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ENVIRONMENTAL IMPACT OF LED LUMINAIRES

THE FUTURE OF SCAN-TO-BIM IN LIGHTING DESIGN

The Global Information Hub for Lighting Technologies and Design

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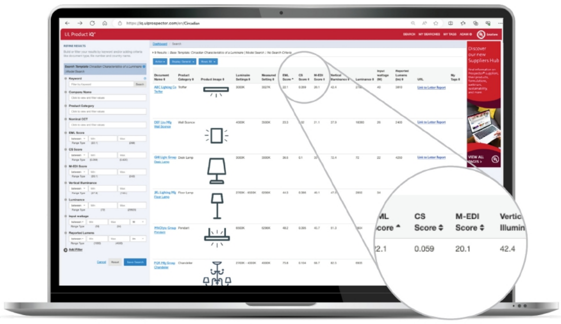

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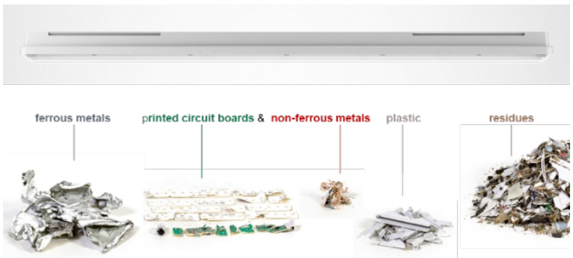

SUMATRA

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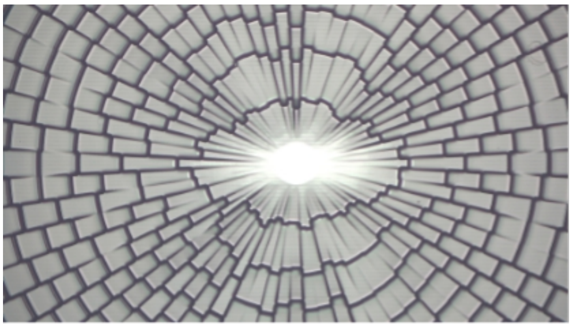

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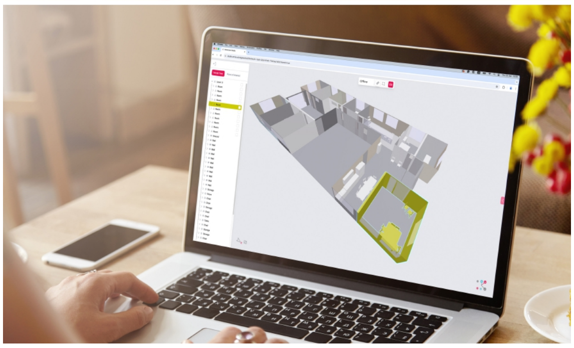

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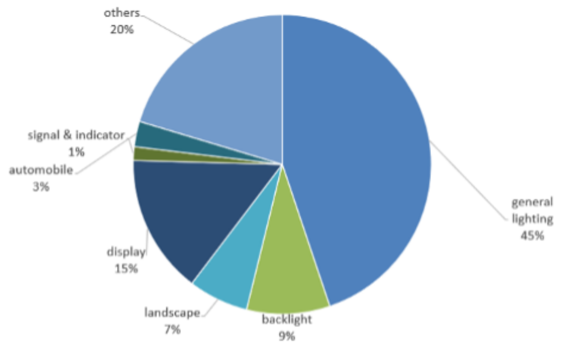

LPS DIGITAL TALKS

Environmental Impacts of LED Luminaires, Recycling Practices, and Recommendations for a More Sustainable Lighting Industry

RESEARCH PROJECT SUMATRA
Dr. Sebastian KNOCHE[1], Researcher at TRILUX and
Dipl.-Ing. Marina PROSKE[2], Researcher at Fraunhofer IZM

We are surrounded by luminaires and artificial light almost everywhere. The costs are correspondingly high: 13% of the German electricity consumption is used for lighting. This is associated with high greenhouse gas emissions. And our life cycle assessments show that the resource consumption for luminaires is of similar relevance as the greenhouse gas emissions.
Life cycle assessments were conducted for a selection of LED luminaires. The results show the potential for making lighting quantitatively more sustainable. If the development of an LED luminaire is guided by life cycle assessments, this potential can be exploited in the best possible way.
We also investigated state-of-the-art recycling processes and assessed the realistic recyclability of luminaires. Here, too, we found potential for improvement. These cannot be exploited through improved product design alone, but require a coordinated approach between manufacturers and recyclers for the simultaneous improvement of product design and recycling processes.

[1] TRILUX GmbH & Co. KG, Heidestraße 4, 59759 Arnsberg, Germany
sebastian.knoche@trilux.com

[2] Fraunhofer Institute for Reliability and Microintegration IZM, Gustav-Meyer-Allee 25, 13355 Berlin, Germany
marina.proske@izm.fraunhofer.de

Introduction

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition of sustainability by the United Nations dates back to 1987 [1]. In essence, this means to act in a way that we can continue doing, basically, forever.

In the research project SUMATRA (**Su**stainable **Mat**erials in Future Luminaire Designs – from **R**ecycling back to **A**pplication), the aim is to do things quantitatively, and not just have a qualitative discussion. To this end, we use environmental Life Cycle Assessments (LCAs). In a life cycle assessment, the environmental impacts that arise over the entire life cycle of a luminaire are measured in various environmental impact categories. This enables quantitative comparisons to be made between different product designs, so that it can be precisely stated whether variant A or variant B causes the lower environmental impact for providing the same benefit. However, it is not possible to make a statement on the absolute achievement of sustainability, as this would require a comparison of the determined environmental impacts of a luminaire with a maximum level that is considered acceptable. This maximum level, called "Safe Operating Space" in the scientific literature of Planetary Boundaries [2,3,4], is difficult to determine for a single luminaire.

Background on Life Cycle Assessments

The following environmental impact categories are considered in our LCAs:

- **ADP elements** (Abiotic depletion potential of the elements): Utilization of resources (minerals, metal ores) that are limited on earth.
- **ADP fossil** (Abiotic depletion potential of the fossils): Consumption of fossil raw materials (oil, coal, gas), which are finite on earth.
- **GWP** (Global Warming Potential): Emission of greenhouse gases, measured in kg CO_2 equivalent.
- **Toxicities** (Fresh Water / Marine / Terrestrial / Human): Release of toxic substances.
- **AP** (Acidification potential): Emission of substances such as sulfur dioxide, which cause acid rain, for example.
- **EP** (Eutrophication Potential): Water bodies being enriched with nutrients (e.g. phosphates); which has adverse effects such as algal blooms, for example.
- **ODP** (Ozone Depletion Potential): Depletion of the ozone layer in the stratosphere (which is our natural UV-C blocker on earth).
- **POCP** (Photochemical Ozone Creation): Creation of ozone near the ground, which is highly reactive and has adverse health effects when inhaled.

The SUMATRA Consortium
The SUMATRA research consortium consisted of:

- TRILUX GmbH & Co. KG:
Dr. Sebastian Knoche, Horst Rudolph, Sonja Beckmann, Gregor Grote-Schulte, Felix Bruchhage, Katrin Discher, Torben Tillmann
- Inventronics GmbH:
Jürgen Schwarz, Markus Ziegler, Peter Kulf, Bernhard Orben, Markus Heckmann, Reinhard Lecheler
- Interzero Circular Solutions Germany GmbH:
Carla Krätz, Torben Kabbe
- Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (IZM):
Marina Proske, Jana Rückschloss, Otmar Deubzer
- Associated partner Kardorff Ingenieure Lichtplanung GmbH:
Gabriele von Kardorff

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SUMATRA

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Part of the Sumatra team: Klaus Röwekamp, Torben Kabbe, Marina Proske, Peter Kulf, Sonja Beckmann, Sebastian Knoche, Carla Krätz, Katrin Discher, Markus Ziegler, Gregor Groteschulte, Boris Safner, Bernhard Orben, and Jürgen Schwarz (left to right).

However, in the first indicative life cycle assessments, we found that most impact categories are very similarly distributed and about 95% of them originate from the electricity consumption in the use phase. It is therefore sufficient to select one representative for these impact categories. Our choice is to focus on the **Global Warming Potential (GWP)**. The GWP can be reduced directly by increasing energy efficiency.

A second metric that is in the focus of our considerations is the **Abiotic Depletion Potential of the elements (ADPe)**. In contrast to the GWP, large contributions occur in the production phase of the luminaire due to the materials used. The ADP is therefore related to **material efficiency**. This complements the aspect mentioned first, (GWP / energy efficiency) in a meaningful way.

Climate Change

There is a broad consensus among scientists that climate change is extremely important for our life on earth, as the reports of the IPCC (Intergovernmental Panel on Climate Change) and their broad authorship show [5]. **Figure 1** shows the evolution of the global mean surface temperature over the past 24,000 years. Large differences are visible; but the last 10,000 years have been in a very stable condition with variances of just $\pm 0.5\,^{\circ}\mathrm{C}$ [6]. This epoch in earth's history is called **Holocene**. Agriculture and advanced civilizations developed during this epoch, and it is considered the reference point of a desirable planet [3].

It is well known that global warming is mainly driven by human activities: emission of greenhouse gases, primarily CO_2 from the burning of fossil fuels [7]. Other greenhouse gases, like methane, also contribute. These other greenhouse gases are converted to their **CO_2 equivalent** [8], i.e. to the amount of CO_2 emissions that would give the same global warming effect. All greenhouse gas emissions are then aggregated in an LCA to determine the global warming potential, measured in kg CO_2 equivalent.

Abiotic Resource Use

Humans extract raw materials (chemical elements and compounds) that are stored in the earth's crust, and use them to build things that have a function for them. This approach can be in conflict with the principle of sustainability, as resources are limited and non-renewable, i.e. they are not continuously produced in the earth.

In an LCA, the metric for measuring abiotic resource consumption is the **Abiotic**

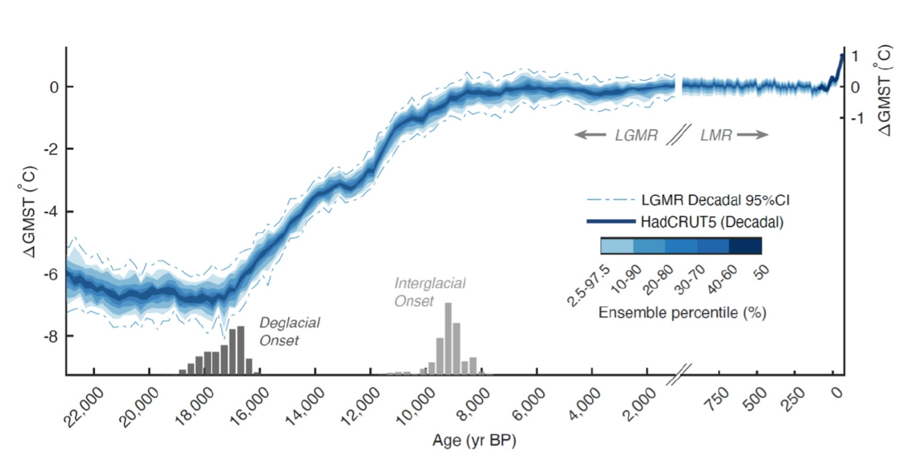

Figure 1: Global Mean Surface Temperature (GMST) change over the last 24,000 years, reconstructed from proxies (blue areas) and temperature measurements (line) [5].

Depletion Potential of the Elements [9,10,11]. All abiotic resources used during the life cycle of a product are assigned a weighting factor. This weighting factor describes the scarcity of a resource and is calculated from the total quantity *R* in the earth's crust ("ultimate reserve", in kg) and the current extraction rate *DR* (in kg/year).

For a resource i it reads:

$$\mathrm{ADP}_i = \frac{DR_i/R_i^2}{DR_{\mathrm{ref}}/R_{\mathrm{ref}}^2} \qquad (1)$$

The reference element is antimony (chemical symbol Sb). Thus, the unit for the Abiotic Depletion Potential of the elements is **kg Sb equivalent**.

The weighting factors differ by many orders of magnitude. For example, aluminum, the third most common element in the earth's crust, has a weighting factor of $\mathrm{ADP}_{Al} = 1.09 \times 10^{-9}$ kg Sb–eq./kg. In contrast, gold has a weighting factor of $\mathrm{ADP}_{Au} = 52$ kg Sb–eq./kg, see reference [9].

Life Cycle Assessment Results

We performed LCAs for eight luminaires of various types produced for professional applications. They have lifetimes (declared by the manufacturer) of 50,000–100,000 h, luminous fluxes between 2,200 lm and 26,700 lm and efficacies between 110 lm/W and 179 lm/W.

Some of them are dimmable and can be controlled by means of the DALI protocol. However, the use phase for all of them was modelled as a constant operation at 100% dimming level over the full lifetime. We calculated with a static electricity mix (Germany 2019).

Background data was taken from the Sphera LCA for experts® database.

Packaging, transport to the customer and the end-of-life treatment have been considered, and we found them to be of minor relevance. For the sake of clarity, they are omitted in the following presentation of the results and analysis of hotspots.

Portfolio Overview

Figure 2 shows the results of the life cycle assessment. Let us focus our attention on the absolute values (upper row of diagrams) first.

The global warming potential ranges between 470 kg and 5,000 kg CO_2-equivalent. Strikingly, the share of the production phase is very low, only between 1% and 5%. Included here is the complete supply chain up to the raw material mining. The vast majority of greenhouse gas emissions occurs during the use phase, i.e. in order to produce the electricity consumed by the luminaire.

In the diagram on the right hand side, it is discernible that the abiotic depletion potential is dominated by the production phase; more specifically by the electronic components (LED module, control gear, wiring). Optics (mostly made from transparent plastics like PMMA or PC) and housings (mostly steel or aluminum) have only small contributions. From the abiotic resource perspective, it seems that the large amounts of steel or aluminum in a housing have less impact than the small amounts of copper or tiny amounts of precious metals in the electronics. There is also a contribution of the use phase to the abiotic depletion potential. This comes from the electricity consumption, not from spare parts. Electricity generation also consumes abiotic resources, for building infrastructure, power plants, solar panels, and so on.

In both impact categories, the high-bay luminaire stands out in particular. In terms of global warming potential, this is mainly due to the high power and in terms of abiotic resource consumption due to the high number of LEDs. But that results in a lot of light (26,700 lm and 70,000 h lifetime).

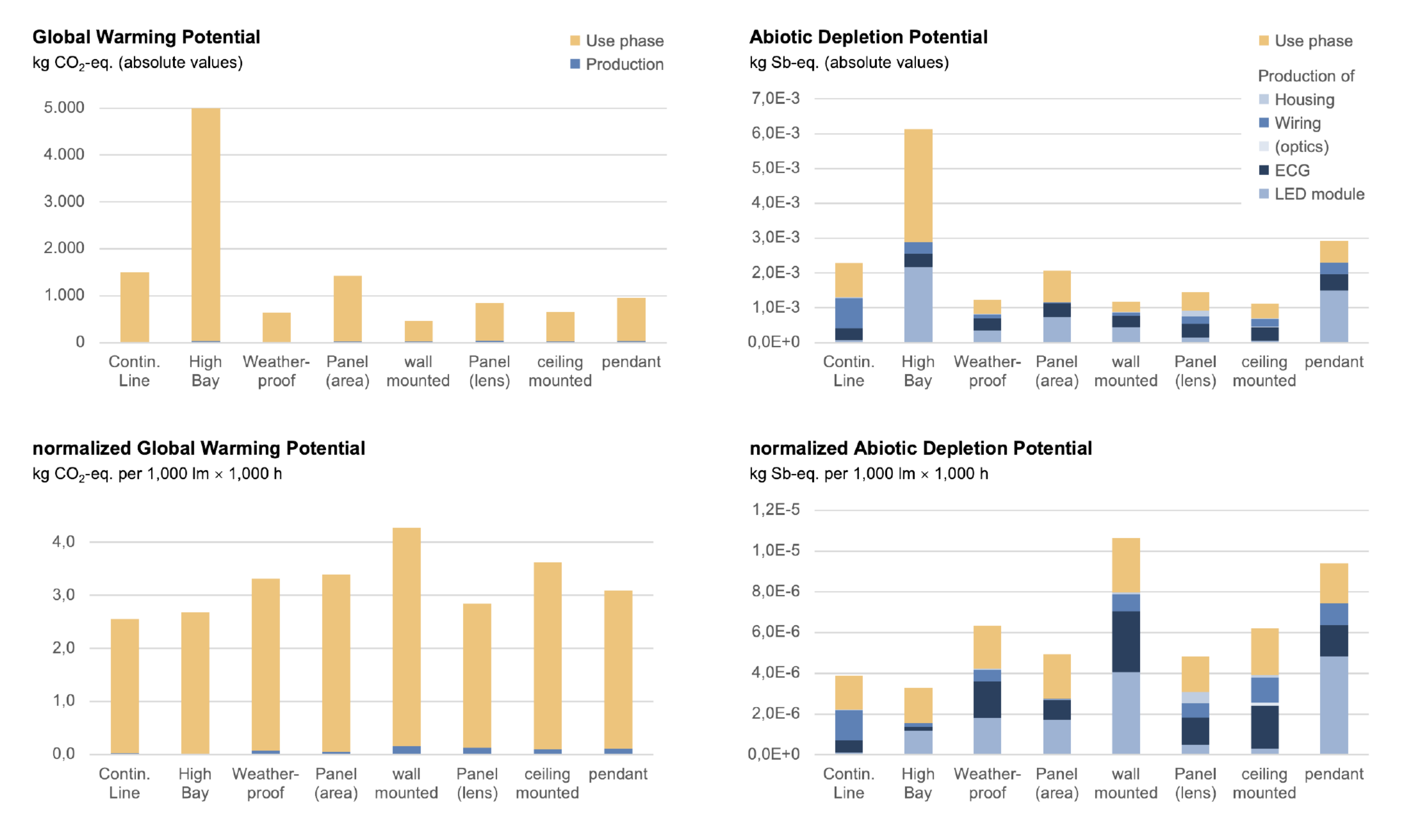

Figure 2: Overview of the Life Cycle Assessment results. The upper row shows the absolute values of the environmental impacts; the lower row shows the environmental impacts normalized to equal flux of 1,000 lm and equal use time of 1,000 h.

Therefore, in addition to the absolute representation, standardized representations for identical luminous flux and identical lifetime are also very useful. For this functional unit, we chose $1{,}000$ lm and $1{,}000$ h of operation. The results are shown in the lower row of **Figure 6**.

In this representation, the high-bay luminaire appears relatively sustainable compared with other luminaire architectures. Now the wall-mounted luminaire has the highest impacts in both categories. The wall-mounted luminaire consists of a large LED module (300 mm in diameter) and a big opal cover. Its luminous flux is relatively low ($2{,}200$ lm) and so is its luminous efficacy (110 lm/W). This explains the relatively large environmental impacts per $1{,}000$ lm and $1{,}000$ h.

It may be useful to deduce an "average" luminaire from the results, for example, to get a rough estimate of the environmental impacts of lighting in a complete building when no detailed data is available, or to start building an intuitive understanding of luminaire LCAs. As the selected luminaires are not representative of all existing LED luminaires, an exact calculation of the mean value makes little sense. In light of the unavoidable inaccuracy, the "smoothest" values possible are therefore selected, see **Table 1**.

GWP	3 kg CO_2–eq.
ADP	6×10^{-6} kg Sb–eq.

Table 1: Estimated average environmental impacts of professional lighting per 1,000 lm · 1,000 h.

An average breakdown of the environmental impacts to the different phases and components is shown in **Figure 3**.

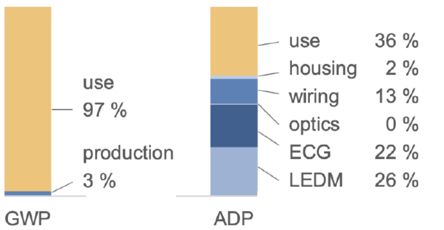

Figure 3: Average breakdown of global warming potential (left) and abiotic depletion potential (right) for a professional LED luminaire.

It is an intriguing question, whether the global warming potential or abiotic depletion potential caused by a luminaire is "more important". Obviously, both metrics use different units and cannot be compared directly. In fact, they describe completely different effects, and any comparison is always subjective. However, a comparison with normalization factors (NF) provides a first indication. The normalization factors are recommended by the Joint Research Centre (JRC) of the European Commission for the evaluation of environmental footprints and describe the global environmental impact of all human activities (determined for 2010), per capita **[12]**.

The comparison made in **Table 2** shows that the climate change potential of an LED luminaire has a higher share of the normalization factor (13%) than the abiotic resource consumption (3%). However, the proportions are of a similar order of magnitude – LCA results often show much more drastic differences. We therefore conclude that both environmental impact categories are equally relevant and that the eco-design of LED luminaires should aim to reduce both environmental impacts.

	Luminaire	NF	Ratio
GWP [kg CO_2–eq.]	$1{,}000$	$7{,}550$	13%
ADP [kg Sb–eq.]	2	63.3	3%

Table 2: Comparison of average environmental impacts for one luminaire with the normalization factor NF.

Detail: LED-Module

As the portfolio overview (**Figure 2**) shows, the LED module can be the largest contribution to the abiotic depletion potential. The LCA of an LED module depends on three factors: The surface area of the printed circuit board (PCB), the type of LEDs, and their amount.

The results for exemplary LED modules are shown in **Figure 4**. A distinction is made between different LED types (flip chip / bond wire) and two PCB layouts either linear (71.9 cm x 2.3 cm, equipped with 96 LEDs) or large area (33.6 cm in diameter, equipped with 64 LEDs). The four possible combinations lead to significantly different environmental impacts.

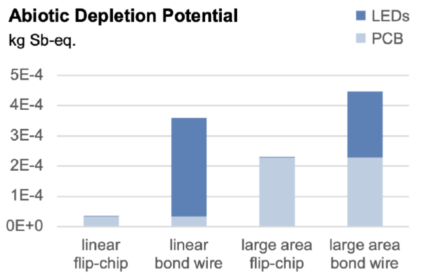

Figure 4: Abiotic Depletion Potential for LED modules of different geometry and with different LED type.

Thus the analysis includes two LED types that may require more explanation. In traditional LED architectures, bond wires, that are made from a gold alloy, are used to contact the emitter chip. More recently, LEDs with flip-chip technology have been introduced to the market. In them, the emitter chip is contacted by solder bumps from below, thus saving the gold for the bond wire. See **Figure 5** for a microscopy image of the two LED types.

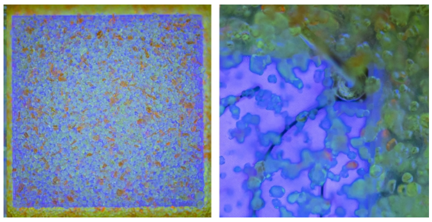

Figure 5: Flip-chip LED on the left and LED with bond wire on the right.

A comparison of the scenarios with and without bond wire in **Figure 4** shows that almost the entire abiotic resource consumption of LEDs is caused by the bond wire. Materials for the chip (e.g. gallium) or for the phosphors (e.g. rare earth elements) appear to play a minor role.

The following conclusion on sustainable LED module design can be drawn:

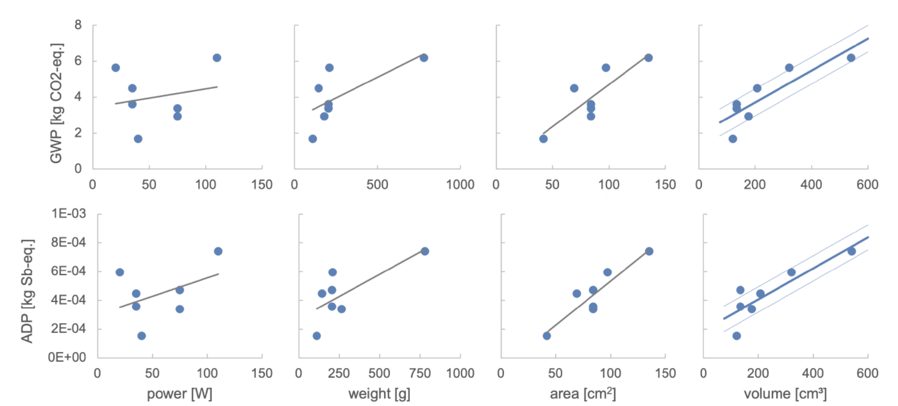

Figure 6: Correlation of the global warming potential (top row) and abiotic depletion potential (bottom row) for the production of an ECG with its power, weight, area and volume.

- Flip-chip LEDs have a significantly lower abiotic resource consumption than LEDs with bonding wire and are therefore preferable.
- The surface area of the LED module is relevant and should be kept as small as possible.

Detail: Electronic Control Gear

The electronic control gear (ECG) of a luminaire has a complex structure and consists of a printed circuit board with a large number of electronic components. A proper life cycle assessment is only possible if the bill of materials is available. In the SUMATRA project, this was the case by the close collaboration of the consortium.

In the portfolio overview (**Figure 2**), we can see that the production of the ECG often has a major impact on the abiotic depletion potential. What are the driving factors behind this result?

Figure 7 shows the result for different series of ECGs. Within the same series (connected by blue lines), we find that the ADP increases only slightly with increasing nominal output power. A comparison of a dimmable and a switchable ECG shows that the switchable ECG consumes around 30% less resources (▲ → △). We also assessed an ECG with safety extra low voltage (SELV). Due to the additional insulation stages in the internal structure, it has a slightly higher abiotic resource consumption than comparable non-SELV devices, the difference is approximately 25% (▲ → ◆).

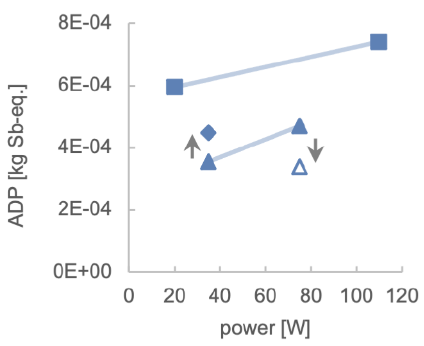

Figure 7: Abiotic depletion potential for the production of different ECGs. Outdoor devices (■), dimmable indoor devices with a linear form factor (▲), non-dimmable device (△) and a device with safety extra-low voltage (◆) were investigated.

Since the variance among commercially available ECGs is very large, a further generalization of the results is desirable in order to estimate the environmental impacts for the production of an unknown ECG. To this end, we analyzed whether the environmental impacts correlate with various parameters that are usually part of the data sheet. The results are shown in **Figure 6**.

It can be seen that the environmental impact does not correlate with the nominal output power; other factors appear to be more important. There is also no strong correlation with weight, as the ECG mass is driven by the housing, potting or heavy capacitors, whereas the environmental impacts are driven by the small, but complex, microelectronics components. The correlations with area and volume are reasonable and can be used for a simple linear model. For electronics, scaling with the base area is often chosen. In our case, however, we use volume as a parameter for the final model. For an otherwise unknown device, the values for GWP and ADP can be estimated based on the volume *V* (in cm^3) of the ECG as follows:

$$\text{GWP} = V \cdot 0.0089\,\text{kg CO}_2\text{–eq./cm}^3 + 1.94\,\text{kg CO}_2\text{–eq.} \quad (2)$$

$$\text{ADP} = V \cdot 1.1 \times 10^{-6}\,\text{kg Sb–eq./cm}^3 + 1.9 \times 10^{-4}\,\text{kg Sb–eq.} \quad (3)$$

This results in root-mean-square deviations of ± 0.5 kg CO_2–eq. and $\pm 8.8 \times 10^{-5}$ kg Sb–eq. respectively, between the regression line and the data points (see thin lines in **Figure 6**).

Detail: Use Phase

For the use phase of the luminaire, we consider an operation at 100% dimming level over the lifetime of the luminaire. Repair and maintenance are not taken into account, since all the luminaires are designed to work for their entire lifetime without any replacement of ECG or LED module.

Calculation of the baseline scenario of the use phase is straightforward: Take the total electrical energy consumed (in kWh), and multiply it by the emission factors (kg CO_2–eq. per kWh and kg Sb–eq. per kWh, respectively). Publicly available emission factors for the grid mix in Germany can be found in reference [13], for example, but only for GWP. In the SUMATRA project, however, we stick to the values included in the Sphera® database, which we cannot disclose here.

Europe is in the middle of an energy transition towards renewables. The calculation of the use phase in such a scenario is more complex, because the emission factors vary over time. Based on a scenario for the energy transition in Germany, termed "KN50" in reference [14], we calculated the annual emission factors, see **Figure 8**. The global warming potential per kWh of electricity decreases over the coming years due to the reduction of coal and gas-fired power plants. On the other hand, the abiotic depletion potential per kWh increases, which is particularly influenced by the increasing use of photovoltaics.

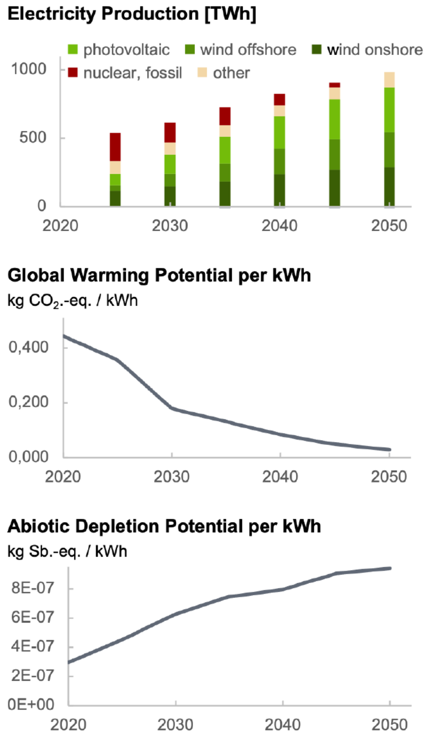

Figure 8: Energy transition scenario in Germany and its environmental impacts.

Calculation of the environmental impacts of the use phase in the energy transition scenario is now feasible: For each year, take the electrical energy consumed and multiply it by the emission factors valid for that year, and sum up all years of operation.

Obviously, the resulting totals will now also depend on the year when the luminaire was put into operation, the annual operating hours, and its usage time in the application.

This calculation process can be mapped to effective values for the emission factors. They are summarized in **Table 3** and correspond to an average over the period of use. The first section of **Table 3** defines four use scenarios with different annual operation hours [15]. In the second section, we demonstrate how long the period of use of a luminaire actually is: A luminaire with 100,000 hours assigned lifetime could be used for 40 years in an office application – e.g. from year 2020 to year 2060. Finally, the third and fourth sections of **Table 3** present the effective emission factors. We can observe a high variance in the values, depending on the assigned lifetime and application scenario. For example, the global warming potential for the German electricity mix is currently a little below 500 g CO_2–eq./kWh, see Reference [13]. For a luminaire with 50,000 h assigned lifetime, being put into a 24/7 operation in 2020, we have an effective emission factor of about 400 g CO_2–eq./kWh during the 5.7 years of use. In contrast, a luminaire with 100,000 h assigned lifetime, being put into an office application, will only use an effective emission factor of about 140 g CO_2–eq./kWh during its 40 years of use.

Annual standard operation hours				
	Office	Industry	Retail	24/7
	2,500 h/a	4,000 h/a	5,000 h/a	8,760 h/a
Period of use (years)				
Assigned lifetime	2,500 h/a	4,000 h/a	5,000 h/a	8,760 h/a
50,000 h	20 a	12.5 a	10 a	5.7 a
70,000 h	28 a	17.5 a	14 a	8.0 a
100,000 h	40 a	25.0 a	20 a	11.4 a
Effective GWP [kg CO_2-eq./kWh]				
Assigned lifetime	2,500 h/a	4,000 h/a	5,000 h/a	8,760 h/a
50,000 h	0.241	0.312	0.347	0.402
70,000 h	0.190	0.262	0.295	0.376
100,000 h	0.142	0.207	0.241	0.326
Effective ADP [kg Sb-eq./kWh]				
Assigned lifetime	2,500 h/a	4,000 h/a	5,000 h/a	8,760 h/a
50,000 h	5.80e-7	4.82e-7	4.41e-7	3.71e-7
70,000 h	6.62e-7	5.52e-7	5.04e-7	4.07e-7
100,000 h	7.45e-7	6.32e-7	5.80e-7	4.65e-7

Table 3: Annual standard operation hours, period of use, and effective emission factors for global warming potential and abiotic depletion potential (luminaire being placed into operation in 2020).

Discussion and Limitations

The most intensively discussed environmental impact is probably the global warming potential. We have shown that the use phase of a luminaire has the dominant influence. The value of the emitted CO_2-equivalents depends sensitively on the electricity grid mix. Both region and time influence the emission factors of the grid mix, which can vary to a great extent. When comparing the CO_2-footprints of two luminaires, careful consideration of the grid mixes is necessary.

When using same assumptions (like grid mixes), the results for the global warming potential are quite robust. However, we have experienced large uncertainties in the results for the abiotic depletion potential. ADP results are highly sensitive to even small amounts of precious metals, e.g. in electronics. Quantifying the exact content of noble metals is difficult, since the exact material composition of the electronics components are often not known by the luminaire manufacturer; and the suppliers are often interested in keeping this information confidential. Using established datasets for electronics components, like Sphera® or Ecoinvent®, is a feasible workaround, but leads to uncertainties. It can be shown, that the choice of life cycle inventory database can lead to different hotspots in the LCA, especially for other impact categories than GWP [16,17].

Estimating the abiotic resource depletion by means of the ADP metric has even more fundamental challenges. For example, the values for *DR* and *R* are not fixed once-and-for-all, but are time dependent [11]. Moreover, it is questionable if all the different abiotic resources should be aggregated, as one depleted resource cannot necessarily be replaced by another one that is still available.

Another limitation of our analysis lies in the selection of environmental impact metrics. We focused on the global warming potential and the abiotic depletion potential. This choice was made after a screening of the results for 12 impact categories. However, there might still be relevant environmental impacts that were not within the scope of our first screening. A frequently asked question concerns the inclusion of the destruction of nature during material mining. This very direct impact on the planet, like in open-pit mining for metal ores, is neither included in the global warming potential, nor in the abiotic depletion potential. Further metrics on land-use or land-use change could be investigated to account for this. For other aspects like loss of biodiversity, there is not yet a widely established indicator.

Recycling of Luminaires

Recycling is one specific form of waste treatment. A short explanation of the common terms seems to be appropriate to enable precise communication. **Waste** is a substance or object that the holder discards or intends or is required to discard. Waste can be sent to **recovery** operations, where it serves a useful purpose. One form is **energy recovery**, i.e. incineration or processing to fuels, another form is **material recovery**. The latter can be divided into (preparing for) **re-use**, **recycling** and **backfilling**. This defines recycling as a recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes, excluding energy recovery or backfilling [18].

The term "recyclability" is even more difficult to grasp than the term "recycling". In literature, a distinction is made between [19]:

- Theoretical recyclability
  (of the material itself)
- Technical recyclability
  (the material must also be able to be identified and separated)
- Realistic recyclability
  (collection systems and sorting facilities must be available, and actual pollution of the materials must be taken into account)

International standards [18,20] require manufacturers to report the realistic recyclability of their products as an environmental claim, not the purely theoretical recyclability.

Reference End-of-Life Treatment Scenario

The central element of a realistic recyclability assessment is a reference end-of-life treatment scenario [18]. There is not yet a standardized reference scenario for luminaires. Based on the standard EN 45555 [18] and a publication that carries out the procedure for smartphones [21], such a scenario was developed in the SUMATRA project, see **Figure** 9.

In our proposed scenario, luminaires are collected together with other small or large electrical appliances. The European WEEE Directive 2012/19/EU establishes some minimum requirements for the recycling, especially the selective treatment of [22]

- Printed circuit boards larger than 10 cm^2
- Plastics with brominated flame retardants
- Gas discharge lamps
- Batteries
- External electrical cables
- PCB-containing capacitors.

In practice, it appears that lamps, components containing harmful substances and batteries are removed manually before shredding. For most LED luminaires (without emergency lighting batteries, no PCB-containing capacitors), it can be assumed that they are shredded directly without manual treatment. The requirement for selective treatment is fulfilled by subsequent sorting.

Figure 10 shows the result of shredding and sorting using the example of a weatherproof luminaire which was sent through the process. It can be seen that the ferrous and non-ferrous metals are sorted out well, the non-ferrous metal fraction containing printed circuit boards from the ECG and LED module. Only small quantities of plastics are separated into an own fraction. The largest proportion of plastics ends up in the residuals, which then only go to incineration, thus escaping material recovery.

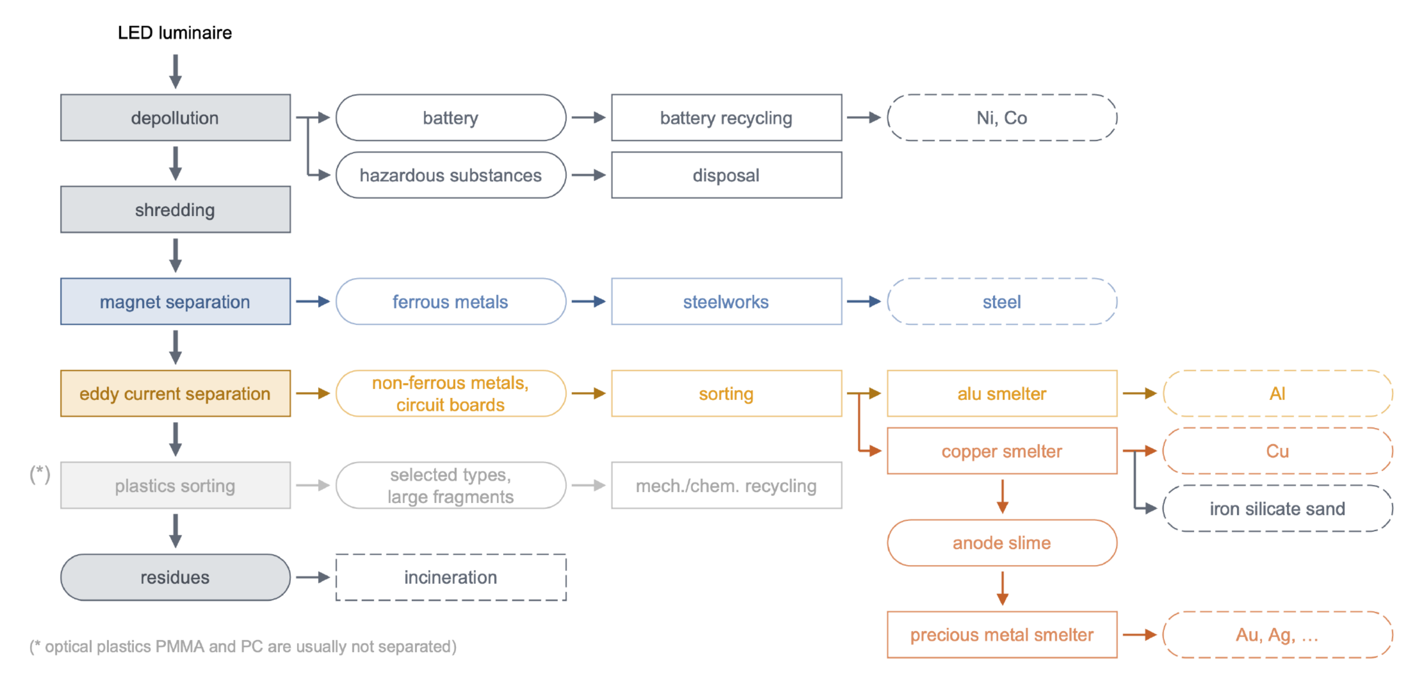

Figure 9: Proposed reference end-of-life treatment scenario for recyclability assessments of LED luminaires based on EN 45555.

There are two reasons for this loss. Firstly, the shredding processes materials like plastics (but also glass) into very small fragments that are almost impossible to sort out. Secondly, only certain types of plastics (target plastics) are sorted out. The polymers PC and PMMA, which are primarily used in the luminaires, are presumably no such target plastics, as they occur in insufficient quantities in the overall waste stream of small or large electric appliances.

These results confirm the data that was determined in IEC Technical Report 62635 back in 2012 [23]. Recycling rates for specific material groups are tabulated there. The data was collected in Europe between 2005 and 2008 and relates to the product groups of small and large household appliances, IT and telecommunications equipment and consumer electronics. Here, too, it can be seen that the plastics PC and PMMA, which are relevant for luminaires, are no longer recycled after shredding. Only the plastics ABS, PP, HIPS and PE are recycled after shredding.

Recyclability Assessment

EN 45555 uses a mass-based approach to define the recyclability rate R_{cyc} of a product [18]:

$$R_{\mathrm{cyc}} = \frac{\sum m_k \cdot R_{\mathrm{cyc},k}}{m_{\mathrm{tot}}} \qquad (4)$$

where m_{tot} is the total product mass, the sum runs over all materials k, with m_k being the mass of material k and $R_{\mathrm{cyc},k}$ being its recyclability factor. The recyclability factors for each material shall include the efficiency of the steps of the reference end-of-life treatment scenario [18].

As no more recent literature values for the recycling rates of specific material groups could be identified, the rates of IEC/TR 62635:2012 [23] are used for the recyclability factors. Material losses are taken into account: for example, steel is in theory completely recyclable, but due to losses to other fractions caused by imperfect sorting, an effective recycling rate of 94% is used.

The recyclability assessment requires a detailed bill of materials and weights of the luminaire. For many mechanical and optical parts, this is quite simple, as they consist of few materials. For ECGs and LED modules, on the other hand, it is quite challenging. Therefore, we studied the material composition of 2 LED modules and 4 ECGs in detail, to derive exemplary recyclability factors for these parts, see **Table 4**.

Component	$R_{\mathrm{cyc},k}$
LED module, epoxy resin substrate	11%
LED module, aluminum substrate	8%
ECG, outdoor application (potted)	12%
ECG, plastic housing	15%
ECG, metal housing	55%

Table 4: Recyclability factors (percentage by weight) of various electronic components of luminaires.

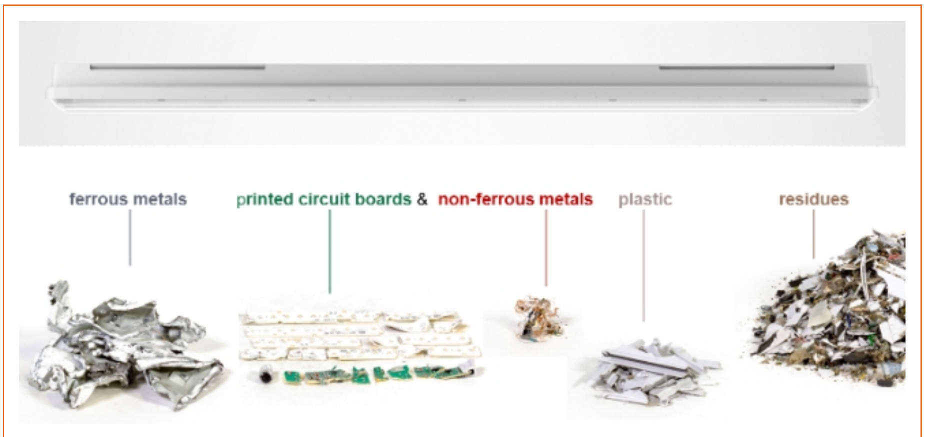

Figure 10: Output of the shredding and sorting process for one single weatherproof luminaire (length 1.2 m, weight 2.3 kg, housing made from grey polycarbonate and optics from clear polycarbonate.

For LED modules, it was assumed that their final treatment step is the copper

		Mass [kg]	Final Treatment	R_{cyc}	Yield [kg]	R_{cyc} theoretical	Yield [kg]
Mechanics	Steel	0.740	Steelworks	0.94	0.695	1.0	0.740
	Stainless Ssteel	0.014	Steelworks	0.94	0.013	1.0	0.014
	PC	0.720	Therm.			1.0	0.720
	Other	0.049					
Wiring	Copper	0.009	Cu Smelter	0.85	0.008	1.0	0.009
	PVC	0.009	Therm.			1.0	0.009
	Other	0.009					
Optics	PC	0.436	Therm.			1.0	0.436
ECG	Metal Housing	0.176		0.55	0.097	0.55	0.097
LED module	Resin Substrate	0.084		0.11	0.009	0.11	0.009
Sum		2.246		37%	0.822	91%	2.033

Table 5: Template for the recyclability assessment based on EN 45555, completed for a weatherproof luminaire. The central result is the value 37% in cell R_{cyc}/sum. The two columns on the right repeat the assessment for the theoretical best case.

smelter. The recycling rates in the copper smelter for the various metals (copper, precious metals, lead, tin, nickel, antimony) were taken from the literature [24]. The material composition of LED modules was determined with suppliers, but are not reproduced here for reasons of confidentiality. The recycling rates for LED modules range from 8% (for aluminum core PCBs) to 11% (for epoxy resin PCBs), which is even lower than the standard values for printed circuit boards classified as “poor” in IEC / TR62635:2012. The main recycling yield comes from copper and tin. Rare earths from the LEDs’ phosphors are lost in the copper smelter, as is the PCB substrate (which makes up the largest proportion by weight). However, the metals recovered from the LED module are also the most “precious” materials and have the highest abiotic resource depletion potential.

For ECGs, we assume that the steel housing and printed circuit board are separated in the shredder, with the housing going to the steelworks and the circuit board to the copper smelter for the final recycling. The main contributions to the recyclability factor are the sheet metal housing and the copper from the PCB and larger components such as inductors. Potted ECGs, often found in outdoor applications, are critical, as they cannot be separated by shredding. We assume that these ECGs are sorted as “non-ferrous metals” despite the heavy potting compound and end up in the copper smelter, where copper and precious metals are recovered while the potting compound burns (i.e. contributes to energy recovery, not recycling).

An example of a complete luminaire assessment is shown in **Table 5**. In this case, the weatherproof luminaire obtains a recyclability of 37%. The main losses are the polycarbonate optics and housing. Though theoretically recyclable, being a thermoplast, it is counted as 0% recycled in the reference end-of-life treatment scenario. This is due to the initial shredding in combination with the literature data of IEC / TR62635:2012 indicating that PC is not recycled after shredding.

To demonstrate the large potential that lies in optimizing the recycling processes, **Table 5** also shows the theoretical best case, based on the recyclability of the material itself. In this scenario, the recyclability of the weatherproof luminaire rises from 37% (realistic) to 91% (best case). This scenario could be reached e.g. by manual or robotic disassembly and sorting. In current recycling practices, this seems to be not viable for economic reasons.

We conducted assessments for ten luminaires. The results are summarized in **Figure 11**. The realistic recyclability varies between 22% and 84%, and is primarily influenced by the contents of plastics in the optics and mechanical structure. Other major losses in the recycling are glass sheets (e.g. in luminaire C). The rather low recyclability of LED modules and ECGs have an impact on the overall recyclability, especially for small luminaires like downlights (luminaire F) or when the LED module is relatively large and heavy (e.g. luminaire H).

Discussion

We presented our method of the recyclability assessment in detail, because we want to enable the lighting community to harmonize this kind of assessment. This is necessary to make fair and comparable claims about the recyclability of luminaires. A very important part of the information lies within the method; not the reported value alone. Today, luminaire manufacturers are found to use different methods to define “their” notion of recyclability, and examples of environmental claims can be found that are even more euphemistic than the “theoretical best case” presented in **Table 5**.

The international standards agree that an assessment of the realistic recyclability of a product is required. However, a standardized reference end-of-life treatment scenario and material-specific recyclability

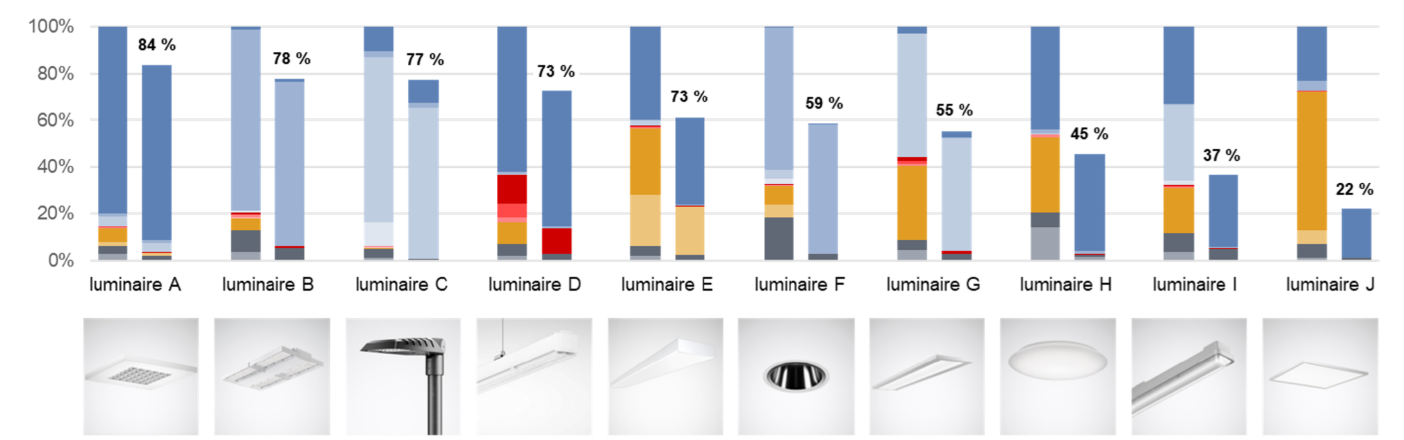

Figure 11: Realistic recyclability results for ten luminaires. The left column shows the masses of the luminaire components in its original state, and the right column shows the weight of materials recovered in the recycling process. Components belonging to the mechanical structure are blue (mostly metals), wiring red, optical components orange (mostly plastics), and electronics gray.

factors are not yet established for luminaires. The standard EN 45555 is, in fact, not to be applied directly for the recyclability assessment of products, but shall serve as a method for writing product or product-group standards [18]. In the SUMATRA research project, we took a short-cut, proposed an end-of-life treatment scenario, and performed the recyclability assessment directly.

Conclusions

Luminaires and lighting do have significant environmental impacts. The relevance for the global warming potential is obvious from the statistics of energy usage: 13% of Germany's electricity is used for lighting [25]; and the energy sector is the major emitter of greenhouse gases in Germany [26]. Our life cycle assessment has shown that the abiotic resource depletion is of similar relevance as the global warming potential when compared to normalization factors, see **Table** 2. This finding might not correspond with our intuition because luminaires seem to be quite "simple" technology. And of course, smartphones, laptops, or electric vehicles contain certainly more precious materials than a luminaire. But think about how ubiquitous luminaires are in our built environment. How many luminaires, per person, are in our homes, at our workplaces, in the streets?

Light is a very common product, and needs careful consideration to make it as sustainable as possible. After years of close collaboration, the SUMATRA researchers agreed on 9 recommendations for lighting industry and policy makers presented in the **Recommendation Box** below. Some of the recommendations are concluded from research activities that were not presented in this article.

The recommendations include a call for more accurate life cycle assessment data, especially of electronics components like the LED modules. This data is difficult to obtain for a luminaire manufacturer, and should be communicated along the supply chain. Only then, reliable LCA results are achievable and informed decisions for more sustainable product designs are possible. Interest in this kind of data will increase, as more and more companies will be required to report their environmental impacts, including scope 3 (supply chain emissions and those associated with the use of their products).

One of the original goals of the SUMATRA project was to design a luminaire with its end-of-life in focus. However, there is little sense in optimizing a luminaire for the shredding process of today's recycling practices. Recycling, in its current form, seems to be one of the least favorable circularity options, it is rather the last resort than the first choice. We conclude our research on the recyclability of luminaires with a call that coordinated activities between manufacturers and recyclers are necessary to make real progress in this very relevant field.

In this article, we presented three facets of sustainability of luminaires in detail: The global warming potential, the abiotic depletion potential, and the recyclability. By using quantitative methods to assess these three aspects, different luminaire designs become comparable. However, we did not find a satisfactory solution for an "overall sustainability rating". This challenge is illustrated in the following example: Imagine two luminaire concepts, A and B, for the same lighting purpose. A may have an 8% lower global warming potential than B, because it reaches a higher luminous efficacy by employing more LEDs and a better heat sink. This leads to B having a 17% lower abiotic depletion potential than A. Furthermore, A surpasses B by 5 percentage points in recyclability. Which concept, A or B, deserves to be called "more sustainable"? We do not even dare to raise the question which luminaire would be justified to be claimed "sustainable" in absolute terms.

Though having made progress in quantifying, explaining and interpreting the environmental impacts, we still have to conclude that sustainability is not measurable. In view of this lack of certainty, we encourage further research and expanded efforts to move the lighting industry towards a more sustainable future, as expressed in our 9 recommendations. ■

Recommendations for the Lighting Industry and Policy Makers

With these recommendations, we want to boost the efforts of turning the lighting business into a more sustainable future, even if some details are still unclear. The recommendations were agreed on by the SUMATRA researchers on their final meeting on 27 September 2023 in Arnsberg, after 28 months of research and intensive collaboration.

01 Light management systems offer great energy saving potentials, and the additional costs are low compared to a non-managed system. They should be employed according to the necessities of the application.

02 Life Cycle Assessments of LED luminaires should focus not only on energy efficiency, but also on resource efficiency.

03 The luminaire should be designed to enable replacement and upgrades of electronic components such as LED modules and electronic control gears (ECGs).

04 Spare parts for luminaires and components should be available in the long term.

05 All components should be designed to identical lifetimes, which should meet the lifetime requirement of the application.

06 Information that makes it easier to replace components should be found on the luminaire label, electronically in the luminaire, or via building information models (BIM).

07 Luminaires should be designed to be separated into uniform material fractions in the recycling process, in order to minimize material losses. At the same time, recycling processes should be optimized. This requires coordinated activities between manufacturers and recyclers.

08 Life Cycle Assessment data-sets for luminaire components, especially LED modules and ECGs, should be completed, standardized and communicated transparently.

09 Manufacturers are recommended to perform Life Cycle Assessments during product development to achieve a meaningful eco-design of their luminaires.

Author Sebastian Knoche studied physics and obtained a doctoral degree in the field of theoretical soft matter physics from TU Dortmund university. In 2015, he changed from academia to industry and started working for the TRILUX Group. Since 2017, he is in lead of the lighting research team and organises the participation of TRILUX in joint research projects. His current research projects are focussed on sustainability.

TRILUX SIMPLIFY YOUR LIGHT.

Author Marina Proske studied environmental engineering at the Technical University of Berlin and completed her doctorate on the subject of "Ecodesign concepts and environmental assessments taking into account product obsolescence". She has been working at Fraunhofer IZM since 2011, where she is leading the "Life Cycle Modeling" group since 2023 and deals with the topics of ecodesign and life cycle assessments. From 2016 to 2022 she was a member of the research group "OHA – Obsolescence as a Challenge for Sustainability". She works in national and European research projects on the environmental impact of electronics, conducts life cycle assessments of ICT devices and regularly reviews LCAs.

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About Fraunhofer IZM: Since 1993 Fraunhofer IZM has been one of the world's leading institutes for applied research and the development and system integration of robust and reliable electronics. For over 30 years, more than 450 employees have been finding technological solutions in co-operation with partners from industry and academia. Emerging challenges are addressed in branches such as automotive and industrial electronics, medical engineering, ICT and semiconductor technology.

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