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# LCA of an industrial luminaire using product environmental footprint method

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ABSTRACT

This paper presents a life cycle assessment (LCA) for the industrial Light Emitting Diode (LED) luminaire by using Product Environmental Footprint (PEF) methodology. The assessment is carried out for raw material, assembly, distribution, use and end of life (EoL) stages, and all upstream emissions are considered. The analysis results show that the electricity consumption in use stage is the significant contributor for the overall impacts. Environmental benefits are identified from the EoL scenario analysis due to the adopted WEEE treatments. Electricity mix for the UK and other European countries are modelled for the comparison study that shows the use of renewable resources for electricity generation has lower overall impacts from the PEF view, but the impact towards land use that is caused by using biomass energy source for electricity production is noticeable, which is barely mentioned in the existing LCA studies. This research has made the following original contributions: 1) it is the first study examining the LED luminaire environmental performance by using the PEF methodology; 2) the electricity mix modelling for the European countries in the comparison study reveals the possible trade-off between using renewable/non-renewable resources for the electricity generation, which would be beneficial for further policy development for lighting and energy sectors; 3) the availability demonstration of the current PEF database for luminaires, and the reported analysis results would assist future similar LCA studies.



## 1. Introduction

Lighting is responsible for about 15% of global electricity consumption and 4.6% of Greenhouse gas (GHG) emissions (UNEP, 2017). The European Commission aims to build an economy with net-zero greenhouse gas emissions by 2050, and key targets for 2030 have been raised in the European Green Deal in order to achieve this aim: at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 32% share for renewable energy, and at least 32.5% improvement in energy efficiency (European Commission, 2020). All lighting products have to comply with this new action in the EU member states, the energy and environmental benefits of LED technologies have been proven but insisting sustainable luminaire development is still crucial for reducing emissions and increase energy efficiency, particularly examining its performance throughout life cycle perspective.

In 2013, the European Commission proposed a multi-standard indicator under the Single Market for Green Products Initiative (European Commission, 2013b), which is named as product environmental footprint (PEF) and aims to measure the environmental performance of a product throughout life cycle (Manfredi et al., 2012; Lehmann et al., 2016; Wu and Su, 2020). The PEF is a mid-point indicator of life cycle impact assessment (LCIA) method developed based on the International Reference Life Cycle Data (ILCD) handbook (Fazio et al., 2018). Common methods to measure and communicate the life cycle environmental performances for PEF and OEF (Organization Environmental Footprint) have been defined in a specific EU recommendation (European Commission, 2013a). PEF and OEF pilots also have been conducted by the European Commission during 2013–2016, which includes 26 pilots covering different type of product or sectors.

Since the completion of the pilots, many PEF studies are developed to reduce the environmental impacts associated with goods and services from this new footprint framework. Soode-Schimonsky et al. (2017) applied the PEF methodology to broadly indicate the environmental impacts of various strawberry

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**Abbreviations**

| | |
|---|---|
| LCA | Life Cycle Assessment |
| LED | Light Emitting Diode |
| PEF | Product Environmental Footprint |
| EoL | End of Life |
| GHG | Greenhouse Gas |
| LCIA | Life Cycle Impact Assessment |
| ILCD | International Reference Life Cycle Data |
| OEF | Organization Environmental Footprint |
| PEFCRs | Product Environmental Footprint Category Rules |
| SSL | Solid-State Lighting |
| FU | Functional Unit |
| WEEE | Waste Electrical and Electronic Equipment |
| LCI | Life Cycle Inventory |
| PMMA | Polymethylmethacrylate |
| PC | Polycarbonate |
| PET | Polyethylene Terephthalate |
| PU | Polyurethane |
| PWB | Printed Wiring Board |
| ABS | Acrylonitrile Butadiene Styrene |
| LFL | Linear Fluorescent Lamps |
| CFL | Compact Fluorescent Lamps |

production systems in Germany and Estonia. Six et al. (2017) used the PEF and OEF guidelines to conduct an efficient assessment for a part of pork production chain in Belgium. Famiglietti et al. (2019) developed a useful instrument in the evaluation of the environmental load of dairy products, allowing the process-hotspots identification through PEF different impact categories. Pyay et al. (2019) investigated the PEF environmental impacts of the primary products from rubber cultivation and intermediate rubber products in Thailand. Russo et al. (2019) used the PEF to assess average olive oil consumed in the European markets to provide an initial benchmark for the PEFCRs (PEF Category Rules) development. Corradini et al. (2019) applied the PEF to a wooden wall element to identify the main hotspots and actions of the supply chain for reducing the environmental impacts. He et al. (2019) developed the detailed calculation model for the PEF in the product life cycle and demonstrated in the agricultural picking robot. Pauer et al. (2019) applied the PEF to food packaging to develop a framework which accommodates selection of key environmental performance indicators for environmental sustainability of food packaging. Kuo and Lee (2019) proposed an approach to design a supply chain network based on the results of PEF. Egas et al. (2020) developed a tool to apply the PEF to dairy products, complying with PEFCR v.6.3 guidance, which was also demonstrated by assessing the PEF performance of raw milk and processed dairy products. Mirzaie et al. (2020) developed a formula for building impacts and circularity improvement by using identical parameters from PEF assessment results. These studies prove that the present PEF is a robust instrument to assess environmental impacts at the level of product and supply chain, although the PEF has been applied in a variety of products and sectors, it is still a relatively new method for LCA related studies. By now, there is also a lack of PEF studies examining environmental performance of the luminaire in the literatures.

LCA is an internationally recognized method for assessing the environmental performance of products and services. Performing LCA has to comply with the ISO 14040 and ISO 14044 standards (ISO, 2006). LCA represents a reference method that helps in analysing products with the aim of improving environmental performances, and the analysis takes account of the material and energy inputs and emissions associated with each stage of a product life cycle.

Environmental impacts of luminaires have been thoroughly examined by using LCA techniques in a great number of studies which have been conducted from different perspectives: product eco-design (Casamayor and Su, 2013; Casamayor et al., 2018; Richter et al., 2019); comprehensive impact assessments by using various LCIA methods (Welz et al., 2011; Tähkämö; Tan et al., 2015; Chen et al., 2017; Kevin et al., 2019); environmental performance assessment for different lighting sources: compact fluorescent and light emitting diode (Principi and Fioretti, 2014), fluorescent lamps (Zhang et al., 2017), solid-state lighting (SSL) (Benveniste et al., 2018); environmental performance assessment for different type of luminaires: downlight luminaires (Tähkämö), street lighting (Shahzad et al., 2018); waste management for EoL luminaire materials (Camañ et al., 2014; Dzombak, 2017; Amato et al., 2019; Liu and Keoleian, 2020). However, by now, no LCA studies have examined luminaires by using PEF. As an initiative promoted by the European Commission at the level of policy implementation, PEF is worth for assessing lighting products taking account of the extensive usage of energy and precious metals, and wastes generated in this sector. Additionally, the lighting products were not included in the PEF pilots, so the outcomes of this study will be supplementary for developing PEF category rules for lighting products. These existing LCA based luminaire studies contribute to the knowledge of applying PEF on luminaires from these identified perspectives, and this study aims to examine the possible result differences between PEF and these existing LCA studies, and to provide PEF based benchmark values for the luminaire product category.

This study aims to apply the PEF methodology to a sustainable featured luminaire used in the industrial environment (e.g. warehouse) in order to assess the luminaire's environmental performance for the impact categories as required by the PEF, and to compile accurate and detailed environmental information relevant to the analysed product system and to identify the main impact contributors. Existing LCA studies have identified that the variation of electricity mix affects the overall LCA assessment results, while this study will examine the PEF impact caused by the electricity mix among a few European countries whose electricity energy supply is variant (i.e. high traditional petroleum resources or high renewable resources). Such an examination combines the PEF application and electricity mix impact assessment and may be useful for developing long-term of energy policies. Moreover, this study also intends to provide recommendations for stakeholders to meet the challenges and benefits from the opportunities presented by reducing environmental emissions from PEF perspective in the lighting sector. This study's results will also be used to develop the manufacturing strategy towards more sustainable industrial luminaires and provide best-practice recommendations.

## 2. Materials and methods

### 2.1. Functional unit

The analysis target is a LED low bay industrial luminaire (Fig. 1) that is manufactured in China and sold in the UK market. The luminaire is usually used in the industrial areas (e.g. warehouses and retail environments) to provide high lumen output.

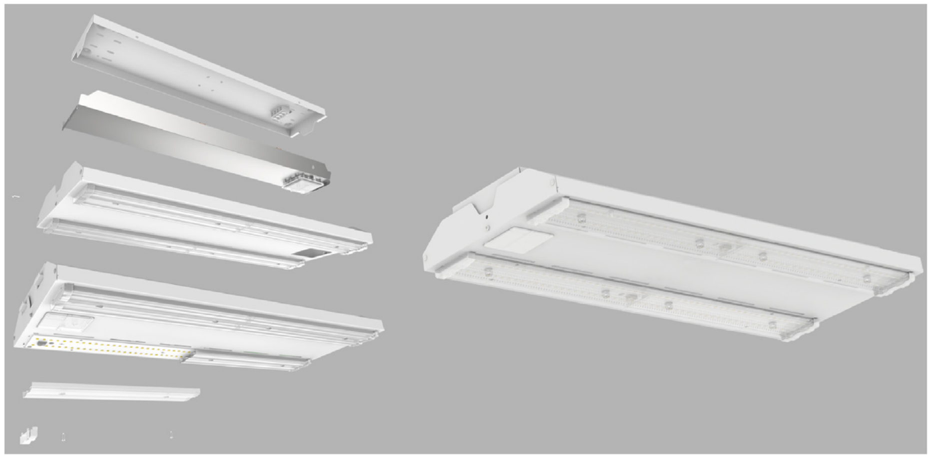

**Fig. 1.** The LED low bay industrial luminaire (Kosnic, 2020).

Defining an appropriate functional unit (FU) is fundamental to LCA, which varies even for the studies examining the same product category and is usually determined by the study's aim and objectives. Following FUs are usually applied in luminaire related LCA literatures: quantity of luminaire (Hartley et al., 2009); luminous flux in a reference period (Welz et al., 2011; Tähkämö and Halonen, 2015); lumen (Osram, 2009) (Sangwan et al., 2014).

The luminous flux of lifetime is selected for FU in this study as it is feasible for results comparison among luminaires with different luminous flux. Therefore, the function unit in this study is defined as the luminaire provides 40,000 h of lighting service.

### 2.2. System boundary

The system boundaries describe the life cycle stages of the studied systems and demonstrates which processes and flows are included in the LCA. For this study, five life cycle stages are from the extraction and processes of raw materials needed for the production (e.g. plastic, metals, packaging film and foam) to the end of life. Within each stage of the life cycles defined in the system boundary, this study examines all identifiable upstream inputs to offer a comprehensive and practical view to examine the impacts associated with the FU's system. For example, electricity consumption flow not only includes the operation of the electricity production, but also the upstream processes such as the production of the petroleum resources for electricity generation. Therefore, the impact caused by the original extraction of raw materials are traceable through the inputs defined in the system boundary. The different life cycle stages taken into account for the FU system boundary are presented in Fig. 2 below.

In this study, all major product components and manufacturing processes have been included in cases where the involved datasets are available from the luminaire manufacturer or the adopted external database. In cases where datasets are not under control or not significant, they have been specified and marked in Fig. 2, which will be helpful for further studies to improve through other data collection methods or using sensitivity analysis to examine the potential significance of the used datasets. Brief explanations for these analysed life cycle stages are presented as below:

- Raw materials and accessories production: The luminaire manufacturer involved in this study, purchase electronics parts and other accessories from its suppliers and focus on design, assembly, and marketing activities.
- Assembly of the luminaire: The luminaire housing manufacturing is the major activity conducted by the manufacture, which includes cutting, bending, and coating for the housing constitutes. The impacts caused from energy consumption for these activities are examined.
- Distribution: This stage includes the transportation from the manufacture factory in China to the UK warehouse, and transportation from the warehouse to the wholesaler's warehouse and end users' premises. The impacts caused by the trans-oceanic ship and lorry are examined.
- Use: Electricity consumption for the functional unit is considered where the UK electricity mix is modelled in the analysis.
- End of life: The EoL luminaire is dealt with Waste Electrical and Electronic Equipment (WEEE) procedures as it is defined as the waste disposal of electrical and electronic equipment in the EU Directive 2012/19/(European Parliament, 2012) and the UK Waste Electrical and Electronic Equipment Regulations (2013).

The system boundaries excluded from the system include: the transportation of raw materials from the suppliers to the luminaire factory, and transportation from end users to waste management facilitates. The reasons are as following:

- Depending on the luminaire manufactures' production capacities and demands, the requirements for raw materials vary for different manufactures, thus the impact associated with one case would be less representative. Previous study (Chen et al., 2017) used the estimated distance from the main producing areas to manufacturing plants in China, which is not adopted in this study taking account into that the associated impacts have been proven minor in that study.
- The associated impacts from transport between end users and recycling centres are generally distributed over the entire impact flows of EoL scenarios (i.e. recycling, landfill, incineration).

### 2.3. Life cycle inventory analysis

The life cycle inventory (LCI) is an inventory of input/output data that relates to the functional unit of the system being studied (ISO, 2006). The foreground processes are based on activity data collected from the luminaire company. The secondary LCI data describing background processes (e.g. transport, electricity production) largely relies on the latest Environmental Footprint

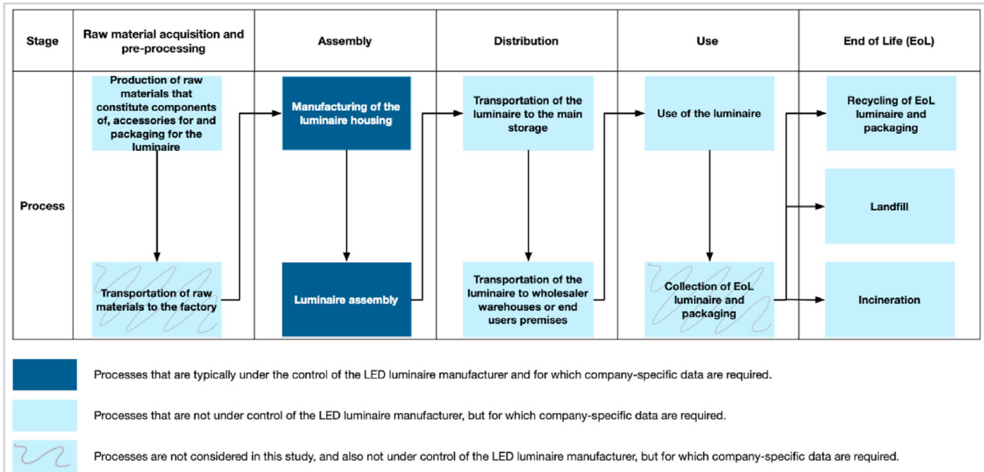


**Fig. 2.** System boundaries for the FU.

secondary database, which is from the Life Cycle Data Network nodes (European Commission, 2019a), and packaged by GreenDelta (https://www.greendelta.com/) into the LCA software tool used in this study.

**Raw material**: Table 1 shows the main components of the FU and their materials and weight.

**Distribution:** Three transportation activities include trans-oceanic ship from China to the UK seaport (9000 km); lorry (>32 ton) (225 km) from the port to the luminaire company warehouse based in Newbury, England; lorry (7.5–12 ton) (321 km) from the warehouse to wholesalers' warehouse or end users. The transportation distances are estimated based on the engineers' suggestion, and the associated impacts are subsequently assessed with the average estimations.

**Electricity for assembly stage:** The housing manufacturing is conducted in the factory based on Suzhou, China, thereby the electricity grid datasets in China (as defined in the PEF database) is adapted in this study which represents the average electricity production.

**Electricity for use stage:** The luminaire is sold in the UK and assumed to be used with full lifetime (40,000 h) in the UK. Electricity production proportion in 2018 (IEA, 2020a) is used to model the electricity consumption for the FU (see Table 2).

**EoL**: The industrial luminaire is usually installed, repaired and disposed by professionals, thus the disposal of wastes and the EoL luminaires are assumed to fully comply with WEEE procedures. The WEEE management company dealing with the EoL luminaires for the luminaire company provides the material treatments after collection (see supplementary materials), which are referred to model the EoL scenarios in this study. UK Statistics on Waste for 2017 (latest) show that 70.0% of UK packaging waste was either recycled or recovered (DEFRA, 2020), which was used in this study to model paraments for EoL packaging materials. Statistics regarding the industrial luminaire waste treatment are unknown,

**Table 1**
Bill of materials for the FU.

| Component | Item | Unit | Amount | Main Material |
|---|---|---|---|---|
| Lighting Unit | LED circuit board | g | 135.7 | Electronic mix |
| Lighting Unit | Optical lens | g | 380 | Polymethylmethacrylate (PMMA) |
| Housing | Gear tray | g | 460 | Steel SGCC |
| Housing | Fixing back plate | g | 1470 | Steel ST12 |
| Housing | Top plate | g | 550 | Steel ST12 |
| Control gear | CCT switch | g | 17 | Polycarbonate (PC) |
| Control gear | LED driver | g | 340 | Electronic mix |
| Control gear | Emergency module | g | 150 | Electronic mix |
| Control gear | Battery | g | 27 | Li-ion |
| Control gear | Push wire terminal | g | 15 | PA66 |
| Control gear | Microwave sensor | g | 22 | Polycarbonate (PC) |
| Control gear | Wiring | g | 37 | Copper |
| Fasteners | Cable clip | g | 0.78 | PA66 |
| Fasteners | Optical lens cap | g | 4.6 | Polycarbonate (PC) |
| Fasteners | Microwave sensor holder | g | 21.5 | Polycarbonate (PC) |
| Fasteners | Bushings | g | 1 | Rubber |
| Fasteners | Earthing plate | g | 0.03 | Stainless steel |
| Fasteners | Washers | g | 0.62 | Stainless steel |
| Fasteners | Decorative screws | g | 23.5 | Steel 1018 |
| Fasteners | Machine screws | g | 4 | Steel 1018 |
| Fasteners | Rivets | g | 7 | Steel q235 |
| Fasteners | Self-Tapping screws | g | 70.56 | Steel 1018 |
| Packaging | Box | g | 605 | Board box |
| Packaging | Film | g | 14 | Polyethylene Terephthalate (PET) |
| Packaging | Form | g | 63 | Polyurethane (PU) |
| Packaging | Manual | g | 21 | Paper |

**Table 2**
The UK electricity mix in 2018.

| Electricity mix - UK | Proportion | Electricity consumed for FU (kWh) based on 40,000 h |
|---|---|---|
| Coal | 4.588% | 275.25512 |
| Natural gas | 38.724% | 2323.43675 |
| Nuclear | 9.676% | 580.542429 |
| Oil | 34.502% | 2070.09794 |
| Hydro | 0.269% | 16.1632765 |
| Wind | 3.455% | 207.2803233 |
| Biofuels | 7.850% | 470.9951373 |

but the recycling rate (44% in 2017) of municipal wastes in the UK is used in this study to model LCI parameters for the rest of EoL materials (mainly cover the electronic mix), which align with statists used in previous similar studies: 30% in average of Europe context (Richter et al., 2019); 40% in northern Europe (Tähkämö).

### 2.4. Life cycle impact assessment method and tool

The adopted PEF (Mid-point indicator) method in this study are based on the JRC Technical Report (Fazio et al., 2018), and are embedded in the PEF database that are used in this study. The brief description of PEF impact categories is listed in the supplementary materials.

openLCA (version 1.10.3) software, developed by GreenDelta was used to develop the LCA modelling and link the reference flows with the LCI database, then to apply the LCI flows with the relevant characterization factors that is defined in the selected LCA method. The PEF database contains data sets from the Life Cycle Data Network nodes (European Commission, 2019a). The PEF data sets for life cycle modelling can also be downloaded for openLCA via https://nexus.openlca.org/databases.

## 3. Results

### 3.1. The overall life cycle impacts

Fig. 3 shows the impacts of the functional unit's life cycle, based on the live cycle inventory given in supplementary materials. These results are presented in a relative way (Fig. 3) by normalizing to the highest impact of each environmental impact categories for the five life cycle stages. However, the absolute values are also reported in Table 3 for transparency.

Overall, it appears that the functional unit has higher impacts in the stage of use and assembly compared to the rest of life cycle stages. The dominating impacts of use stage is in agreement with the findings of previous luminaire studies by using different LCA approaches (Welz et al., 2011; Tähkämö; Chen et al., 2017; Zhang et al., 2017).

Raw material and EoL are the significant contributors for environmental burdens related to climate change – biogenic impact, which are significantly caused by the packaging box production (78.6%) and landfill treatments for EoL box and papers (81.84%). For ozone depletion impact, the assembly stage is the significant contributor (46.78%), which is mainly caused by the powder production processes (46.56%) that is used for the painting of the luminaire housing. Significant impact (92.90%) of resource use, minerals and metals come from the raw material that are caused by the production processes of LED circuit board (39.13%), medium power transistor (20.78%), and standard transformer for Printed Wiring Board (PWB) (14.33%), steel cold production (13.71%).

### 3.2. Impact results of each life cycle stage

Raw material stage has significant contributions on resource use, minerals and metals (92.9%), and water use (38.04%) (Fig. 4). For resource use, minerals and metals impact, major impacts are from lighting unit (39.14%), control gear (35.37%), housing (13.71%). For lighting unit, dominant impacts (39.13%) are from light emitting diode production; drivers (35.33%) contribute significant impacts for control gear, the impact of which are shared by the medium power transistor (20.78%) and standard transformer for PWB (14.33%); for the impact from housing, steel cold production

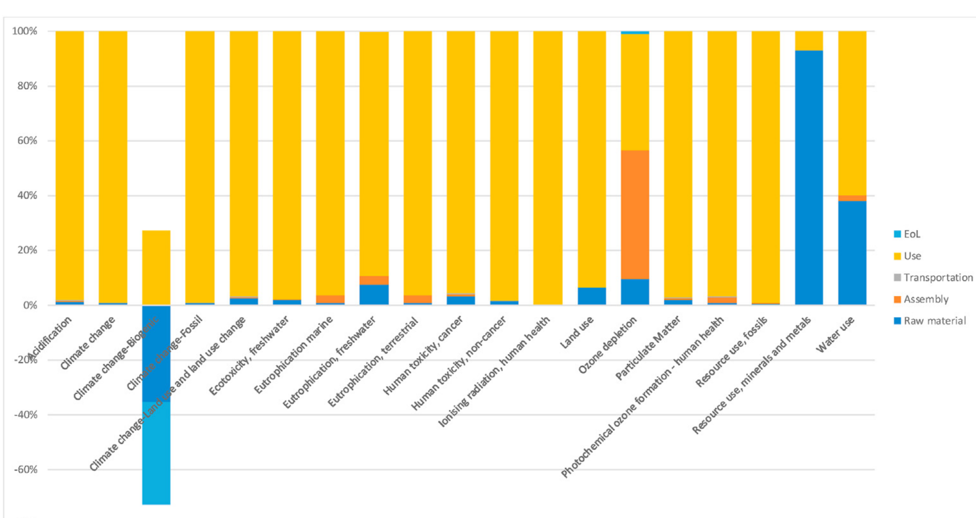


**Fig. 3.** Relative contributions of each life cycle stage for the functional unit.

**Table 3**
Absolute values for the overall impact results.

| Impact Category | Unit | Raw material | Assembly | Transportation | Use | EoL |
|---|---|---|---|---|---|---|
| Acidification | mol | 0.209056 | 0.145592 | 0.023313 | 21.04386 | 0.00124 |
| Climate change | kg | 23.08489 | 2.482348 | 0.837385 | 3282.95 | −0.35221 |
| Climate change-Biogenic | kg | −0.28636 | 0.001181 | 0.000444 | 0.216648 | −0.30417 |
| Climate change-Fossil | kg | 23.36034 | 2.480141 | 0.835147 | 3282.311 | −0.04808 |
| Climate change-Land use and land use change | kg | 0.010915 | 0.001026 | 0.001794 | 0.421896 | 3.83E-05 |
| Ecotoxicity, freshwater | Item(s) | 6.387002 | 1.523825 | 0.151568 | 350.5391 | −0.02337 |
| Eutrophication marine | kg | 0.026522 | 0.072032 | 0.006107 | 2.732282 | 7.46E-05 |
| Eutrophication, freshwater | kg | 8.05E-05 | 3.39E-05 | 1.67E-06 | 0.000969 | −3.4E-06 |
| Eutrophication, terrestrial | mol | 0.286682 | 0.78843 | 0.067016 | 29.83676 | 0.001038 |
| Human toxicity, cancer | Item(s) | 1.65E-07 | 2.73E-08 | 7.52E-09 | 4.63E-06 | 6.97E-11 |
| Human toxicity, non-cancer | Item(s) | 1.61E-06 | 2.76E-07 | 3.94E-08 | 0.000114 | −4.1E-09 |
| Ionising radiation, human health | kBq | 0.45247 | 0.070444 | 0.001505 | 239.6139 | 0.087161 |
| Land use | Item(s) | 1399.52 | 5.914999 | 3.310761 | 20682.86 | 2.492673 |
| Ozone depletion | kg | 1.07E-09 | 5.14E-09 | 1.6E-12 | 4.68E-09 | 9.68E-11 |
| Particulate Matter | Item(s) | 3.03E-06 | 1.27E-06 | 1.79E-07 | 0.000156 | 2.05E-08 |
| Photochemical ozone formation - human health | kg | 0.083878 | 0.186733 | 0.01636 | 8.572821 | 0.00034 |
| Resource use, fossils | MJ | 294.9236 | 32.09999 | 10.56297 | 50585.89 | 4.144315 |
| Resource use, minerals and metals | kg | 0.001334 | 1.75E-06 | 4.87E-08 | 0.0001 | 6.91E-08 |
| Water use | m3 | 21.96502 | 1.110555 | 0.011552 | 34.64473 | 0.005968 |

(13.71%) is the main contributor. The resources used in these processes mainly include precious metals, e.g. gold, platinum, copper, lead, palladium, silver and zinc. Major impacts come from air pollutes emitted from direct emissions of manufacturing these electronic units. Notable pollutants are sulfur, sulfur dioxide, nitrogen dioxide.

For water use impact category, significant impacts are from control gear (27.14%) and lighting unit (8.69%). For control gear, medium power transistor production (27.92%) again dominates the impact caused by the drivers (26.98%), it has to note that the recycling of Acrylonitrile Butadiene Styrene (ABS) contributes 1.31% positive impacts under the drivers' impacts. For Lighting unit, production of LED contributes major impacts (8.29%), and the PMMA granulate production (for optical lens) causes relatively small impacts (0.4%).

The considered processes under assembly stage are housing manufacturing (bending, cutting, coating for steel sheets), thereby the impacts are associated with the electricity consumption and powder production. Assembly is the significant contributor (46.78%) of ozone depletion impact and has minor contributions to the rest of PEF impact categories (i.e. 3.13% for eutrophication, freshwater; 2.54% for eutrophication marine). For ozone depletion impact, it shows that 46.56% impact come from the coating powder production, which are air pollutants emitted from the powder production processes. Notable pollutants are CFC-10, HCFC-22, 1,1,2-trichlorotrifluoroethane.

The assembly stage has small contributions for eutrophication marine (2.54%), eutrophication, freshwater (3.13%), eutrophication, terrestrial (2.54%), which are mainly caused by the air pollutants (nitrogen dioxide) from the electricity consumption of machine operations. It is noted that the electricity mix used in the current PEF database represent the 2013 energy source supply in China, which constitutes hard coal (74.23%), hydro (16.9%), etc. The 2020 electricity mix in China is hard coal (64.6%), hydro (16.9%), so the environmental impacts from this stage are expected to be smaller of representing the latest scenario.

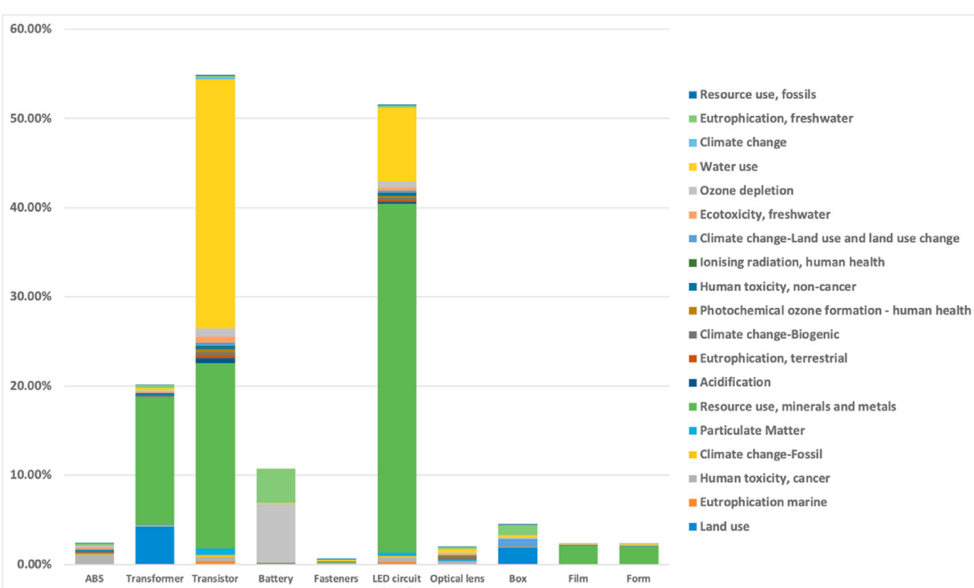


**Fig. 4.** Impacts of raw materials.

For climate change fossil impact (assessing GHG in PEF method), the electricity consumption in assembly stage contributes 1.62768 kg $CO_2$ eq. (0.05%), which is neglectable compared with that caused by the electricity consumption in the use stage (3282.31103 kg, 99.25%). Considering the impact caused by the use stage is dominant, a focused analysis was further conducted where the system boundary excludes the use stage but keep all other life cycle stages and their LCI data given in this study. The assessment results show that the climate change fossil impact caused by electricity consumption in assembly stage (1.62768 kg, 6.11%) is less than that caused by the manufacturing processes of driver (8.70168 kg, 32.68%), housing (7.61834 kg, 28.61%), LED circuit board (3.67021 kg, 13.78%), optical lens (6.39%, 1.70107 kg). This absolute value for climate change fossil impact is in agreement with the results of previous similar study: 6.59E−01 kg for LFL (Linear Fluorescent Lamps), 3.07 E+00 kg for CFL (Compact Fluorescent Lamps) in China (Tan et al., 2015).

While assessing the impact of generating the same amount of electricity in the EU based on the EU average energy source proportion as defined in the PEF database (i.e. 2012 datasets), the results show that the absolute value for climate change fossil is 0.71789 kg, which means generating the same amount of electricity in China and the EU, the climate change fossil impact in China would be approximately 2.26 times than that in the EU, due to the high proportion (approx. 70%) of traditional petroleum resources for electricity generation in China compared to the counterpart (approx. 40%) in the EU.

Distribution has extremely (relatively) low impacts for PEF impact categories (see supplementary materials), which are neglectable compared with the impacts caused by the rest of FU life cycle stages. This finding also align with the results of existing similar studies that examine the environmental performance of the luminaires (Principi and Fioretti, 2014; Tan et al., 2015).

Fig. 5 provides contribution percentage of each electricity generation route for PEF impact categories based on the electricity mix modelling inputs given in Table 2, overall it shows that the traditional petroleum resources (e.g. oil, natural gas, and hard coal) are the main contributors for majorities of PEF impacts. It is surprisingly noted that as the renewable resource, the biofuels cause major impacts for a few PEF impact categories, e.g. 92.94% for land use, 86.70% for climate change-land use, 74.01% for human toxicity, non-cancer, 54.23% for eutrophication, freshwater. Last, the nuclear resource dominates the impact of ionising radiation, human health, which are noticeable compared to its neglectable contributions into the other impact categories. The damages for land use refer the changes of these actives in ecosystem quality, land occupation and delays recovery (Koellner et al., 2013).

Fig. 6 shows the comparison of environmental impacts that are caused by different electricity generation in the UK. The results show that the hydro shows better environmental performance compared with biofuels and wind. For the UK electricity production, the consumption of biofuels accounts for 7.85% of the total electricity consumption in the use stage, but it generates 26.53% of the total environmental impacts, while the 3.455% and 0.269% electricity consumption from wind and hydro generation routes contribute about 0.03% and 0.002% impacts which are virtually neglectable. Similar notable results are also shown in the comparison between coal and nuclear: 4.588% and 9.676% of electricity consumption from coal and nuclear generate about 4.42% and 7.74% environmental impacts respectively. The oil power shows the worst environmental performance, accounting for about 36.12% of the total impacts with 34.502% of the electricity contribution.

As the system boundary given above, the EoL of FU is assumed to follow with WEEE treatment. Overall, the EoL stage contributes relatively minor negative impacts for majority of the PEF impacts, but contributes 81.71% positive impact for climate change biogenic, which means the avoidance of certain amount of biogenic methane emissions to the air.

Fig. 7 shows the impacts of different treatments for the luminaire components, it overall appears the recycling of steel contributes significant (approx. 90.55%) environmental benefits for majority of PEF impact categories except the eutrophication, freshwater. Recycling of electronic units also contribute major (8.13%) environmental benefits to the overall benefits, which comes from the reuse of the precious metals. The landfill for EoL packaging paper (including box) and incineration of electronic units are the main two sources generating the highest environmental burdens for PEF impact categories.

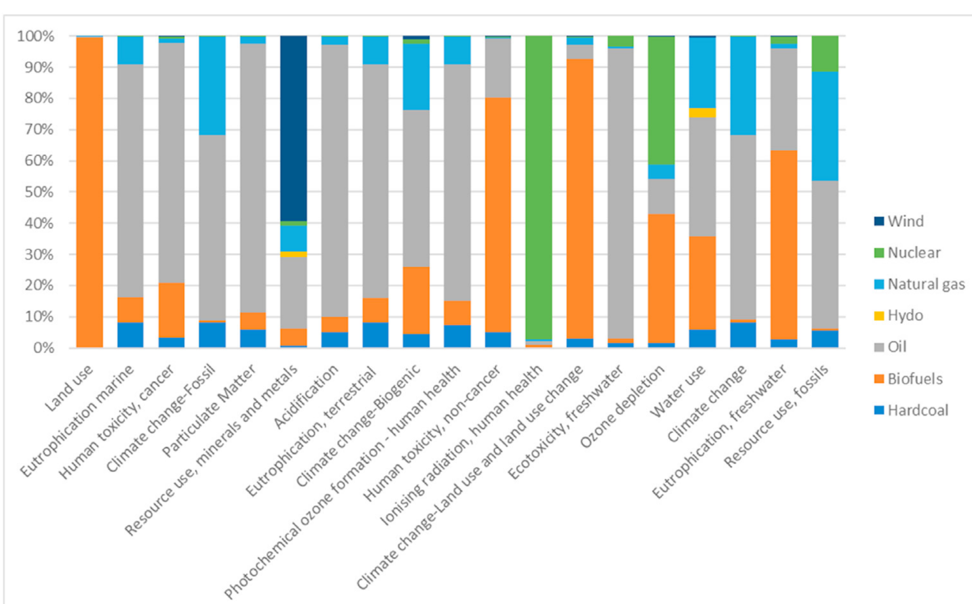


**Fig. 5.** Contribution analysis of using electricity mix to produce electricity for 1 FU.

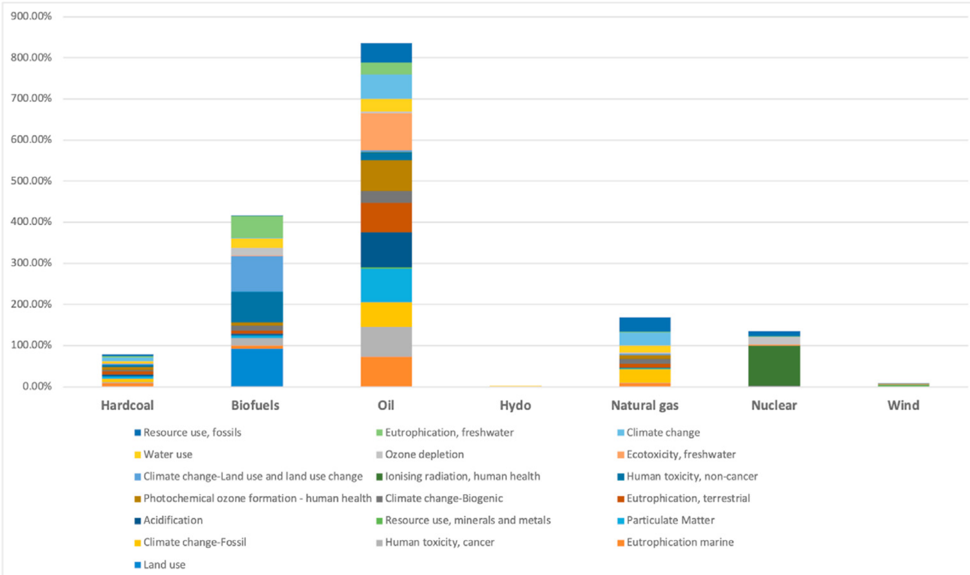


**Fig. 6.** Comparison of the environmental impacts caused by different electricity generations.

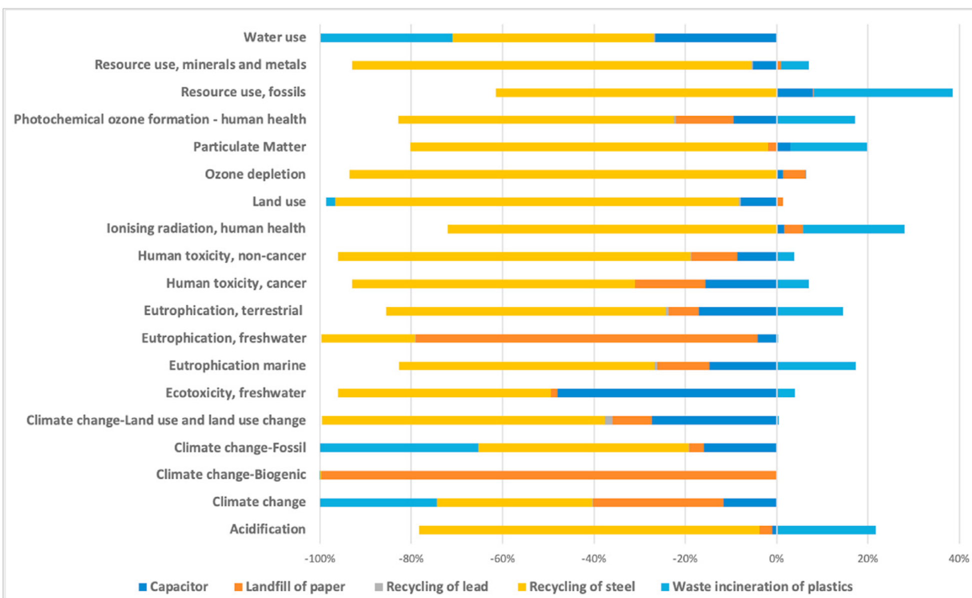


**Fig. 7.** Impacts of EoL scenario.

### 3.3. Sensitivity and uncertainty analysis

The parameters and scenario assumptions given in the system boundary of the FU indicate some degree of variability. It is necessary to assess if those chosen parameters and assumption affect the results of this study, and to what extent the results rely on those choices. As requested by the ISO14044 standard, sensitivity analysis is applied to evaluate the impact caused by the variability in relation to the FU modelling and its calculation results, then their robustness and reliability are proven.

Climate change, land use, resource use fossils impact categories have been selected in the sensitivity analysis, as they are with higher absolute values for the FU overall impact results in the default scenario (Table 3), and they are also proven in previous studies (Principi and Fioretti, 2014; Benveniste et al., 2018) to be able to better represent the environmental performance of the luminaire. On the other hand, calculation of key processes of raw materials and use stages (due to their high impact contributions) have been conducted with 100% variation (i.e. increase and decrease 100%) of all the parameters given in the LCI. Table 4 offers the sensitivity analysis results, which show that these parameters with variation of 100% contribute more than 0.49% (i.e. the range between the relative differences) to the total impact results for the selected impact categories.

Climate change is the most affected impact (98.42%) by the variations of electricity consumption process in the use stage. Variations of LED circuit board in raw material stage are the major contributors (89.50%) of the changed results of resource use fossils. The variation of housing, optical lens and drivers (electronic mix) cause small result changes on the three selected impact categories.

**Table 4**
Sensitivity analysis results for the FU.

| | Climate change value (kg) | Relative difference | Land use value (items) | Relative difference | Resource use fossils value (MJ) | Relative difference |
|---|---|---|---|---|---|---|
| Values for the overall impact | 3309.002413 | | 22094.09843 | | 50927.62088 | |
| Housing value increase 100% | 3476.0345 | 5.05% | 22167.889 | 0.33% | 52123.721 | 2.35% |
| Housing value decrease 100% | 3301.3917 | −0.23% | 21885.356 | −0.94% | 50797.378 | −0.26% |
| Difference between scenarios | | 5.28% | | 1.28% | | 2.60% |
| Use value increase 100% | 5652.8312 | 70.83% | 22295.375 | 0.91% | 51118.474 | 0.37% |
| Use value decrease 100% | 2395.9765 | −27.59% | 21921.614 | −0.78% | 50379.367 | −1.08% |
| Difference between scenarios | | 98.42% | | 1.69% | | 1.45% |
| Optical lens value increase 100% | 3326.1971 | 0.52% | 23126.487 | 4.67% | 52028.312 | 2.16% |
| Optical lens value decrease 100% | 3276.4964 | −0.98% | 21623.387 | −2.13% | 49991.312 | −1.84% |
| Difference between scenarios | | 1.50% | | 6.80% | | 4.00% |
| LED circuit board value increase 100% | 3387.195 | 2.36% | 22166.481 | 0.33% | 76891.214 | 50.98% |
| LED circuit board value decrease 100% | 3228.117 | −2.44% | 22057.213 | −0.17% | 31311.227 | −38.52% |
| Difference between scenarios | | 4.81% | | 0.49% | | 89.50% |
| Drivers value increase 100% | 3384.715 | 2.29% | 22381.238 | 1.30% | 52022.231 | 2.15% |
| Drivers value decrease 100% | 3279.123 | −0.90% | 21779.127 | −1.43% | 49865.121 | −2.09% |
| Difference between scenarios | | 3.19% | | 2.73% | | 4.24% |

The sensitivity analysis results prove that the uncertainty analysis is needed to determine the confidence level of the processes and impacts that were identified in the sensitive analysis, i.e. electricity generation process to the climate change; LED circuit board to the resource use fossils. Monte Carlo analysis is used to conduct uncertainty analysis in this study, which also has been introduced and reported in existing LCA studies (Benveniste et al., 2018; Kevin et al., 2019; Qiu and Suh, 2019). For the climate change impact, a variation of 20% is set for the FU's original energy consumption in the use stage, while for the resource use fossils impact, a variation of 20% is set for the original weight of LED circuit board. 1000 iterations of Monte Carlo simulations were conducted by using openLCA software tool, to estimate the range of impact results. In this analysis, the model parameters are assumed to follow normal distribution, taking into account of 95% of confidence level, their uncertainty ranges are reported in Table 5.

## 4. Influence of the EU electricity mix context

Electricity mix affecting the total LCA results have been reported in existing studies (Welz et al., 2011; Principi and Fioretti, 2014; Tan et al., 2015; Richter et al., 2019). Meanwhile, dominant impacts from electricity consumption in the use stage also have been proven under the PEF framework, which reveals that the influences of electricity generation are needed for deep investigation. Thereby, a few European countries (i.e. France, Spain, Germany, Italy, Sweden) using massive traditional petroleum resources or renewable resources for electricity generation are selected to compare with the impact caused by the UK electricity mix, in order to examine the environmental impact variations caused by the electricity mix from the PEF point of view. Table 6 reports the electricity mix of these countries in 2018, which is used to model the electricity consumption parameters in this analysis.

Despite the varies of electricity mix in the six countries, Fig. 8 shows that the electricity generation overall contributes significant impacts to the impact category of land use and resource use, fossils. The land use impact is mainly for the land damage caused by using biomass resources for electricity generation. Resource use fossils impact is contributed by non-renewable energy resources from or in ground, which are mainly crude oil, natural gas, hard coal, and uranium that are used for electricity generation. The electricity generation from these countries also contributes major impacts for climate change fossil and climate change, the main pollutants and emissions of which are air pollutants (carbon dioxide and methane) emitted from electricity generation processes by using oil, coal and natural gas resources.

**Table 6**
EU average electricity mix in 2018 (IEA, 2020b).

| Electricity source | UK | France | Spain | Germany | Italy | Sweden |
|---|---|---|---|---|---|---|
| Coal | 4.59% | 3.67% | 9.00% | 22.76% | 5.68% | 4.42% |
| Natural gas | 38.72% | 14.91% | 21.66% | 24.35% | 39.52% | 2.01% |
| Oil | 34.50% | 28.82% | 42.34% | 32.46% | 33.81% | 20.83% |
| Nuclear | 9.68% | 43.68% | 11.62% | 6.56% | 0.00% | 35.89% |
| Hydro | 0.27% | 2.28% | 2.36% | 0.51% | 2.79% | 10.75% |
| Wind | 3.45% | 1.64% | 5.85% | 4.78% | 6.05% | 2.96% |
| Biofuels | 7.85% | 7.20% | 6.41% | 9.97% | 9.64% | 25.66% |

As shown in Table 6 and Fig. 8, although more renewable resources (i.e. hydro, wind, biofuel) are used for electricity generation in Spain (14.61%), Germany (15.26%), Italy (18.47%) and Sweden (39.37%), the overall environmental impacts caused by the use stage are higher than the UK where uses less renewable resources (11.57%). Therefore, a significant trade-off exists between using renewable/non-renewable resources for electricity generation and environmental impacts. Moreover, the comparison also shows that the land use impact (mainly caused by biomass energy) in the UK is dramatically smaller than its counterparts in the rest of five countries.

Comparing the electricity generation impacts between the UK and France, given their similar usage for renewable resources (11.57% vs 11.12%), it appears that the electricity generation in France still have approximately 8.35% impacts higher than that in

**Table 5**
Uncertainty analysis results by using Monte Carlo method for the select impacts.

| Processes | Original amount | Variation | Climate change mean value | Resource use fossils mean value | Uncertainty range (95% confidence) |
|---|---|---|---|---|---|
| Energy consumption in use stage | 6000 kWh | 20% | 3282.8 kg | N/A | ±39.25 |
| LED circuit board | 200 items | 20% | N/A | 44.3 MJ | ±0.0028 |

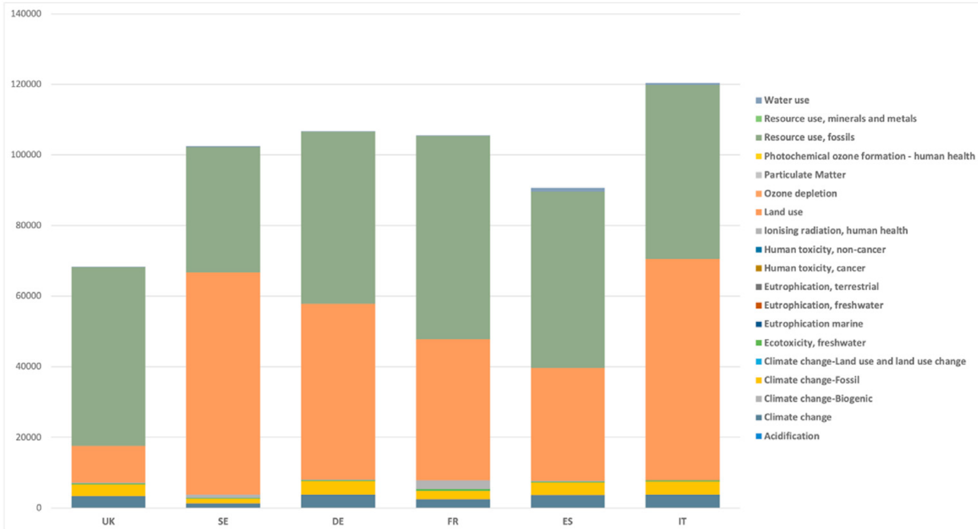


**Fig. 8.** Comparison between the environmental impacts in the European countries and UK electricity mix production.

the UK. As shown in Fig. 8, the impacts on land use from France is noticeably higher than that from the UK, electricity generation from biomass energy is the dominant contributor for the land use impact in the UK (99.77%) and France (99.86%). The absolute values for land use impact are 1.03035E4 Items and 3.99562E4 items for the UK and France respectively, it can be interpreted as that generating same amount of electricity in the UK and France, the caused environmental burden (for land use) in France will be approximately 3.88 times than that in the UK. Therefore, it can be concluded that the technology differences used in the biomass energy based electricity generation may cause the result difference in terms of land use impact.

## 5. Discussion

### 5.1. Assumption and limitation in this study

Certain assumptions and limitations involved in the current modelling input, which are presented below:

- Electricity consumptions for the use phase are equally divided based on the UK electricity mix proportion, which are also applied to the electricity mix modelling for other European countries in the comparison study. For most of industrial luminaire application environment, certain electricity sources (e.g. renewable energy) are requested or encouraged by national or regional authorities, therefore, the proportion of preferred energy sources should be weighted for LCI modelling when it occurs.
- Although the packaging impact is minor compared with the impacts from other life cycle stages, the overall impact of packaging is expected to be lower in reality. As packaging materials of industrial application are more easily to be recycled and reused compared to the disposal of packaging materials for domestic luminaire products.
- Energy consumption for research and design, and equipment testing are neglected in this study due to the minor energy consumptions, and the objective of this study (focusing on the impact in the Europe, which is determined by the characterization factors of PEF impact categories).

There are also certain study limitations caused by the current status of PEF methodology and its compatible database. By now, the current PEF database is only compatible with the PEF methodology, which means that the PEF database cannot be set up with other LCIA methods (e.g. ReCiPe, CML), and its methodology also cannot be installed in other existing LCI database (e.g. ecoinvent). Therefore, results of current PEF based LCA studies cannot be examined by using other LCA data sources or methodologies.

### 5.2. Recommendations for stakeholders

In this section, three type of stakeholders are broadly classified, and impact reduction recommendations are provided with some practical and achievable boundaries.

#### 5.2.1. For academia

This is the first study by using PEF to conduct LCA towards the industrial luminaire, the LCI (see supplementary materials) in this study clearly demonstrates the availability and feasibility of the current PEF process flows for the lighting sector. It has to be noted that the process flows in the current PEF compatible database are already well-established (e.g. energy related datasets) and cover various different industry categories, but the process flows under the End of Treatment category are relatively limited, particularly majority of the processes under the End of Treatment category only provide average value for the European countries instead of providing specific value for individual European county, which may raise challenges when evaluating impacts caused by recycling/reuse activities in different countries. Therefore, more attention has to be paid to enrich the current PEF database.

#### 5.2.2. For LED manufacturers

It is a common business model that luminaire manufacturers purchase standard electronic components from suppliers, design and manufacture the mechanical components, then assemble them together. One possible conclusion can be drawn from here is that the space for the individual manufacturer to reduce environmental impact is limited in reality. Therefore, the followings are recommended from a broad business aspect, based on the LCA results obtained from this study and the emerging policy requirements observed.

The impact caused by the electricity in use stage is emphasised by plenty studies, but the impact caused by that in manufacturing site is also noticeable and barely mentioned in the previous studies. The LCA results show that per FU contributes 1.62768 kg of GHG in the assembly stage when the manufacturing site uses national grid as it uses high proportion (approx. 70%) of petroleum resources for electricity generation, which is relatively high and major reduction (0.90979 kg) is achievable even when the petroleum resources decrease into approx. 40%. Considering that more than 80% luminaires in the global market are manufactured in China (Franz and Wenzl, 2017) and the GHG reduction from this domain are significant, therefore, it is encouraged for the manufacturers to use renewable energy as much as possible, which is important and should be considered to push from the legislation level.

This LCA assumes the luminaire operates 40,000 h and will be replaced with a new one, which excludes the potential of prolonging this life span by modular design, by which the broken components are easily replaced instead of disposing the whole luminaire. The modularity need emphasise the electronic modules (e.g. drivers, LED array) as they overall contribute significant impact (92.90%) for resource use, minerals impact category.

The lighting company in this study only manufacture products for European markets, hence the increasing climate impact reduction pressure is from the regulations initiated by 2030 climate & energy framework and 2050 long-term strategy in Europe. As the sensitivity analysis implies that the climate change impact reduction is evident through design modifications, e.g. reducing the weight of metal, LED circuit board. Therefore, implementing ecodesign and eco-procurement with their suppliers should be considered as the long-term strategy paving the road to the European lighting market.

European Commission has legislated that various non-LED lighting products will be phased out, e.g. fluorescent T8 lamps will be phased out starting September 1, 2023 (European Commission, 2019b), which means more customers are possibly entering into the LED lighting market, thereby providing new business model or service as added value for clients will be more important in the market competition. The lighting company involved in this study introduce the luminaire leasing services with offering full maintenance cover and flexible payment options. This service should be widely adopted in the lighting product manufacturing sector to help in saving on potential waste of EoL luminaires, additionally, it will also avoid big financial investment and reduce electricity bill for clients.

#### 5.2.3. For policy makers

The luminaire company involved in this study operates assembly and manufacturing activities in China and focuses on marking and installation/maintenance services in the UK, which is a typical business model in the present LED lighting sector either in the UK or other European countries. Thereby the impact and emission reduction activities in the Europe may need prioritize on the energy source improvement, waste management, and legislation on the importing LED products.

The overall LCA results show that the drivers cause significant impacts (35.33%) among all of the control units, which is the major impact contributor for the overall impacts. This finding is supported by the new EC regulation, i.e. Regulation for ecodesign requirements for light sources and separate control gears (EU) 2019/2020, which firstly set requirements for control parts (i.e. various drivers) and will be implemented from September 2021 in order to save energy and reduce impacts.

The examination on electricity mix for the luminaire use stage in different countries, shows that the electricity mix affects the overall and scenario analysis results by using PEF method, which is in agreement with the existing literature findings. The examination for energy source used in the selected European countries also shows that trade-off between using renewable/non-renewable resources for electricity generation exists, which would be valuable for developing and improving policies for both LED lighting and energy sectors. Moreover, the electricity generation by using biomass energy has dominant contribution for impact of land use, which is a noticeably finding that has been barely mentioned in the existing LCA studies. This is relevant for policies considered on the EU level and in considering future EU climate and energy policies. But before converting these findings into further actions, it should also be noted that the presence of trade-offs in an LCA-only approach highlights the need to consider multiple tools and strategies for decision-making, and it is important to consider a broad range of impacts in order to fully assess these trade-offs.

## 6. Conclusion

This study reports the assessment results of an industrial luminaire by using PEF methodology from the life cycle perspective, taking into account all the stage of the luminaire life cycle. The results show that the impacts of use stage dominate the overall impacts compared with the impacts caused by the rest life cycle stages, which are mainly due to the electricity consumptions. Raw materials also contribute major impacts, which are mainly caused by the manufacturing processes for electronic units and metals. EoL stage has lower environmental impacts as WEEE treatment procedures are easily applied for the industrial applications, thereby, positive impacts are restored by recycling the EoL materials, e.g. energy generation by the plastics incineration treatment. Last, the distribution and packaging contribute minor environmental impacts.

For the impacts caused by the electricity consumption, using the renewable energy sources overall has lower environmental impacts compared with using the petroleum-based energy sources. This finding is applicable to the Europe context by using the PEF framework. The land use impact caused by using renewable energy source (i.e. biomass) for electricity generation is evident through the examination for all the selected countries, and the result difference for this impact between the UK and the other European countries is also noticeable, which maybe require further work to examine the cause from the technology view regarding the biomass based electricity production.

## Author contribution

You Wu: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization.

Daizhong Su: Conceptualization, Methodology, Supervision, Writing - review & editing, research grant holder.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.2021.127159.

## References


Amato, A., et al., 2019. Sustainability analysis of innovative technologies for the rare earth elements recovery. In: Renewable and Sustainable Energy Reviews, vol. 106. Elsevier Ltd, pp. 41–53. https://doi.org/10.1016/j.rser.2019.02.029. December 2018.

Benveniste, G., et al., 2018. Life cycle assessment of spectrally tunable light engines. Int. J. Life Cycle Assess. 23 (2), 279–294. https://doi.org/10.1007/s11367-017-1313-z.

Camañ, V., et al., 2014. The influence of different recycling scenarios on the mechanical design of an LED weatherproof light fitting. Materials 7 (8), 5769–5788. https://doi.org/10.3390/ma7085769.

Casamayor, J.L., Su, D., 2013. Integration of eco-design tools into the development of eco-lighting products. J. Clean. Prod. 47, 32–42. https://doi.org/10.1016/j.jclepro.2013.02.011. Elsevier Ltd.

Casamayor, J.L., Su, D., Ren, Z., 2018. Comparative life cycle assessment of LED lighting products. In: Lighting Research and Technology, vol. 50. SAGE Publications Ltd, pp. 801–826. https://doi.org/10.1177/1477153517708597, 6.

Chen, S., Zhang, J., Kim, J., 2017. Life cycle analysis of greenhouse gas emissions for fluorescent lamps in mainland China. In: Science of the Total Environment, vol. 575. Elsevier B.V., pp. 467–473. https://doi.org/10.1016/j.scitotenv.2016.07.058, 100.

Corradini, G., Pierobon, F., Zanetti, M., 2019. 'Product environmental footprint of a cross-laminated timber system: a case study in Italy', International Journal of Life Cycle Assessment. Int. J. Life Cycle Assess. 24 (5), 975–988. https://doi.org/10.1007/s11367-018-1541-x.

DEFRA, 2020. UK Statistics on waste. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/918270/UK_Statistics_on_Waste_statistical_notice_March_2020_accessible_FINAL_updated_size_12.pdf.

Dzombak, R.V., 2017. Harmonizing Technological Innovation and End-Of-Life Strategy in the Lighting Industry. UC Berkeley.

Egas, D., Ponsá, S., Colon, J., 2020. CalcPEFDairy: a Product Environmental Footprint compliant tool for a tailored assessment of raw milk and dairy products. J. Environ. Manag. 260. https://doi.org/10.1016/j.jenvman.2019.110049. April 2019.

European Commission, 2013a. 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations text with EEA relevance. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179#ntr5-L_2013124EN.01000101-E0005. (Accessed 15 November 2020).

European Commission, 2013b. Communication from the Commission to the European Parliament and the Council Building the single market for green products facilitating better information on the environmental performance of products and organisations. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0196. (Accessed 15 November 2020).

European Commission, 2019a. European platform on life cycle assessment nodes: approved or waiting for approval. Available at: https://eplca.jrc.ec.europa.eu/LCDN/contactListEF.xhtml. (Accessed 16 November 2020).

European Commission, 2019b. Laying down ecodesign requirements for light sources and separate control gears pursuant to Directive 2009/125/EC of the European Parliament and of the Council and repealing Commission Regulations (EC) No 244/2009, (EC) No 245/2009 and (EU) No 1194/2012. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2019.315.01.0209.01. (Accessed 6 April 2021). ENG&toc=OJ:L:2019:315:TOC.

European Commission, 2020. 2030 climate & energy framework | Climate Action, 2020. Available at: https://ec.europa.eu/clima/policies/strategies/2030_en. (Accessed 15 November 2020).

European Parliament, 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE).

Famiglietti, J., et al., 2019. Development and testing of the product environmental footprint milk tool: a comprehensive LCA tool for dairy products. Sci. Total Environ. 648, 1614–1626. https://doi.org/10.1016/j.scitotenv.2018.08.142. Elsevier B.V.

Fazio, S., et al., 2018. Supporting information to the characterisation factors of recommended EF life cycle impact assessment methods, version 2, from ILCD to EF 3.0, new models and differences with ILCD. EUR. https://doi.org/10.2760/002447.

Franz, M., Wenzl, F.P., 2017. Critical review on life cycle inventories and environmental assessments of led-lamps. In: Critical Reviews in Environmental Science and Technology, vol. 47. Taylor and Francis Inc., pp. 2017–2078. https://doi.org/10.1080/10643389.2017.1370989, 21.

Hartley, D., et al., 2009. Life Cycle Assessment of Streetlight Technologies. University of Pittsburgh, Mascaro Center for Sustainable Innovation.

He, B., et al., 2019. Product environmental footprints assessment for product life cycle. J. Clean. Prod. 233, 446–460. https://doi.org/10.1016/j.jclepro.2019.06.078. Elsevier Ltd.

IEA, 2020a. Europe total primary energy supply, 2018. Available at: https://www.iea.org/regions/europe. (Accessed 16 November 2020).

IEA, 2020b. Total Primary Energy Supply. IEA, 2018.

ISO, 2006. 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. International Standard Organization, Geneva, Switzerland.

Kevin, B., et al., 2019. Life cycle assessment of lighting systems and light loss factor: a case study for indoor workplaces in France. Electronics 8 (11). https://doi.org/10.3390/electronics8111278.

Koellner, T., et al., 2013. Principles for life cycle inventories of land use on a global scale. Int. J. Life Cycle Assess. 18 (6), 1203–1215. https://doi.org/10.1007/s11367-012-0392-0.

Kosnic, 2020. Kosnic evolve 4. Available at: https://storage.electrika.com/flips/8930-evolve4-20/index.html. (Accessed 24 November 2020).

Kuo, T.C., Lee, Y., 2019. Using Pareto optimization to support supply chain network design within environmental footprint impact assessment. Sustainability 11 (2). https://doi.org/10.3390/su11020452.

Lehmann, A., Bach, V., Finkbeiner, M., 2016. 'EU product environmental footprint—mid-term review of the pilot phase', Sustainability. Multidiscip. Dig. Publ. Inst. 8 (1), 92.

Liu, L., Keoleian, G.A., 2020. 'LCA of Rare Earth and Critical Metal Recovery and Replacement Decisions for Commercial Lighting Waste Management', Resources, Conservation and Recycling, vol. 159. Elsevier, p. 104846. https://doi.org/10.1016/j.resconrec.2020.104846. April.

Manfredi, S., et al., 2012. Product Environmental Footprint (PEF) Guide. Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517 including Amendment No 1 from December 2010.

Mirzaie, S., Thuring, M., Allacker, K., 2020. 'End-of-life modelling of buildings to support more informed decisions towards achieving circular economy targets', International Journal of Life Cycle Assessment. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-020-01807-8.

Osram, 2009. Life Cycle Assessment of Illuminants: A Comparison of Light Bulbs, Compact Fluorescent Lamps, and LED Lamps. OSRAM Opto Semiconductors GmbH Regensburg, Germany.

Pauer, E., et al., 2019. Assessing the environmental sustainability of food packaging: an extended life cycle assessment including packaging-related food losses and waste and circularity assessment. Sustainability 11 (3). https://doi.org/10.3390/su11030925.

Principi, P., Fioretti, R., 2014. A comparative life cycle assessment of luminaires for general lighting for the office - compact fluorescent (CFL) vs Light Emitting Diode (LED) - a case study. J. Clean. Prod. 83, 96–107. https://doi.org/10.1016/j.jclepro.2014.07.031. Elsevier Ltd.

Pyay, S., et al., 2019. A life cycle assessment of intermediate rubber products in Thailand from the product environmental footprint perspective. J. Clean. Prod. 237, 117632. https://doi.org/10.1016/j.jclepro.2019.117632. Elsevier Ltd.

Qiu, Y., Suh, S., 2019. 'Economic Feasibility of Recycling Rare Earth Oxides from End-Of-Life Lighting Technologies', Resources, Conservation and Recycling, vol. 150. Elsevier, p. 104432. https://doi.org/10.1016/j.resconrec.2019.104432. August.

Richter, J.L., Tähkämö, L., Dalhammar, C., 2019. Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts. J. Clean. Prod. 226 (1194), 195–209. https://doi.org/10.1016/j.jclepro.2019.03.331.

Russo, C., et al., 2019. Product environmental footprint in Tte olive oil sector: state of the art. Environ. Eng. Manag. J. 15 (9), 2019–2027.

Sangwan, K.S., et al., 2014. Life Cycle Assessment of Incandescent, Fluorescent, Compact Fluorescent and Light Emitting Diode Lamps in an Indian Scenario, vol. 15. Elsevier, pp. 467–472. Procedia CIRP.

Shahzad, K., et al., 2018. An ecological feasibility study for developing sustainable street lighting system. J. Clean. Prod. 175, 683–695. https://doi.org/10.1016/j.jclepro.2017.12.057.

Six, L., et al., 2017. 'Using the product environmental footprint for supply chain management: lessons learned from a case study on pork', International Journal of Life Cycle Assessment. Int. J. Life Cycle Assess. 22 (9), 1354–1372. https://doi.org/10.1007/s11367-016-1249-8.

Soode-Schimonsky, E., Richter, K., Weber-Blaschke, G., 2017. Product environmental footprint of strawberries: case studies in Estonia and Germany. J. Environ. Manag. 203, 564–577. https://doi.org/10.1016/j.jenvman.2017.03.090. Elsevier Ltd.

Tähkämö, L., et al., 2013. Life cycle assessment of light-emitting diode downlight luminaire - a case study. Int. J. Life Cycle Assess. 18 (5), 1009–1018. https://doi.org/10.1007/s11367-012-0542-4.

Tähkämö, L., et al., 2014. Life cycle assessment of a fluorescent lamp luminaire used in industry - a case study. Light. Res. Technol. 46 (4), 453–464. https://doi.org/10.1177/1477153513480518.

Tähkämö, L., Halonen, L., 2015. Life cycle assessment of road lighting luminaires–comparison of light-emitting diode and high-pressure sodium technologies. J. Clean. Prod. 93, 234–242. Elsevier.

Tan, Q., Song, Q., Li, J., 2015. The environmental performance of fluorescent lamps in China, assessed with the LCA method. Int. J. Life Cycle Assess. 20 (6), 807–818. https://doi.org/10.1007/s11367-015-0870-2.

The waste electrical and electronic equipment regulations 2013. Available at: https://www.legislation.gov.uk/uksi/2013/3113/contents/made–. (Accessed 16 November 2020).

UNEP, 2017. Accelerating the global adoption of energy-efficient lighting - united for

efficiency. Available at: https://united4efficiency.org/resources/accelerating-global-adoption-energy-efficient-lighting/. (Accessed 15 November 2020).
Welz, T., Hischier, R., Hilty, L.M., 2011. Environmental Impacts of Lighting Technologies - Life Cycle Assessment and Sensitivity analysis Environmental Impact Assessment Review, vol. 31. Elsevier Inc., pp. 334–343. https://doi.org/10.1016/j.eiar.2010.08.004, 3.
Wu, Y., Su, D., 2020. Review of life cycle impact assessment (LCIA) methods and inventory databases. In: Su, D. (Ed.), Sustainable Product Development: Tools, Methods and Examples. Springer International Publishing, pp. 39–55. https://doi.org/10.1007/978-3-030-39149-2.
Zhang, H., Burr, J., Zhao, F., 2017. A comparative life cycle assessment (LCA) of lighting technologies for greenhouse crop production. J. Clean. Prod. 140, 705–713. https://doi.org/10.1016/j.jclepro.2016.01.014. Elsevier Ltd.