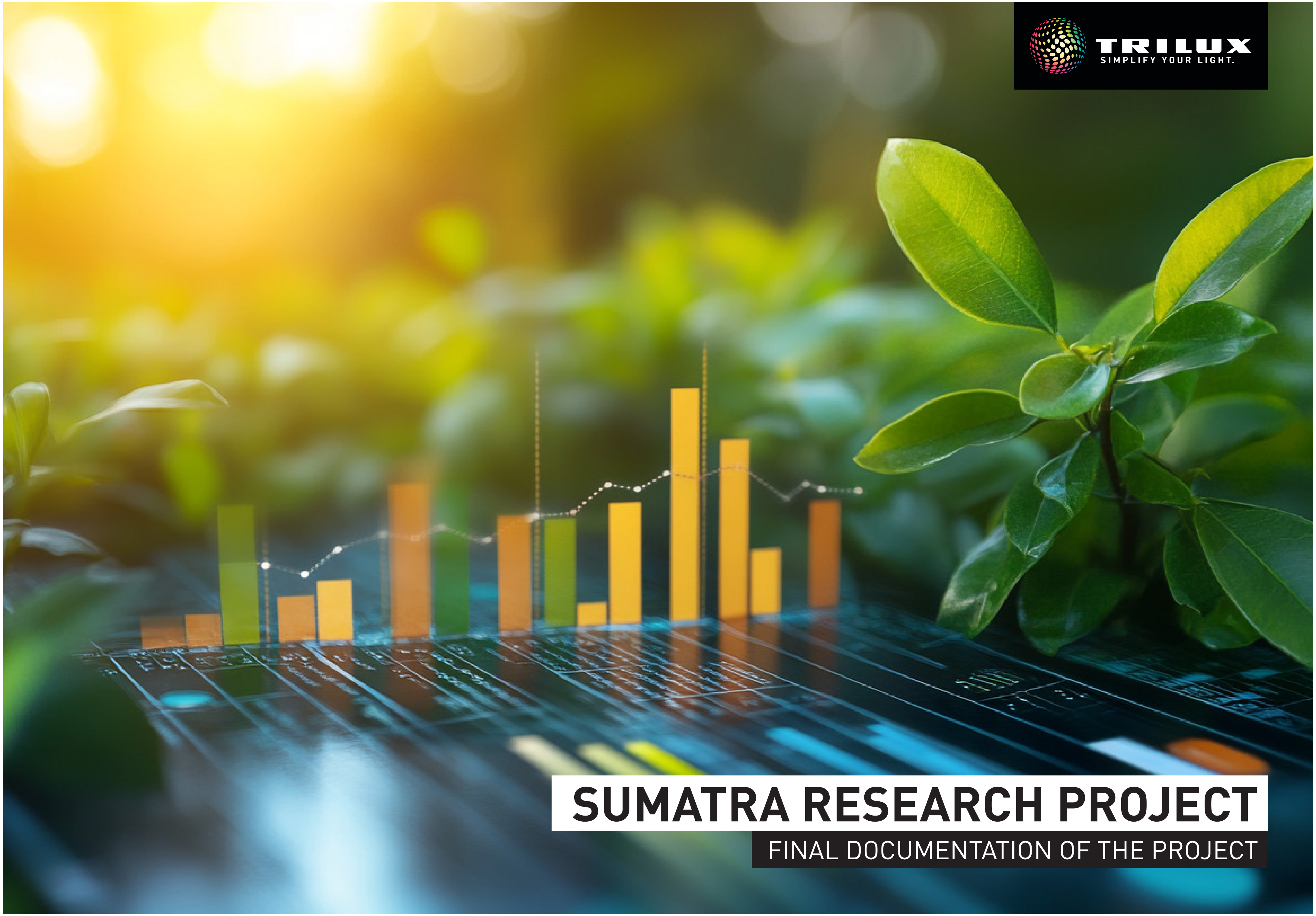
TRILUX
SIMPLIFY YOUR LIGHT.



SUMATRA RESEARCH PROJECT

FINAL DOCUMENTATION OF THE PROJECT

INHALT

SUMATRA – SUSTAINABLE MATERIALS IN FUTURE LUMINAIRE DESIGNS.

PROJECT PARTNERS, FUNDING AND DEVELOPMENT OF THE PROJECT

"We are the first project in the research area"

"Resource efficiency in the context of the energy transition".

Duration: 01.06.2021 – 30.09.2023

TRILUX LED luminaires
Inventronics LED systems
Fraunhofer IZM life cycle assessment
Interzero Recycling

SUMATRA

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

SUSTAINABILITY

WHAT IS SUSTAINABILITY?
A DEFINITION

The simple core: to act in such a way that we can fundamentally go on like this forever. The definition is thus close to the original meaning of the German term **sustainable** (lasting and effective over a longer period of time, German Dictionary of the Brothers Grimm, 1869) and to the first use of the term in **forestry** (not to fell more wood than can grow back, Hans Carl von Carlowitz, 1713).

SCIENTIFIC LITERATURE

The following publications provide more detailed descriptions of the facets of sustainability:
• Three-pillar model (1990s, Germany) – ecological, social and economic sustainability
• 17 Sustainable Development Goals (UN 2016)

OVERARCHING STRATEGY

Three guiding strategies help to achieve sustainable development.
• Sufficiency: frugal consumption – how many (products, services) do I need?
• Efficiency: generate the same output with less effort (resources, energy)
• Consistency: use environmentally compatible substances – especially for substances that are not managed in a closed technical cycle in a fail-safe manner

„Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

United Nations, Our Common Future (1987)

THE BUILDING BLOCKS OF SUSTAINABILITY

ENVIRONMENTAL IMPACT CATEGORIES IN LIFE CYCLE ASSESSMENTS AND POSSIBLE EFFECTS ON THE ENVIRONMENT

In the life cycle assessments of the SUMATRA project, the environmental impacts listed below were analysed. It was not possible to reach a conclusion on how "absolute" sustainability can be achieved according to the principles of the Ecological Footprints or Planetary Boundaries models within the scope of the project.

ADP ELEMENTS

Abiotic depletion potential, elements

Utilisation of resources (minerals, metal ores) that are limited on Earth..

ADP FOSSIL

Abiotic depletion potential, fossil

Consumption of fossil raw materials (oil, coal, gas), which are finite.

GWP

Global Warming Potential

Causation of greenhouse gas emissions, measured in kg of CO_2 equivalent.

TOXICITIES

Fresh Water / Marine / Terrestic / Human

Release of toxic substances. However, there are methodological difficulties here.

„Konzepte im Zusammenhang mit Nachhaltigkeit sind äußerst kompliziert und werden noch untersucht. Gegenwärtig gibt es keine bestimmten Verfahren zur Messung von Nachhaltigkeit oder zu ihrer Bestätigung."

ISO 14021: Umweltkennzeichnungen und -deklarationen – Umweltbezogene Anbietererklärungen (2021)

AP
Acidification potential

Emission of substances such as sulphur dioxide which cause e.g. acid rain.

EP
Eutrophication potential

Waters are enriched with nutrients (e.g. phosphates); has detrimental effects such as algal blooms.

ODP
Ozone Depletion Potential.

Depletion of the ozone layer in the stratosphere (which is our natural UV-C blocker).

POCP
Photochemical Ozone Creation

Generation of ozone near the ground, which is highly reactive and unhealthy to inhale

HOW IS SUSTAINABILITY DETERMINED?

ATTEMPTS TO QUANTIFY SUSTAINABILITY (ECOLOGICAL)

APPROACH 1: THE ECOLOGICAL FOOTPRINT

The ecological footprint

The footprint measures how much biologically productive land is needed to enable all human activities and compensate for their impact. This is compared to the biocapacity of the land or the Earth. The measurements include:

- Absorption of CO2
- Cultivation of food
- Pasture land
- Cultivation of forest products
- Built-up areas
- ...

Global Footprint Network®
Advancing the Science of Sustainability

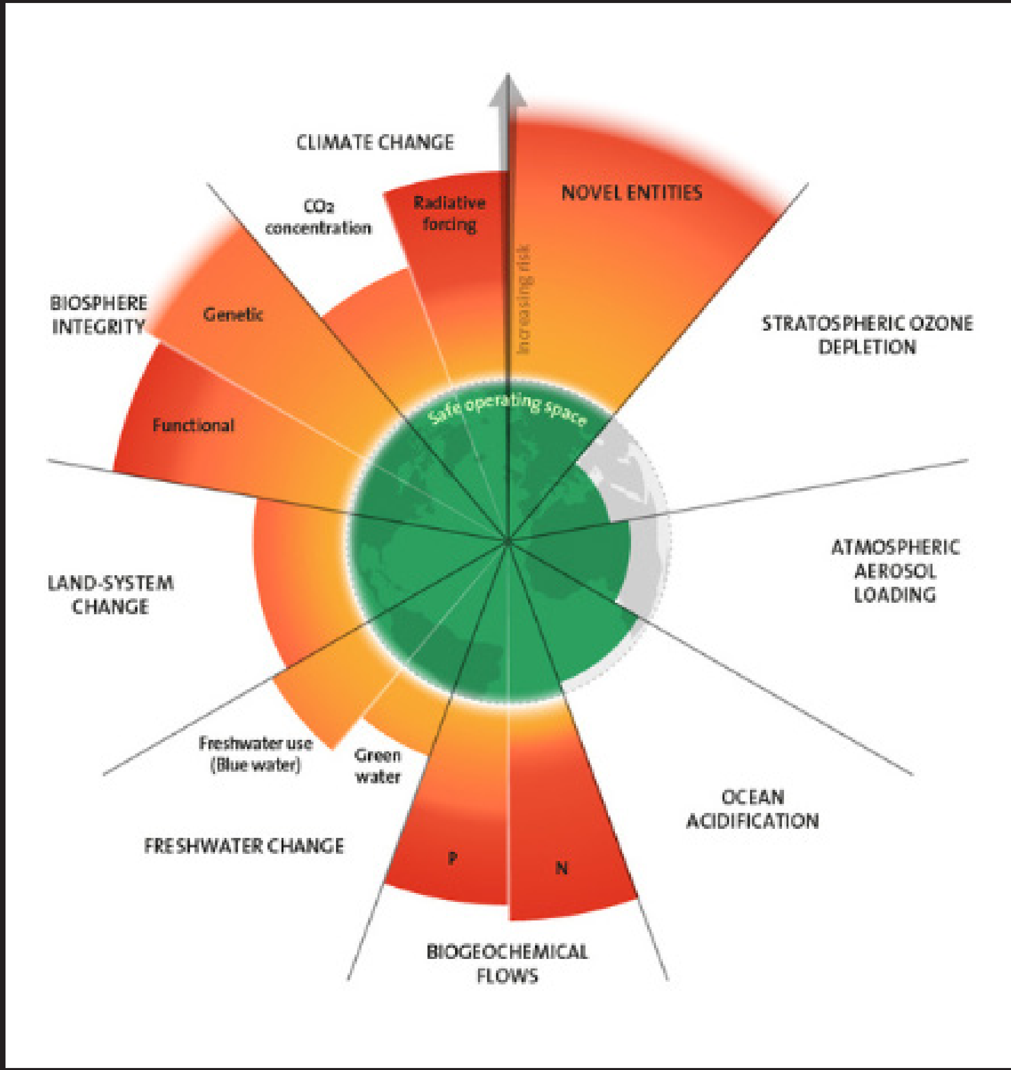
The ecological footprint is used to calculate the Earth Overshoot Day. This describes when we will have exhausted the Earth's biocapacity. In 2024 this critical point was reached worldwide on 1 August, and in Germany as early as 4 May.

APPROACH 2: PLANETARY BOUNDARIES

Planetary Boundaries Framework

The Planetary Boundaries Framework describes planetary health using nine categories that can lead to global environmental change. The model was developed by Rockström et al. (2009) and is currently being updated by them for the third time. (Nature, 2023).

- Several boundaries have already been crossed.
- Particularly significant:
  - Climate change
  - Integrity of the biosphere (biodiversity)



TEMPERATURE COMPARISON

GLOBAL WARMING

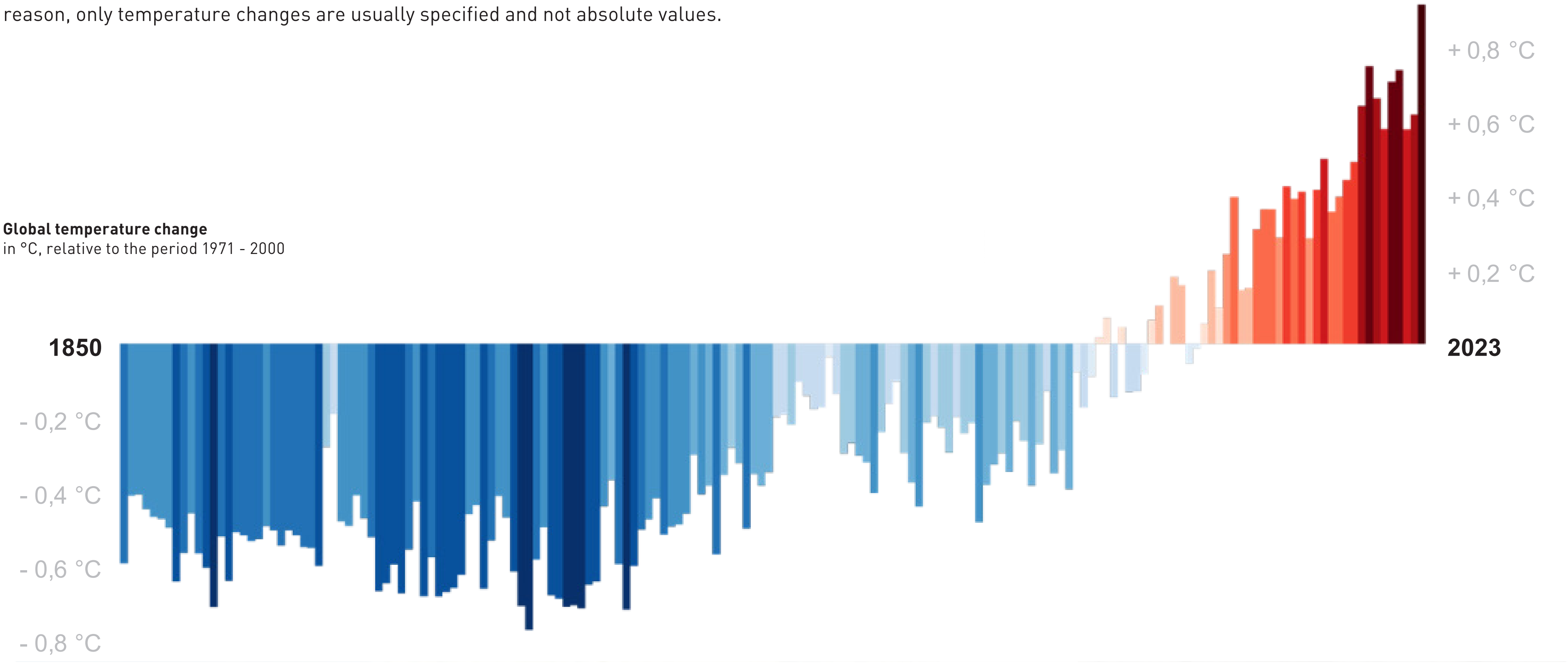
MEASURABLE TEMPERATURE INCREASE IN PRE-INDUSTRIAL TIMES

The climate is changing: the global average temperature is already over 1.2 °C higher than in the pre-industrial era. The IPCC (Intergovernmental Panel on Climate Change) has specified the period 1850 - 1900 as the "pre-industrial era". During this reference period, the global average temperature was approximately 14 °C. The climate target of 1.5 °C adopted by the IPCC is understood in relation to the period 1850 - 1900. For this reason, only temperature changes are usually specified and not absolute values.

VIEW WITH WARMING STRIPES

The Warming Stripes by climatologist Ed Hawkins are a highly respected, excellent and frequently reproduced visualisation of the temperature curve. However, the reference period here is 1971 - 2000, and the pre-industrial period is in the first quarter of the timeline.

Global temperature change
in °C, relative to the period 1971 - 2000



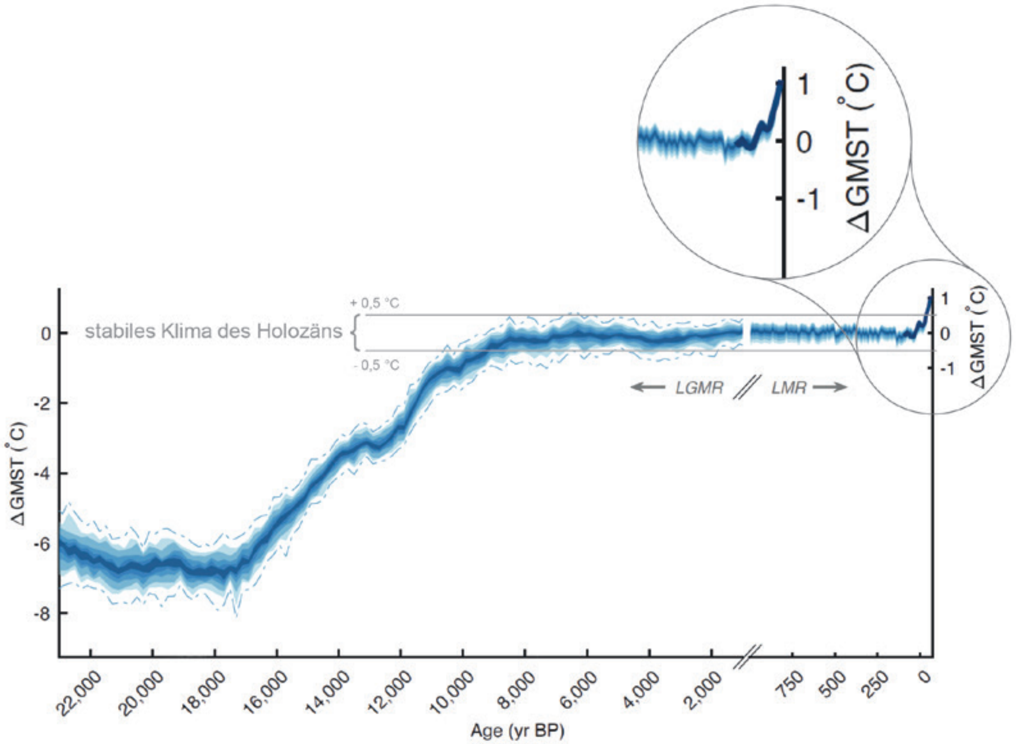
(Source: #ShowYourStripes, license: Deed - Attribution 4.0 International - Creative Commons)

TIPPING POINTS ARE LOOMING

THE 1.5° TARGET IS NOT A POLITICAL ISSUE, BUT A NECESSITY

THE HOLOCENE – 11,000 YEARS OF STABLE CLIMATE
The Holocene is the epoch of the past 11,000 years of the Earth's history and is characterised by very low variability in climatic conditions. Agriculture and advanced civilisations developed in this epoch.

TIPPING POINTS – CAUTION, IRREVERSIBLE PROCESSES
Studies show that the first tipping points in the Earth system are already reached at 1.5 °C global warming, e.g. the melting of the Greenland ice sheet and the dying of all tropical coral reefs.



"The Holocene is the reference point of a desirable planet. We are already well into the Anthropocene – the epoch in which humans shape the earth."

Professor Johann Rockström, Potsdam Institute for Climate Impact Research, Frontiers Forum 2023

Global Mean Surface Temperature (GMST)
Change over the last 24,000 years based on the Last Glacial Maximum Reanalysis (LGMR), the Last Millennium Reanalysis (LMR) and the HadCRUT5 measurement dataset (solid line). The magnification shows how quickly we are currently leaving the stable phase of the Holocene (variability ± 0.5 °C). [Osman et al. 2021]

HEAT RADIATION IN IMBALANCE

GREENHOUSE GASES AND CO_2 EQUIVALENTS

CALCULATING THE CLIMATE IMPACT

In addition to carbon dioxide, there are other greenhouse gases that have a similar effect on the Earth's radiation balance and thus cause climate change, e.g. methane (CH_4), nitrous oxide (N_2O), etc. Their climate impact is described in the form of a CO_2 equivalent.

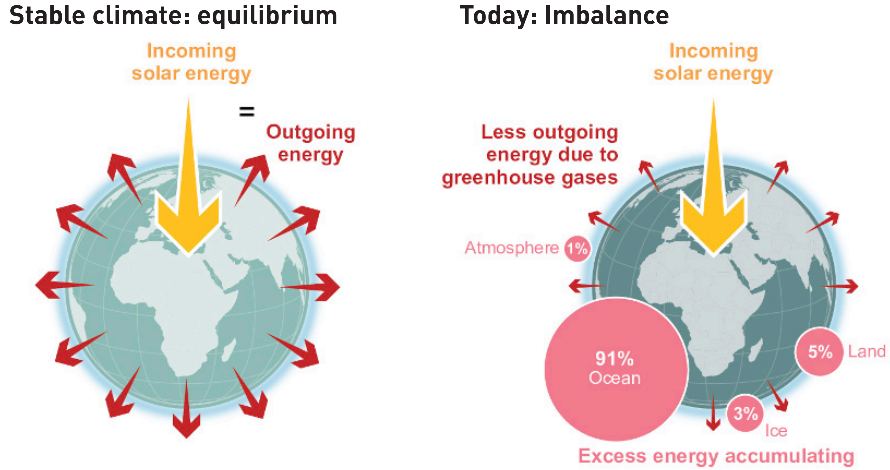
Conversion factors in CO_2 equivalents

To assess the climate change potential, all greenhouse gas emissions are converted into CO_2 equivalents according to their impact.

As the gases have different dwell times in the atmosphere, the conversion factors depend on the time period of the effect under consideration. The most common approach runs for 100 years and is known as GWP-100 (Global Warming Potential, 100 years).

	Lebensdauer	GWP-100
CO_2	multiple	1
CH_4-fossil	11.8 years	29.8
CH_4-non fossil	11.8 years	27.0
N_2O	109 years	273

[Tab. 7.15 in IPCC, Climate Change 2021: The Physical Science Basis]



[FAQ 7.1 Figure 1 in IPCC, Climate Change 2021: The Physical Science Basis]

TRAPPED RADIANT ENERGY

Gases that affect the climate lead to a reduction in the "atmospheric window" in which heat radiation is emitted from the Earth's surface into space. This leads to the radiative forcing of climate change.

GASES AFFECTING THE CLIMATE

Global warming is fuelled by the emission of CO_2, which was previously stored in fossil resources in the ground. Added to this are emissions of e.g. methane, nitrous oxide, aerosols etc. which increase global warming.

WHAT WE CAN DO AND WHAT EFFECT IT WILL HAVE

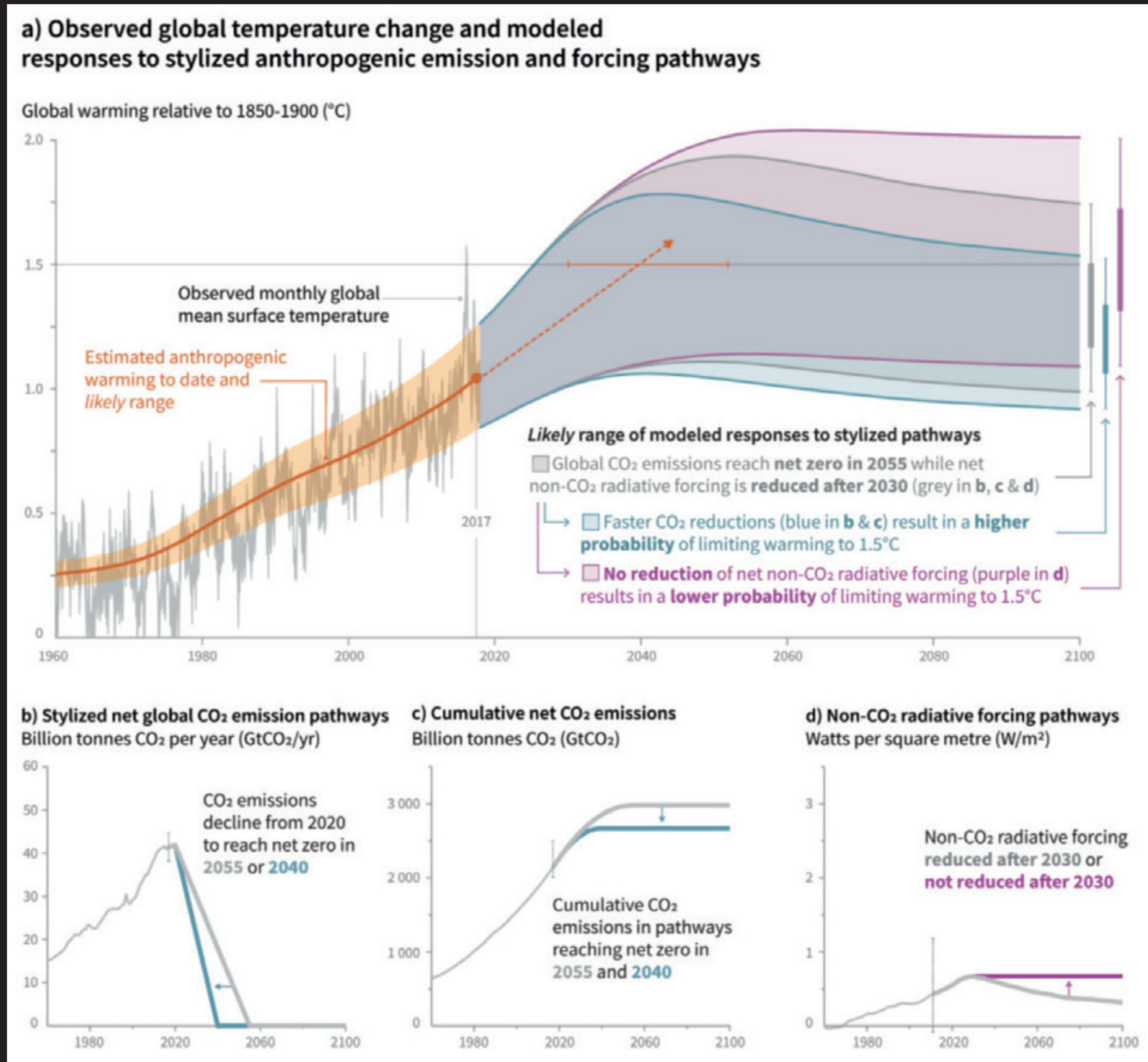
CAUSE AND COUNTERMEASURES

SCENARIOS WITH AND WITHOUT COUNTERMEASURES

The projections of the IPCC (Special Report, 2018) show possible future temperature trends, depending on the countermeasures taken:

- Orange: without countermeasures, the 1.5 °C target will be exceeded between 2030 and 2052
- Grey projection: CO_2 emissions are reduced to (net) zero by 2055 (see b, c), and the other greenhouse gases are also reduced (d).
- Blue projection: as grey, but accelerated CO_2 reduction (nett zero in 2040)
- Violet projection: as grey but without reduction of the other greenhouse gases

The vertical axes in c) and d) are scaled to represent similar major heating effects.



CONSERVING VALUABLE RAW MATERIALS

ABIOTIC RESOURCES

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 conflict with sustainability, as resources are limited and are not renewable, i.e. they are not continuously produced in the earth.

MEASURING RESOURCE CONSUMPTION

The **Abiotic Depletion Potential of the Elements ADP,** measured in **kg antimony equivalent, is used to quantify resource consumption.**

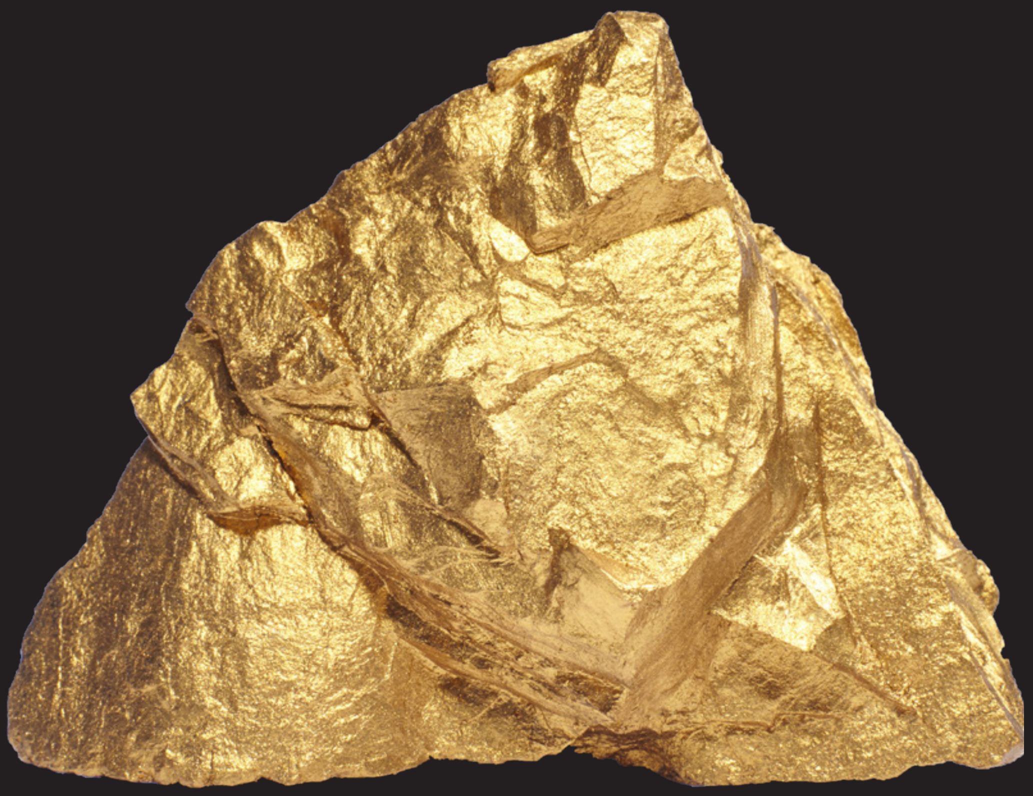
The weighting factors for the consumption of various elements are calculated from the total quantity in the earth's crust Ri ("ultimate reserve", in kg) and the current extraction rate DRi (in kg/year):

$$ADP_i = \frac{DR_i / R_i^2}{DR_{ref} / R_{ref}^2}$$

Element	ADP_i [kg Sb-eq. / kg]
Aluminium	0.00000000109
Copper (Cu)	0.00137
Iron (Fe)	0.0000000524
Gold (Au)	52.0
Silber (Ag)	1.18
...	

The reference is antimony (chemical symbol Sb; it was the first element in the alphabet for which the data for R and DR were completely available when the metric was developed).

The metric only takes into account the presence of elements in the Earth's crust, but not geopolitical risks. This is done in the CRMs (critical raw materials).



Source: Oers & Guinée 2016, Oers et al. 2020, Oers et al. 2022

EARTHLY TREASURES – FROM ANTIMONY TO VANADIUM

FIFTH LIST OF CRITICAL RAW MATERIALS (CRMS 2023)

German	Englisch	Bezug zur Lichtindustrie
Antimon	Antimony	Semi-metal, used as a flame retardant
Arsen	Arsenic	
Aluminium und Bauxit	Aluminium and Bauxite	Housing material
Baryt	Baryte	
Beryllium	Beryllium	
Bismut	Bismuth	
Bor	Boron	Use in glass production
Kobalt	Cobalt	
Kokskohle	Coking Coal	
Kupfer	Copper	Wiring and electronic components
Feldspat	Feldspar	Use in glass, ceramic and porcelain production Flussspat
Flussspat	Fluorspar	
Gallium	Gallium	Use: ICs (75%), **LEDs (25%),** photovoltaics (5%) Germanium
Germanium	Germanium	
Hafnium	Hafnium	
Helium	Helium	
Schwere seltene Erden	Heavy Rare Earth Elements	
Leichte seltene Erden	Light Rare Earth Elements	Luminescent materials (and many other applications - with some elements, lighting accounts for **up to 25% of use)**
Lithium	Lithium	
Magnesium	Magnesium	
Mangan	Manganese	Alloying element in many types of steel
Natürlicher Grafit	Natural Graphite	
Nickel – Batteriequalität	Nickel – battery grade	Alloying element in many steel grades Niob
Niob	Niobium	Alloying element in many steel grades
Phosphorit	Phosphate rock	
Phosphor	Phosphorus	
Metalle der Platingruppe	Platinum Group Metals	
Scandium	Scandium	
Siliciummetall	Silicon metal	Cast aluminium alloys, silicones, wafers for LED and chip production
Strontium	Strontium	
Tantal	Tantalum	Use in capacitors
Titanmetall	Titanium metal	in oxidised form (TiO2) as a white pigment in colours Wolfram
Wolfram	Tungsten	formerly used for light bulbs
Vanadium	Vanadium	Alloying element in many types of steel

PLASTICS

CURSE OR BLESSING?

MINIMUM ADP

Plastics are long-chain molecules. Chemically, they consist of long chains of carbon (C), hydrogen (H) and oxygen (O); silicones consist of long chains of silicon (Si) and oxygen. None of these are rare elements, and therefore plastics have negligible values for the abiotic depletion potential ADP.

NEVERTHELESS PROBLEMATIC

Why are plastics considered by the public to be particularly unsustainable?

1. The high **CO_2 footprint of the global plastics industry:** the bottom line is that carbon or oil is extracted and ultimately ends up as CO2 in the atmosphere.
2. Long-standing **environmental pollution** caused by microplastics (washing synthetic clothing, tyre abrasion) and macroplastics (packaging)
3. Some **substances of concern** during production or in the end product (halogens such as in PVC, bisphenol-A in polycarbonate, flame retardants etc.)

AVOIDANCE STRATEGY

Points 1 and partly 2 are above all the result of the **absurdly high quantity** that we produce and that are **uncontrollably** in circulation on Earth. Packaging plastic is particularly critical. Simply replacing plastic with other materials does not go far enough because the alternative materials also have an environmental impact (see case study). Point 3 is critical for **tech plastic** and therefore also for the lighting market.

CASE STUDY OF PLASTIC BAG

A paper bag has a higher CO_2 footprint than a plastic bag.

It would have to be reused three times more often than a plastic bag for the ecological balance to equalise.

A cotton bag even has a 50-150x higher CO2 footprint than a plastic bag.

[NABU: Plastic bags? Avoid instead of replace!]

SUSTAINABLE SCENARIO FOR PLASTICS

RISING DEMAND AS A CHALLENGE

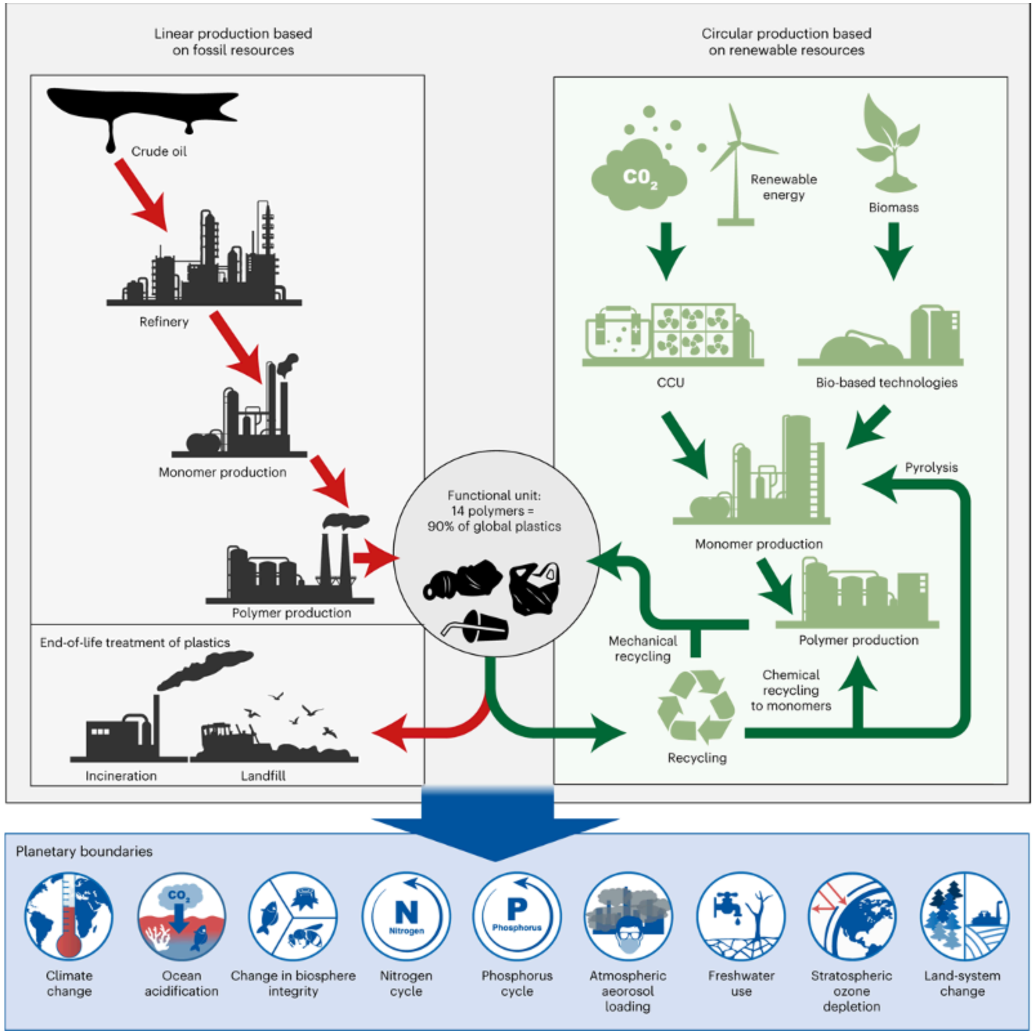
The paper 'Towards circular plastics within planetary boundaries' (Bachmann et al., Nature, 2023) examines whether the global plastics industry can function within the planetary boundaries. The results show the challenges facing the global economy.

SUSTAINABLE SCENARIO 2030

The demand for plastics in 2030 could be produced sustainably – but only if the recycling rate is increased to > 75% (it is currently 23%).

NO SUSTAINABLE SCENARIO POSSIBLE FOR 2050

The high projected demand for 2050 cannot be generated sustainably even with a 95% recycling rate.



LEVERS FOR THE SUSTAINABLE USE OF PLASTICS

- **Mechanical recycling** for packaging plastics, chemical recycling for tech plastics
- **Bio-based plastic** is climate-friendly, but cannot be scaled up without exceeding the planetary boundaries of the nitrogen cycle and biosphere integrity
- **CCU** (carbon capture and use) processes are therefore necessary. They are worthwhile as soon as enough renewable electricity is available.

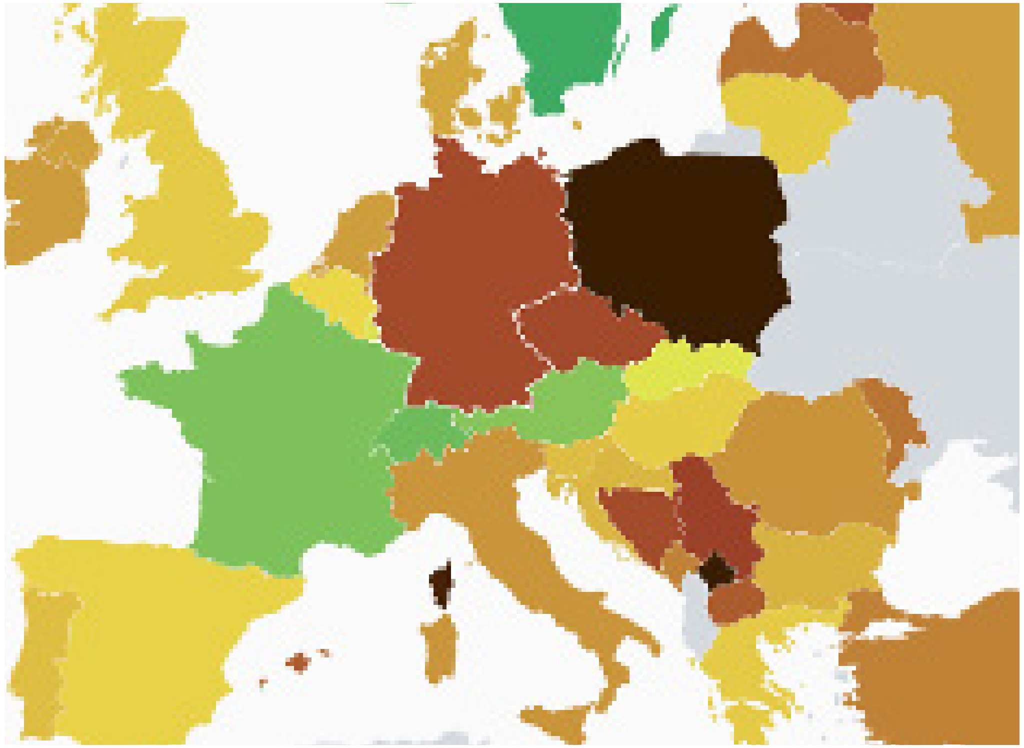
ENERGY TRANSITION AND DEFOSSILISATION

GREEN POWER FOR SUSTAINABLE LIGHT

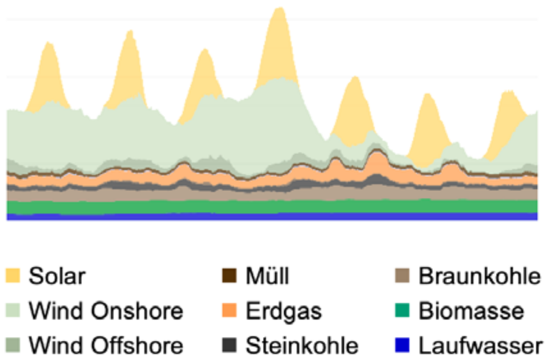
ENVIRONMENTAL IMPACT OF ELECTRICITY GENERATION AND THE ENERGY TRANSITION

In the case of energy-related products such as luminaires, the highest CO_2 emissions are generally caused by electricity consumption during the utilisation phase. Depending on the electricity mix, there are different **emission factors** (kg of CO_2-eq pro kWh).

CO_2 emissions in a European comparison
Germany is in the midfield



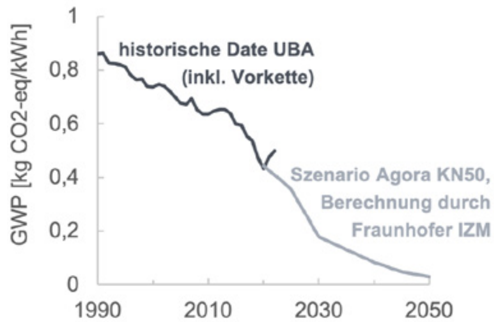
Source app.electricitymaps.com for 22.08.2023



RENEWABLE ENERGIES ON THE RIGHT TRACK

At times, the majority of electricity generation comes from renewable energy.

Public net electricity generation 31/2023 [Fraunhofer ISE]



GOOD FORECAST UNTIL 2050

The emission factor has fallen and studies show ways for the future course of the energy transition.

[Federal Environment Agency 2023, Agora Energiewende 2020]

MODELLING THE ENERGY TRANSITION

With the energy transition, CO_2 emissions are falling, but the abiotic consumption of resources for the production of electricity is increasing.

The latter is primarily due to photovoltaics – similar resources are used for solar panels as for the construction of luminaires, and they also have a finite service life.

In general, even with 100 % green energy in the grid, we will never be able to splash out on energy as we please - in that case we would have installed overproduction. Energy will still remain a scarce commodity throughout the energy transition.

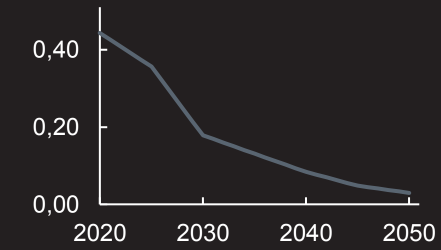
Model of the energy transition according to

- Prognos, Öko Institute, Wuppertal Institute (2020): Climate-neutral Germany. Data appendix. Study commissioned by Agora Energiewende, Agora Verkehrswende and Stiftung Klimaneutralität.(Scenario "Climate Neutral 2050")
- Life cycle assessment of the scenario by Fraunhofer IZM (graphic on page 21)

Global warming potential per kWh

kg CO_2-eq. / kWh

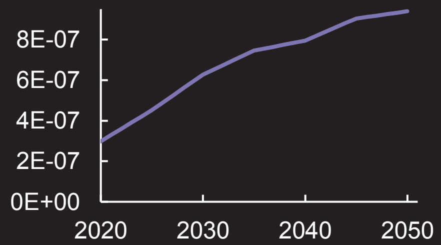
Expansion of renewable energies leads to falling carbon emissions



Abiotic resource consumption per kWh

kg Sb.-eq. / kWh

high proportion of photovoltaics leads to increasing abiotic resource consumption



WHAT WILL HAPPEN BY 2050?

PARALLEL FORECASTS FOR THE FUTURE

In the lighting environment, the following will (have to) develop in parallel in the transition to a sustainable economy by 2050.

RISING ELECTRICITY DEMAND, MORE SUSTAINABILITY

Electricity generation will increase by 2050, with the share of renewable energy from photovoltaics and onshore and offshore wind growing.

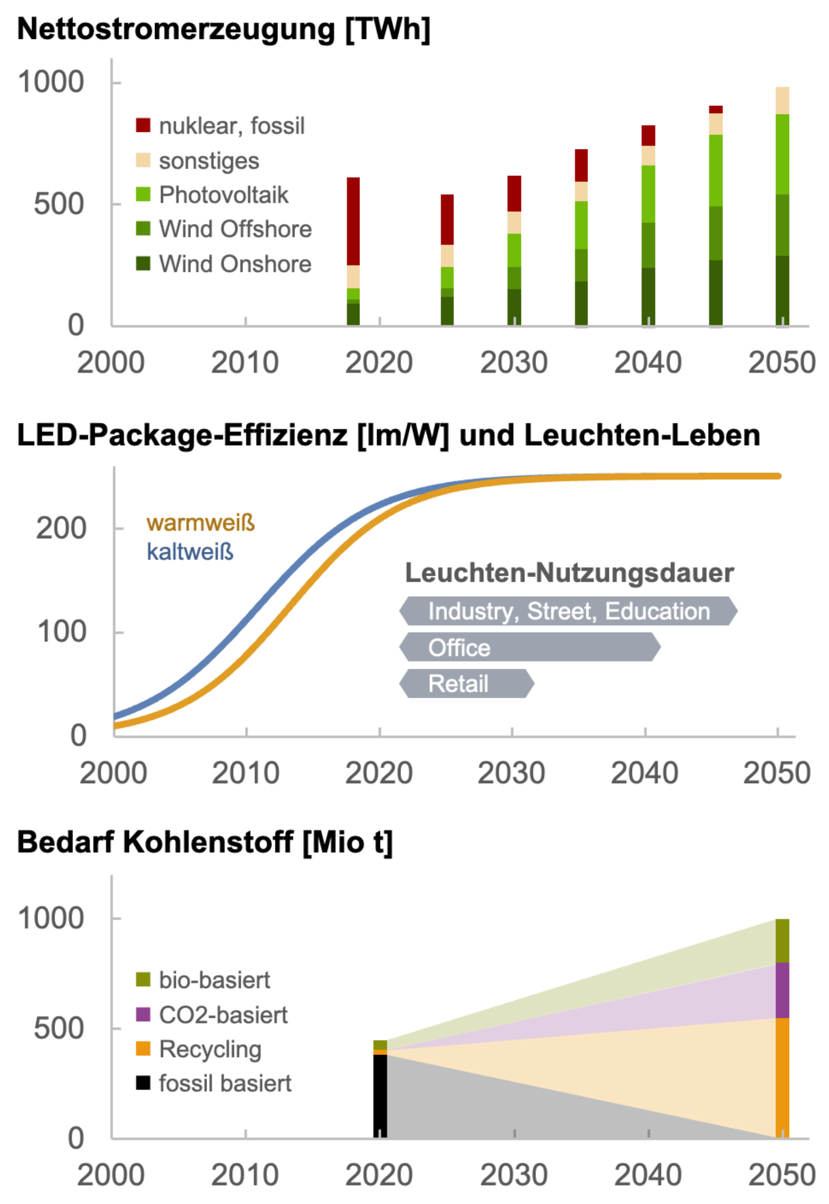
DEVELOPMENT OF LED LIGHTING

- Efficiency is already as good as exhausted
- A luminaire installed now will live in some applications until the energy transition is almost complete
- According to internal estimates, around 30% of luminaires in the field will be LED luminaires by 2022
- We should now convert everything to LED as quickly as possible in order to save as much of the electricity currently generated by fossil fuels as possible

AN END TO FOSSIL CARBON

Chemicals and derived materials will also be defossilised, carbon is an essential component of the materials. In future it will have to be obtained in other ways.

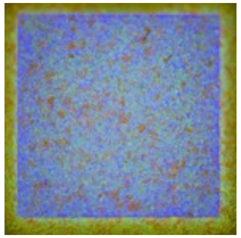
- from the **technosphere (recycling)**
- from the **atmosphere (CO2 capture-and-use process)**
- from the **biosphere (bio-based raw materials)**

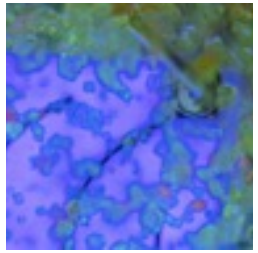


LIFE CYCLE ASSESSMENTS – MODELLING OF INDIVIDUAL PARTS AND PROCESSES

LIFE CYCLE ASSESSMENT OF LED MODULES
HIGH SAVINGS POTENTIAL

LEDs are particularly critical if they contain bonding wires (gold alloy). LEDs with bonding wire require 500 times more abiotic resources than flip-chip LEDs, which do not require bonding wire.


LED with flip chip (contacting the chip from below)


LED with bonding wire for contacting (top right)

Notes on the printed circuit boards
- For round PCBs, the balanced area corresponds to the enclosing square (offcuts)
- The environmental impacts apply to PCBs from China (single-sided, FR4, lead-free HAL (SnCu) coating)

Notes on the LEDs
- The high abiotic resource consumption is caused almost exclusively by the gold in the bonding wire
- Flip-chip LEDs (without bonding wire) are the newer state of technology and are probably more robust (because the bonding wire cannot tear) and at least as efficient » only offer sustainability benefits

Conclusion on sustainable LED module design

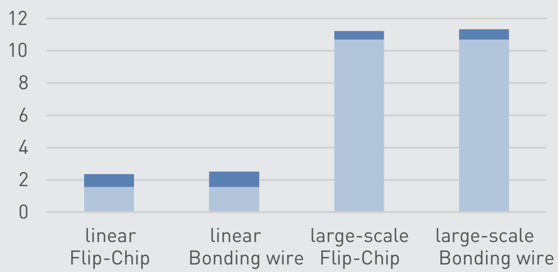
- **Flip-Chip LEDs** have a significantly lower abiotic resource consumption than LEDs with **bonding wire**
- The surface area of the LED module is relevant and should be kept as small as possible

Exemplary life cycle assessments
the manufacture of LED modules

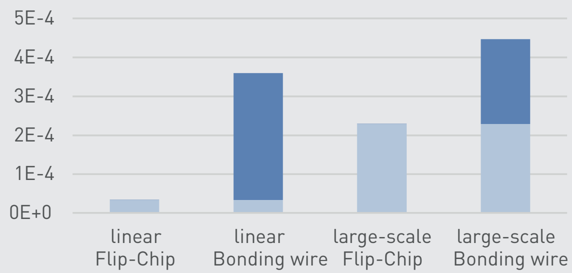
linear:
71.9 x 2.3 cm with 96 LEDs

large-scale:
33.6 cm diameter with 64 LEDs

GWP [kg CO_2-eq.]



ADP [kg Sb-eq.]



■ LEDs
■ PCB

ECG – LIFE CYCLE ASSESSMENT OF PRODUCTION

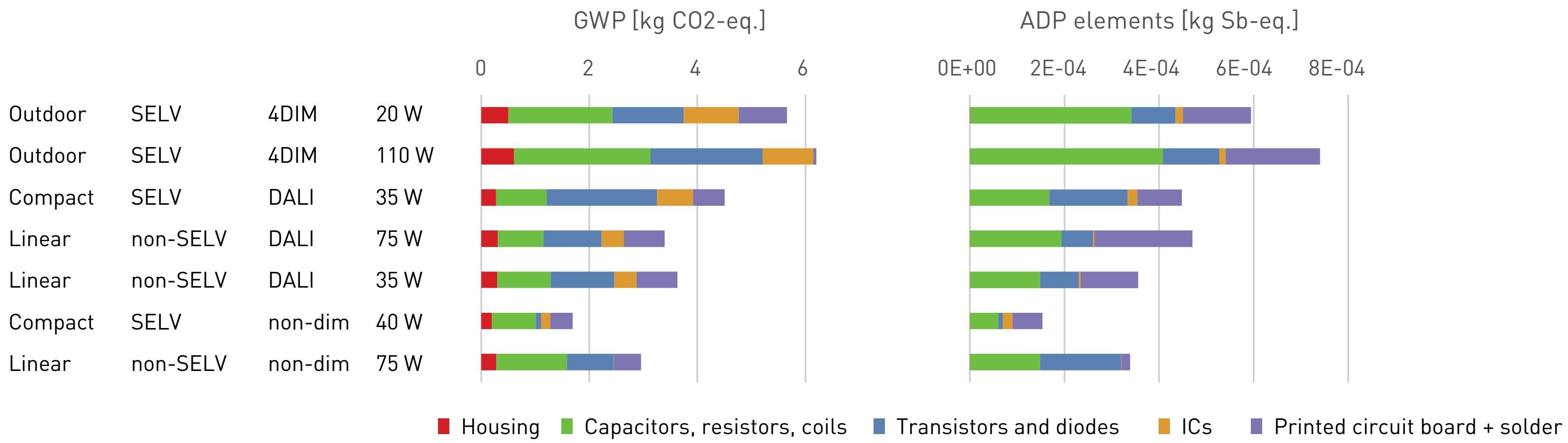
MAXIMUM INFLUENCE ON ADP

In the SUMATRA project, 7 ECGs from the consortium partner Inventronics were analysed. They were selected in such a way that the following properties and their influence on the life cycle assessment can be compared:

- Dependence on performance
- DALI versus switchable
- SELV versus non-SELV

In the context of the complete luminaire, the ADP is particularly important (see portfolio overview).

DEPENDENCE OF GWP AND ADP ON ECG TYPE



LIFE CYCLE ASSESSMENT OF UNKNOWN ECGS

ECGS - CONNECTIONS WITHIN A SERIES

USE KNOWN ECGS AS BASE VALUE

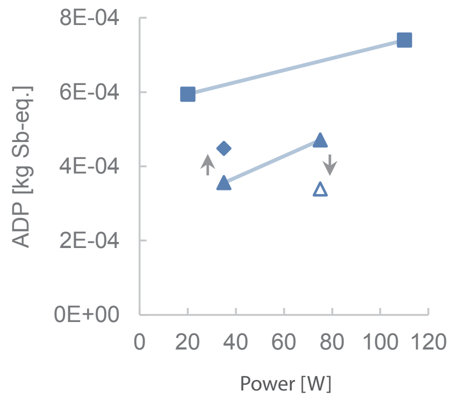
To estimate the life cycle assessment of an unknown ECG, the values of an ECG that has already been balanced can be used – provided that it is very similar to a known ECG and differs only in terms of electrical output or another characteristic. The correction factor can be determined using the gradients and offsets from the tables. The value for the GWP can then be estimated from the correlation of GWP and ADP:

$$GWP = ADP \cdot 7934\ \frac{\text{kg CO2−eq.}}{\text{kg Sb−eq.}} + 0{,}49\ \text{kg CO2−eq.}$$

THE MOST IMPORTANT RESULTS

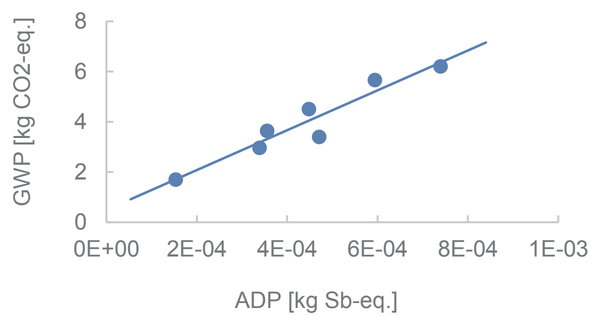
- The higher the power, the higher the ADP value – however, this correlation only applies within a series and with identical other features
- A non-dim device saves some ADP compared to a DALI device
- A SELV device requires slightly more ADP than a non-SELV device

Correction factors for the life cycle assessment of unknown ECGs



■ Outdoor · 4DIM		
Gradient △ADP / △P	1,6e-6	kg Sb-eq. / watt

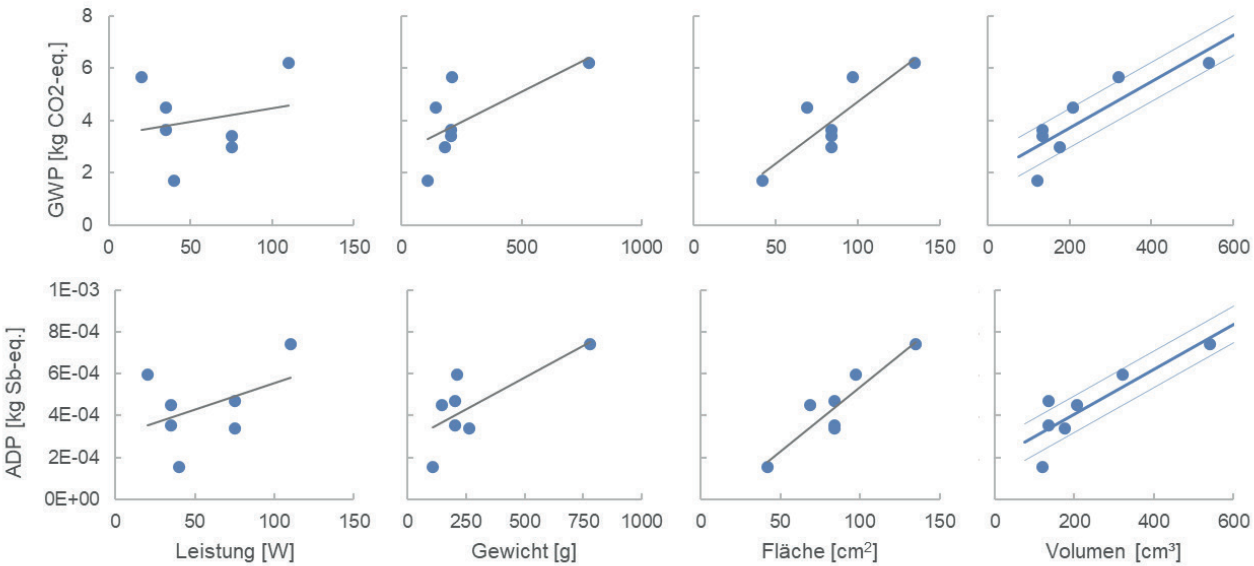
▲ Indoor · DALI · non-SELV · linear		
Gradient △ADP / △P	2,9e-6	kg Sb-eq. / watt
Offsets		
DALI → non-dim (△)	- 1,3e-4 (- 28 %)	kg Sb-eq.
non-SELV → SELV (◆)	+ 9,3e-5 (+ 26 %)	kg Sb-eq.



POWER, WEIGHT, AREA, VOLUME

ECGS – CONNECTIONS WITHIN A SERIES

DEPENDENCE OF GWP AND ADP ON DIFFERENT CONTROL GEAR UNITS



For an otherwise unknown device, the values for GWP and ADP can be estimated on the basis of the volume V (in cm³) of the ECG:

Estimation of the GWP

$$GWP = V \cdot 0{,}0089 \frac{\text{kg CO2}-\text{eq.}}{\text{cm}^3} + 1{,}94 \text{ kg CO2}-\text{eq.}$$

Estimation of the ADP element

$$ADP = V \cdot 1{,}1 \cdot 10^{-6} \frac{\text{kg Sb}-\text{eq.}}{\text{cm}^3} + 1{,}9 \cdot 10^{-4} \text{ kg Sb}-\text{eq.}$$

This results in root mean square deviations of ± 0.75 kg CO2-eq or ± 8.8e-5 kg Sb-eq.

THE MOST IMPORTANT RESULTS

- No correlation with the output – other factors are too important here (ECG type)
- No correlation with the weight – factors such as potting compound or housing are more decisive here
- Reasonable correlations for area and volume – the volume is more plausible, as the volume is usually simply determined by the largest component (coil, capacitor) and is therefore an indicator of the total amount of material

ECGS – AN OVERVIEW

FAZIT ZUM NACHHALTIGEN EVG-DESIGN

MINIMUM POWER LOSS

Energy efficiency is the most important lever for reducing the GWP. Improvements pay off in the total cost of ownership.

- Example ECG with 100 W: with an efficiency improvement of just 0.5%, this results in energy savings of 50 kWh after 100,000 h

STRATEGIES

- Do without the anti-glow circuit in the ECG, use resistors on the LED module instead (approx. 1% point efficiency improvement in the ECG)
- Utilisation of high secondary voltages (as losses ~ I^2)
- Select the optimum operating point (in the LEDM/ECG combination), otherwise up to 8% efficiency is wasted
- Reduce the standby consumption of DALI ECGs as much as possible (EU standard is 500 mW)
- If required, use dimmable ECGs so that the luminaires can be operated with a light management system.

MATERIAL EFFICIENCY

Operating several luminaires on one ECG reduces material requirements and costs by saving on ECGs

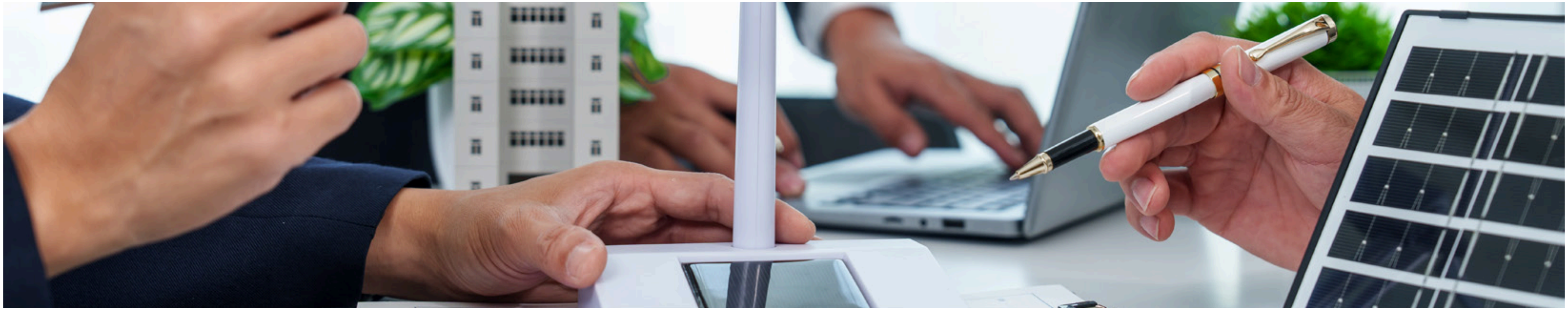
- ADP and costs are disproportionately low compared to ECG performance

HOUSING

- Aluminium and steel sheet have similar ADP
- If the housing can be done without, this primarily results in a cost advantage (hardly any advantages for GWP/ADP)
- Use recycled plastic

COMPONENTS

- The following is valid for coils, transistors, ICs: the smaller it is, the lower the ADP
- Capacitors can contain platinum (high ADP)
- PCBs: HAL Pb-free surface finish is best. The fewer the layers the better. ADP proportional to the area.
- Avoidance of toxic substances, e.g. by using halogen-free printed circuit boards and components that do not require leaded high-temperature solder internally



MODELLING THE UTILISATION PHASE OF A LUMINAIRE

BASIC ASSUMPTIONS FOR ASSESSING

To determine the ecological impact of a luminaire during the utilisation phase and to ensure comparability, various framework conditions are defined as a baseline.

ELECTRICITY MIX

A constant electricity mix (Germany 2019) is assumed with GWP 0.452 kg CO_2-eq. / kWh and ADP 2.95 10-2 kg Sb-eq. / kWh

DIMMING LEVEL

For operating the luminaire a dimming level of 100% is assumed.

SERVICE LIFE

For the calculation, the utilisation of the luminaire over its entire service life is postulated (rated service life as specified by the manufacturer). The table below shows what this means for various applications and usage scenarios.

annual standard utilisation hours			
Office	**Industry**	**Retail**	**24/7**
2.500 h/a	4.000 h/a	5.000 h/a	8.760 h/a

Luminaire	**maximum possible useful life (years)**			
Service Life	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 a	20 a	11,4 a

DEVELOPMENT UNTIL 2040

MODELLING THE UTILISATION PHASE OF A LUMINAIRE TAKING INTO ACCOUNT THE ENERGY TRANSITION

How will the energy transition affect the ecological balance of a luminaire in the coming years? The environmental impacts were calculated on the basis of a reference luminaire commissioned in 2020 according to the assumptions on page 28)

Example

Environmental impact of electricity consumption when operating a luminaire in Germany

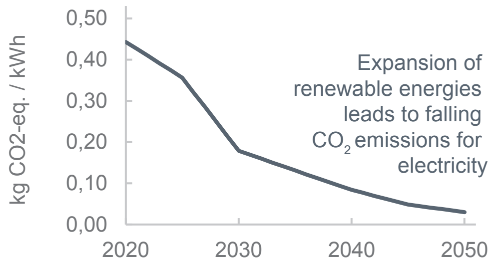
- 47 W electrical power
- 4,000 h/a over 17.5 years, starting in 2020
- total of 70,000 h
  grey: Global Warming Potential
  violet: Abiotic Depletion Potential

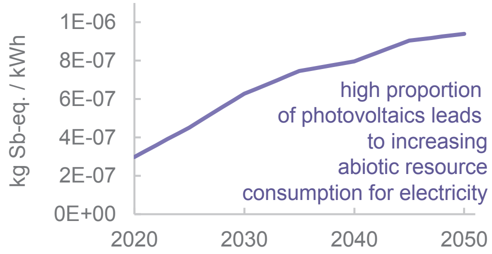
Result

- GWP = 861 kg CO_2-eq.
- ADP = 1.8 · 10-3 kg Sb-eq.

Environmental impact per kWh

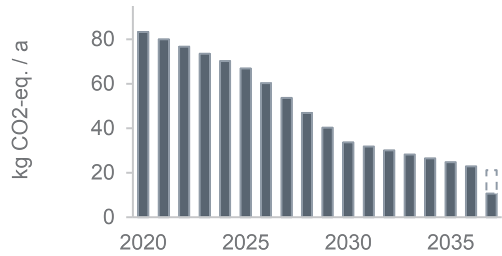
of power generation

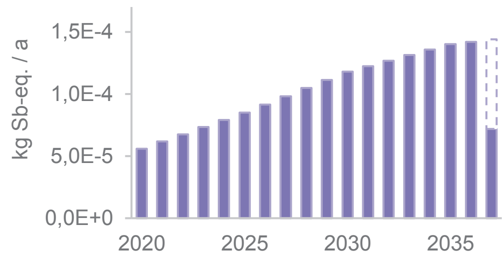




annual environmental impact

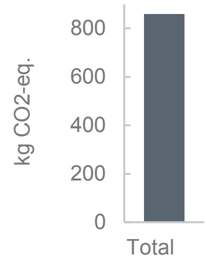
through use of the luminaire

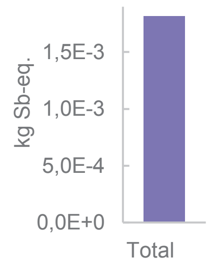




Total

of utilisation phase





THE MOST IMPORTANT RESULTS

- The expansion of renewable energies leads to falling CO_2 emissions for electricity
- A high proportion of photovoltaics leads to increasing abiotic resource consumption for electricity

PRODUCTION AND UTILISATION

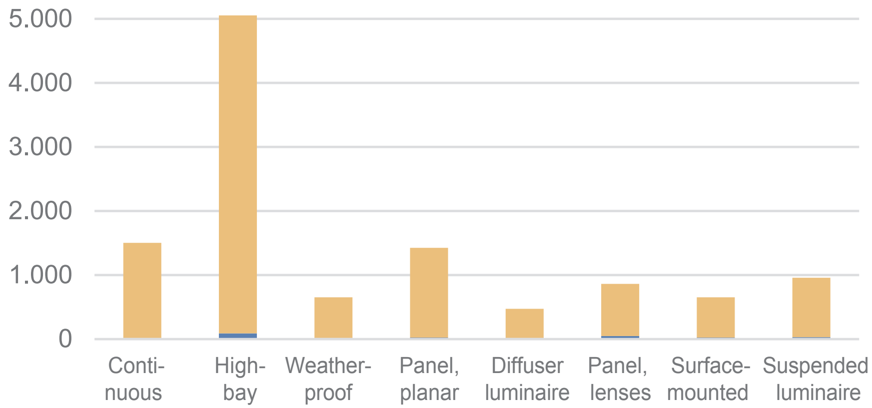
LIFE CYCLE ASSESSMENT PORTFOLIO OVERVIEW – ABSOLUTE VALUES

Fig. 1 shows the results of the life cycle assessment for the production of the luminaire and its use over the complete service life of the luminaire – always in relation to the specific application.

- The absolute values are shown. Packaging is not shown in the ADP as its production accounts for < 0.05%.
- The utilisation phase is modelled with a static electricity mix (Germany 2019) and operation at 100% dimming level.
- The highbay luminaire stands out in particular. This is mainly due to the high output of the GWP (157 W) and the high number of LEDs (600) in the ADP. On the other hand there is a lot of light (26,700 lm and 70,000 h service life).

Global Warming Potential

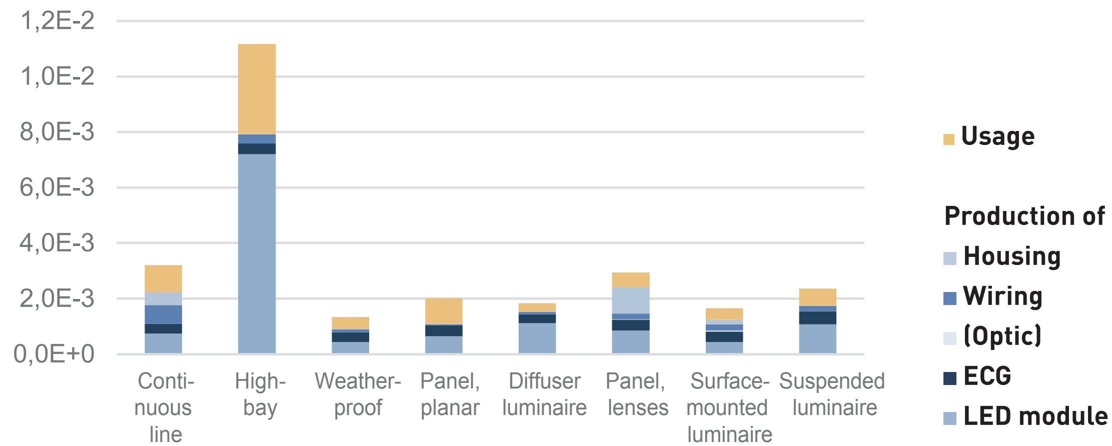
kg CO_2-eq. (absolute values)



The GWP ranges from 470 to 5,000 kg CO2 equivalent. The production phase accounts for only 1 - 5 %.)

Abiotic Depletion Potential

kg Sb-eq. (absolute values)



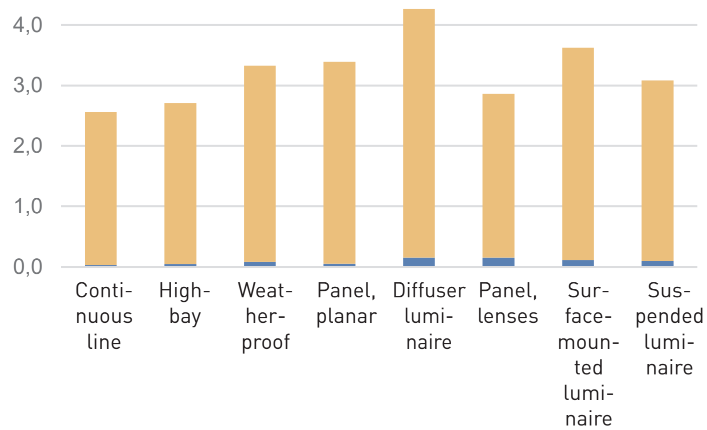
The ADP ranges from 1.1 · 10-3 to 6.1 · 10-3 kg antimony equivalent. The production phase accounts for 47 - 79%.

ESTABLISHING COMPARABILITY

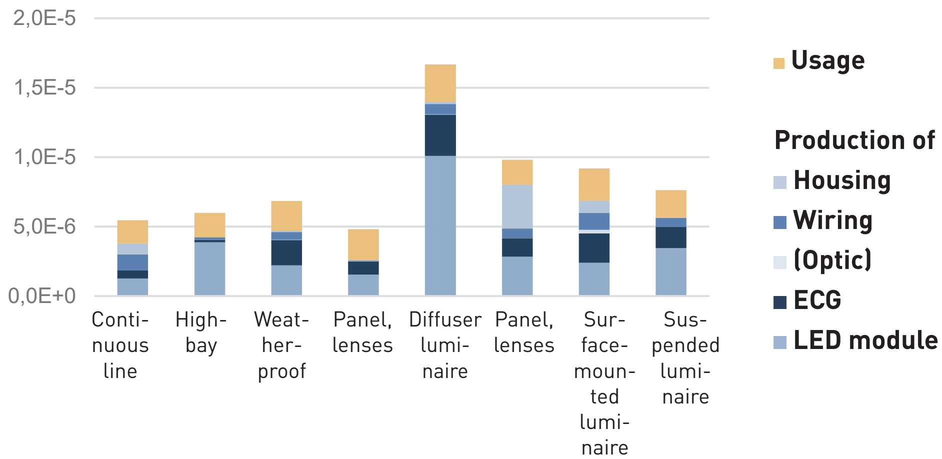
LIFE CYCLE ASSESSMENT PORTFOLIO OVERVIEW – STANDARDISED

By standardising the results from the life cycle assessments, luminaires from different applications can be objectively compared with each other. In the following diagrams, the values have been standardised to 1,000 lm luminous flux and 1,000 hours of service life.

Global Warming Potential
kg CO_2-eq. pro 1.000 lm x 1.000 h



Abiotic Depletion Potential
kg Sb-eq. pro 1.000 lm x 1.000 h



THE MOST IMPORTANT RESULTS

- In terms of GWP the luminaires are close to each other due to their similar luminous efficacy.
- With the ADP, the diffuser luminaire stands out, where a very large LED module (33 cm diameter) is used for relatively little light (2,200 lm).

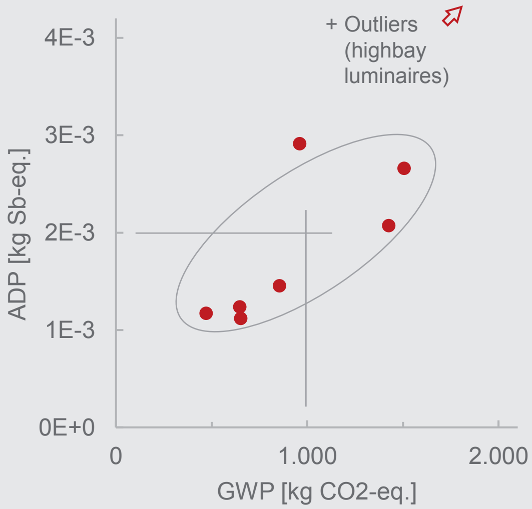
ADP OR GWP – WHICH IS MORE IMPORTANT?

RELEVANCE COMPARED TO THE ANNUAL GLOBAL ENVIRONMENTAL IMPACT

The question of whether the global warming potential caused by lighting or the abiotic consumption of resources is 'more important' cannot be answered objectively. The comparison with normalisation factors (NF) gives an indication.

GWP AND ADP

Depiction of Global Warming Potential and Abiotic Depletion Potential for the analysed luminaire portfolio (without highbays). For the definition of a 'representative luminaire', 1,000 $kg_{CO2-eq.}$ and 0.002 kg Sb-eq. offer themselves as smooth values (use over the entire luminaire service life with electricity mix DE 2019).



NORMALISATION FACTORS

The normalisation factors NF are recommended by the EU for the assessment of environmental footprints, and describe the global environmental impact of all human activities (determined for 2010) per head per year. [JRC 2022].

	one LED luminaire	NF	Share
GWP [kg CO_2-eq.]	1.000	7.550 (per Person)	13 %
ADP [kg Sb-eq.]	$2 \cdot 10^{-3}$	$6.36 \cdot 10^{-2}$ (per Person)	3 %

WP and ADP are both similarly significant (to the same magnitude)

It is also known that lighting accounts for 12.9% of total German electricity consumption [AG Energiebilanzen, database 2021], and therefore also a non-negligible proportion of Germany's energy-related greenhouse gas emissions. For this reason we have to take the contribution of lighting seriously

Conclusion: the global warming potential and the abiotic resource consumption of lighting are both significant.

RECYCLING

CLARIFICATION OF TERMS

DEFINITION OF RECYCLING

Recycling means any recovery operation by which waste is reprocessed into products, materials or substances, either for the original purpose or for other purposes; it includes the reprocessing of organic materials, but not energy recovery and processing into materials intended for use as fuel or for backfilling.

[Circular Economy Act, §3 (25)]

Utilisation

Material Utilisation
- Reuse
- Recycling
- Backfilling

Energetic utilisation
- Combustion
- Preparation for Fuel

Disposal
- Landfills
- Discharge into water bodies
- Permanent storage (see nuclear waste)
- …

DISTINCTION BETWEEN RECOVERY AND DISPOSAL

Recovery is any process whose main result is to put the waste to a useful purpose by replacing other materials that would otherwise have been used to fulfil a specific function.

Disposal is any process that is not recovery, even if the process has the secondary consequence of recovering materials or energy.

THEORETICAL IS NOT ENOUGH

APPROACH TO THE CONCEPT OF RECYCLABILITY

SCIENTIFIC DIFFERENTIATION

In his article "On theoretical and real recyclability (2020)", Professor Roland Pomberger distinguishes between

• theoretical recyclability (of the material itself)
• technical recyclability: the material must also be able to be separated, recognised and discharged
• real recyclability: takes into account collection system, regional availability of sorting facilities, real pollution

CREATE A REFERENCE SCENARIO

The European standard EN 45555 (General methods for assessing the recyclability and recoverability of energy-related products) describes the recyclability of energy-related products. It is not actually directly applicable to product evaluation, but a procedure for developing product-specific rules. This requires a representative reference scenario of end-of-life treatment and an estimation of material losses in each step of the process. This procedure was carried out for smartphones and described in the scientific literature, e.g. at Fraunhofer IZM by Schischke et al. (2022).

OCCUPY INFRASTRUCTURE

DIN EN ISO 14021 (Environmental labels and declarations – Self-declared environmental claims) also requires that statements about the recyclability of products must include evidence of existing collection-, sorting- and transport systems and their use.

SUMMARY

Standards and literature are unanimous: an assessment of the theoretical recyclability of the material itself is not sufficient. Weak points in the process must also be communicated..

WEATHER-PROOF LUMINAIRE

Length **1.2 m** | Weight **2.3 kg** | Housing **polycarbonate grey** | Optic **polycarbonate clear**

Ferrous metals

Printed circuit boards &

non-ferrous metals

Plastic

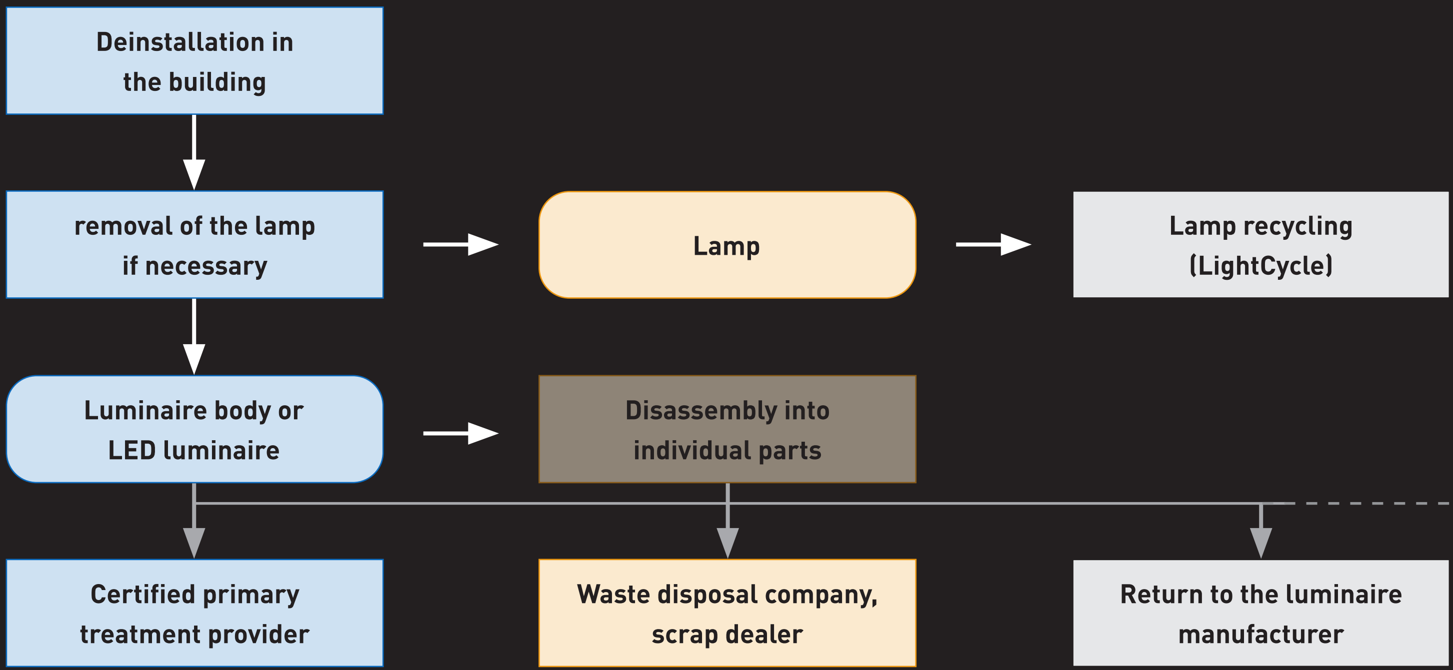
residues

ROAD LUMINAIRE

Weight **17.2 kg** | Housing **die-cast aluminium** | Optic **PMMA lens + glass panel**

PROCESS AND RESPONSIBILITIES

HOW A LUMINAIRE FINDS ITS WAY INTO RECYCLING PLANTS



Certified primary treatment provider

- Legally correct path
- Primary treatment provider registers the devices (weight) and reports to the EAR Foundation (Stiftung EAR)
- Contributes to the fulfilment of the collection quota
- Can be organised via service providers (container provision, logistics)

Waste disposal company, scrap dealer

- In this way, the electrical contractor may be able to earn a little extra money for the scrap (path shown in grey)
- Bypassing primary treatment also avoids registration as separately collected waste equipment
- Valuable components correctly pass to recycling

Return to the luminaire manufacturer

- Legally possible if the manufacturer is certified as a primary treatment provider
- Example of WILO (for heating pumps)

Notes on the recycling process

During the initial treatment, pollutants are first removed. In the case of luminaires, these can be batteries (with emergency luminaires) or PCB-containing capacitors (with fluorescent lamps).

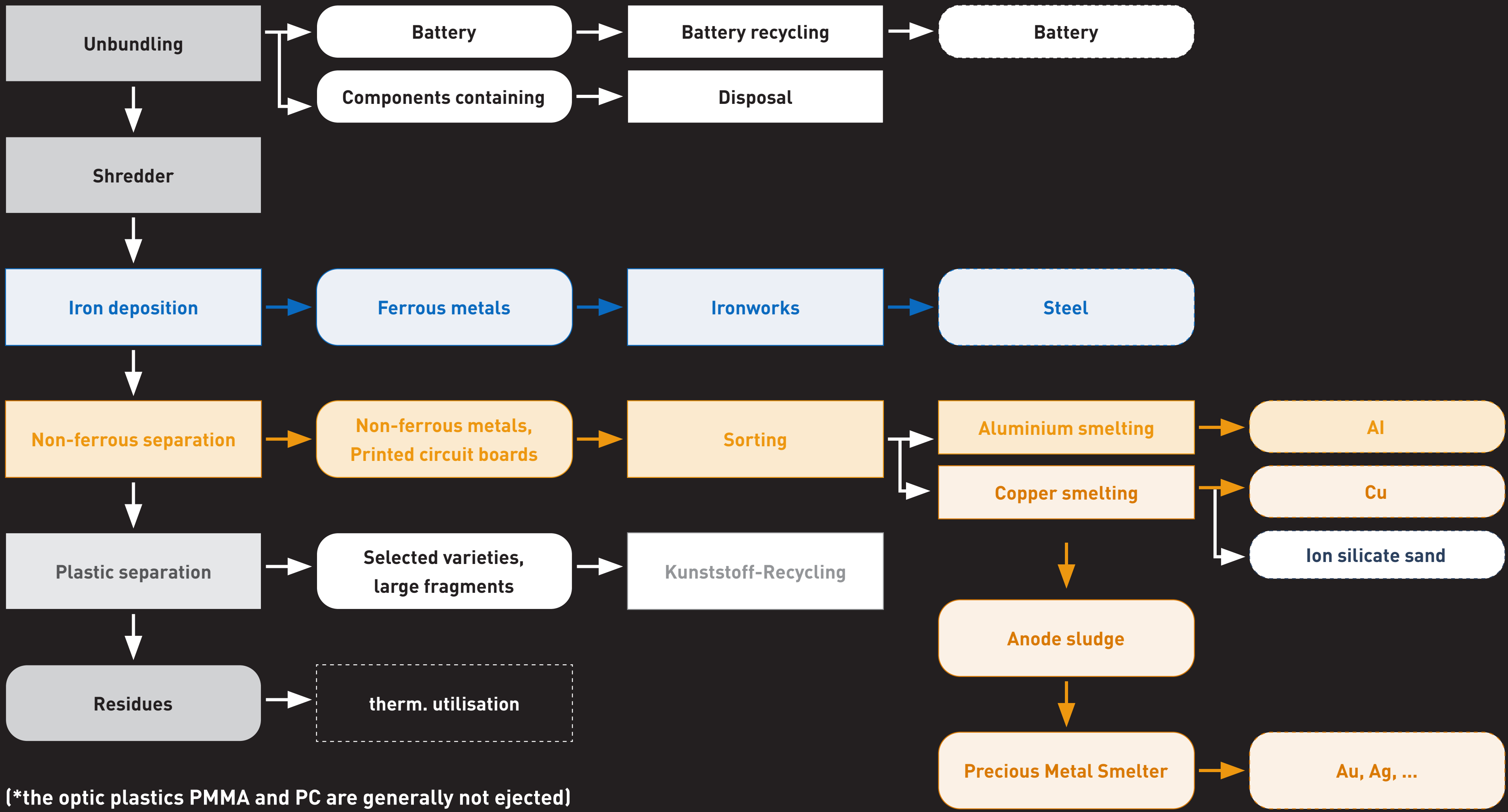
In the recycling process, the most controversial question is whether plastic (with luminaires and mainly PC and PMMA) is channelled out and recycled or not. Our shredder test did not yield any significant quantities of separately sorted plastic. Feedback from Interzero, LightCycle and from the plenary session at Lighting Europe (21.02.2023) also state that plastic is usually thermally recycled.

The reasons given for this are, on the one hand, possible contamination with brominated flame retardants (which renders an entire batch unusable). In addition, PC and PMMA occur in relatively small quantities in the entire flow of small and large electrical appliances.

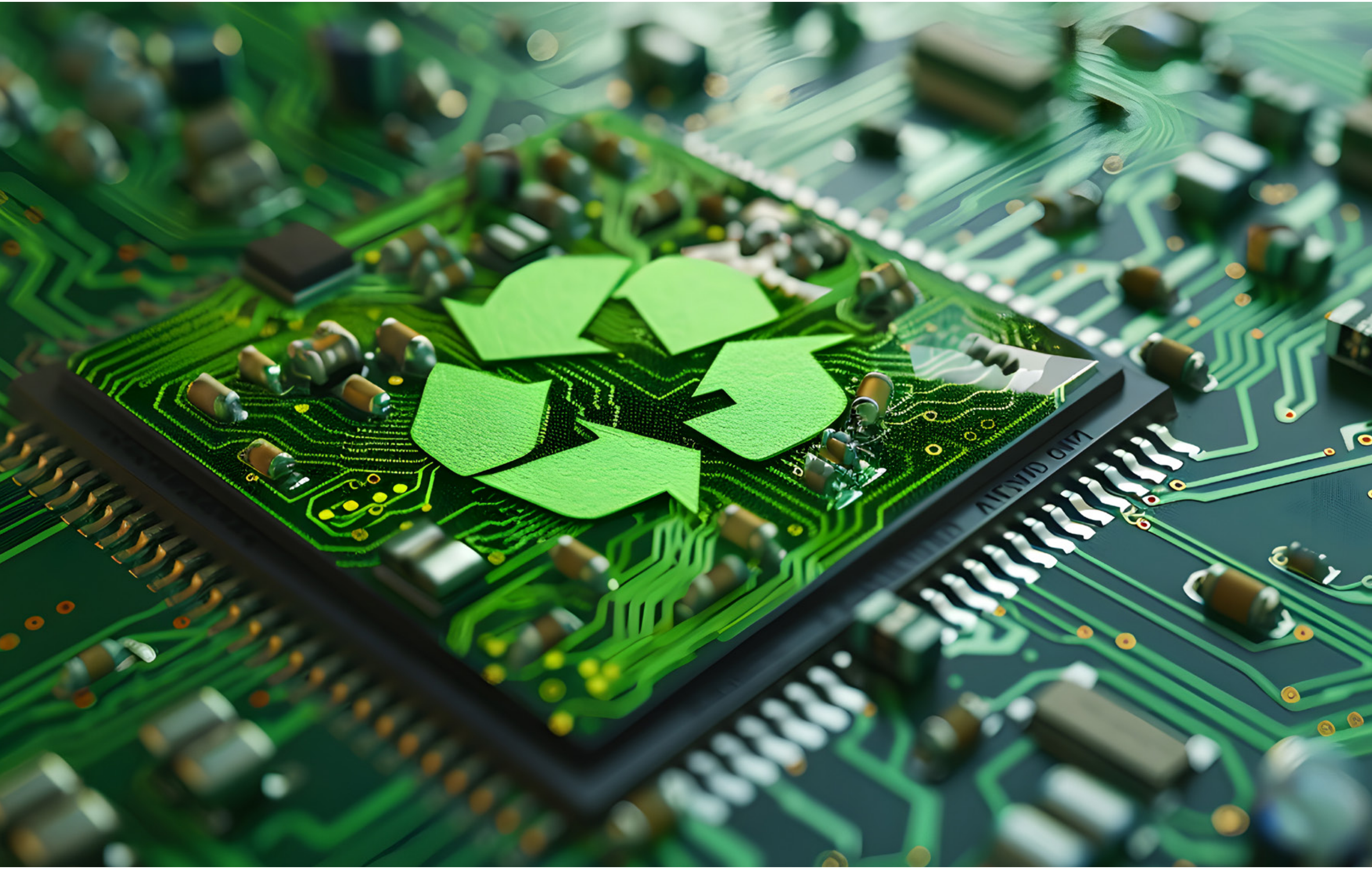
PROPOSED REFERENCE END-OF-LIFE TREATMENT SCENARIO

FOR RECYCLABILITY ASSESSMENTS BASED ON EN 45555

With a so-called reference scenario for the treatment of a product at the end of its life, detailed statements can be made on the recycling of the various resources and material groups.



(*the optic plastics PMMA and PC are generally not ejected)



MINIMUM REQUIREMENT ACCORDING TO WEEE AND ELEKTROG

The ElektroG (Electrical and Electronic Equipment Act) transposes the European WEEE Directive (Waste of Electrical and Electronic Equipment) 2012/19/EU into German law

The ElektroG stipulates a number of minimum recycling requirements:

- Minimum requirements for the selective treatment of components from waste electrical equipment according to WEEE Annex 7
- PCBs over 10 cm^2 (*)
- Plastic with brominated flame retardant
- Gas discharge lamps
- Batteries
- External electrical cables
- PCB-containing capacitors

(* with PCBs this is practically eliminated by shredding and sorting – with batteries though, this would be highly dangerous)

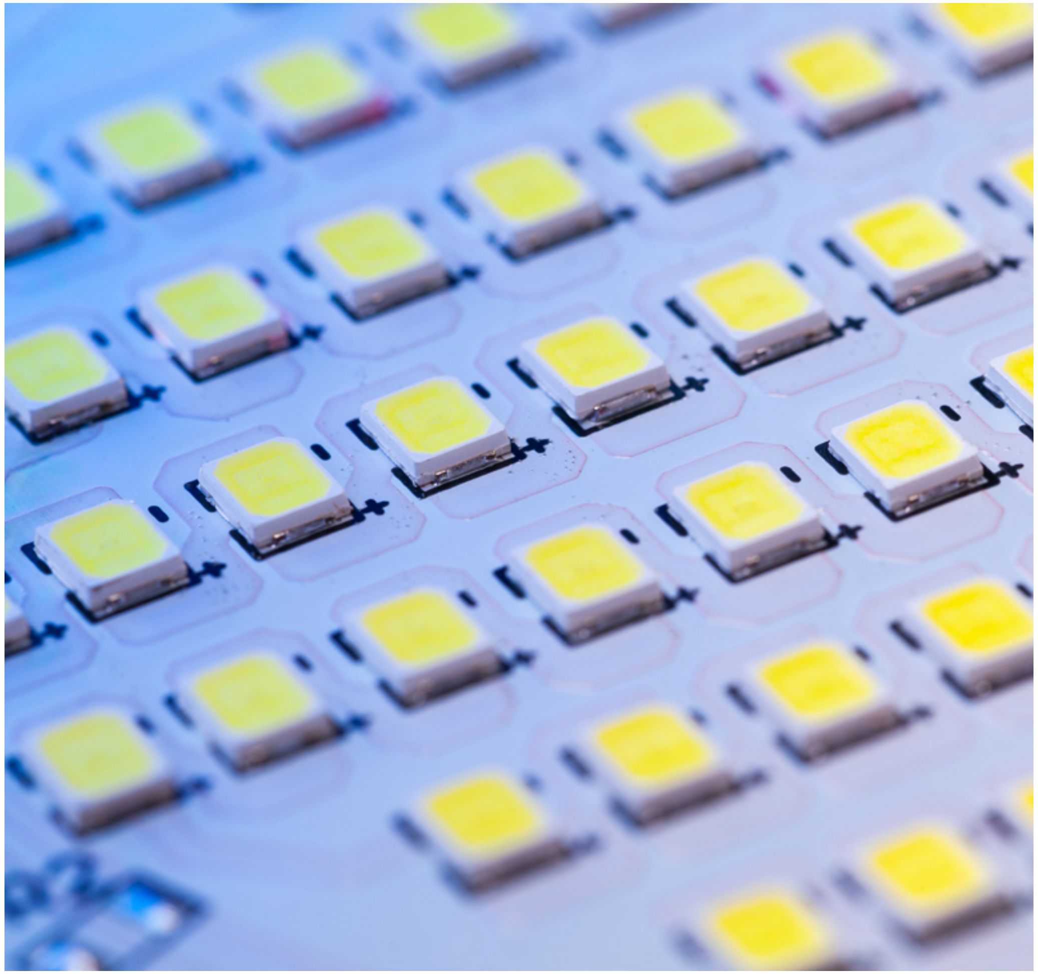
METALS ARE BETTER RECYCLED THAN PLASTICS

CALCULATION BASED ON STANDARD VALUES FOR RECYCLING RATES

Specific information on recycling rates of materials in e-waste is given in IEC / TR 62635:2012, differentiated according to manual dismantling or shredding with subsequent sorting. Data in % by weight.

CONCLUSION: The relevant metals are recycled at high rates. The plastics relevant for luminaires (PMMA, PC) are not recycled after shredding.

	Recycling Rate	
Material	**manual dismantling**	**shredding**
ABS	94 %	74 %
ABS with additives	94 %	0 %
PP	94 %	90 %
PP + EPDM	94 %	90 %
PP + glass fibres	94 %	90 %
PP + natural fibres	0 %	0 %
PP with other additives	94 %	0 %
HIPS	94 %	83 %
HIPS with additives	94 %	0 %
PE	94 %	90 %
SAN	94 %	0 %
PC with or without additives	94 %	0 %
ABS-PC blend	94 %	0 %
PA, PA-6 with or without additives	94 %	0 %
Other polymers	0 %	0 %
Steel	95 %	94 %
Aluminium	95 %	91 %
Copper	95 %	85 %
Other metals	95 %	70 %



Representativeness of the data

Product groups: Small and large household appliances, IT and telecommunications equipment, consumer electronics

Geographical: Europe

THE COPPER SMELTER: RECYCLING OF LED MODULES AND CONTROL GEAR UNITS

Electronic components are recycled in the copper smelter and refined in an electrolysis process. The by-product is an anode sludge from which precious metals are recovered.

The melt is filled with
- copper scrap, PCBs
- scrap iron as a reducing agent
- sand

} produces large quantities of iron silicate sand

Steel and aluminium components go into the slag, which is marketed as iron silicate sand e.g. for the construction industry and therefore counts as a recycled product. For a material-specific use though, steel and aluminium are lost here, which is why we do not include them in the recycling yield below.

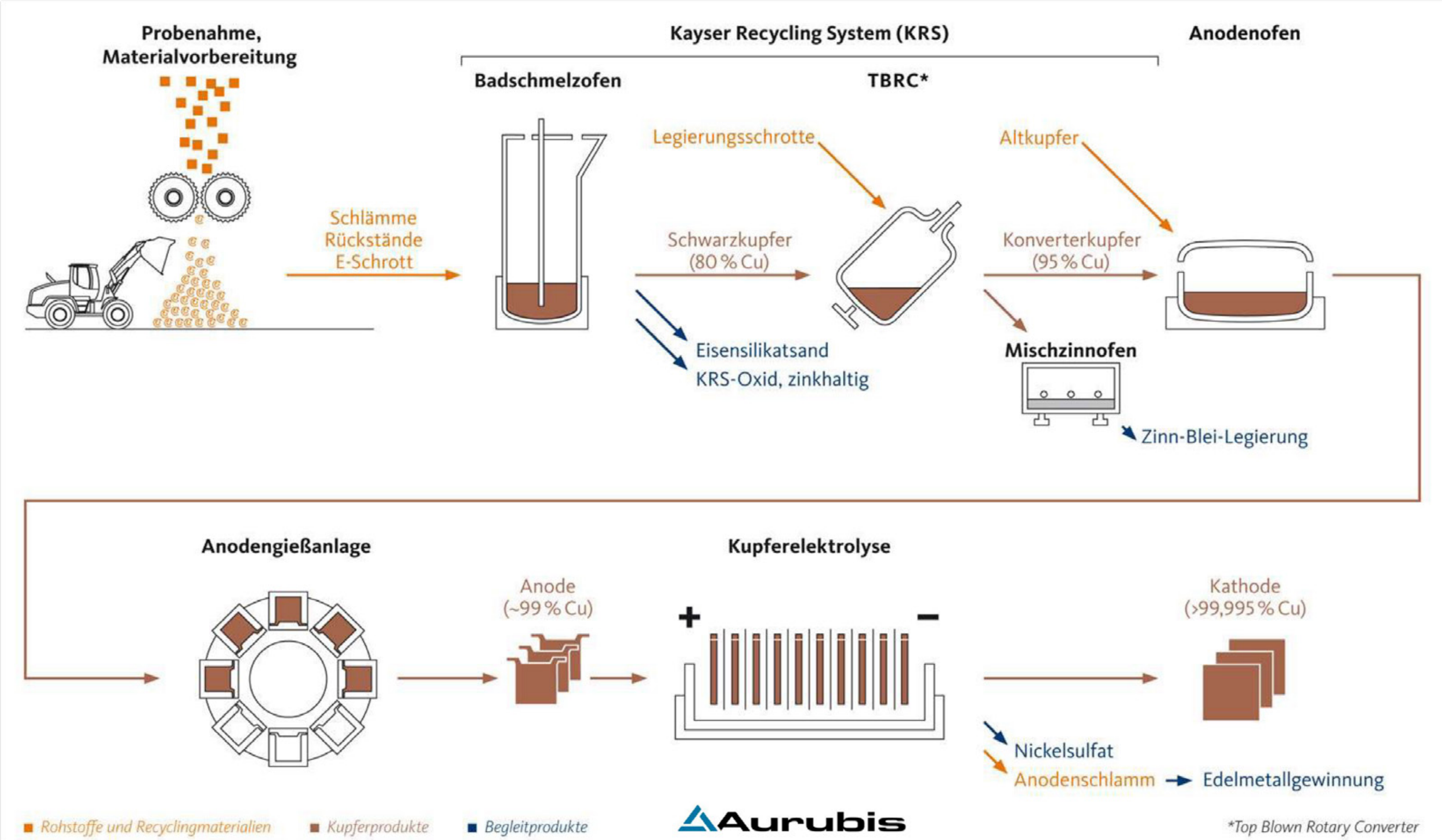
Organic components (plastic, PCB substrates) are used as fuel in the oven and are relevant for the company or plant's CO_2 trading.

Overview of recycling rates
in the copper smelter at Aurubis, Lünen
Figures in % by weight.

Metal	recycling rate
Copper	> 90 %
Silver	> 90 %
Gold	> 90 %
Palladium	> 90 %
Lead	> 90 %
Tin	> 75 %
Nickel	> 90 %
Antimony	> 80 %

[Chancerel & Marwede, Feasibility study for setting-up reference values to support the calculation of recyclability/recoverability rates of electr(on)ic products, JRC technical reports (2016)]

RECYCLING OF LED MODULES

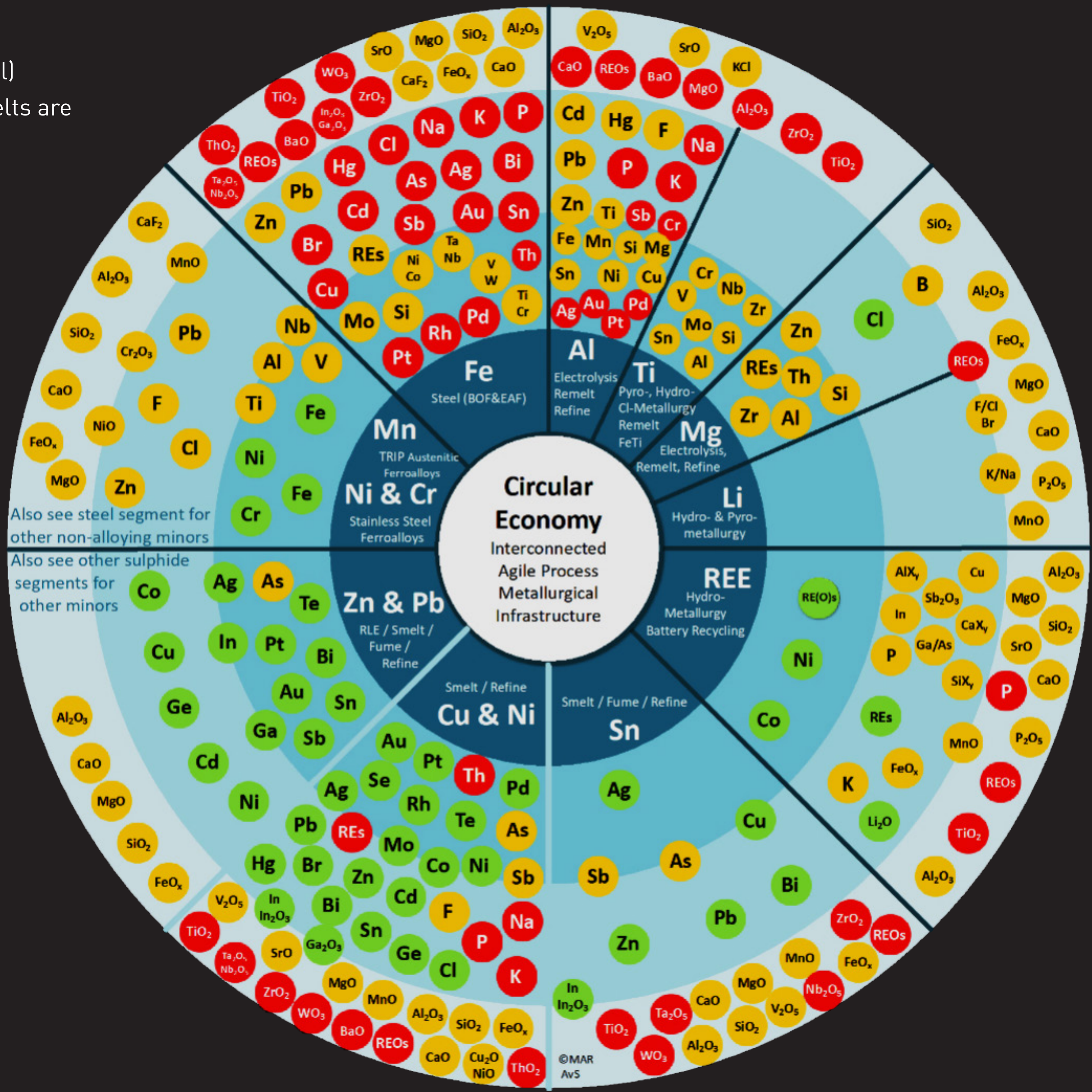


SEPARATING, MELTING, UTILISING

FURTHER METAL MELTING AND THE "METAL WHEEL"

There are other smelters for other base metals (sectors of the metal wheel) in the recycling system. The metal wheel shows which metals in which melts are recovered, are lost, or even cause quality problems. Here it can be seen:

- Aluminium and iron are lost in the copper smelter (in the slag, outermost ring, in oxidised form FeOx and Al2O3)
- Copper and precious metals are lost in the iron or copper smelting process or even contaminate it: "Copper is toxic in iron recycling".



SUMMARY

It should be possible to separate luminaire bodies into compatible fractions (according to the metal wheel), otherwise they will be lost for further material-specific utilisation.

- in the metal phase
- in slag/fly ash, processing possible
- in slag/fly ash
- recoverable elements
- cannot be separated, remains inseparable as a functional
- component, reduces the quality of the main metal

PRACTICAL RESULTS
RECYCLING OF LED MODULES

If recycled correctly, LED modules end up in the copper smelter.
The PCB substrate accounts for the largest mass. There are two scenarios here:

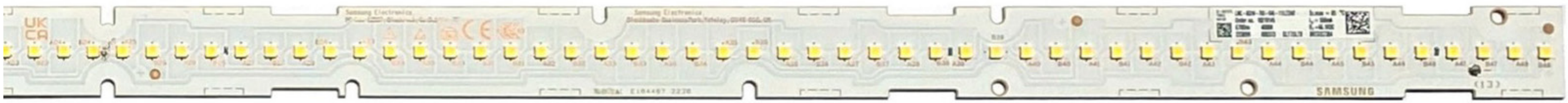
- Organic substrate (e.g. FR4, CEM3) burns in the copper smelter
- Aluminium core PCB: the substrate cannot be separated from the strip conductors and components and oxidises in the copper smelter (serves as a reducing agent and ends up in the slag). Despite the large quantity of aluminium, aluminium core PCBs should not be recycled in the aluminium smelter because the copper carried in is toxic for the aluminium smelter. Also, the scarcer metals (according to ADP elements) are recovered in the copper smelter.

Emission factors for transport and journeys

LED-Modul	recycling rate R_{cyc}
CEM3 substrate (731x22 mm) with 96 mid-power LEDs	11 %
aluminium substrate (147x45 mm) with 12 high-power LEDs	8 %

R_{cyc} is the weight percentage of the recycling yield in relation to the weight of the module.

FINDINGS FROM THE DETAILED ASSESSMENTS:
- Only a small proportion of the mass is recycled, but these are the metals with the largest ADP elements contribution.
- Applying strip conductors and LEDs to aluminium or directly to sheet steel prevents the aluminium or steel from being recycled.
- Results of 8-11% are even lower than the standard values for poorly assembled PCBs from IEC TR62635:2012



PRACTICAL RESULTS

RECYCLING OF CONTROL GEAR UNITS

Two scenarios were considered, of which it is currently not possible to judge which is more realistic:
1) The housing and PCB are separated in the shredding process and forwarded for separate recycling
2) The ECG goes completely into the copper smelter without separation and the housing burns as a reducing agent

Control gear unit	R_{cyc} with separation	R_{cyc} without separation
Outdoor	impossible	12 %
Compact	15 %	14 %
Linear DALI	50 %	13 %
Linear non-dim	59 %	15 %

Angaben in Gewichts-%

→

Flat-rate values for furtheruse	
Outdoor EVG	12 %
ECG (plastic)	15 %
ECG (sheet metal)	55 %

FINDINGS FROM THE DETAILED ASSESSMENTS

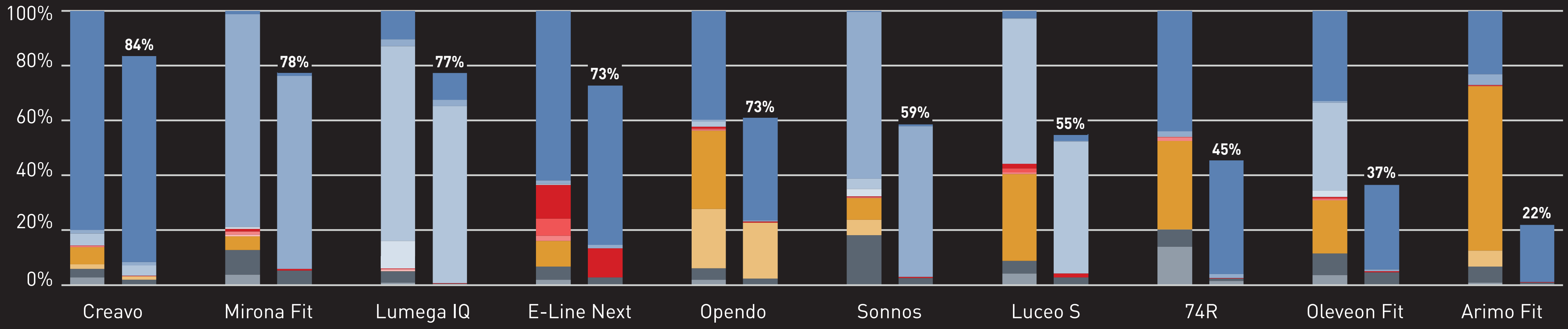
- The main recycled weight fractions come from the housing (if sheet metal) and the copper.
- For ECGs with plastic housings (Outdoor, Compact), the housing is not recycled, resulting in low recycling rates of 12-15%. A potting compound definitely prevents the housing and PCB from separating.
- ECGs with sheet metal housings achieve recycling rates ≥ 50% if the housing and PCB can be easily separated, i.e. if they already separate from each other in the shredder.

LOSS ACCOUNT

WHAT REMAINS AFTER RECYCLING

The left column shows the weight composition of the luminaire when new, and the right column shows what remains of it after recycling.

Mechanics
Wiring
Optic
Electronics



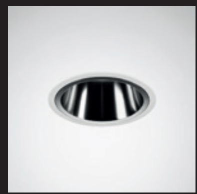
- PMMA optic

- PC optic

- Glass cover
- ECG, sealed

- Cable insulation
- PMMA optic

- PMMA parts of the optic



- PC-Optik,
- relative heavy ECG

- PMMA optic

- PMMA Diffuser
- large LED module

- Housing part and
- Optic made of PC

- relative heavy PMMA Covers

THE COMMON PRACTICE

RECYCLING OF PLASTIC AFTER THE END OF LIFE

According to the current state of technology, the plastic from LED luminaires is incinerated
• because it occurs in too small quantities in the general stream of electronic waste (PC and PMMA)
• because it could be contaminated with flame retardants

SUMMARY
It is uncertain which recycling technologies will be practised in 20 years' time and which substances will then be banned. Even when luminaire diffusers and housings are separated by type, there are still many challenges concerning recycling:

transparent PC – yellowed

grey PC – soiled and with adhesions

white PMMA – soiled with dust and wall paint

FINAL CONCLUSIONS

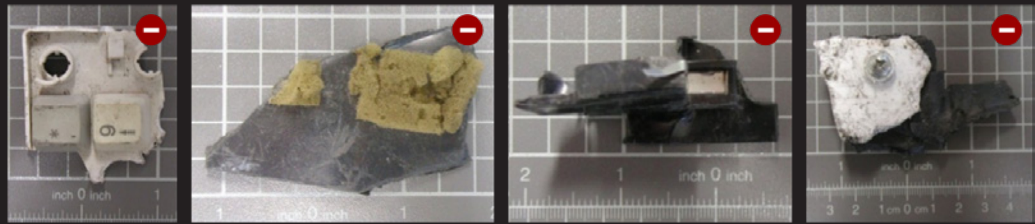
FOR RECYCLABLE LUMINAIRE DESIGN

Metals

- (+) It should be possible to separate luminaire bodies into metallurgically compatible fractions, as specified by the metal wheel.
- (o) Organic adhesions (paint, plastic, adhesive) on metal fractions are tolerable, burn in the melting furnace
- (−) No copper adhesion to steel if it is to be recycled (e.g. nickel-plated springs, copper-plated)
- (−) No copper adhesion to aluminium if it is to be recycled

Plastics

- (o) In the current state of recycling technology, the relevant plastics for luminaires are only recycled if they are removed manually.
- (−) Adhesions (metal, adhesive, rubber etc.) on plastic prevent recycling.
- (−) Flame retardants in the plastic prevent recycling.



Polymer/polymer clipping, polymer/foam sticking, polymer/metal insertion, metal screwing [photos: Maris et al. 2015]

Electronics

- (+) PCBs should be easily removable from housing materials (in the shredder).
- (+) The main metals recovered are the (more precious) metals such as Cu, Ag, Au etc.
- (−) Other critical raw materials such as gallium or rare earths are not recovered because they oxidise during the process.

FROM PRODUCT BACK TO RAW MATERIAL

VALUE CREATION AND DESTRUCTION

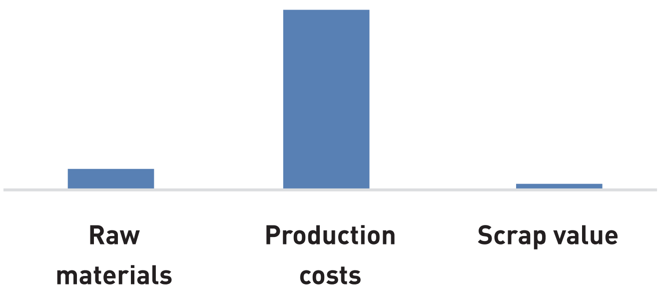
Some of the raw materials are recovered during recycling. Most of the 'value' is lost in the process, because it is not in the raw materials but in the way in which these substances are combined to form a useful unit.

Raw materials: approx. € 5
– Steel, copper, aluminium, precious metals (according to market prices), plastic granulate

Production costs: € 40-50
– Purchase prices of components, semi-finished products and materials
– Sheet metal processing, assembly, testing, packaging

List price: a few hundred euros
– Reference value for the end customer (includes three-stage distribution)

Scrap value: just over € 1
– For the type-specific sale of coated steel, plastics, cable scrap, assembled PCBs



CONCLUSION: because the value of the product is higher than that of the recycled raw material by several times, it makes economic and ecological sense to use the product for as long as possible.

CIRCULAR ECONOMY
ALTERNATIVES TO RECYCLING

Preliminary conclusion
It seems that recycling is the least favourable option (also economically) in the circular economy. It is the 'last resort', not the first choice.

Higher-value strategies
In current literature, 5 to 10 'R-strategies' are discussed as parts of the circular economy: re-think, repair, re-use etc., all of which are prioritised higher than recycling, as they promise greater savings. In the butterfly diagram (see right), the best strategies describe the smallest circles – as this is where the least effort is involved in the process of putting the materials back into use (grey circle).

Our challenge in the professional lighting market
The useful lives are usually very long. We currently get back luminaires that, at 25 years old, are completely outdated, and we will get most of our current luminaires back in another 25 years.