On Life Cycle Assessment to Quantify the Environmental Impact of Lighting Products

The lighting industry has made great efforts to increase energy efficiency around the world with a strong participation from governmental organizations, multilateral organizations and agencies. However, energy consumption is not the only aspect that needs to be considered for transforming the lighting industry. Víctor Ferreira, Deidre Wolff, and Cristina Corchero from Catalonia Institute for Energy Research (IREC) will explore relevant environmental metrics to help inform the reader about circular economy and Industry 4.0 strategies to achieve a sustainable lighting product.

In the last decade, the introduction of LEDs and other energy efficient lighting technologies have contributed to these efforts saving around 480TWh and 200 million tons of CO_2 emissions per year for European consumers. Furthermore, LEDs have radically changed the lighting industry with their ability to reach efficacies of more than four times higher than fluorescent lamps. New designs, like that being developed in the Repro-light project (funded by the European Union), aim to initiate a further transformation in the European lighting industry through the creation of customizable and sustainable products with high functional value. The Repro-light design is being developed considering the circular economy principles, which are to design out waste and pollution, to keep products and materials in use, and to regenerate natural systems. As energy consumption is not the only aspect that needs to be considered, the impact categories that have been addressed in previous environmental life cycle assessments of lighting products are identified. The impact categories and their importance in measuring the impact of lighting product designs that aim to meet the circular economy principles and improve the sustainability of the product will be explained.

Introduction

The lighting industry accounts for the consumption of approximately 16 to 20% of worldwide electricity production, the majority of which originates from residential and commercial use. For this reason, the development of new lighting technologies has focused on improvements in energy efficiency, which resulted in the deployment of LEDs and other efficient lighting systems. This technology advancement has contributed to savings of around 480 TWh of electricity and 200 million tons CO_2 emissions per year for European consumers in the last decade [1]. Furthermore, LEDs have the potential to reach higher efficacies through technological advancements, meaning that even more energy savings are obtainable. However, besides improvements in energy efficiency as a means to achieve a more sustainable product, technological innovations should also focus on designing products that consider the circular economy principles, which are to design out waste and pollution, to keep products and materials in use, and to regenerate natural systems.

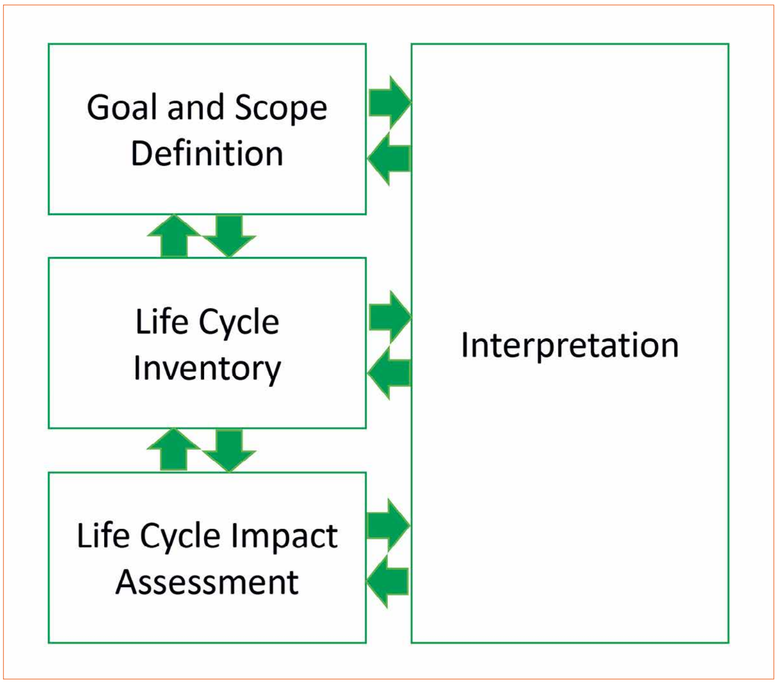

Figure 1: **Phases of an LCA study, ISO 14044:2006 [3]**

The European project, Repro-light (Re-usable and re-configurable parts for sustainable LED-based lighting systems) is one research project that aims to include the circular economy principles in the production of LED luminaires. The Repro-light luminaire is designed to be reconfigurable, dimmable, exchangeable and customizable. It not only demonstrates improvements in energy efficiency through smart technologies such as daylight control, but also reveals possible economic and social benefits, including the creation of job opportunities and new sustainable business models based on serviceability of the luminaires. The project aims to demonstrate the ability to design a more sustainable lighting product and most importantly, to initiate a transformation towards circularity in the European lighting industry by the year 2020.

In order to quantify improvements in sustainability, Life Cycle Assessment (LCA) is one methodology that can be used. LCA is a holistic tool that considers the life cycle of a product or system from raw material extraction through to final end-of-life disposal. This methodology follows guidelines presented in the international standards, ISO 14040:2006 [2] and ISO 14044:2006 [3]. Other guidelines have also been developed from these standards for specific products or systems in order to harmonize the methodology used to assess their impact. For example, Product Category Rules (PCRs) have been developed to guide LCA studies of specific products. These rules must be followed for developing Environmental Product Declarations (EPDs) [2,3], which are independently verified and aim to allow for comparison of LCAs of specific products. All of these guidelines use the four iterative steps of an LCA (Figure 1).

All of these guidelines use the four iterative steps of an LCA:

- Goal and scope definition
- Life cycle inventory (LCI)
- Life cycle impact assessment (LCIA) and (iv) interpretation

In the goal and scope definition, the objective of the study is defined as well as the functional unit, the system boundary, and all other methodological considerations. The functional unit describes the function of the product. In the case of lighting sources, the functional unit may be a specific amount of lumen-hours [4,5,6,7], or the illuminance of a surface or room. The system boundary defines the inputs and outputs included in the LCA. The data for these inputs and outputs is collected during the LCI step and related to the functional unit. The LCIA step is where the environmental impacts are calculated using the results of the LCI. And lastly, the interpretation states the conclusions and recommendation of the study and checks that the goal and scope definition has been met.

This paper identifies the impact categories used in the LCIA stage that have been addressed in previous environmental life cycle assessments of lighting products and gives a description of their environmental significance. As stated above, energy consumption is an important impact to assess for lighting, however, LED luminaires also contain electronic components and LED spots which consist of non-renewable raw materials that should also be considered.

Environmental Impact Categories in the LCA of Lighting Products

Several LCA studies have been conducted in the past three decades for comparing the incandescent lamp, CFL and LED lighting sources. Across these LCA studies, various impact categories have been considered in the LCIA (Table 1). Impact categories represent environmental issues of concern. Characterization factors relate the impact of a specific emission or output in the LCI data to the impact of a reference emission as defined by the characterization model for the specific impact category [3]. Each characterization factor (CF_i) is multiplied by the LCI result (LCI_i) to yield the LCIA result. This is repeated for all outputs of the LCI (n) that are categorized in the same impact category. The sum is then taken to yield the total result for the impact category (IC). Taking m to be the LCI result associated with the IC, the total impact can be calculated using equation 1 for each impact category.

Table 1: Summary of impacts categories considered in LCA studies of lighting

Impact category	Ref.	Year
Global warming, Acidification, Carcinogenics, Non-carcinogenics, Respiratory effects, Eutrophication, Ozone depletion, Ecotoxicity, Smog and Cumulative energy demand	[15]	2017
GWP (excluding biogenic carbon), HTP and TET	[16]	2016
AP, Climate change, EP, Freshwater aquatic eco-toxicity, Freshwater sediment eco-toxicity human toxicity, Marine aquatic eco-toxicity, Marine sediment eco-toxicity, Terrestrial eco-toxicity, Ionizing radiation, Land use, Maladours air, Abiotic depletion, Photochemical and Stratospheric Ozone depletion.	[17]	2014
PED, Renewable energy, Non-renewable energy, ADP, Water consumption, Hazardous waste, Inert waste, GWP, AP, Air pollution, Water pollution, ODP, POCP, EP.	[18]	2013
ADP, AP, EP, GWP, ODP, POCP	[19]	2012
GWP; AP; POCP, ODP; HTP; freshwater aquatic, marine aquatic, and terrestrial ecotoxicities; EP; ecosystem damage; ADP; land use; hazardous, non-hazardous, and radioactive wastes	[20]	2012
PED, GWP, EcoIndicator'99	[21]	2011
PED, GWP	[22]	2009
GWP, AP, EP, POCP, ADP, HTP, Primary Energy Demand (CED)	[5]	2009
ADP; GWP; ODP; HTP; AP; EP; POCP; freshwater aquatic, marine aquatic, and terrestrial ecotoxicities; carcinogens; respiratory effects; minerals; fossil fuels	[23]	2006
PED, Hg emissions, radioactive materials	[24]	1996
GWP, SO2, NOx, CH4, ashes, Hg, solid waste	[25]	1991

Equation (1) to calculate impact:

$$IC\ Result = \sum_{i=m}^{n} LCI_i \cdot CF_i \qquad (1)$$

Various characterization models can be used to derive the characterization factors, such as CML (base line and no-baseline) [8], Eco-indicator 99 [9], ReCiPe [10], TRACI [11], USEtox™ [12,13] and Cumulative Energy Demand [14].

From Table 1, seven impact categories were chosen for more detailed discussion of their impact models and environmental significance, including global warming, acidification, eutrophication, abiotic depletion, photochemical ozone creation, ozone depletion, and primary energy demand. These categories have also been used in the preparation of Environmental Product Declarations (EDPs) by Philips [26] and David Trubrige [27], and can be derived using the recognized CML method, which was developed by the Institute of Environmental Sciences at Leiden University in The Netherlands [28].

The descriptions that follow intend to educate the reader on the various impact categories that can be assessed in LCA studies. It should be noted that while some impact categories are considered robust, others are still immature and require significant development to ensure that their use does not lead to incorrect decisions being made [29]. The scientific debate around LCIA methodologies has increased with the increase in projects [29], such as Repro-light, however, conclusions and recommendations can still be made through comparative LCA studies.

Global warming

Gobal warming is an increase in global temperature over time, which is enhanced by human activities that impact radiative forcing. Radiative forcing results when greenhouse gases in the atmosphere absorb infrared radiation reflected from the earth's surface and re-emit it in all directions, thus redirecting it from passing through the earth´s atmosphere and into space. In other words, radiative forcing is a measure of how the energy balance of the earth-atmosphere system is influenced when factors that affect climate are altered [30]. Carbon dioxide (CO_2) emissions have caused the largest radiative forcing over the period of industrial era started from 1750. In fact, CO_2 has accounted for about 82% of the increase in radiative forcing over the past decade [31]. Apart from CO_2, other greenhouse gases, such as CH_4, N_2O and CFCs and SF_6, can also cause this. Changes in global temperature can lead to climatic disturbance, desertification, rising sea levels and the spread of disease.

The characterization factors measuring the global warming effect of each greenhouse gas are called Global Warming Potentials (GWPs). Each factor is an estimate of a chemical atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference value CO_2. Thus, global warming potential is calculated in kilograms of carbon dioxide equivalents (kg CO_2-eq). In detail, each greenhouse gas is assigned a GWP index expressing the ratio between the increased infrared absorption due to the instantaneous emission of 1 kg of the substance and that due to an equal emission of CO_2. In other words, it describes the increase of the concentration of greenhouse gas and radiative forcing with respect to CO_2 considering the time after the release. In this sense, the GWP can be calculated applying

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different time horizons (20, 100 and 500 years), but a usual period is 100 years, which is also used in the Kyoto protocol. A list of GWPs is compiled by theIntergovernmental Panel on Climate Change (IPCC) and it is periodically updated [32,33].

Acidification

Acidification is associated to the capacity of some substances to create and release protons (H^+). For example, sulfur dioxide (SO_2) can react with water in the atmosphere to form acid rain (a process known as acid deposition). Another molecule with a significant contribution to acidification is nitrogen oxide that reacts to form nitric acid (HNO_3). Acid rain can fall a considerable distance from the original location of the gas released. As a consequence, ecosystems can be damaged to different degrees affecting soil and materials (buildings).

Acidification Potentials (APs) are characterization factors used to assess acidification [34]. The AP of a substance was defined by Heijungs et al. [35] as the number of H^+ that can potentially be produced per kg substance with respect that produced per kg of SO_2 [34]. Therefore, AP is expressed as sulfur dioxide equivalents (kg SO_2-eq) [36]. It is worth noting that AP varies according to regional characteristics and atmospheric environments. Several methods as described by Guineé et al. [34] have been proposed to deal with local differences in sensitivity to acidification. Nevertheless, LCA practitioners assume that the life cycle emissions from a global supply chain occur within the continent referring to the geographical scope of the characterization method [37].

Eutrophication

Eutrophication is caused by the release of nitrogen and phosphorus, such as from landfills, sewage, and fertilizers that can cause an enrichment of nutrients in a certain place. It can affect aquatic ecosystems by causing excess plant (algae) growth and depleting oxygen levels. The growth of plants can block sunlight from reaching other organisms, reducing photosynthesis and oxygen levels that further help to decompose dead algae. This depletion of oxygen eventually leads to the death of species, such as fish, and to anaerobic decomposition. The latter generates methane and hydrogen sulfide and can lead to loss of species diversity among other consequences. Eutrophication can also affect terrestrial eco-systems by causing the amount of nitrogen necessary for a maximum harvest to be exceeded. This leads to enhancements of the nitrate concentration in the soil and groundwater, which then contributes to an increase of biomass formation.

The CML characterization model to derive the Eutrophication Potential (EP) characterization factors uses phosphate (PO_4^{3-}) as the reference substance. EP is defined as the ratio between the potential contributions of one mole of substance to one mole of phosphate using the molar mass (kg/mol) [35]. The contribution to biomass formation caused by eutrophication in the EPs considers Nitrogen, Phosphorous and Carbon, which are measured in terms of the Chemical Oxygen Demand (COD). It is based on the average chemical composition of aquatic organisms ($C_{106}H_{263}O_{110}N_{16}P$), assumed to be representative of average composition for biomass [34]. The EPs assume that one mole of Phosphorus contributes as much to the formation of biomass as does 16 moles of Nitrogen and 138 moles of Oxygen to degrade the organic matter emitted assuming that those moles are required to degrade 1 mole of biomass [35].

Abiotic resource depletion

Abiotic resources are defined as inorganic or non-living materials at the time of their extraction [38]. This impact category focuses on the depletion of non-renewable abiotic resources, including fossil energy resources, metals, and non-metal minerals [39]. The risk to the availability of these resources can depend on multiple factors, such as the ability to recover the resource after use (for example fossil fuels are converted to energy and cannot be recovered), the pressure from increasing demand for the resource, and the geographical accessibility of the resource [39]. Abiotic resource depletion is one of the most debated impact categories and there are multiple methods used to derive the characterization factors, each of them originating from justifiable perspectives of the problem definition and none of them able to be empirically verified despite over 20 years of research [29,38,40].

Variation in the problem definition leads to various opinions on whether to include stocks (deposits) in the environment, stocks in the economy, or both in the characterization models, as well as whether to consider material criticality and what reserve value to use as the reference for depletion, being the ultimate reserve, ultimately extractable reserve, reserve base or the economic reserve [40]. The ultimate reserve refers to the quantity of a resource estimated to be available in the earth's crust, the ultimate extractable reserve is the quantity that can be technically extracted, the reserve base is quantity the meets the current requirements for mining regulation, and the economic reserve is the quantity that can be economically extracted [40].

In terms of criticality, the United Nations has created a list of Critical Raw Materials that include chemical elements that have a high supply risk and are also important for the EU economy [41]. This criticality can be a result of geological, technical, environmental, social, economic and/or political aspects. One argument against the inclusion of criticality in environmental LCA studies is based on the fact that it is not only an environmental problem, but also includes both economic and social aspects, and thus criticality does not measure the same environmental problem defined with abiotic resource depletion [40]. However, it is suggested that assessments of criticality may be useful for studies that combine Life Cycle Costing, environmental LCA and social LCA, thus expanding the assessment to include other aspects besides environmental. For this reason, criticality is not included in the CML model of the Abiotic Depletion Potential (ADP) characterization factors.

The CML characterization model defines the problem as the environmental depletion of abiotic resources, considering only stocks in the environment and using the ultimate reserve as the reference to which depletion is measured [40]. The reason for choosing the ultimate reserve in this case is to act as an estimation of the ultimately extractable reserve for which data is not available. In line with this, the focus is placed on the stocks in the environment because of the lack of data. The CML model derives two sets of characterization factors for ADP, being ADP Elements (ADPe) and ADP Fossil (ADPf). ADPe and ADPf are both quantified with reference to Antimony. Antimony was chosen as the reference as it is the first element (alphabetically) that had the required data available for quantifying both its extraction rate and its ultimate reserve [40]. The characterization factors are quantified by dividing the ratio of their extraction rate to square of their ultimate reserve by the same ratio for Antimony. ADPe is expressed in units of kilogram of antimony equivalents (kg Sb-eq.) and ADPf in Megajuoles (MJ).

Ozone depletion

The ozone layer (15-20 km high) surrounds the planet like a bubble and acts as a filter against harmful UV-B radiation produced by the sun. Ozone (O_3) is formed in the stratosphere through the reaction of oxygen (O_2) with oxygen atoms (O) produced from the dissociation of oxygen with exposure to short-wavelength UV-light ($O_2 \rightarrow O + O$), thus giving the simplified reaction mechanism of $O_2 + O \rightarrow O_3$. Anthropogenic emissions deplete the ozone allowing solar UV-B radiation to reach earth´s surface, which causes harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials [42]. According the Montreal Protocol, 200 individual substances have been assigned an Ozone Depletion Potential (ODP), including chloro-fluorocarbons (CFCs), halons, carbon tetrachloride (CTC), hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs), among others [43].

Ozone Depletion Potentials (ODPs) are the characterization factors (expressed in kg CFC-11-eq.) to aggregate and assess the interventions for the impact category stratospheric ozone depletion. The ODP concept was introduced by Wuebbles in 1988 and it is taken by the CML method [34]. The model indicates that the ODPs represent the relative changes in the ozone column due to an instantaneous emission to the atmosphere, i.e., the ratio between the change in the stratospheric ozone column in the equilibrium state due to the annual emissions of a determined substance and the change in this column in the equilibrium state due to the annual emissions of CFC-11 [34].

Photochemical ozone creation

Ozone can be formed from the reaction between volatile organic compounds (VOCs) and nitrogen oxides in the presence of heat and sunlight in the troposphere. This is known as photochemical ozone production, also called as summer smog. Radiation from the sun and the presence of nitrogen oxides (NOx) and hydrocarbons imply complex chemical reactions, producing aggressive products, one of which is ozone. Although ozone plays an important role to protect the stratosphere, it is classified as damaging at ground level. High concentrations of ozone are toxic to humans and it is suspected to damage vegetation and material.

The characterization factors derived are Photochemical Ozone Creation Potentials (POCPs), and are measured in kilograms of ethene equivalents (kg C_2H_4-eq.). The CML method does not use specific POCPs for volatile organic compounds (VOCs), but an average based on the estimated quantity of ozone formed photochemically by a given VOC [34]. Although, Nitrogen oxides act as a catalyst in the chemical reactions involved in photochemical smog formation, they are not considered in this model. In this sense, Heijungs et al. [35] has also suggested to calculate POCPs on the basis of a marginal approach in which NOx would also be included.

Primary energy demand

Primary energy demand refers the quantity of energy directly from the hydrosphere, atmosphere or geo-sphere or energy source without any anthropogenic changes. Therefore, this category is a useful indicator to estimate the depletion of energy resources considering a whole lifecycle of product or system. PED can be divided in two types of energy requirements, renewable and non-renewable resources. The first one is generally considered separately and includes hydropower, wind power, solar energy and biomass. The second one includes energy source such as natural gas and crude oil, both considered to produce energy and raw materials, for example for plastics, lignite and coal also for energy production and uranium being only used for electricity production in nuclear power stations.

For calculating the primary energy demand, the lower (net calorific value) or to the upper heating value (gross calorific value) of primary energy resources can be used, where the latter includes the evaporation energy of the water present in the flue gases. The net calorific value is the higher heating value minus the heat of vaporization of the water. In the case for standard combustion processes the re-condensation occurs in the surrounding environment, thereby the energy to vaporize the water is not recovered [36,44].

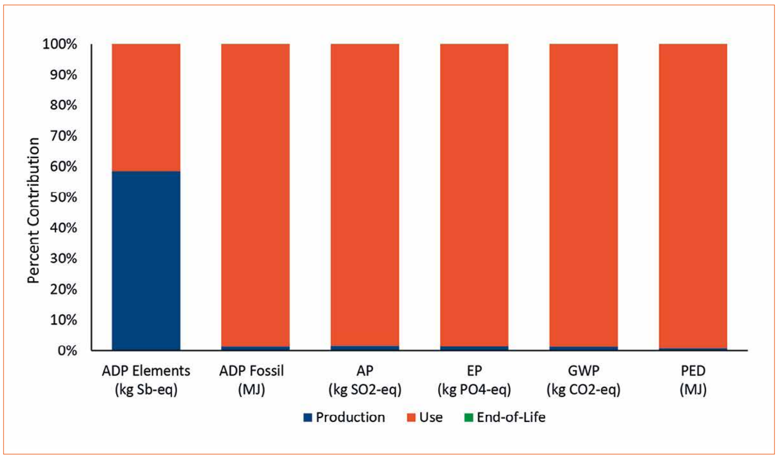

Figure 2: Percent contribution of the production, use and end-of-life disposal life cycle stages to each impact category for conventional LED luminaires studied as part of the Repro-light

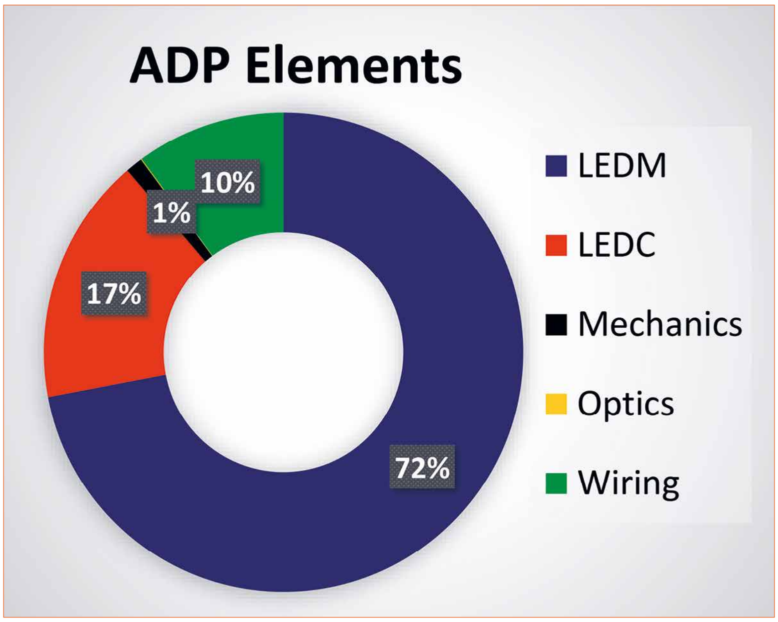

Figure 3: Percentage distribution of each component of the conventional LED luminaires assessed in Repro-light. LEDM: LED Module, LEDC: LED control system, Mechanics: Mechanical parts, Optics: Optical element and Wiring: Copper wires

Discussion and Concluding Remarks

The impact categories discussed in the previous sections can all be included in the LCIA stage of an LCA study. Including these impacts will help reflect the overall environmental impact of a product along its life cycle, including raw material extraction, production, manufacture, transport, use, and end-of-life disposal. Furthermore, including multiple impacts in an LCA study will not only allow for identification of the life cycle stage or process that contributes the most to the overall impact for one category, but also the differences amongst the impact categories. In this sense, comparisons can be used to optimize the design of a product across all impact categories towards the most sustainable option, as well as to avoid shifts of an impact from one category to another. It should be noted that there are other impact categories that exist that have not been discussed. However, the intention of this paper is to identify the common impact categories that have been used in LCA studies of lighting products and to explain their environmental importance.

For LCA studies of lighting products, results suggest that the use stage energy consumption is the most contributing aspect to the overall impact for most impact categories considered [45][18][46]. Therefore, new technologies that reduce the energy consumed during the use phase will lead to reductions in these impacts. This aspect is being considered in the project, where technological advancements such as daylight control are being included in the LED luminaire design. Furthermore, improvements in the efficacies achieved by LEDs will reduce this use phase impact further. Changing the electricity grid mix may also lead to reductions of the impact due to electricity consumption for some categories, such as GWP. However, this fact should be studied in detail considering all environmental impact categories described above, as some renewable energy sources may vary the requirement for non-renewable raw materials used for electricity production, such as photovoltaic solar panels.

Since LED luminaires consist of electronic components and LED spots that have a specific material composition, the impact of these materials is also important. Assessment of the ADPe can be used to identify and compare the use of these materials in multiple luminaire design scenarios. Studies have further found that the electricity consumed during melting and casting during the production of circuit boards and aluminum heat sinks can have a considerable impact on the GWP and AP for the manufacturing phase [5]. Furthermore, the release of sulfur dioxide emissions during the smelting and converting processes in copper production can contribute significantly to the overall AP of the manufacturing stage [5,47].

For improvements to the impact from the end-of-life for luminaires, some scenarios could be considered that account for recovery of metals. This would be in line with one of the principles of the circular economy keeping materials and products "circulating" in the techno sphere, which avoids the extraction and production of raw materials. There are two methods for modeling end-of-life recycling in LCA studies, including closed-loop and open-loop recycling. Closed-loop recycling can be used if the characteristics of the recycled material are not considerably different compared to the virgin material [48] and thus it is able to be recycled back into the production of the product. Open-loop recycling, on the other hand, models the recovery of a material for use in other applications [48], thus contributing to the global view of the circular economy of keeping materials in use. The impact categories discussed can be used to assess different scenarios for end-of-life disposal and thus provide recommendations for strategies to improve circularity of lighting products. ■

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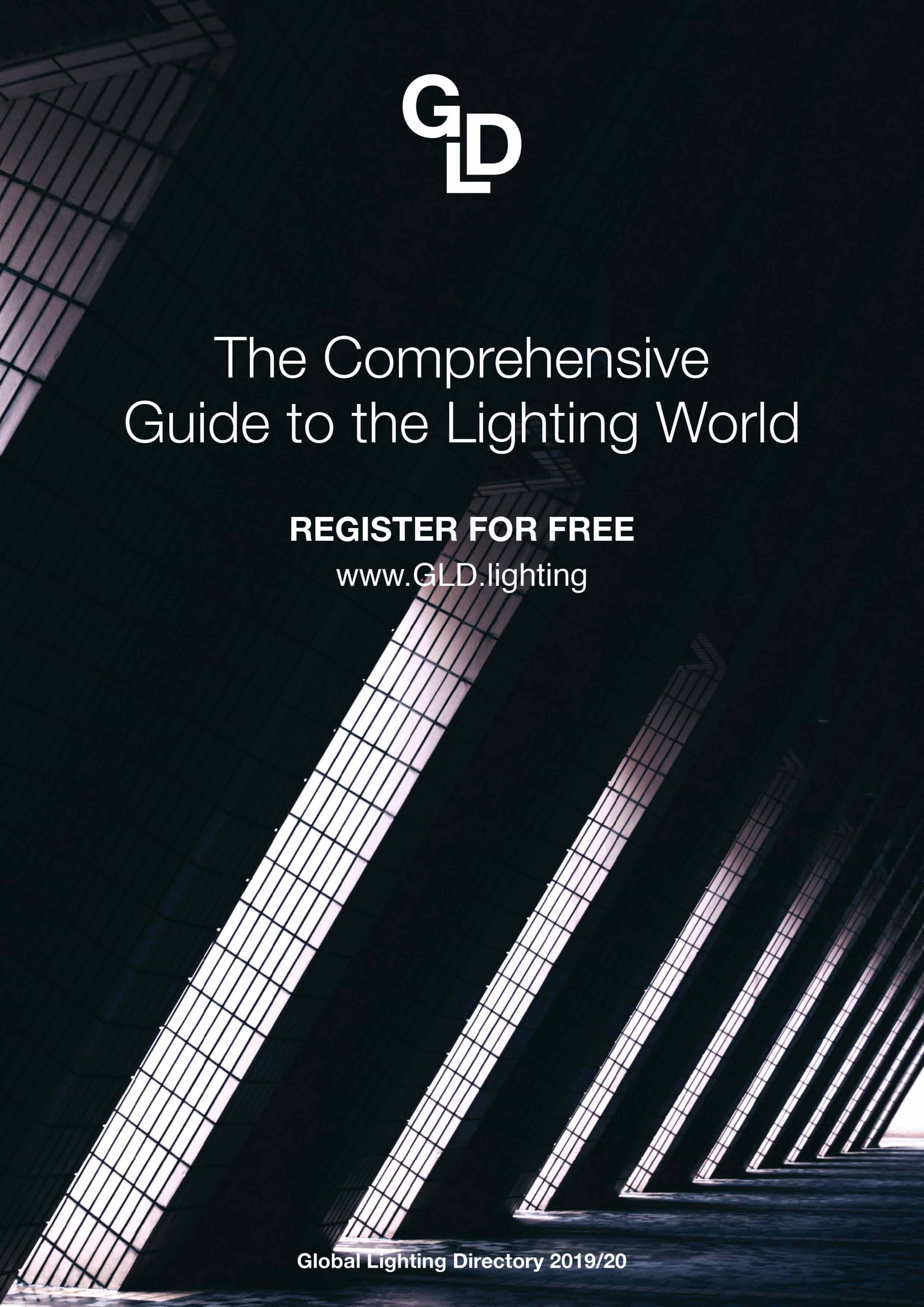
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