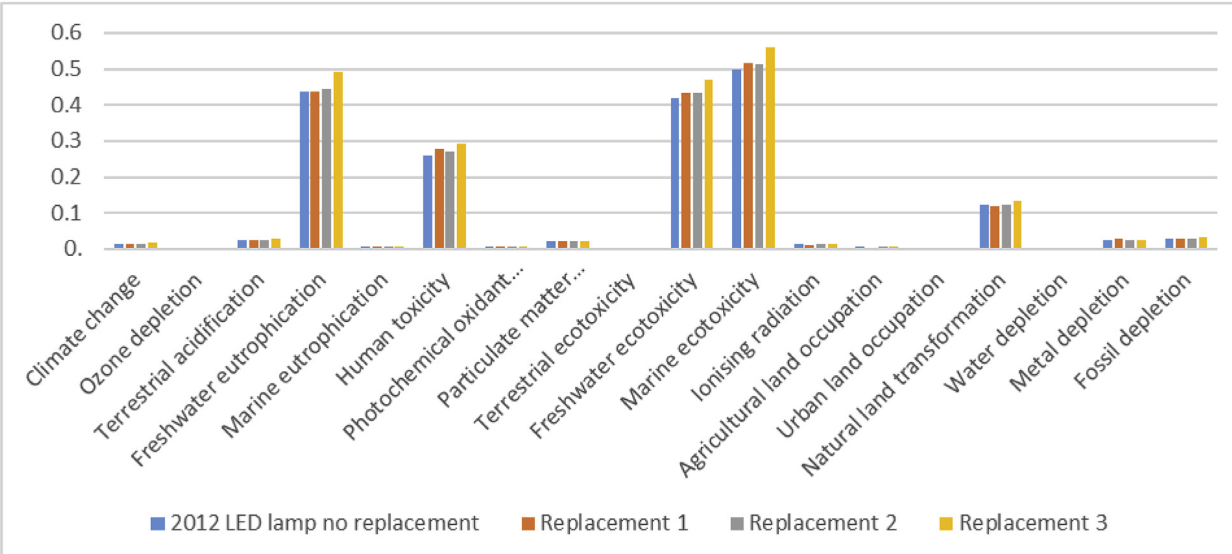

Fig. 10. Normalised environmental impacts of no replacement (i.e. base case – blue column) compared to 3 replacement options (original lamp replaced after 5000 h of use) in the context of EU electricity mix and considering 30% lumen depreciation throughout the lamp lifetime (using the ReCiPe midpoint hierarchist, normalised method). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

light, also deterioration of light (i.e. lumen maintenance/depreciation) and quality. Casamayor, Su & Sarshar (2017) conducted a sensitivity analysis of lumen depreciation in which the lifetimes of the luminaires considered were varied (similar to the static scenario presented in section 3.1). As the LED product lifetimes are the focus of this analysis, this kind of sensitivity analysis for lumen depreciation as it relates to lifetime has already been demonstrated.

However, lumen depreciation also affects the functional unit if considering decreasing lumen output, requiring additional product input to meet the 20.3 mlmh functional unit. While there is very little specific data on lumen depreciation rates as lamps are only tested for a portion of their expected lifetime (commonly 6000 h is standard), there are methods for estimating the lumen maintenance based on the LM-80 and TM-21 standards, both of which are used for extrapolating the rate of lumen depreciation and determining the lifetime (i.e. when 70% of the original lumen output is reached) (see Royer, 2014). It can be assumed then that the LED lamps lose 30% of their lumen output during their lifetimes.

The reference flows in the improving product EU scenario can be adjusted to account for this, as shown in Fig. 9. The figure further illustrates the difference this assumption makes in comparison to the original analysis of this scenario (Fig. 3). While replacement product 1 still has lower impacts in many of the impact categories, the difference has been minimised due to the need for slightly more products to fulfil the same functional unit (see Fig. 10). Fig. 10 shows the normlised results for this scenario set, showing the normliased impacts of no replacement can be less than replacement 1 for the impact categories with the highest normalised impacts (i.e. toxicity and eutrophiication categories).

4. Discussion

4.1. Retrospective scenario approach

Using additional scenarios in considering product improvements for LED lamps revealed significant differences compared to the standard LCA sensitivity approach varying only the lifetimes. Fig. 9 shows the difference between considering replacement at 5000 h with the same 2012 product versus a more energy efficient replacement. The findings from the improving product EU scenario set (section 3.2) resulted in the opposite finding compared to the static sensitivity approach (section 3.1). Fig. 11 demonstrates the difference between considering a static replacement at 5000 h (approach of previous LED LCAs) and replacement 1 at 5000 h, which accounts for real LED product development. This underscores the need to consider appropriate dynamic factors such as improving technologies when considering lifetimes in LCAs.

Past studies have attempted to arrive at absolute numbers for optimal lifetime (Bakker et al., 2014; Kim et al., 2006) based on general assumptions about product characteristics (i.e., average efficiencies of products and materials used). The retrospective case approach in this study highlighted how influential assumptions can be, as there were different outcomes for the 3 possible replacement products considered. The consumer would not necessarily choose the most energy efficient option in reality, in which case the more modest product improvements represented by replacement products 2 and 3 were not preferable to keeping the original product its full lifetime.

However, this study also found that even when the specific product characteristics are known, acquiring specific data for upstream processes can be challenging, and this challenge has been highlighted more generally for LED inventories (Franz and Wenzl, 2017). Using specific lamp data for the comparisons can also limit the generalisability of the results. As could be seen from the case of the three different 2017 products, different conclusions could be drawn depending on what products were considered. The same could be true for the 2012 product, of which there was only data for one product. That particular product had been chosen for its high efficacy (65 lm/W) compared to other LED lamps in 2012 (Scholand and Dillon, 2012), so can be considered a better than average lamp for the market at that time.

The analysis also showed sensitivity to the functional unit, for instance, by including lumen depreciation in the calculation of reference flows. While lumen-hours is a common functional unit for lamps, in reality the household user (as opposed to a professional or special use application) is unlikely to notice lumen depreciation and account for it (Next Generation Lighting Industry Alliance, 2014). This might also mean that in this application, simply hours may be a suitable functional unit.

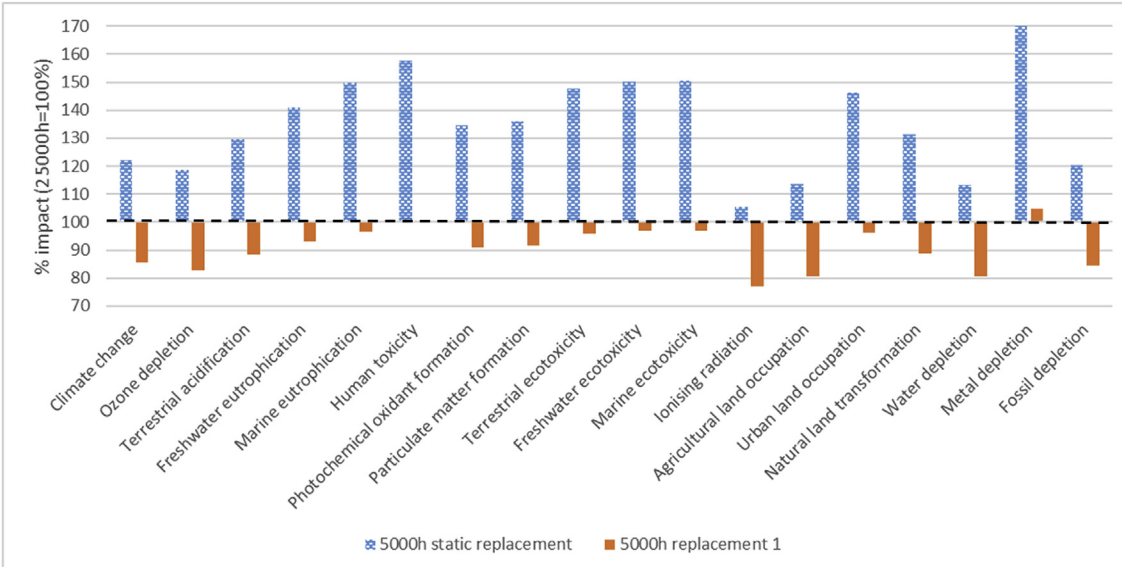

Fig. 11. Comparison of relative environmental impacts of the no replacement baseline scenario (dotted line) with the static replacement (i.e. no product development considered) and more energy efficient replacement product 1.

While rated lifetimes were used in this analysis, it is known that LED lamps can also fail earlier than the rated lifetime (Narendran et al., 2016). Even if products improve in terms of energy efficiency, if a replacement fails prematurely, the replacement lamp is likely to be similar in terms of energy efficiency and other product characteristics (as less time will have elapsed between installation and replacement). Premature failure would then lead to a more static scenario (or even replacement product 2 or 3) in which replacement products do not offer enough benefits in comparison to durable products. Minimum quality and lifetime requirements then are still very relevant in the policy context to ensure products are not replaced too rapidly.

The research demonstrated that normalisation and calculation of single aggregated scores can be useful for clearly identifying the scenarios with the lowest impact. However, the usefulness of normalisation for decision-making in comparative LCAs has been questioned, as it is observed that toxicity-related impacts tend to be emphasised by normalisation methods regardless of LCIA method used (see Prado et al., 2017). The same emphasis is evident in the ReCiPe and ILCD normalisations seen in Figs. 7 and 8 of this study. Moreover, some impacts such as water depletion could not be normalised with the available data. So while normalisation appears useful for putting trade-offs into perspective, there are caveats to using it as the basis for decision-making (Prado et al., 2017).

4.2. Are longer lifetimes better?

The findings of this research have confirmed the complexity of considering longer product lifetimes for improving products but indicate the factors and contexts under which longer lifetimes are preferable. While previous LCA of LED products has shown favourable results for long lifetimes (Casamayor et al., 2017; Tähkämö, 2013; Tähkämö and Dillon, 2017), the comparison was made as a sensitivity analysis considering identical product assumptions. In reality shorter lifetimes also mean that consumers can replace products with more energy-efficient and improved products can make the benefits of durability less straightforward.

Previous scenario-based research on durability for other product categories reached conclusions that more durable options were favourable in many types of many energy-using products, but not for all impact categories if there were substantial energy efficiency improvements (Ardente and Mathieux, 2014; Bobba et al., 2016; Iraldo et al., 2017). The case of LED lamps in this study indicated that shorter life products and faster replacement cycles appear to be beneficial in terms of energy-related environmental impacts if replaced with improved products in the context of fossil fuel based energy mixes. However, shorter lifetimes resulted in higher impacts in metal depletion and toxicity categories (depending on what replacement product is considered).

The results indicate that promoting durability in the context of improving products and an electricity mix with fossil fuels is likely to result in trade-offs between energy and material/toxicity-related environmental impacts. It is important to consider a broad range of impacts in order to fully assess these trade-offs. It should also be considered that LCA does not capture all impacts or issues which may be important in assessing these trade-offs (i.e. criticality of materials – see Klinglmair et al., 2014). The presence of trade-offs in an LCA-only approach also highlights the need to consider multiple tools and strategies for decision-making (Berlin and Iribarren, 2018).

Assumptions about what product is used as a replacement also matters to the results of the LCA. The case of LED lamps demonstrated that in addition to efficiency, material design, such as decreased use of aluminium for heat sinks, lower weight of metals and other materials, or smaller electronics, can also influence trade-offs, particularly for toxicity-related impact categories. Despite the availability of improved products on the market in 2017, the 65 lm/W efficiency of the 2012 product modelled in this case was a common efficacy for lamps in the low price sector in Europe (see Franz and Wenzl, 2017), indicating that the static scenario can also be a reality for many consumers. The better policy in this context might be to influence product choice towards improved products through eco-labelling and more ambitious minimum energy performance standards.

This research also confirmed the importance of electricity mix for environmental impacts. While earlier LCA research on LED lamps by (Tähkämö, 2013) found that the assumption of a Norwegian energy mix resulted in the relative impact of manufacturing phase to increase compared to the use phase, this study further illustrated that energy-related impacts are less significant overall (for example the climate impacts in the improving product scenario were 168.2 kg CO2 eq. for the 2012 product and 137.3 kg CO2 eq. for the more energy-efficient replacement 1, while the climate impacts were 23.5 and 29.5 kg CO2 eq., respectively, in the Norwegian context - see absolute impact figures in Appendix). This, in turn, minimises the trade-offs between environmental impacts in the case of improving product efficiencies. It is important that developments leading towards decarbonisation of the electricity mix are considered in determining the overall impact of longer product lifetimes as it was shown to both minimise the overall impacts of the LED lamps and minimise the trade-offs. This is relevant for policies considered on the member state level and in considering future product policies and their interaction with EU climate and energy policies promoting decarbonisation.

In considering product durability policies for lamps and other improving products, it is important to also look forward at projections of how the products will continue to develop. The context of this study was a period of rapid LED lamp development between 2012 and 2017. This development has even continued, as there are now LED lamps more than twice as efficient, using less materials (Philips Lighting, 2018), though many (but not all) have significantly shorter lifetimes than previous projections (Franz and Wenzl, 2017). Such lamps begin to approach the projected limits for efficiency improvement for LEDs (Navigant, 2016; U.S. Department of Energy, 2016). Moving towards the limits for efficiency developments means that replacement lamps will not present significant efficiency improvements, implying that as LED lamp technology matures the scenarios will increasingly resemble the static scenario set, in which early replacements or shorter lifetimes do not offer advantages from an environmental perspective (assuming no technology replaces LEDs before they mature).

5. Conclusion

This research has demonstrated some of the important factors to consider in whether longer lifetimes for products with improving technology are beneficial from an overall environmental perspective. The scenario-based approach indicated that considering improved efficiency, improved material design and decarbonisation of electricity supply can all influence whether longer lifetimes have lower environmental impacts for LED products. Policies to promote longer life for such products may only be appropriate in contexts with relatively decarbonised electricity supply, where trade-offs can be clearly weighed and valued, or for mature product categories where further substantial energy efficiency improvements are unlikely. The retrospective modelling approach presented in this paper identified that there are key factors beyond energy efficiency alone that should be considered in answering questions about optimal product lifetimes and that it is important to recognise trade-offs between different environmental impacts and when these are minimised as EU policy seeks to transition to both a circular and low carbon economy.

Author contributions

J.L.R. conceived the idea for this research, and developed the research design in collaboration with L.T. and C.D; J.L.R. modelled the LCA in SimaPro, conducted the analysis and made all graphs and figures, with comments provided by L.T.; J.L.R. wrote the article with review and comments provided by C.D. and L.T.

Conflicts of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.03.331.

Appendix

Table A-1
Lifecycle inventory for LED lamp products considered (based on Scholand and Dillon, 2012; Dillon et al., 2019).

Material	Unit	2012 LED lamp	2017 LED lamp 1	2017 LED lamp 2	2017 LED lamp 3	Ecoinvent process (market for | Alloc Def, U/)
LEDs units	p	12	11	20	8	LED unit (based on Scholand and Dillon, 2012).
Remote Phosphor[a]	g	1	0	0	0	Rare earth concentrate, 70% REO, from bastnasite {GLO}
Plastic Phosphor host	g	11	0	0	0	Polycarbonate {GLO}
Aluminium	g	68.20	11.03	20.69	0	Aluminium, cast alloy {GLO}
Copper	g	5	0	0	0	Copper {GLO}
Nickel	g	0.003	0	0	0	Nickel, 99.5% {GLO}
Brass	g	1.650	0	0	0	Brass {RoW}
Cast iron	g	4	0	0	0	Cast iron {GLO}
Chromium	g	0.0002	0	0	0	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
Galvanised Steel	g	0	1.919	2.190	1.904	Zinc concentrate/Steel, low-alloyed {GLO}
Silicon	g	0	1.322	0	0	Silicon, electronics grade {GLO}
Light Plastic	g	0	12.49	25.15	25.27	Polymethyl methacrylate, sheet {GLO}| market for | Alloc Def, U
Heavy Plastic	g	0	6.772	10.56	2.277	Polycarbonate {GLO}
LED board	g	0	1.734	4.665	6.320	Printed wiring board, surface mounted, unspecified, Pb free {GLO}
Printed board	g	15	3.466	1.617	1.927	Printed wiring board, surface mounted, unspecified, Pb free {GLO}
Inductor	g	4.8	0.668	0.804	0.913	Copper concentrate {GLO}
IC Chip	g	0.158	0	0.079	0	Integrated circuit, logic type {GLO}
Capacitor SMD	g	0.377	0.023	0.050	0.115	Capacitor, for surface-mounting {GLO}
Electrolytic Capacitor	g	24.73	1.747	5.637	4.920	Capacitor, electrolyte type, < 2 cm height {GLO}
Diode	g	1.091	0.139	0.181	0.222	Diode, glass-, for surface-mounting
Resistor SMD	g	0.993	0.104	0.136	0.253	Resistor, surface-mounted {GLO}

Table A-1 (*continued*)

Material	Unit	2012 LED lamp	2017 LED lamp 1	2017 LED lamp 2	2017 LED lamp 3	Ecoinvent process (market for | Alloc Def, U/)
Resistor	g	0.993	0.104	0.136	0.253	Resistor, wirewound, through-hole mounting {GLO}
Transistor	g	1.387	0.085	0.608	0	Transistor, wired, big size, through-hole mounting {GLO}
Transformer	g	30.15	4.956	7.384	2.667	Transformer, low voltage use {GLO}
Resin Glue	g	4.5	0	0	0	Epoxy resin, liquid {GLO}
Solder paste	g	0.3	0.3	0.3	0.3	Flux, for wave soldering {GLO}
Product Mass	**g**	**176.0**	**45.66**	**81.96**	**47.09**	
Paper packaging	g	37	17.99	18.91	19.80	Corrugated board box {GLO}
Plastic packaging	g	0	0	11.77	6.915	Polymethyl methacrylate, sheet {GLO}
Total Mass	**g**	**213.00**	**63.65**	**100.9**	**66.88**	

[a] Phosphor for 2017 units is modelled as part of the LED unit.

Table A-2. Comparison of environmental impacts of improving product scenario (2012 LED lamp 25000 h versus 3 replacements at 5000 h in context of EU average electricity mix)

Impact category	Unit	2012 lamp	Replacement 1	Replacement 2	Replacement 3
Climate change	kg CO2 eq	168.2036	137.3253	143.5552	157.4445
Ozone depletion	kg CFC-11 eq	2E-05	1.57E-05	1.67E-05	1.84E-05
Terrestrial acidification	kg SO2 eq	0.794248	0.665028	0.68884	0.751399
Freshwater eutrophication	kg P eq	0.172309	0.151666	0.154243	0.168752
Marine eutrophication	kg N eq	0.061574	0.057489	0.05836	0.060963
Human toxicity	kg 1,4-DB eq	147.4093	147.9493	143.8671	154.5649
Photochemical oxidant formation	kg NMVOC	0.391296	0.337471	0.346231	0.375215
Particulate matter formation	kg PM10 eq	0.276833	0.240556	0.245906	0.266147
Terrestrial ecotoxicity	kg 1,4-DB eq	0.013443	0.012412	0.019883	0.020732
Freshwater ecotoxicity	kg 1,4-DB eq	4.26944	4.016406	3.99953	4.320185
Marine ecotoxicity	kg 1,4-DB eq	4.029693	3.779661	3.768118	4.073004
Ionising radiation	kBq U235 eq	78.19658	59.15445	63.78136	71.10953
Agricultural land occupation	m2a	22.07145	17.11072	18.30404	20.26817
Urban land occupation	m2a	1.252462	1.162318	1.156899	1.244858
Natural land transformation	m2	0.018849	0.015756	0.0164	0.017879
Water depletion	m3	2.431133	1.885543	2.015163	2.232203
Metal depletion	kg Fe eq	14.83869	17.29755	16.33812	16.45904
Fossil depletion	kg oil eq	44.51786	35.935	37.75395	41.50693

Table A-3
Comparison of environmental impacts of decarbonised product scenario set (2012 LED lamp 25000 h versus 3 replacements at 5000 h in context of NO average electricity mix)

Impact category	Unit	2012 lamp	Replacement 1	Replacement 2	Replacement 3
Climate change	kg CO2 eq	23.4966	29.5117	26.9876	26.98504
Ozone depletion	kg CFC-11 eq	3.15E-06	3.2E-06	3.15E-06	3.26E-06
Terrestrial acidification	kg SO2 eq	0.137775	0.175924	0.160644	0.160182
Freshwater eutrophication	kg P eq	0.038276	0.051806	0.046062	0.047704
Marine eutrophication	kg N eq	0.018324	0.025266	0.023419	0.02187
Human toxicity	kg 1,4-DB eq	65.13799	86.6533	77.48768	80.28738
Photochemical oxidant formation	kg NMVOC	0.082491	0.107397	0.098118	0.097458
Particulate matter formation	kg PM10 eq	0.066037	0.083503	0.076473	0.076478
Terrestrial ecotoxicity	kg 1,4-DB eq	0.005489	0.006486	0.006069	0.006154
Freshwater ecotoxicity	kg 1,4-DB eq	2.145389	2.433888	2.284923	2.40167
Marine ecotoxicity	kg 1,4-DB eq	1.986474	2.257366	2.119854	2.228591
Ionising radiation	kBq U235 eq	5.147194	4.729208	4.784018	5.099449
Agricultural land occupation	m2a	4.558123	4.062463	4.155017	4.437871
Urban land occupation	m2a	0.395683	0.523977	0.4711	0.476809
Natural land transformation	m2	0.007978	0.007657	0.007637	0.008073
Water depletion	m3	9.90344	7.452764	8.055053	8.989434
Metal depletion	kg Fe eq	12.60326	15.63205	14.67001	14.57633
Fossil depletion	kg oil eq	5.681647	7.000191	6.463242	6.487943

Table A-4
Comparison of environmental impacts of decarbonised product scenario set (2012 LED lamp 25000 h versus 3 replacements at 5000 h in context of SE average electricity mix)

Impact category	Unit	2012 lamp	Replacement 1	Replacement 2	Replacement 3
Climate change	kg CO2 eq	30.4599	34.69969	32.61394	33.27987
Ozone depletion	kg CFC-11 eq	2E-05	1.58E-05	1.68E-05	1.85E-05
Terrestrial acidification	kg SO2 eq	0.20019	0.222427	0.211076	0.216605
Freshwater eutrophication	kg P eq	0.040665	0.053585	0.047992	0.049863
Marine eutrophication	kg N eq	0.026766	0.031555	0.03024	0.029501
Human toxicity	kg 1,4-DB eq	71.59839	91.46661	82.70769	86.12759
Photochemical oxidant formation	kg NMVOC	0.137307	0.148238	0.14241	0.147012
Particulate matter formation	kg PM10 eq	0.089488	0.100975	0.095421	0.097678
Terrestrial ecotoxicity	kg 1,4-DB eq	0.011906	0.011267	0.011254	0.011956
Freshwater ecotoxicity	kg 1,4-DB eq	2.227805	2.495291	2.351515	2.476173
Marine ecotoxicity	kg 1,4-DB eq	2.082555	2.328952	2.197488	2.315449
Ionising radiation	kBq U235 eq	131.2554	98.68578	106.6795	119.1013
Agricultural land occupation	m2a	53.34824	40.4134	43.57743	48.54414
Urban land occupation	m2a	0.887749	0.89059	0.86869	0.921636
Natural land transformation	m2	0.0099	0.009089	0.00919	0.00981
Water depletion	m3	2.267833	1.763876	1.885482	2.086845
Metal depletion	kg Fe eq	13.73016	16.47164	15.58055	15.59506
Fossil depletion	kg oil eq	7.189354	8.123504	7.68147	7.85091

References

Narendran, N., Liu, Y., Mou, X., Thotagamuwa, D.R., Eshwarage, O.V.M., 2016. Projecting LED product life based on application. In: Fifteenth International Conference on Solid State Lighting and LED-Based Illumination Systems, vol. 9954. International Society for Optics and Photonics, p. 99540G. https://doi.org/10.1117/12.2240464.

André, H., Soderman, M.L., Tillman, A., 2016. Circular economy as a means to efficient use of scarce metals?. In: 2016 Electronics Goes Green 2016+ (EGG), pp. 1–8. https://doi.org/10.23919/EGG.2016.8396923.

Ardente, F., Mathieux, F., 2014. Environmental assessment of the durability of energy-using products: method and application. J. Clean. Prod. 74, 62–73. https://doi.org/10.1016/j.jclepro.2014.03.049.

Bakker, C., Wang, F., Huisman, J., den Hollander, M., 2014. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028.

Bennich, P., Soenen, B., Scholand, M., Borg, N., 2015. Updated Test Report - Clear, Non-directional LED Lamps. Retrieved from. https://www.energimyndigheten.se/Global/F%C3%B6retag/Ekodesign/Produktgrupper/Belysning/Report%20on%20Testing%20of%20Clear%20LED%20lamps%20v5%205.pdf.

Berlin, J., Iribarren, D., 2018. Potentials and limitations of combined life cycle approaches and multi-dimensional assessment. In: Benetto, E., Gericke, K., Guiton, M. (Eds.), Designing Sustainable Technologies, Products and Policies: from Science to Innovation. Springer International Publishing, Cham, pp. 313–316. https://doi.org/10.1007/978-3-319-66981-6_34.

Bobba, S., Ardente, F., Mathieux, F., 2016. Environmental and economic assessment of durability of energy-using products: method and application to a case-study vacuum cleaner. J. Clean. Prod. 137, 762–776. https://doi.org/10.1016/j.jclepro.2016.07.093.

Boulos, S., Sousanoglou, A., Evans, L., Lee, J., King, N., Facheris, C., et al., 2015. The Durability of Products: Standard Assessment for the Circular Economy under the Eco-Innovation Action Plan. Report for European Commission, DG Environment.

Buchert, M., Manhart, A., Bleher, D., Pingel, D., 2012. Recycling critical raw materials from waste electronic equipment. Freiburg: Öko-Institut EV 49 (0), 30–40.

Casamayor, J., Su, D., Sarshar, M., 2015. Extending the lifespan of LED-lighting products. Architect. Eng. Des. Manag. 11 (2), 105–122. https://doi.org/10.1080/17452007.2013.834813.

Casamayor, J., Su, D., Ren, Z., 2018. Comparative life cycle assessment of LED lighting products. Light. Res. Tech. 50 (6), 801–826. https://doi.org/10.1177/1477153517708597.

Cooper, D.R., Gutowski, T.G., 2017. The environmental impacts of reuse: a review,. J. Ind. Ecol. 21 (1), 38–56.

Dillon, H., Ross, C., 2015. Updating the LED Life Cycle Assessment. Retrieved from https://www.energy.gov/sites/prod/files/2015/11/f27/dillon_lifecycle_portland2015.pdf.

Dillon, H., Ross, C.B., Dzombak, R., 2019. Environmental and Energy Improvements of LED Lamps over Time: A Comparative Life Cycle Assessment. LEUKOS. https://doi.org/10.1080/15502724.2018.1541748.

Dzombak, R., Padon, J., Salsbury, J., Dillon, H., 2017. Assessment of end-of-life design in solid-state lighting. Environ. Res. Lett. 12 (8), 084013. https://doi.org/10.1088/1748-9326/aa7ab1.

EU Commission, 2015, December 2. Communication from the EU Commission, Closing the Loop - an EU Action Plan for the Circular Economy. COM/2015/0614 final. Retrieved from. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

Franz, M., Wenzl, F.P., 2017. Critical review on life cycle inventories and environmental assessments of LED-lamps. Crit. Rev. Environ. Sci. Technol. 47 (21), 2017–2078. https://doi.org/10.1080/10643389.2017.1370989.

Gerke, B.F., Ngo, A.T., Fisseha, K.S., 2015. Recent Price Trends and Learning Curves for Household LED Lamps from a Regression Analysis of Internet Retail Data. Lawrence Berkeley National Laboratory, Berkeley, CA. Retrieved from. https://ees.lbl.gov/sites/all/files/lbnl-184075.pdf.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008. A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, vol. 1, pp. 1–126.

Hendrickson, C.T., Matthews, D.H., Ashe, M., Jaramillo, P., McMichael, F.C., 2010. Reducing environmental burdens of solid-state lighting through end-of-life design. Environ. Res. Lett. 5 (1), 014016.

Hixon, T., 2012. LED Light Bulbs Mature. At Last. Forbes. Retrieved from. https://www.forbes.com/sites/toddhixon/2012/12/13/led-light-bulbs-mature-at-last/.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., et al., 2016. ReCiPe 2016: a Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. National Institute for Public Health and the Environment, Netherlands, pp. 138–147. Retrieved from. http://link.springer.com/10.1007/s11367-016-1246-y.

Iraldo, F., Facheris, C., Nucci, B., 2017. Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. J. Clean. Prod. 140 (Part 3), 1353–1364. https://doi.org/10.1016/j.jclepro.2016.10.017.

ISO, 2006a. Environmental Management-Life Cycle Assessment - Requirements and Guidelines. ISO, p. 14044.

ISO, I., 2006b. 14040 International Standard. Environmental Management—Life Cycle Assessment—Principles and Framework.

Itten, R., Frischknecht, R., Stucki, M., Scherrer, P., Psi, I., 2012. Life Cycle Inventories of Electricity Mixes and Grid.

Katona, T.M., Pattison, P.M., Paolini, S., 2016. Status of solid state lighting product development and future trends for general illumination. Annual Review of Chemical and Biomolecular Engineering 7, 263–281.

Kim, H.C., Keoleian, G.A., Horie, Y.A., 2006. Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. Energy Policy 34 (15), 2310–2323. https://doi.org/10.1016/j.enpol.2005.04.004.

Klinglmair, M., Sala, S., Brandão, M., 2014. Assessing resource depletion in LCA: a review of methods and methodological issues. Int. J. Life Cycle Assess. 19 (3), 580–592. https://doi.org/10.1007/s11367-013-0650-9.

Lighting, Philips, 2018. Dubai Lamp. Retrieved 9 April 2018, from. https://www.philips.ae/c-m-li/dubai-lamp.

Machacek, E., Richter, J.L., Habib, K., Klossek, P., 2015. Recycling of rare earths from fluorescent lamps: value analysis of closing-the-loop under demand and supply uncertainties. Resour. Conserv. Recycl. 104 (Part A), 76–93. https://doi.org/10.1016/j.resconrec.2015.09.005.

MacKinnon, J.B., 2016. The L.E.D. Quandary: Why There's No Such Thing as "Built to Last". *The New Yorker*. Retrieved 30 January 2019 from. http://www.newyorker.com/business/currency/the-l-e-d-quandary-why-theres-no-such-thing-as-built-to-last.

Maitre-Ekern, E., Dalhammar, C., 2016. Regulating planned obsolescence: a review of legal approaches to increase product durability and reparability in Europe. Rev. Europ. Comp. Int. Environ. Law 25 (3), 378–394. https://doi.org/10.1111/reel.12182.

Montalvo, C., Peck, D., Rietveld, E., 2016. A Longer Lifetime of Products: benefits for consumers and companies. *European Parliament, Directorate-General for Internal Policies - Policy Department A: Economic and Scientific Policy, IP/A/IMCO/2015-11.*

Retrieved 10 February 2017 from http://www.europarl.europa.eu/thinktank/en/document.html?reference=IPOL_STU(2016)579000.
Navigant, 2016. Energy Savings Forecast of Solid-State Lighting in General Illumination Applications. U.S. Department of Energy. Retrieved from. https://energy.gov/sites/prod/files/2016/09/f33/energysavingsforecast16_2.pdf.
Next Generation Lighting Industry Alliance, 2014. LED Luminaire Lifetime: Recommendations for Testing and Reporting (No. 3). Retrieved from. http://www.nglia.org/pdfs/led_luminaire_lifetime_guide_sept2014.pdf.
Nissen, N.F., Middendorf, A., Wittler, O., Lang, K.-D., 2012. Eco-reliability – a combined approach to balance environment with reliability. In: Matsumoto, M., Umeda, Y., Masui, K., Fukushige, S. (Eds.), Design for Innovative Value towards a Sustainable Society. Springer Netherlands, Dordrecht, pp. 409–412. https://doi.org/10.1007/978-94-007-3010-6_78.
Owsianiak, M., Laurent, A., Bjørn, A., Hauschild, M.Z., 2014. IMPACT 2002+, ReCiPe 2008 and ILCD's recommended practice for characterization modelling in life cycle impact assessment: a case study-based comparison. Int. J. Life Cycle Assess. 19 (5), 1007–1021.
Pizzol, M., Laurent, A., Sala, S., Weidema, B., Verones, F., Koffler, C., 2017. Normalisation and weighting in life cycle assessment: *quo vadis*? Int. J. Life Cycle Assess. 22 (6), 853–866. https://doi.org/10.1007/s11367-016-1199-1.
Prado, V., Wender, B.A., Seager, T.P., 2017. Interpretation of comparative LCAs: external normalization and a method of mutual differences. Int. J. Life Cycle Assess. 22 (12), 2018–2029. https://doi.org/10.1007/s11367-017-1281-3.
Prakash, S., Dehoust, G., Gsell, M., Schleicher, T., Stamminger, R., 2016. Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz “. Umweltbundesamt.
PRé Sustainability, 2018. ReCiPe. Retrieved 3 December 2018, from. https://www.pre-sustainability.com/recipe.
Recycling, Nordic, 2016. Use of Fractions. Retrieved 30 August 2014, from. http://www.nordicrecycling.se/nr/18-recycling-evy.
Richter, J.L., Koppejan, R., 2017. Extended Producer Responsibility for Lamps in Nordic Countries: Best Practices and Challenges in Closing Material Loops. J. Clean. Prod. 123, 167–179. https://doi.org/10.1016/j.jclepro.2015.06.131.
Richter, J.L., Dalhammar, C., Tähkämö, L., 2017. Considering Optimal Lifetimes for LED lamps: a mixed approach and policy implications. In: Presented at the Product Lifetimes and the Environment (PLATE). TU Delft.
Richter, J.L., Van Buskirk, R., Dalhammar, C., Bennich, P., 2019. Optimal durability in least life cycle cost methods: the case of LED lamps. Energy Efficiency 12 (1), 107–121. https://doi.org/10.1007/s12053-018-9662-4.
Rivera, J.L., Lallmahomed, A., 2016. Environmental implications of planned obsolescence and product lifetime: a literature review. Int. J. Sustain. Eng. 9 (2), 119–129. https://doi.org/10.1080/19397038.2015.1099757.
Rollat, A., Guyonnet, D., Planchon, M., Tuduri, J., 2016. Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon. Waste Manag. 49, 427–436. https://doi.org/10.1016/j.wasman.2016.01.011.
Roos, G., 2017, December 27. China's LED Chip Capacity Expansion Halts Price Hikes, Tight Supply. EPS News. Retrieved from. https://epsnews.com/2017/12/27/chinas-led-chip-capacity-expansion-halts-price-hikes-tight-supply/.
Royer, M., 2014. Lumen maintenance and light loss factors: Consequences of current design practices for LEDs. Leukos 10 (2), 77–86. https://doi.org/10.1080/15502724.2013.855613.
Sala, S., Benini, L., Mancini, L., Pant, R., 2015. Integrated assessment of environmental impact of Europe in 2010: data sources and extrapolation strategies for calculating normalisation factors. Int. J. Life Cycle Assess. 20 (11), 1568–1585. https://doi.org/10.1007/s11367-015-0958-8.
Scholand, M., Dillon, H.E., 2012. Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products Part 2: LED Manufacturing and Performance. Pacific Northwest National Laboratory (PNNL), Richland, WA (US). Retrieved from. http://www.osti.gov/scitech/biblio/1044508.
Tähkämö, L., 2013. Life Cycle Assessment of Light Sources–Case Studies and Review of the Analyses. Aalto University. Retrieved 30 January 2018 from. https://aaltodoc.aalto.fi/handle/123456789/10905.
Tähkämö, L., Dillon, H., 2017. Life cycle assessment of lighting technologies. In: Handbook of Advanced Lighting Technology. Retrieved from. http://link.springer.com/content/pdf/10.1007/978-3-319-00295-8_41-1.pdf.
Tähkämö, L., Bazzana, M., Ravel, P., Grannec, F., Martinsons, C., Zissis, G., 2013. Life cycle assessment of light-emitting diode downlight luminaire—a case study. Int. J. Life Cycle Assess. 18 (5), 1009–1018.
Tähkämö, L., Martinsons, C., Ravel, P., Grannec, F., Zissis, G., 2014. Solid State Lighting Annex: Life Cycle Assessment of Solid State Lighting. Energy Efficient End-Use (4E). International Energy Agency. Retrieved from. http://ssl.iea-4e.org/files/otherfiles/0000/0068/IEA_4E_SSL_Report_on_LCA.pdf.
Tunsu, C., Petranikova, M., Gergorić, M., Ekberg, C., Retegan, T., 2015. Reclaiming rare earth elements from end-of-life products: a review of the perspectives for urban mining using hydrometallurgical unit operations. Hydrometallurgy 156, 239–258. https://doi.org/10.1016/j.hydromet.2015.06.007.
U.S. Department of Energy, Solid-State Lighting Program, 2016. Solid-State Lighting R&D Plan (No. DOE/EE-1418). Retrieved January 30 2018 from. https://energy.gov/sites/prod/files/2016/06/f32/ssl_rd-plan_%20jun2016_2.pdf.
Welz, T., Hischier, R., Hilty, L.M., 2011. Environmental impacts of lighting technologies — life cycle assessment and sensitivity analysis. Environ. Impact Assess. Rev. 31 (3), 334–343. https://doi.org/10.1016/j.eiar.2010.08.004.
Wolf, M.-A., Pant, R., Chomkhamsri, K., Sala, S., Pennington, D., 2012. The International Reference Life Cycle Data System (ILCD) Handbook-JRC Reference Reports.