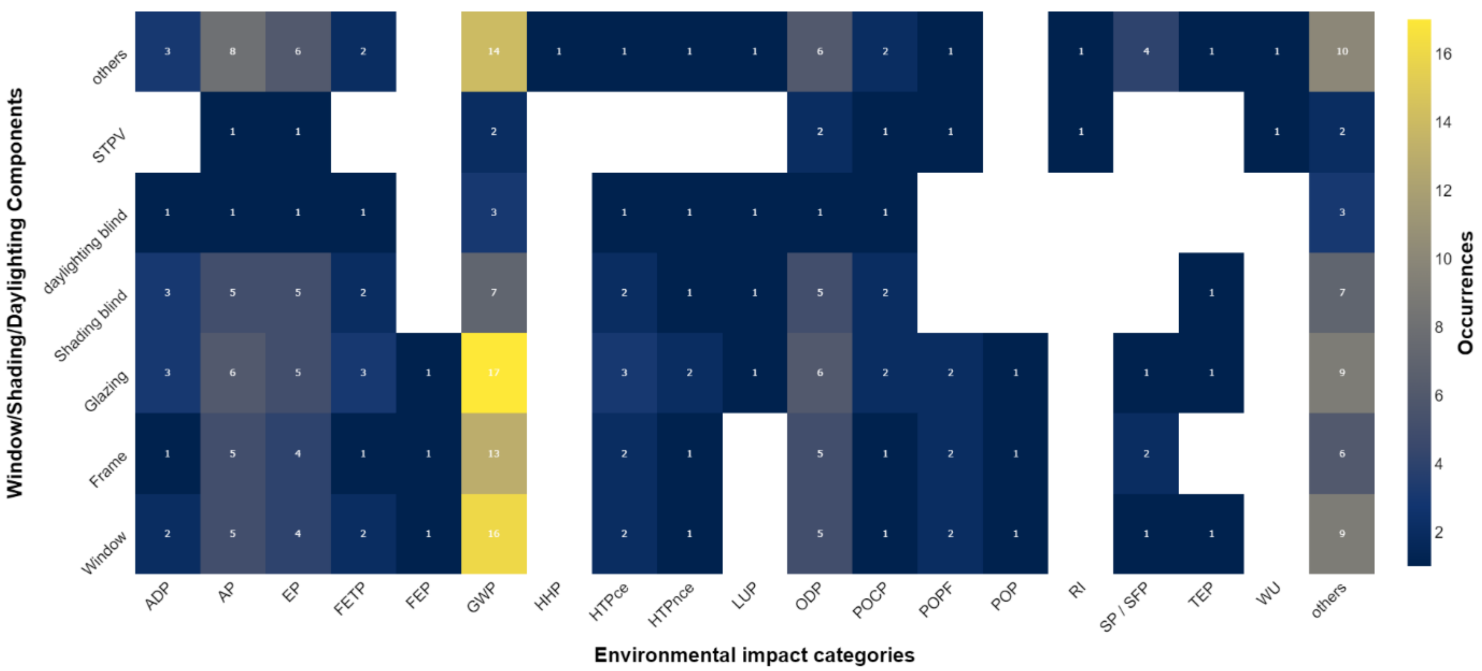
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Life Cycle Assessment in Lighting – International Survey and Status quo of Scientific Literatur



IEA SHC TASK 70 | EBC Annex 90: LOW CARBON, HIGH COMFORT INTEGRATED LIGHTING

Technology Collaboration Programme
by iea

Solar Heating & Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

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- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

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- SHC Solar Academy
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- SHC International Conference

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Programme (IEA EBC) at a moderate level. For more information on the IEA SHC work, including many free publications, please visit www.iea-ebc.org.

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Life Cycle Assessment in Lighting- International Survey and Status quo of Scientific Literature

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KEYWORDS

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PREFACE

Lighting accounts for 15 % of the global electrical energy consumption and 5 % of global CO_2 emissions. Thus, widening the rating perspective of lighting solutions to a more holistic view of its impact on CO_2 emissions, encompassing the whole life cycle chain also in the context of regional energy markets aspects, interaction with other building trades, etc. is urgently deemed necessary. This goes far beyond the pure LED lamp-driven energy efficiency gains.

The aim of IEA SHC Task 70 / EBC Annex 90 "Low Carbon, high comfort integrated lighting" is to identify and support implementing the potentials of lighting (electric, façade: daylighting and passive solar) in the decarbonization on a global perspective while aligning the new integrative understanding of humans' light needs with digitized lighting on a building and a building related urban scale. This includes the following activities:

- Actively support broadening the view on lighting solutions as a whole in the context of decarbonization. Help bridge the gap between a component view (manufacturer's focus) and design-oriented system approaches. Support the transition from a rather pure energy focused view so far to a life cycle assessment (LCA) perspective. On this basis, identify key impact factors, and develop the most effective strategies and roadmaps while including regional specifics.
- Contextualize this with the fast-developing digitization of buildings/lighting installations on the technology, design and operational side. Add to selected open points in the digital chain like better design processes.
- Align this with the still growing understanding of user needs; here specially build upon results from earlier IEA projects (e.g. IEA SHC Task 61 / EBC Annex 77).
- Integrate competencies: Bring the different involved players (electric lighting, façade, industry, controls) so far not connected on low carbon solutions together in workshops and specific projects. Create added value also by transferring into standardization, regulations and building certificates.
- Foster the broad implementation of low carbon solutions, also and especially in developing countries, by promoting tailored "Low Tech – High Impact Solutions" through demonstration, design guidelines, and workshops.

To accomplish these objectives, the work plan of IEA SHC Task 70 / EBC Annex 90 is organized according to the following four main subtasks.

Subtask A: Low Carbon Lighting and Passive Solar: Scenarios, Strategies, Roadmaps.
Subtask B: Visual and non-visual User Requirements.
Subtask C: Digitalized Lighting Solutions (Technology & Design Tools / Process).
Subtask D: Application and Case Studies.

EXECUTIVE SUMMARY

To better understand the current status quo of LCA with respect to lighting technology, including electric lighting as well as daylighting and façade issues

- a survey among 15 participating countries of IEA SHC Task 70 / EBC Annex 90 “Low Carbon, high comfort integrated lighting” and
- a review of scientific literature based on 59 relevant research articles

have been conducted.

The conducted survey investigated the general level and kind of decarbonization efforts and LCA use in the overall building section, of which lighting and façade/daylighting aspects are part of. The main identified open issues in integrating Life Cycle Assessment (LCA) better into building practice are the need for more accessible LCA tools and databases, increased transparency in LCA methodologies, lack of LCA focus in training architects and engineers, and the complexity of LCA. There's a need for simpler tools to quantify environmental performance of projects. A need for carbon emission limits in building regulations is expressed, similar to energy consumption limits.

The scientific literature shows that future trends in Life Cycle Assessment (LCA) for luminaires emphasize a more integrative approach across product development stages, incorporating circular economy principles and modular design. Designing for disassembly and reassembly enhances maintenance efficiency and reduces environmental impact. Modular LED luminaires can lower carbon footprints by approximately 30 % through component replacement instead of full unit disposal. Despite these benefits, challenges remain, including labour costs, certification gaps, and limited data transparency from manufacturers. Standardized data collection and closer collaboration between manufacturers and environmental analysts are essential for improving LCA accuracy and sustainable lighting design. Façade / daylighting systems have been found to be less studied in literature, with most of the focus on windows, frames and glazing, while shading systems remain underexplored. Simulation-based studies dominate over real-case studies and applications. Regardless of lighting scenarios, the use phase has the highest environmental impact, emphasizing the need for efficient planning, energy-conscious operation, and proactive maintenance to sustain performance.

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1 Introduction

Lighting accounts for 15 % of global electricity consumption and 5 % of related global greenhouse gas emissions. The LCA (Life cycle assessment) methodology is usually applied to assess the environmental impacts in the entire life cycle of products. This covers all stages from raw material extraction, production and manufacturing, use and end of life (EoL), generally following the standard procedures of ISO14040/44 and ISO14067. To better understand the current status quo of LCA with respect to lighting technology, including electric lighting as well as daylighting and façade issues

- a survey among participating countries of IEA SHC Task 70 / EBC Annex 90 “Low Carbon, high comfort integrated lighting” and
- a review of scientific literature

have been conducted.

From the survey, conducted in the period September 2023 throughout July 2024, an overview on the rather practical side of LCA implementation in participating countries was derived in chapter 2. This covers the level and state of art of LCA implementation addressing e.g. publicly available data and methodologies, existing regulations and regional impact factors. The investigated principal indicator was the global warming potential (GWP). Specifically, section 2.1 addresses general aspects of decarbonization LCA approaches on building level in a cross-country comparison. This is then followed in 2.2 by findings in the field of electric lighting and in 2.3 on façade / daylighting level. The presentation of subjective judgements of the national contact persons, who answered the questions, wraps up the chapter on the survey in section 2.4.

The literature review documents and discusses in chapter 3, on a more fundamental level, the current state of scientific literature on life cycle analysis (LCA) for lighting related products and systems. It aims at identifying key factors to consider. The literature was classified into categories of daylight and artificial lighting systems and is further divided by analyses focused on specific components and case studies conducted either in real-world applications or theoretical simulations. Alongside these product categories, the review as well evaluated relevant standards and national norms. The literature analysis also addressed BIM workflows which claim to seamlessly incorporate LCA analysis into the comprehensive planning process in the lighting field. Based on an introduction of the methodology in section 3.1, some statistics in section 3.2 the findings from the review are then presented and discussed for electric lighting in chapter 3.3, for façade and daylighting aspects in chapter 3.4.

Chapter 4 presents a conclusion and an outlook from both activities. Overall, it is to be mentioned that the report represents a snapshot of a fast-developing field, which turns more and more embodied and operational carbon into one of the main KPIs for assessing and steering the future development of our built environment. Conclusions and findings should be put into the context of possibly more recent findings after publication of this report.

2 Survey on LCA and Lighting in 15 countries

2.1 Survey design and participating countries

The survey, conducted in the period September 2023 throughout July 2024, aimed at obtaining a practical overview and common understanding of the level of LCA in participating countries of IEA SHC Task 70 / EBC Annex 90 to assess the environmental impacts of lighting. The survey addresses in 2.2 general decarbonization and LCA aspects. This is then followed in 2.3 by findings in the field of electric lighting and in 2.4 on façade / daylighting level. The presentation of subjective judgements of the national contact persons, who answered the questions, wraps up the survey in section 2.5. The survey template is attached in the appendix.

Questionnaires from 15 participating countries were filed, including Austria, Brazil, Belgium, China, Denmark, Germany, Greece, Italy, Japan, Norway, Poland, South Africa, Sweden, Turkey and the United States. The key findings are presented in the following section. A full collection of answers to the specific questions of the survey can be obtained from the authors. Some additional information were provided directly by participating experts.

2.2 General LCA aspects

<u>Level and kind of LCA use (Question 1.a))</u>

The level of LCA use varies in the countries from “None” with 13 % up to “Mandatory” in 20 %. The approaches are in 27 % “Only established” and “Partially mandatory” in 40 %, rf. Figure 1. The survey results show that, most of the countries have established LCA methodologies in the building sector, but so far only Denmark, Sweden and South Africa have made it completely mandatory.

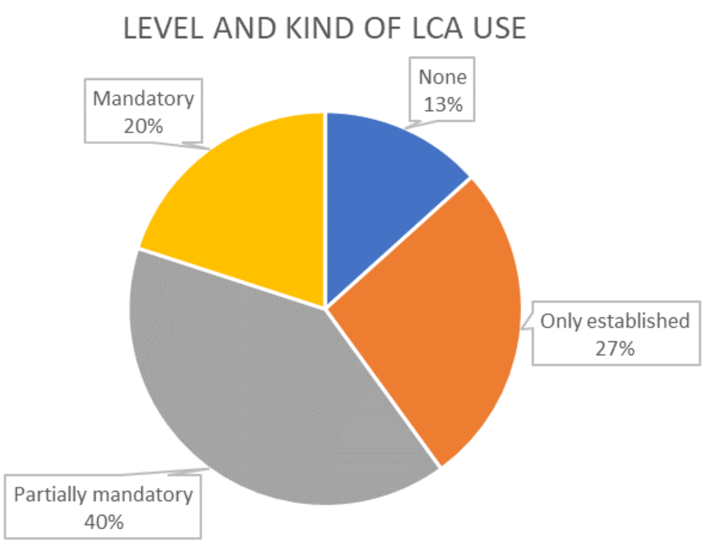

Figure 1: Level and kind of LCA use (2024, June).

<u>Free provision of rating instruments (Question 1.b))</u>

Building Practice is supported with 87 % by authorities in most of the countries by some free available databases and rating instruments, as depicted in Figure 2.

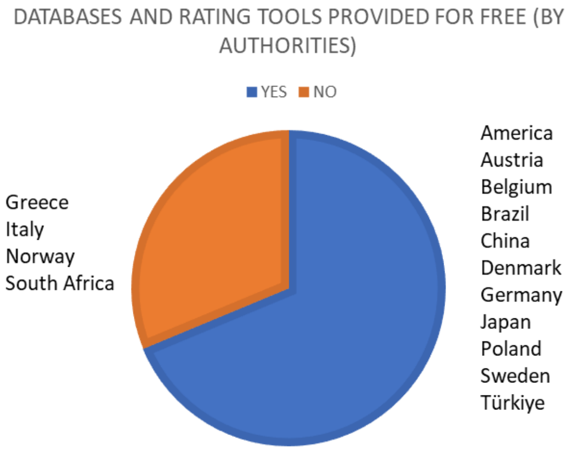

Figure 2: Databases and rating tools provided for free (by authorities) (2024, June).

CO_2 pricing (Question 1.c))

Many countries have, as displayed in Figure 3, explicitly priced CO_2 emissions. Sweden has the highest CO_2 price at 120€/t and China the lowest at 9.80€/t. CO_2 is currently not priced in Brazil and Türkiye.

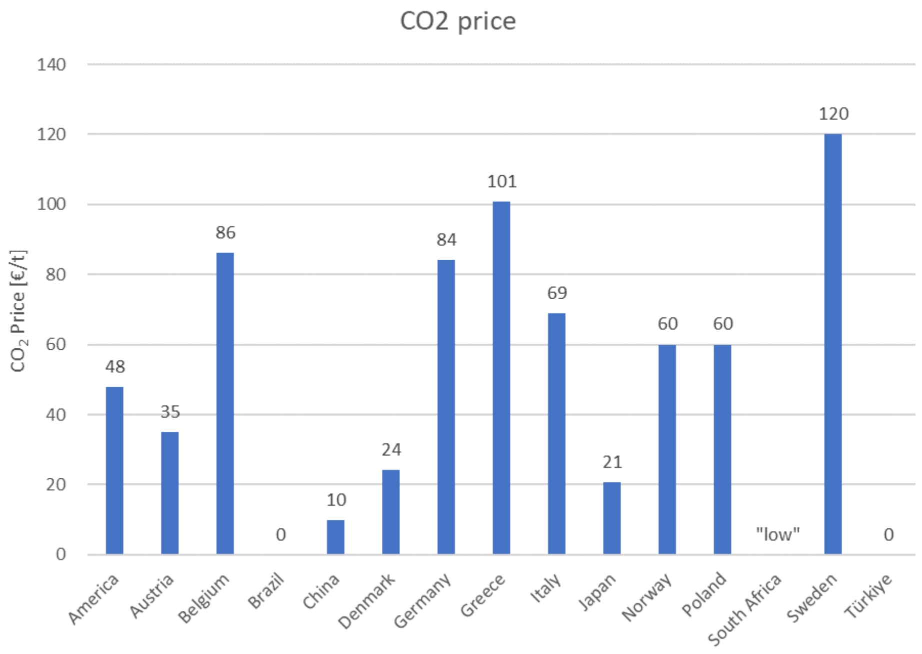

Figure 3: CO_2 Price among all countries analyzed (2024, June).

Relevant indicators (Question 1.d))

Most countries take GWP (global warming potential) as the main indicator of LCA, sometimes considering environmental indicators such as AP (acidification potential of land and water) and PENRT (total use of non-renewable primary energy resources) as well.

Energy ordinances about operational energy? (Question 1.e))

All the countries have codes, standards or certificates for building energy consumption. From these easy estimates of the operational carbon demand can be derived by weighing with appropriate carbon emission factors of the energy sources used.

Impact on real estate value? (Question 1.f))

Based on the responses provided, it appears there is a consensus that the current impact of Life Cycle Assessments (LCAs) on real estate value is minimal or negligible. However, high energy efficiency buildings are identified as more market valuable due to their lower operational energy and carbon. There is little to no awareness or internationalization of embodied environmental flows into building cost, but there is an expectation this will change soon due to emerging regulations on embodied greenhouse gas emissions. Buildings that are energy-inefficient may have lower rental/sale values. The LCA is starting to gain attention due to greenhouse gas emission inventories and ESG. Once ETS-2 is introduced, GWP estimation is expected to significantly impact construction and real estate. Buildings with higher energy ratings or national green certificates may currently have higher real estate values. Overall, the real estate market is not evaluating LCAs significantly yet, but there is anticipation of this changing in the coming years due to regulatory and environmental pressures.

Where are authorities heading? (Question 1.g))

All the countries are starting to pay more attention to carbon emissions, carbon neutrality, but at the moment there are no mandatory measures on carbon emissions in each country, but many people think there may be in the medium term. And some countries already have subsidies and financial requirements.[1]

Do people have experiences / sensitivity to CO_2 and building operation? (Question 1.h))

People generally have a greater awareness and sensitivity towards energy usage in buildings rather than CO_2 emissions or embodied environmental impacts. This awareness is largely driven by energy efficiency certifications and regulations. However, awareness of embodied environmental impacts and greenhouse gas emissions, though less prevalent, is growing, particularly among professionals in the field. Large construction companies and environmental certification bodies are leading in this regard.

[1] Note from the authors: The EU will be requiring assessing and publishing the life cycle GWP of buildings in the near future, following: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive]. It is planned: for large new buildings from 2028, for all new buildings from 2030.

The requirement for energy identification documents for occupancy permits also reflects growing regulatory attention to building energy and carbon performance.

What are the main open issues? (Question 1.i))

The main issues in integrating Life Cycle Assessment (LCA) into building practice include: the need for more accessible LCA tools and databases, increased transparency in LCA methodologies, lack of LCA focus in training architects and engineers, and the complexity of LCA. There's a need for simpler tools to quantify environmental performance of projects. LCA is currently mostly for specialized professionals, suggesting a need for more widespread education and understanding. The carbon footprint of our lifestyle and housing needs to be better communicated. There's a call for carbon emission limits in building standards, similar to energy consumption limits. Finally, there's a need for clear regulations, incentives for carbon-neutral activities and better use of recycled materials.

2.3 Electric Lighting

2.3.1 LCA Databases

Most countries have developed databases for LCA analysis. Austria, Belgium, Brazil, China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, The Netherlands, Norway, Poland, Portugal, Slovenia, Spain, Sweden, United States and as well the European Union provide free databases (Table 2 in the appendix). Although some institutions and organizations can conduct life cycle assessments of specific products, and issue professional EPDs (Environmental Product Declaration), it is a complicated task for lighting products due to the numerous and delicate components. Many databases only contain basic environmental indicators of construction materials and components and only the databases of China, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Poland, Sweden and EU so far contain luminaires. Czech, Danish, Finnish, French, Irish, Italian, Dutch, Norwegian, Polish, Portuguese, Slovenian, Spanish, EU databases provide EPDs for various building component and products. The databases of Denmark, Germany, Ireland, Italy, Norway and the European Union are more detailed and comprehensive than others, including the materials, weight, life, power, and carbon emissions at multiple important life cycle stages, and indicate the criteria, following e.g. EN 15804:2012 + A2:2019.

2.3.2 LCA Rating tools

Austria, Belgium, Brazil, China, Denmark, Germany, Sweden and The Netherlands provide free rating tools (see Table 3 in the appendix). Most existing and well-established rating tools are for the life cycle assessment of the whole building, cannot be used for the life cycle assessment of a single product. China provides free software for calculating product carbon emissions, called “nenghaobao”, developed by Alibaba, relying on CPCD (China Products Carbon Footprint Factors Database), with a complete logic and framework, but is not fully completed for use. Two international rating tools allow the calculation of embodied carbon of materials and whole buildings (or part of it) considering the context of different countries: Embodied Carbon in Construction Calculator (EC3) tool from Carbon Leadership Forum and Excellence in Design for Greater Efficiencies (EDGE) from Internacional Finance Corporation (IFC).

Along with the rating tools listed above, there are different commercial databases and assessment tools like SimaPro (The Netherlands), Ecoinvent (Switzerland), GaBi (Germany) and efootprint (China).

2.4 Façade (Daylighting)

2.4.1 LCA Data

Compared with electric lighting, although the relevant databases are unchanged, there are more EPDs and more types because the structure of facade such as windows is simpler and there are fewer components (Table 4 in the appendix). The databases of Austria, Belgium, China, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Norway, Poland and Sweden have facade-related products. Similar to 2.3.1, the databases of Denmark, Germany, Ireland, Italy and Norway are more detailed and comprehensive than others, including the materials, weight, life, power, and carbon emissions at multiple important life cycle stages.

2.4.2 LCA Rating tools

Since both are used to assess the environmental impact of products, the rating tools for facade are the same as the those used for electric lighting (2.3.2).

2.5 Personal judgment of national contacts / experts

In the last section of the survey the persons answering the survey were asked for their personal judgement and conclusions. This revealed a diverse yet converging perspective on the status and development of decarbonization and the application of Life Cycle Assessment (LCA) methods in the lighting and facade sector.

In the majority of the countries, the facade sector appears to be more advanced than the lighting sector in terms of LCA application. For instance, in Brazil, the LCA concept is still new but is expected to grow strongly due to the push for low/zero carbon targets. Similarly, in China, it's predicted that standards for low carbon lighting will become mandatory, just like energy consumption requirements. In Austria, specifically for the solar shading perspective, PVC free products are requested; generally, LCA is judged as of not a major concern yet.

The survey also revealed a universal call for more extensive LCA databases and guidelines. Countries like Denmark, Germany, Greece and Spain highlighted the need for more comprehensive and accessible information on the environmental impact of products in the lighting and facade sector. Germany, in particular, stressed the need for a “middle ground” in LCA approach and better integration of LCA in design processes.

The role of legislation and government initiatives in driving the implementation of LCA methods was emphasized in multiple responses. Sweden identified the legislation of A1–A5 stages of LCA as a driving factor, while Norway mentioned support schemes for re-use mapping and feasibility studies in the construction industry.

The lighting sector was identified as a significant contributor to the carbon footprint in building life cycles, particularly due to high energy consumption. This was highlighted by Greece, South Africa and Spain, which called for better design and improved energy efficiency in lighting.

Recycling and reusing components was another common theme, with Poland and Japan mentioning the importance of considering these factors in facade and lighting design.

In conclusion, while there are regional differences in the application and understanding of LCA methods in the lighting and facade sector, the overarching trend is towards increased awareness and implementation. The need for better LCA databases, guidelines, and legislation, as well as the focus on energy efficiency in lighting design, are common across many countries.

3 Literature review of LCA in lighting

3.1 Analysis Method

This analysis covered scientific literature from the past decade (2014–2025) and included data from both, independent and publisher-owned databases including ScienceDirect, Web of Science, Taylor & Francis and the Journal of Lighting Research and Technology. A systematic literature search was conducted using a keyword-based method (TAK–Text, Abstract, Keyword), where finally 59 relevant research articles were selected for inclusion in the analysis after a detailed screening process.

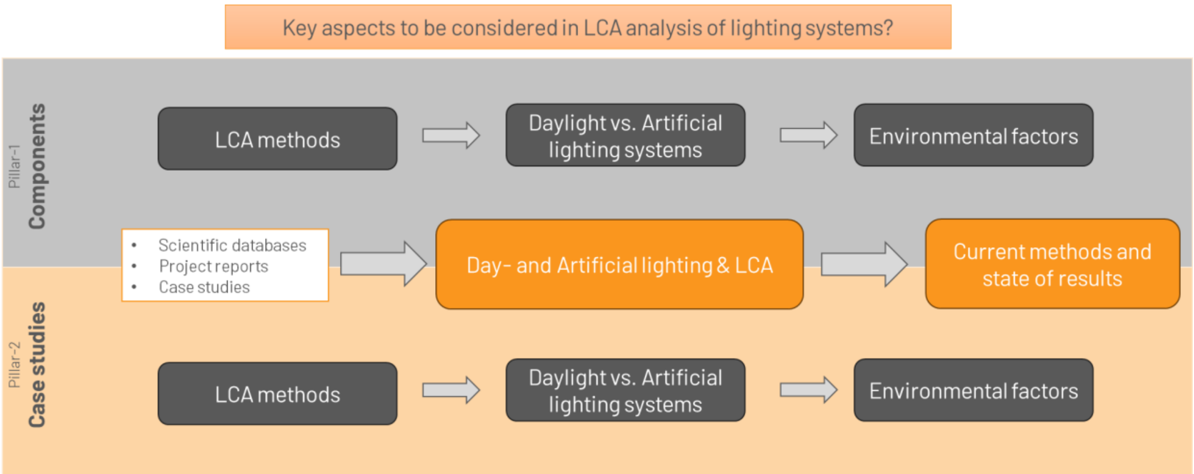

Figure 4: Scientific literature review – analysis method.

The selected papers were grouped into artificial lighting systems and daylighting systems, and after that further separated into a group of papers including LCA studies focusing on lighting components and papers focusing more on case-studies of artificial lighting systems. The same separation was done for the selected papers belonging to daylighting systems into a group of papers focusing on LCA studies on daylight/shading/façade systems and another group of papers focusing on LCA case studies.

All papers were analysed in detail regarding the applied LCA methods – including software, databases and standards – to extract statistical insights from LCA studies conducted in the field of lighting systems. Each paper was reviewed for the environmental impact categories considered and classified into three groups: artificial lighting components, daylighting systems and combined day- and artificial lighting systems.

The various components of artificial lighting systems (e.g. luminaires, LED drivers, power supplies) and daylighting systems (e.g. windows, frames, glazing, shading elements) assessed in these studies were also examined to identify the key elements most commonly analyzed in LCA research. Based on this overview, recommendations have been proposed to guide future investigations and highlight areas requiring further research.

Based on the categorized analysis of all papers and their separation into the highlighted subgroups, following **research questions** have been answered by analyzing the selected paper study and summarized in this report:

- RQ1: What are the key aspects considered when it comes to **LCA of lighting components**?
  - Applied LCA-tools, methods and standards, functional units, Environmental Impact categories.
  - Most considered lighting components in LCA studies?
- RQ2: What are the key aspects considered when it comes to **LCA of lighting systems (case studies)**?
  - Applied LCA-tools, methods and standards | Functional units | Environmental Impact categories.
  - Most considered lighting components in LCA studies?
  - Where are the boundaries of most LCA lighting case studies?
- RQ3: What are the key aspects considered when it comes to **LCA of daylighting/shading systems**?
  - Applied LCA-tools, methods and standards | most considered components | Functional units | Environmental Impact categories.
  - Most considered daylighting/facade components in LCA studies?
  - Where are the boundaries of most LCA daylighting studies?
- RQ4: How can LCA-methods be further elaborated towards a better integration into integral lighting design?
  - Workflows & Tools: Which design workflows exist to consider LCA in the early-stage design?
  - What efforts are available in the BIM-context?

3.2 Statistics

Literature network

Based on an extensive literature review, 59 analysed papers were examined and visualized using the bibliometric analysis tool VOS viewer. The keyword cloud emphasizes the most frequently occurring terms, represented by both the letter size and node size in the visualization. Life cycle assessment (LCA) is shown to be particularly significant as a method for evaluating environmental impact. Notably, this type of analysis is most associated with components of artificial lighting systems, identified as key terms grouped within a gray-colored network.

A second main section can be found in the field of building-related LCA analysis with special regard to daylighting products, visualized within a violet-colored network. This cluster frequently examines case studies, with emphasis on windows, energy assessments, and materials. While the gray and violet networks largely focus on component-based assessments, the third network, highlighted in yellow, represents studies at the lighting system level. This network also centers on artificial lighting, along with aspects of production, energy consumption and material reduction.

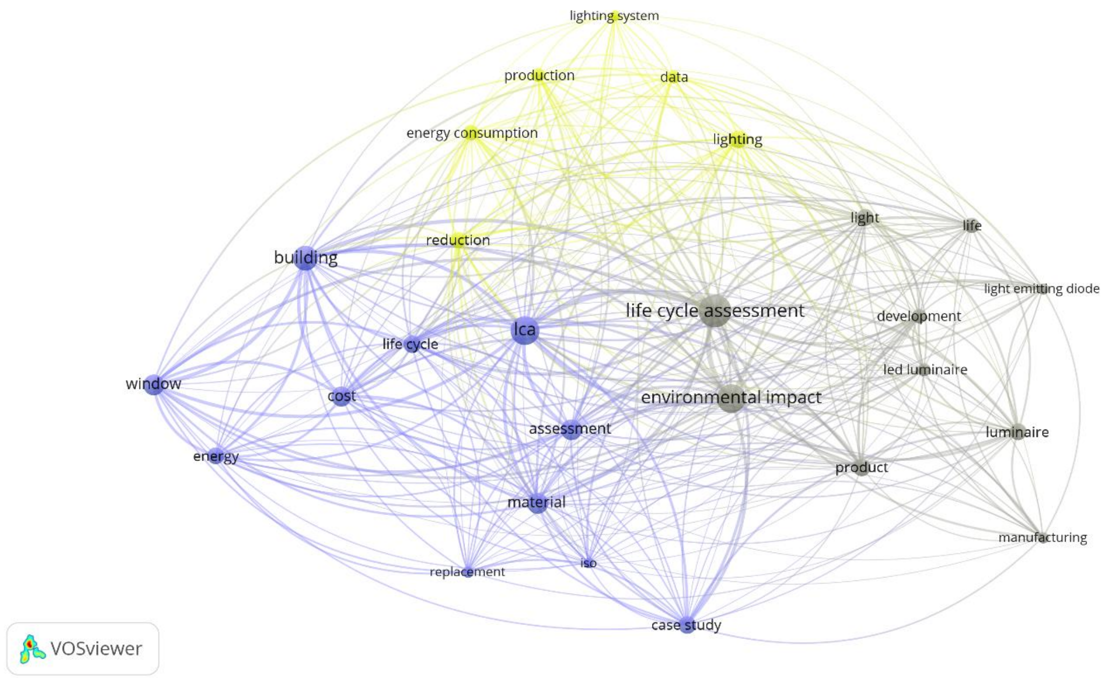

Figure 5: Resulting network diagram among all 63 analyzed articles.

Paper statistics

Additional statistical insights emerge when looking at Figure 6: by examining the distribution of selected publications across search engines: **Web of Science** yields the highest number of relevant publications in the area of circularity and life cycle assessment (LCA) for lighting products. **ScienceDirect** and **Taylor & Francis** follow, though with nearly half the count found on Web of Science. Interestingly, while the journal **Lighting Research & Technology** (LRT) specializes in lighting, it offers the fewest relevant papers. This is likely due to its narrower focus on artificial lighting and limited reach.

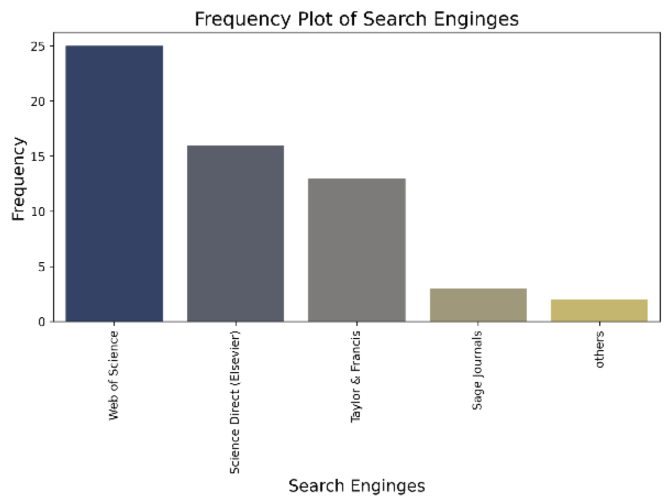

Figure 6: Number of papers found per Search Engine.

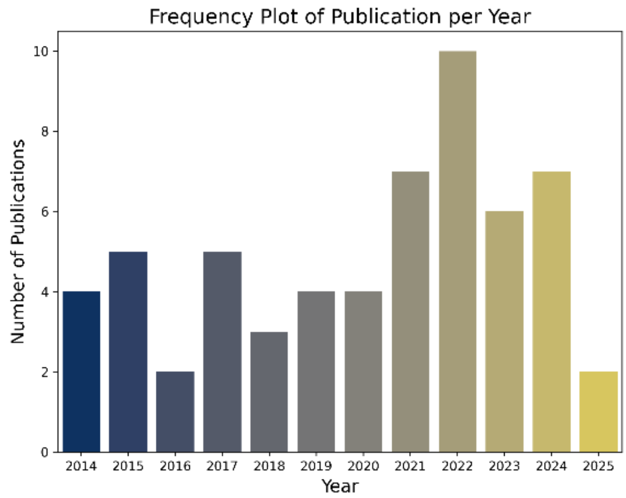

Figure 7: Distribution of selected papers among the year of publication.

When analyzing the number of published papers per year within the search period (see Figure 7:), it reveals a clear trend of increasing publications in recent years, highlighting the growing importance of this topic in lighting research and design. Especially the year 2022 reports a peak number in published papers, but this shows a similar trend also in other research fields, where the corona pandemic probably showed their influences.

For 2025, only the months until March are considered in the search period, therefore it can be expected by extrapolating the current number until end of the year to reach a similar or even higher number on relevant publications again for this year.

Distribution of analysis fields and their interrelations

The diagram in Figure 8 illustrates the connections among the analysed categories – daylighting, artificial lighting and their combination including controls – alongside various application methods, such as simulation-based studies, theoretical assessments and real case studies. The diagram highlights a high volume of simulation-based studies focused on daylighting, with a similar distribution of theoretical assessment studies across both daylighting and artificial lighting fields. Real-case studies are primarily associated with artificial lighting systems. Generally it shows, that the LCA studies considering day- and artificial lighting as well as studies on controls are very limited.

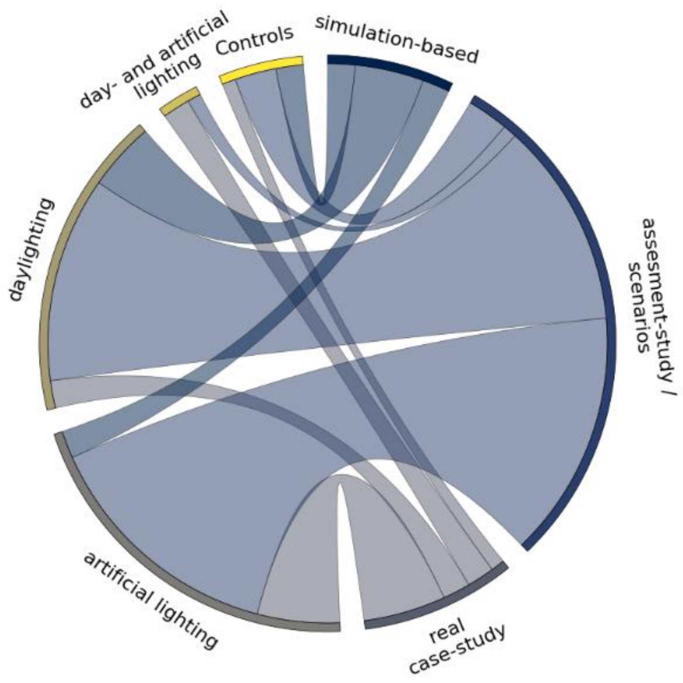

Figure 8: Content interrelation of works between the different analyzed papers.

A more detailed analysis of the researched literature is shown in Figure 9, which connects the different categories (artificial lighting, daylighting, day- and artificial lighting, controls) with the used LCA tools and their databases behind. Thus, SimaPro is well established in both, day- and artificial lighting, while openLCA is clearly focusing on artificial lighting. LCA for experts is also equally separated between daylighting and artificial lighting. Also here, the category of "no software named" is quite high, which accounts for more individual tools, methods applied or more simplified approaches for environmental balancing (Excel sheets etc.).

On the right side, the relevance of the different databases is shown in relation to the applied simulation tool and the analysis category. Therefore, a clear overlap is seen for Ecoinvent as a database mainly applied for SimaPro, in both day- and artificial lighting, and GaBi LCI database as a basis for LCA for Experts tool, which also applies on both day- and artificial lighting. A high amount, which uses no specific database, might be connected to custom inventory datasets specifically provided by a manufacturer or for a specific study, and is also connected with the papers, which mention no dedicated software tool.

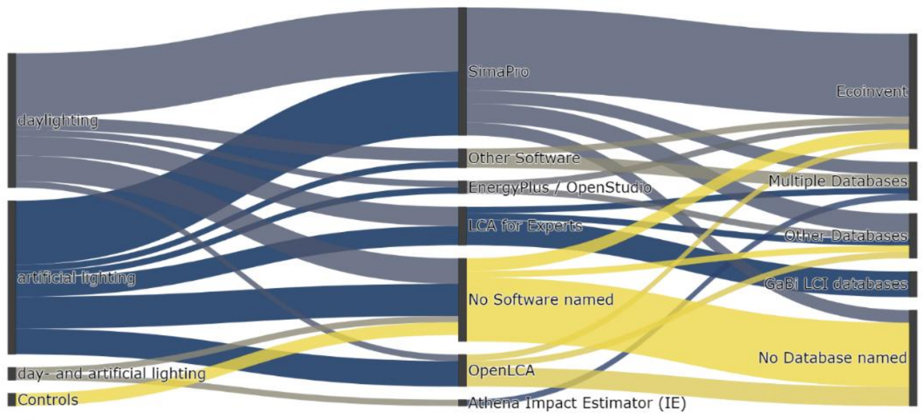

Figure 9: Content interrelation of works between the different analyzed papers.

3.3 Electric lighting

3.3.1 LCA Databases

Across all 57 selected articles, the Ecoinvent is the most frequently used database across studies, providing robust life cycle inventory data for lighting systems, including LED luminaires and building materials (see Figure 10). Also, the GaBi database has been evaluated as mainly used one, commonly applied in endpoint life cycle impact assessments, particularly for emissions and human health impacts. Other databases, like custom inventory databases are very specific and rely on tailored inventory data specific to manufacturing processes, especially for modular luminaires and small-scale enterprises, where else several works also accessed multiple databases in their work.

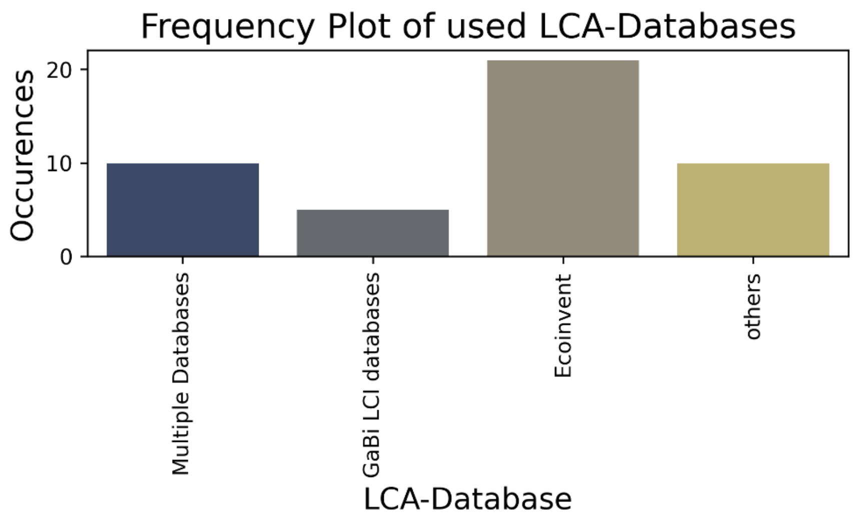

Figure 10: Mainly applied databases in the literature reviewed.

LCA studies rely on **standardized databases** like **Ecoinvent** for consistent and harmonized datasets, ensuring methodological reliability. In contrast, **custom inventory data** offer flexibility by accurately modeling unique manufacturing processes or regional conditions, benefiting small enterprises and emerging technologies. However, custom data often lack standardization, making comparability across studies challenging. While **Ecoinvent** has improved regionalized datasets, achieving similar accuracy with custom data requires significant effort and expertise (Ferreira, 2021; Mazzei, 2023).

3.3.2 LCA Software tools

Several specialized software tools are used for conducting LCA analysis, whereas each offers unique features: **GaBi** and **SimaPro** are leading commercial LCA software solutions with extensive built-in databases, while **openLCA** provides an open-source alternative with flexibility for custom modelling.

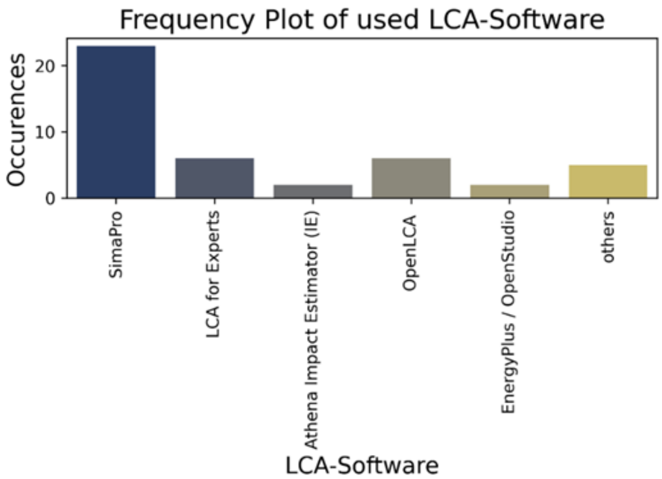

Figure 11: Mainly applied LCA-tools in the literature reviewed.

By looking at the different software tools applied in individual studies in the lighting field (see Figure 11), also SimaPro is the most used LCA-tool, particularly for LED luminaires and lighting systems, with integrating the Ecoinvent database for life cycle inventory data (Ibrahim, 2024; Dillon, 2020).

Besides GaBi, which applies to endpoint life cycle impact assessments, including human health impacts and emissions throughout the life cycle, also the open-source tool LCA for Experts (openLCA) is widely used in the lighting field. BIM-integrated frameworks are emerging and incorporate LCA-tools like OneClick LCA and Tally from GreenBuildingStudio to evaluate environmental impacts of building materials and systems, including lighting. These allow LCA workflows to be easily integrated into state-of-the-art BIM software like Archicad Revit and other tools.

EnergyPlus is regularly used as whole-building LCA methodologies to model energy consumption during the use phase, including lighting systems (Zhang, 2022). Other mentioned tools are only used limited and show not high relevance in the lighting field. Also, relevant publications in the field of daylighting did not yield relevant results for LCA software.

3.3.3 Standards and regulations

From a standards and regulations perspective, among international standards, ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework and ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines, which establish the basic framework and principles of LCA, state that LCA should include four parts: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation.

Relevant standard for Type III environmental product declarations is ISO 14025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and procedures.

Product carbon footprint accounting standards include ISO14067:2018 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification and PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

At the corporate, organizational activity level, the relevant carbon footprint standard is the ISO 14064 family of standards:

ISO 14064-1:2018 Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. This document specifies principles and requirements at the organization level for the quantification and reporting of greenhouse gas (GHG) emissions and removals. It includes requirements for the design, development, management, reporting and verification of an organization's GHG inventory.

ISO 14064-2:2019 Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements. This document specifies principles and requirements and provides guidance at the project level for the quantification, monitoring and reporting of activities intended to cause greenhouse gas (GHG) emission reductions or removal enhancements. It includes requirements for planning a GHG project, identifying and selecting GHG sources, sinks and reservoirs (SSRs) relevant to the project and baseline scenario, monitoring, quantifying, documenting and reporting GHG project performance and managing data quality.

ISO 14064-3:2019 Specification with guidance for the verification and validation of greenhouse gas statements. This document specifies principles and requirements and provides guidance for verifying and validating greenhouse gas (GHG) statements. It is applicable to organization, project and product GHG statements.

IEC 63366, which is being prepared by IEC, will be used for product category rules for life cycle assessment of electrical and electronic products and systems.

In addition, there are ISO 22057:2022 – Sustainability in buildings and civil engineering works – Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM) and other relevant standards.

The most well-developed standard is the European standard system at the national and regional levels. Europe has formulated a series of standards:

EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method, specifies the calculation method, based on LCA and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment. The standard is applicable to new and existing buildings and refurbishment projects.

EN 15804:2012 + A2:2019 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, provides core product category rules (PCR) for Type Ⅲ environmental declarations for any construction product and service, defines the indicators to be declared, describes which stages of a products' life cycle are considered in the EPD and which processes are to be included in the life cycle stages, includes the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment, and includes the rules for reporting environmental and health information, that is not covered by LCA for a product, construction process and construction service.

EN 50693:2019 Product category rules for life cycle assessments of electronic and electrical products and systems, defines product category rules (PCR) for electronic and electrical products and systems (EEPS), and specifies the process and requirements on how to conduct life cycle assessment in the context of environmental declarations.

Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) from EU Commission Recommendation 2021/2279. The PEF and OEF are the EU recommended LCA based methods to quantify the environmental impacts of products (goods or services) and organisations.

Level(s) – European framework for sustainable buildings. It provides a common language for assessing and reporting on the sustainability performance of buildings and can be applied to residential buildings or offices.

Corresponding to ISO 14040/14044, China has formulated and proposed GB/T 24040 "Environmental Management – Life Cycle Assessment – Principles and Framework" and GB/T 24044 "Environmental Management – Life Cycle Assessment – Requirements and Guidelines", which provide initial understanding and promotion of life cycle assessment. In the lighting area, the national standard "Standard for carbon footprint quantification of lighting product" is being compiled to refine the specific situation of lighting products.

3.3.4 LCA Method

Overall, two key approaches can be mentioned in the context of LCA: **cradle-to-grave** and **cradle-to-cradle**. The **cradle-to-grave** model assesses impacts from raw material extraction to end-of-life disposal, covering production, use and waste management. In contrast, the **cradle-to-cradle** approach promotes a circular economy by designing products for recyclability and reuse, minimizing waste. Among the various LCA methods, the majority of published studies utilize a cradle-to-grave approach. Some studies also incorporate combined evaluations, such as LCA with energy assessments when it comes to whole-building LCA methodologies (Zhang, 2022), or LCA with Life Cycle Costing (LCC).

The **Life Cycle Costing (LCC) method** is used alongside **Life Cycle Assessment (LCA)** to evaluate both the economic and environmental impacts of a product over its lifespan. LCC considers costs related to raw materials, manufacturing, energy consumption, maintenance and end-of-life disposal, providing a comprehensive financial perspective.

When applied to **LED luminaires**, LCC helps assess long-term cost savings from energy efficiency and durability, complementing LCA's focus on environmental sustainability. This combined approach supports informed decision-making for eco-friendly and cost-effective lighting solutions (Picardo, 2023).

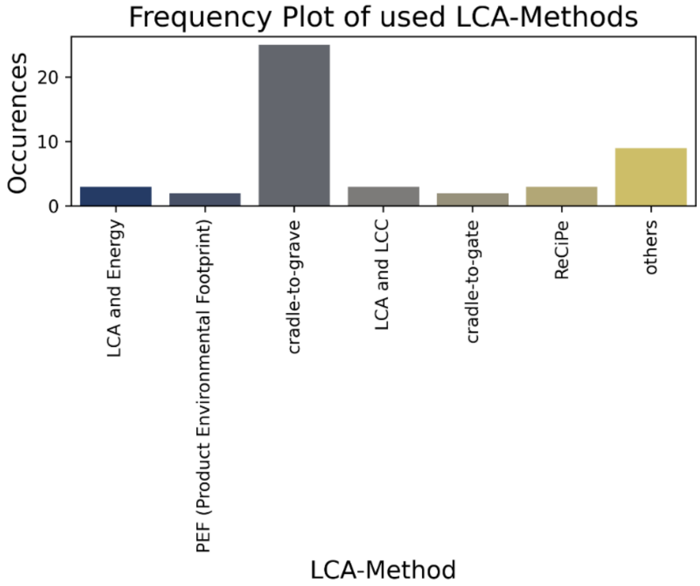

Figure 12: Mainly applied databases in the literature reviewed.

The **Product Environmental Footprint (PEF)** is a standardized life cycle assessment methodology developed by the European Commission to ensure consistency and comparability in environmental impact assessments. It evaluates products from raw material extraction to end-of-life, using standardized impact categories such as global warming potential and resource depletion. Applied to **industrial luminaires**, PEF helps identify environmental hotspots, optimize material choices, and support sustainability efforts. By providing reliable and transparent data, PEF enhances eco-design strategies and regulatory compliance (Wu, 2021).

The **ReCiPe method** is a widely used impact assessment approach in **Life Cycle Assessment (LCA)** that translates environmental emissions into measurable impact categories. It operates at two levels: **midpoint**, which evaluates specific environmental issues like climate change and ozone depletion, and **endpoint**, which assesses broader damage areas such as human health, ecosystems, and resource availability. **ReCiPe** helps standardize LCA results, making it useful for evaluating the environmental footprint of products, including **LED luminaires**, by providing a comprehensive view of their sustainability impacts (Şengül, 2017).

3.3.5 Environmental Impact categories applied

For impact assessment, methods like **ReCiPe** play a crucial role in translating emissions into measurable environmental effects. ReCiPe operates at two levels: midpoint, which focuses on specific environmental issues such as climate change, eutrophication and toxicity and endpoint, which assesses broader damage categories, including human health, ecosystems and resource depletion. This method enhances LCA results by offering a structured approach to quantify environmental burdens. Other methods, such as CML (midpoint-focused) and Eco-Indicator 99 (endpoint-focused), provide alternative frameworks for impact evaluation.

Table 1: Environmental impact categories mentioned in the literature review.

Abbrev.	Name	Description
ADP	Abiotic Depletion Potential	Measures the depletion of non-living (abiotic) resources like minerals, fossil fuels, and metals.
AP	Acidification Potential	Refers to the potential for acidification of soil and water due to emissions like Sulfur Dioxide (SO_2) and Nitrogen Oxides (NO_x).
CED	Cumulative Energy Demand	Represents the total energy demand throughout the life cycle of a product or process, from resource extraction to disposal.
EP	Eutrophication Potential	Measures the impact of nutrient enrichment (nitrogen, phosphorus) on ecosystems, leading to excessive plant and algal growth, which depletes oxygen in water bodies.
FETP	Freshwater Ecotoxicity Potential	Refers to the potential of chemicals released to the environment to harm freshwater aquatic ecosystems.
FEP	Freshwater Eutrophication Potential	Specific to the over-enrichment of nutrients in freshwater systems, leading to the disruption of aquatic environments.
GWP	Global Warming Potential	Represents the contribution of emissions to climate change, expressed in terms of CO_2 equivalents over a specific time horizon.
HHP	Human Health Particulate Matter Formation	Relates to the impact of fine particulate matter (PM) on human health, which can cause respiratory and cardiovascular diseases.
HTPce	Human Toxicity Potential, cancer effects	Indicates the potential of toxic substances to cause cancer in humans due to emissions during the life cycle of a product.
HTPnce	Human Toxicity Potential, non-cancer effects	Refers to the potential for non-cancer-related health effects in humans due to toxic emissions.
LUP	Land use potential	Measures the impact on land use, including biodiversity loss, soil erosion, and deforestation.

MEP	Marine Eutrophication Potential	Relates to the potential for nutrient enrichment in marine environments, leading to harmful algal blooms and oxygen depletion in oceans.
FW	Freshwater consumption	Reflects the total consumption of freshwater resources throughout the life cycle of a product or process.
ODP	Ozone Depletion Potential	Measures the potential of certain emissions, such as CFCs, to deplete the stratospheric ozone layer, which protects life from harmful ultraviolet radiation.
POCP	Photochemical Ozone Creation Potential	Also known as "summer smog", it measures the potential for substances to form ground-level ozone through reactions in the presence of sunlight.
POP	Persistent Organic Pollutants	Refers to the presence of long-lived organic compounds that can persist in the environment, bioaccumulate in food chains and pose risks to human health and the environment.
SP/SFP	Persistent Organic Pollutants	Refers to the presence of long-lived organic compounds that can persist in the environment, bioaccumulate in food chains and pose risks to human health and the environment.
TEP	Terrestrial Eutrophication Potential	Represents the potential for terrestrial ecosystems to be affected by nutrient enrichment, which can alter plant growth and biodiversity.

According to Figure 13, the Global Warming Potential (GWP) is the most widely evaluated environmental factor in the lighting industry, for both artificial lighting and daylighting. For artificial lighting, especially the factors of Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity Potential (HTPce,nce) and Ozone Depletion potential (ODP) are other widely used factors.

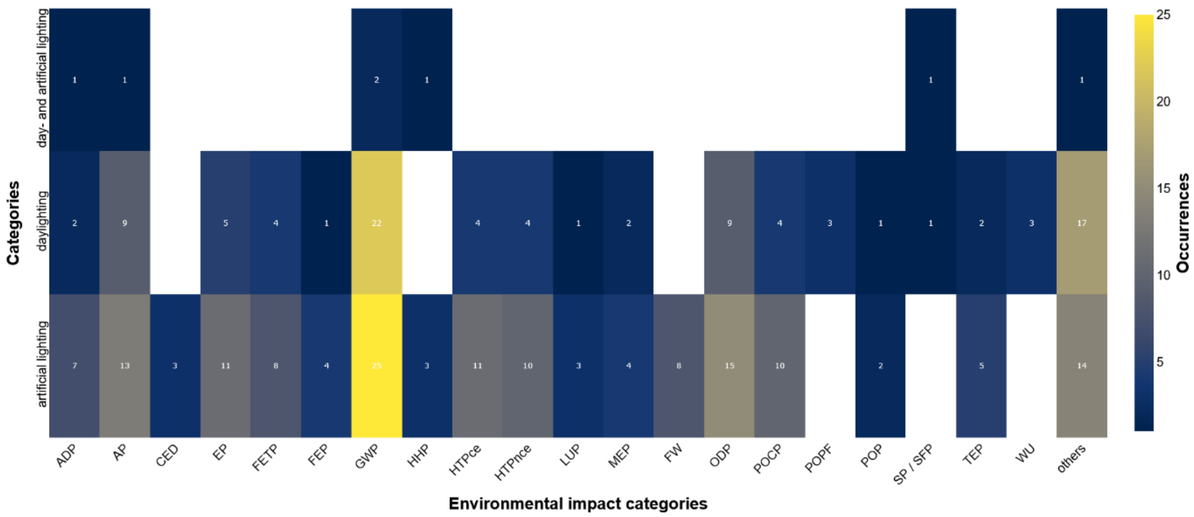

Figure 13: Overview on occurrences of Environmental Impact categories applied on LCA studies about the lighting categories.

A more detailed analysis gives the chart in Figure 13, which separates the occurrences between the different luminaire components. Again, it gives a clear focus on the impact categories of GWP, ODP, AP, ADP, EP – but also it shows a clear focus on the components of luminaire body, housing, LED drover, power supply and light source. Optical components, Sensors and Control units are very under representative. In both cases, also the category “others” is quite often defined, which shows a high number of studies with individual analysis.

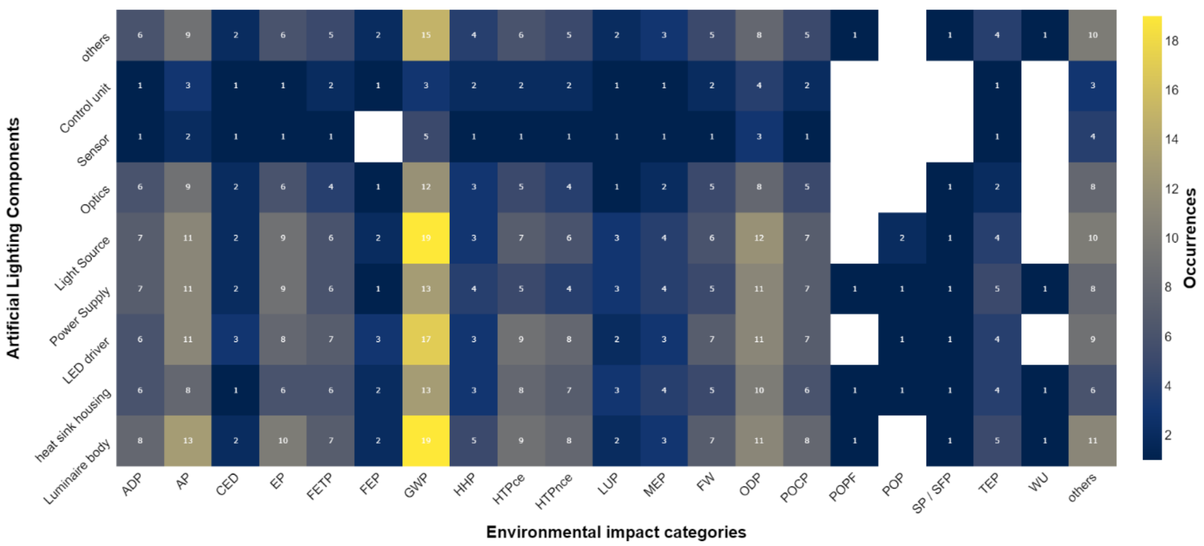

Figure 14: Overview of occurrences of Environmental Impact categories applied on LCA studies about luminaire components.

3.3.6 Key findings from LCA-studies on electric lighting systems and components

LCA methodologies for luminaires vary based on scope and application. The cradle-to-grave approach assesses environmental impacts across all life cycle stages, while the Product Environmental Footprint (PEF) offers a standardized framework for industrial luminaires. Combining Life Cycle Assessment (LCA) with Life Cycle Costing (LCC) enables a dual evaluation of environmental and economic impacts, particularly in road lighting. The CIBSE TM65 method quantifies embodied carbon in building services but differs from traditional LCA approaches. Standardization is ensured through ISO 14040/14044, which provide guidelines for consistency and comparability. Additionally, databases like Ecoinvent are widely used for inventory data in LCA studies (Mazzei, 2023; Wu, 2021; Picardo, 2023; Klüppel, 2005).

LCA studies on LED luminaires primarily focus on the LED package and driver, as these components have the highest environmental impact due to material and energy use. Research highlights the need to improve their efficiency and lifespan to reduce overall impacts. Housing and packaging are also analyzed, particularly for recyclability and waste reduction. Retrofit solutions receive significant attention for their energy savings and environmental benefits. However, optical components, end-of-life scenarios and human health impacts remain underrepresented in LCA studies, despite their importance in luminaire performance and sustainability (Ibrahim, 2024; Dillon, 2020; Liu, 2023; Casamayor, 2022; Şengül, 2017).

Optical components, such as lenses and reflectors, are underrepresented in LCA studies due to a lack of detailed inventory data on their material composition and manufacturing processes (Lozano-Miralles, 2019). Instead, optical components are often studied as part of the overall luminaire system, making it difficult to isolate their specific environmental impacts. Recycling and disposal options for optical components are rarely addressed and endpoint impacts related to light exposure during the use phase, which are influenced by optical components and significant on human health impacts, are underexplored in LCA studies.

Also, **sensors and control units** are not explicitly addressed in the LCA analysis in the literature. However, control units and sensors are implied to contribute to energy efficiency during the use phase, which is a dominant factor in environmental impacts. Therefore, their specific contribution to LCA results remains underexplored (Ibrahim, 2024). Even though, future luminaire designs are suggested to incorporate control systems with circular economy principles, no detailed LCA studies on these components are available – a gap which has to be addressed in future studies.

As **Environmental Impact categories,** LCA studies on LED luminaires primarily focus on global warming potential (GWP), analyzing carbon emissions across manufacturing, use and end-of-life phases. Energy consumption is a key factor, with the use-phase dominating environmental impacts, particularly influenced by electricity sources. Research also examines hazardous waste reductions in newer LED designs and ozone depletion and photochemical oxidant formation, especially in endpoint assessments. However, human health impacts, circular economy metrics, and social and economic factors remain underrepresented, highlighting gaps in sustainability assessments (Ibrahim, 2024; Zhang, 2022; Dillon, 2020; Şengül, 2017; Beu, 2018; Bertin, 2019).

Further analysed categories are ODP (Ozone depletion potential), AP (acidification potential), EP (Eutrophication potential), ADP-elements (Abiotic depletion potential for non-fossil resources), ADP-fossil fuels (Abiotic depletion potential for fossil resources), REPE (total use of renewable primary energy), NRE (total use of renewable primary energy). Other impacts represent together the 1,2 %.

In the LCA studies analysed, the highest percentage of environmental impact for most of impact categories is concentrated in the operational phase. The Abiotic depletion potential reaches the higher percentage during the manufacturing phase, mainly due to the use of aluminium housing, LED driver and LED module.

As **Functional units**, LCAs studies on LED luminaires commonly use lumen-hours (lm-h) as a functional unit, representing total light output over time, with 40 million lumen-hours often applied in indoor studies. A more refined approach maintained megalumen-hour, accounts for factors like lumen depreciation and dirt accumulation, making it particularly relevant for workplace lighting. Additionally, lighting distribution and installed power are used in retrofit studies to emphasize energy efficiency gains. However, research highlights the need for tailored functional units that better capture the long lifespan and high efficacy of LED systems (Ibrahim, 2024; Bertin, 2019; Beu, 2018).

While LCA studies on LED luminaires rely on various tools, databases and standards for accurate environmental assessments, SimaPro is widely used for high-power white LEDs and integrates built-in databases, while GaBi focuses on endpoint impact assessments, including human health effects. A common database is Ecoinvent, which provides robust inventory data, and custom inventory datasets tailored to specific manufacturing processes. Methodological consistency is ensured through ISO 14040/14044, while NF EN 12464-1 is applied in workplace lighting assessments, incorporating factors like lumen depreciation and dirt accumulation (Ibrahim, 2024; Şengül, 2017; Dillon, 2020; Lozano-Miralles, 2019; Bertin, 2019).

In terms of **LCA phases,** most of the LCA studies are currently focused on the operational phase, being evaluate as the most impacting phase along the lifecycle of a LED lamp. However, most of the studies are conducted considering the current energy mix of a country of use where electricity is mostly generated by fossil fuel. This is also the reason of being the Global Warming Potential (GWP) the most widely evaluated Environmental factor in current LCA studies on lighting systems.

By analyzing studies conducted for instance in France (7,2 % fossil electricity mix), the results in the LCA differs considerably, showing decrease from 93 % to 76 % of potential impact of LED downlight luminaire during the use phase in respect to other European countries (Bertin, 2019). Scenarios that take into account the changes in the energy mix over the years, identify the embodied carbon as relevant in the next decades, showing a decrease in the operational carbon. A sample of forecasted changes in the UK energy mix is shown in Figure 13 (Shanker, 2025).

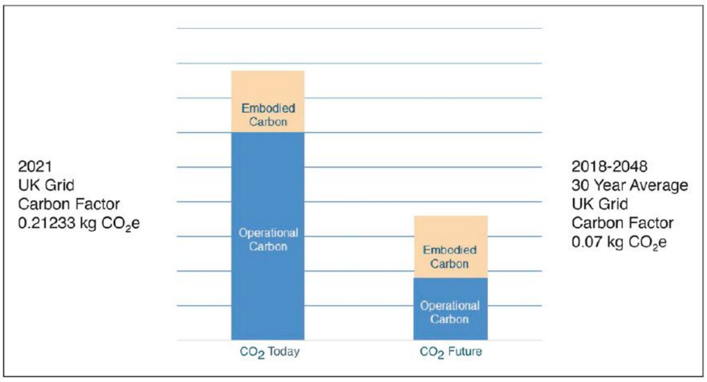

Figure 15: Comparison of embodied and operational CO_2 emissions of a luminaire evaluated using emission factors valid for 2021 ("CO_2 today" and 30-year predictions ("CO_2 Future")).

When the operational phase has less impact of the manufacturing one, a longer lifetime of a lighting system will consistently reduce the potential impact of LED products, distributing the impacts of the manufacturing over a longer period. Also LED lamps with higher lumen output should be preferred, as they could reduce the general amount of material by reducing the number of lamps required to respect the same illuminance values.

Furthermore, only few studies show how the light loss factor affects the LCA results during the operational phase. Analyzing also room dirt depreciation and luminaire dirt depreciation, a maintenance phase every 3 years should be considered.

EoL studies are mainly focused on material dismission by landfilling or recycling and most of the studies focus on a cradle-to-grave analysis. A cradle-to-cradle approach is investigated only rarely and mainly focuses on the re-utilization of the luminaire case. For LED lamps only glass and electronic equipment are usually considered in the EoL phase and present a low recycling rate (max. 30 %). However, in the overall analysis transport and EoL are the less impacting phase in relation to operational phase and manufacturing.

Future trends follow a more integrative approach, in better align application and LCA analysis in the different product development stages:

Circular Economy and Retrofit Solutions: Retrofitting luminaires with LED components reduces installed power and carbon footprint but highlight challenges such as high labor costs and lack of certification for retrofitted products (Beu, 2018). By Eco-Redesign integration, LCA is integrated into eco-design processes to identify environmental hotspots and guide towards a more sustainable redesign of lighting products. This iterative approach combines LCA with specific eco-lighting design strategies, making it compatible with existing design workflows. By this, Eco-redesign strategies focus on reducing environmental impacts by targeting specific life cycle stages and components, such as material selection and manufacturing processes (Casamayor, 2022). Future luminaire designs should integrate circular economy principles, enabling easier retrofits and reducing waste (Beu, 2018).

Whole-Building LCA: LCA methodologies are applied to entire buildings, including lighting systems, using tools like EnergyPlus to model energy consumption during the use phase. This approach integrates lighting LCA into BIM workflows for holistic environmental impact analysis (Zhang, 2022).

3.3.7 Key findings from LCA-case studies on electric lighting

3 different case studies on the adoption of modular LED luminaires are highlighted exemplary:

Industrial Application: A life cycle assessment (LCA) of a modular LED luminaire designed for industrial environments demonstrated a reduction of approximately 30 % in environmental impact categories due to replaceable components. This study highlights the benefits of modular architecture in sustainable design decision-making (Ferreira, 2021).

Lighting Installation Impact: Another case study analyzed the environmental impacts of LED luminaires in lighting installations, emphasizing their advantages over traditional systems in terms of energy efficiency and reduced life-cycle impacts (Albu, 2023).

Office Lighting Comparison: A comparative LCA of compact fluorescent lamps (CFL) and LED luminaires for office lighting showed that modular LED systems outperform CFLs in eco-efficiency, particularly during the use phase (Principi, 2014).

The following main conclusions could be made from LCA case-studies for LED luminaires from the literature:

Energy Consumption: Most studies highlight that the use phase, particularly energy consumption, dominates the environmental impacts of lighting systems, accounting for up to 93 % of total impacts in some cases (Figure 16). This is highly dependent on the energy source used during operation and emphasizes the importance of cleaner energy sources to mitigate these impacts (Tähkämö, 2014). LED systems powered by renewable energy are among the most eco-efficient lighting solutions, reducing impacts by up to 80 % compared to halogen lamps powered by grid electricity (Picardo, 2023).

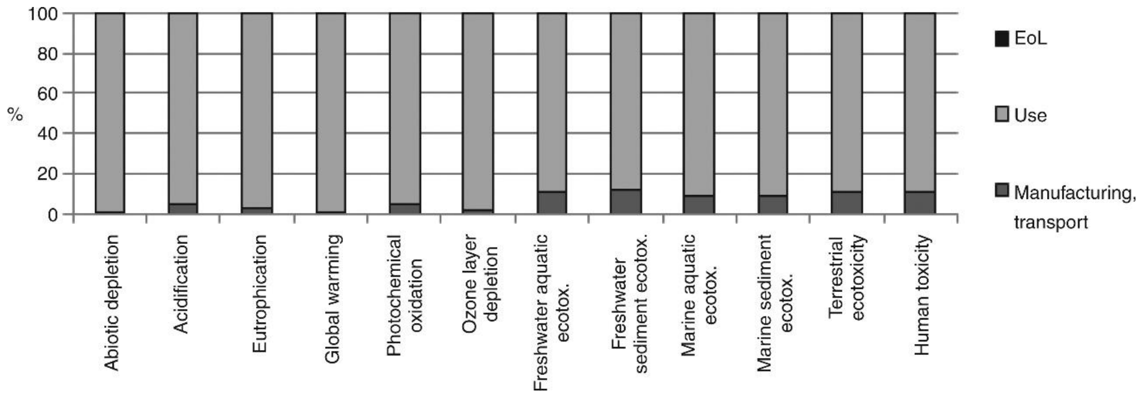

Figure 16: Environmental impacts of the luminaire life cycle into the manufacturing (includes transport), the use of the luminaire for 20 years (Finnish average electricity) and end-of-life (actual recycling scenario) (Tähkämö, 2014)

But while the use phase is dominant, manufacturing and raw material extraction also contribute significantly, particularly for advanced lighting technologies like spectrally tuneable light engines (Benveniste, 2018). Modular luminaires concepts instead often incorporate advanced LED technologies, which are more energy-efficient during the use phase. This further enhances their environmental performance, especially when paired with renewable energy sources (Ferreira, 2021).

Modular Design Benefits: Modular LED luminaires show significant environmental benefits, with replaceable components (e.g. LED modules or drivers) instead of discarding the entire luminaire, it reduces environmental impacts by approximately 30 % compared to traditional designs. Modular designs optimize material use by focusing on repairability and recyclability. This reduces the demand for raw materials and minimizes the environmental burden associated with extraction and processing. The modular approach also extends the lifespan of lighting systems, as damaged or outdated parts can be replaced without affecting the rest of the luminaire. This reduces the need for frequent manufacturing and disposal, lowering the overall carbon footprint (Ferreira, 2021).

Modular luminaires offer advantages such as replaceable components and extended lifespan; however, they also present several challenges. Higher initial costs may limit adoption in cost-sensitive markets, while maintenance complexity can arise due to the need for specialized knowledge or tools. Additionally, the use of extra materials for connectors and housings may reduce some environmental benefits, and end-of-life disposal remains a concern, particularly for electronic components requiring specialized recycling processes (Ferreira, 2021).

The following applications, mentioned in the literature, are especially benefiting from modular LED luminaires:

1. **Industrial Environments**: Modular LED luminaires are particularly beneficial in industrial settings due to their durability and adaptability and their high-demand applications (Ferreira, 2021).
2. **Office Spaces**: Modular luminaires are advantageous in offices, where lighting systems often require upgrades or replacements. Their energy efficiency and extended lifespan contribute to lower operational costs and environmental impacts (Principi, 2014).
3. **Road and Highway Lighting**: Modular LED systems, especially when paired with renewable energy sources like photovoltaics, are highly eco-efficient for road lighting (Picardo, 2023).
4. **Building Retrofits**: Modular luminaires are effective in energy retrofits for buildings, improving energy efficiency and reducing life-cycle environmental impacts (Belány, 2021).

Comparative Analysis: LED systems generally outperform other lighting technologies (e.g. halogen or compact fluorescent lamps) in terms of eco-efficiency and environmental impact, especially when paired with renewable energy sources (Picardo, 2023).

The following ranking can be made in most energy-efficient lighting technologies and found relevant studies:

1. **Light-emitting diode (LED)** lamps are consistently identified as the most energy-efficient lighting technology. They outperform halogen and compact fluorescent lamps (CFLs) in terms of energy consumption and environmental impact, especially during the use phase (Principi, 2014; Tähkämö, 2014).

2. **LED lamps powered by standalone photovoltaic systems** further enhance eco-efficiency, reducing environmental impacts by up to 80 % compared to halogen lamps powered by grid electricity.
3. **Modular LED Luminaires**: Modular LED luminaires offer additional benefits by enabling component replacement, which reduces waste and extends product lifespan (Ferreira, 2021).
4. **Spectrally Tuneable Light Engines**: as an advanced LED technology offers customizable lighting solutions for specific applications, improving energy efficiency and environmental performance. While not surpassing LEDs yet, they represent a significant evolution in lighting technology, provide energy savings while offering customizable lighting solutions for specific applications (Benveniste, 2018).

Material and Manufacturing Impacts: While the use phase is dominant, manufacturing and raw material extraction also contribute significantly, particularly for advanced lighting technologies like spectrally tunable light engines (Benveniste, 2018).

Gao et.al. emphasizes the importance of optimizing resource use during the manufacturing phase to reduce environmental impacts. He provides in his paper a detailed analysis of the environmental footprint of LED lamp production, highlighting areas for improvement in green manufacturing practices and advocates for adopting sustainable production methods to align with global environmental goals, such as reducing carbon emissions and material waste (Goa, 2025).

Retrofit Strategies: Energy retrofits, including lighting system upgrades or switching to energy-efficient lighting and renewable energy sources, are effective in reducing life-cycle environmental impacts, though some categories like ozone depletion may see limited improvement (Hu, 2019).

The following Environmental categories are mainly affected by lighting systems according to literature:

1. **Climate Change (Global Warming Potential)**: Lighting systems contribute significantly to greenhouse gas emissions, primarily during the use phase due to energy consumption. This impact is highly dependent on the energy source used (Tähkämö, 2014; Picardo, 2023).
2. **Human Health Effects**: Lighting systems can indirectly affect human health through emissions during energy production, particularly in scenarios relying on fossil fuels. These emissions can lead to respiratory and cardiovascular issues due to air pollution (Picardo, 2023).
3. **Ozone Depletion Potential**: Energy retrofits, including lighting upgrades, generally reduce environmental impacts but may have limited effects on ozone depletion (Hu, 2019).
4. **Material and Resource Use**: Manufacturing and raw material extraction contribute to environmental impacts, especially for advanced lighting technologies (Benveniste, 2018).

Challenges in LCA case-studies of LED Luminaires: A review of LCA methods for LED light sources identifies uncertainties in data and the need for standardized approaches to assess their environmental performance comprehensively (Tähkämö, 2012; Casamayor, 2018; Principi, 2014; Picardo, 2023).

1. **Lack of Detailed Data**: There is insufficient detailed and peer-reviewed data on the environmental impacts of a wide range of LED lighting products. This limits the ability to

comprehensively assess their life cycle impacts. Differences in environmental impact results across studies are often due to variability in input data, such as energy consumption during the use phase and manufacturing processes.

2. **Uncertainty in Life Cycle Stages**: Challenges arise in accurately modeling certain life cycle stages, such as manufacturing and end-of-life processes. These stages often lack standardized data, leading to variability in results.
3. **Functional Unit Definition**: The choice of functional unit (e.g. lumens or hours of operation) can introduce uncertainty and significantly affect LCA outcomes, especially when comparing different lighting technologies. For LEDs, novel functional units tailored to their specific characteristics are required, but these are not universally adopted.
4. **End-of-Life Scenarios**: Variability in end-of-life options (e.g., recycling vs. disposal) significantly affects LCA outcomes, creating uncertainty in comparative analyses.
5. **Dynamic Technological Advancements**: Rapid improvements in LED technology, such as increased luminous efficacy and longer lifetimes, make it challenging to establish consistent benchmarks for environmental performance.
6. **Integration with Cost Analysis**: Combining LCA with life cycle costing (LCC) introduces additional uncertainties, particularly in estimating long-term economic and environmental trade-offs.

To enhance the quality of available database, authors recommend a standardized data collection of luminaires, better manufacturer collaboration, and advanced databases for accurate assessments. Dynamic modelling can address uncertainties from evolving technologies, while more peer-reviewed studies strengthen analytical foundations. Integrating eco-design strategies can reduce environmental impacts by up to 60 %, and sector-specific applications, such as modular luminaires in industrial settings, show a 30 % impact reduction (Tähkämö, 2012; Casamayor, 2018; Ferreira, 2021).

But are there any hindering reasons?

Anyhow, Manufacturers often hesitate to share detailed data on production processes, material composition, and energy use due to concerns about intellectual property and competitive advantage (Tähkämö, 2012). The lack of standardized methods for data collection and reporting creates inconsistencies, making it difficult to integrate manufacturer-provided data into LCA models. Also, manufacturers often do not track end-of-life scenarios for their products, leading to uncertainties in LCA results (Casamayor, 2018). Furthermore, smaller manufacturers may lack the resources or expertise to provide comprehensive LCA data, the fast-paced evolution of LED technologies makes it challenging for manufacturers to provide up-to-date data, especially for emerging designs like modular luminaires (Ferreira, 2021). In the end, manufacturers may prioritize cost reduction and market competitiveness over environmental data collection, which can hinder collaboration for LCA studies (Picardo, 2023).

3.4 Daylighting

3.4.1 Standards and regulations

In addition to some of the general standards and regulations mentioned in 4.3 for carbon emission calculations, the China Engineering Construction Standardization Association (CECS) has put forward several standards related to green building materials evaluation for doors, windows, and curtain walls. These standards include T/CECS 10041-2019 "Evaluation of Green Building Materials – Profiles for Doors, Windows and Curtain Walls", T/CECS 10034-2019 "Evaluation of Green Building Materials – Energy-saving Glass for Buildings", T/CECS 10027-2019 "Evaluation of Green Building Materials – Building Curtain Walls" and T/CECS 10065-2019 "Evaluation of Green Building Materials – Daylighting systems". These standards specify the requirements for carbon footprint in building curtain walls and materials. Additionally, the Chinese government in various provinces also requires building materials to provide certifications for green building products.

3.4.2 Environmental Impact categories applied

An analysis of the applied Environmental Impact categories on the different components of daylighting and shading systems including Windows and semi-transparent PV elements is shown in Figure 17. A clear focus is, similarly to electric lighting systems, on GWP, ADP, AP, EP and ODP. While window as a whole or single components (glazing, frame) are mostly studied so far, louvers and especially PV elements are rarely analyzed until now. Also here, in both cases the category "others" is quite often defined, which shows a high number of studies with individual analysis.

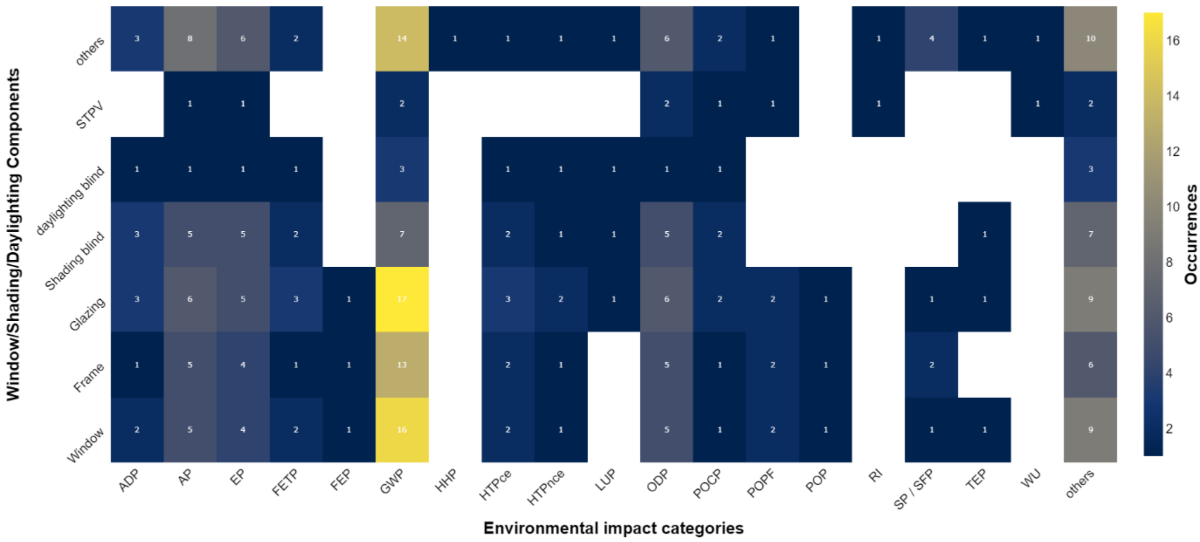

Figure 17: Overview of occurrences of Environmental Impact categories applied on LCA studies about daylighting- and shading components.

3.4.3 Key findings from LCA-studies on daylighting systems and facade components

Reviewed literature on LCA-studies about façade systems mainly focus window and facade components like glazing materials, shading devices and frame materials. Double-glazed units with various infill gases are widely analyzed for their embodied energy, while semi-transparent photovoltaic windows offer both daylighting and energy generation benefits and therefore gain some positive aspects in the analysis especially for human health effects.

Also shading systems including exterior blinds and photovoltaic-integrated solutions, are assessed for their impact on energy efficiency and thermal comfort. Frame materials, such as timber, aluminum, and composites, are evaluated for their environmental performance, with aluminium-clad timber frames receiving particular attention. Daylighting systems in specific were only of minor part in the collected study works, indeed no specific work on daylighting systems in connection with LCA was found (Asif, 2019; Souviron, 2019; Li, 2021; Babaizadeh, 2015; Fouad, 2019). Thermochromic VO2 windows and semi-transparent photovoltaic windows show significant energy savings and reduced environmental impacts compared to standard windows. Thermochromic windows, for example, reduce CO_2 emissions and energy demand during the use phase (Sirvent, 2022).

Most daylighting studies use the cradle-to-grave approach, assessing environmental impacts across production, use and end-of-life phases, with a strong focus on energy consumption during operation and recycling strategies. Additionally, most studies also integrate frameworks combining energy simulations with LCA are applied to optimize facade and fenestration designs, particularly in net-zero energy buildings, enhancing sustainability assessments (Fouad, 2019; Minne, 2015; Feehan, 2021).

For LCA studies focusing on daylighting and shading systems, the following **key aspects** can be summarized:

1. Applied LCA Tools, Methods, and Standards:
    - SimaPro and GaBi are the most commonly used tools for LCA studies, leveraging databases like Ecoinvent for life cycle inventory data.
    - Most Studies align with ISO 14040 and ISO 14044 standards for methodological consistency.
2. Most Considered Components:
    - Key components include glazing materials, shading devices, and frame materials (e.g. timber, aluminum and infill gases like Argon, Krypton and Xenon).
3. Functional Units:
    - Functional units often focus on energy performance, such as "kWh saved per square meter of window area" or "maintained daylight autonomy over 30 years".
4. Environmental Impact Categories:
    - Commonly analyzed categories include Global Warming Potential (GWP), embodied energy and resource depletion. But studies often also assess visual comfort and daylight autonomy to consider the human health impact.

Recommended materials for daylighting systems prioritize energy efficiency, durability and environmental performance. Low-emissivity glass with optimized g-values (0.30–0.50) and visible transmittance (Tvis 0.50–0.75) enhances daylight autonomy and visual comfort. Semi-transparent photovoltaic windows provide additional energy generation benefits. Photovoltaic-integrated shading systems (PVIS) are environmentally favourable, particularly when recycling or recovery scenarios are applied at the end of life. Durable exterior window shadings contribute to energy savings, especially in residential applications. Innovative materials, such as VO2-based thermochromic windows, offer passive thermal control with lower environmental impacts. Additionally, aluminium-clad timber frames are frequently analysed for their durability and sustainability (Eisazadeh, 2022; Li, 2021; Fouad, 2019; Babaizadeh, 2015; Sirvent, 2022; Souviron, 2019).

It was recognized that the definition of a "daylighting system" was not that strict throughout the reviewed literature, sometimes simple glazing units were mentioned as "daylighting system" in the literature, as it also serves to provide daylight to the room.

For reducing the environmental footprint of daylighting systems, **recycling** plays a crucial role in lowering end-of-life emissions and embodied energy. In the published literature photovoltaic-integrated shading systems demonstrate significantly lower emissions in recycling and recovery scenarios, enhancing their long-term sustainability. Also recycling aluminium and glass components in double-glazed windows reduces CO_2 emissions, with aluminium recycling being particularly beneficial due to its energy-intensive production. VO2-based thermochromic windows also show improved sustainability when recycled, minimizing production-related impacts. Additionally, recycling metals and polymers used in exterior window shadings further reduces life cycle impacts, particularly in residential applications (Fouad, 2019; Asif, 2019; Souviron, 2019; Sirvent, 2022; Babaizadeh, 2015).

3.4.4 Key findings from LCA-case studies on daylighting

The main purpose of the building envelope is to prevent heat loss and ensure thermal comfort. The window system has a particular influence on energy efficiency. The thermal performance of a window element depends on several factors, e.g. building orientation, window-to-wall ratio and material-related properties such as thermal conductivity. The thermal conductivity must be considered for frames and glazing. Highly insulated windows can reduce heat loss in winter by up to 40 %. Windows therefore have a major influence on the energy performance of the building (Tushar et al., 2022; Eisazadeh et al., 2022). It is therefore not surprising that the use phase is the main factor for the environmental impact. LCA is a quantitative analysis method used to quantify and assess the environmental impact of products and processes (Azari, 2010).

Irrespective of the focus on the use phase, the production processes and disposal must therefore also be evaluated. A complete life cycle assessment covers the entire production phase, including the extraction and processing of raw materials, intermediate transportation, final production, assembly, maintenance and replacement and finally disposal at the end of life (Manfredi and Vignali, 2014). To evaluate life cycle considerations economically, life cycle costing (LCC) has recently gained popularity (Zhang et al., 2020). The main purpose of performing life cycle costing LCC is to quantify the optimal allocation of resources between life cycle stages. In addition, LCC considers the entire cash flow, from acquisition to operation and disposal. In this way, it provides a sound basis for decision-making on investments and long-term profitability analyses (Tushar et al., 2022).

In their study, Tushar et al. present a holistic approach to optimizing the window system that combines LCA and LCC (2022). The study determines the optimal energy efficiency solutions when varying window system (27 different), window-to-wall ratio (WWR), thermal conductivity, climatic diversity, building orientation, LCC and LCA. Regression analyses were performed to predict energy consumption when varying the design parameters. The results show that the most energy efficient and economical window selection depends on climatic region, building orientation and WWR. The ISO 14040-14044 standards were followed in life cycle assessment modelling.

The simultaneous evaluation of economic efficiency and environmental analysis is also carried out in the study by (Haddad et al., 2022). For the climatic conditions in Algeria, the numerical study evaluates various passive measures to improve the energy efficiency of a classroom. Analogous to (Tushar et al., 2022), these include thermal insulation, WWR and window configuration, supplemented in (Haddad et al., 2022) using shading to reduce summer overheating, as well as a window overhang and night ventilation. The variation of the influencing variables is not only evaluated in terms of energy, but also in terms of LCC and amortization time. While the energy potential of increased insulation and external blinds could be worked out, the energy price is identified as a decisive factor in economic profitability for the study situation (Haddad et al., 2022).

For a Central European climate situation (Brussels, Belgium) and for the use case of medical buildings, (Eisazadeh et al., 2022) investigate the effects of different window system configurations on energy consumption, daylight comfort and environmental performance. Dynamic energy simulations and thermal and visual comfort analyses are used to analyse different design alternatives based on glazing characteristics, WWR (6 different variations), façade orientation (4 different variations) and shading elements. The simulation tools used were Grasshopper, Ladybug, Honeybee, EnergyPlus, Radiance and Daysim. The energy assessments show that south-facing orientation with suitable glazing properties and shading systems can reduce energy consumption and CO_2 emissions as much as possible in Belgium's temperate climate. The life cycle assessment study is carried out using the SimaPro software and the “MMG + _KU Leuven” tool. The results show that the environmental impact of window systems depends mainly on the amount of flat glass, while the influence of coatings is comparatively small. Shading elements, especially slats, significantly reduce the cooling loads and can lead to lower environmental costs despite the additional material input (Eisazadeh et al., 2022).

Several software tools and databases are available for LCA assessment. The tools most used in the literature include SimaPro and Sphera LCA for Experts (formerly GaBi). This was also highlighted in the literature review (see Chapter 2). The study by (Sečkár et al., 2024) compares tools for wood-aluminum windows. The results can vary considerably depending on the databases used, which underlines the need for practitioners to check the data sources used by the software. Many of the previously identified Environmental Impact categories (see Chapter 2) were compared. The largest impacts and differences were in hardware production for toxicity. The results show that the GaBi software had a lower impact score than the SimaPro software for almost every impact category, due to differences in the calculation methodology and database (Sečkár et al., 2024).

4 Conclusions and recommendations

The conducted **survey among participating countries** first investigated the level and kind of decarbonization efforts and LCA use in the overall building section, of which lighting and façade/daylighting aspects are part of. These efforts are established in most of the countries, nevertheless mandatory in only 3 out of 15. A diverse situation is found for CO_2 pricing, between lowest at 9.80 €/t up to highest at 120 €/t; no pricing currently is found in 2 countries. The most relevant parameter in LCA is the GWP (global warming potential). All countries have energy ordinances in place, from which simple operational carbon estimates can be obtained. Regarding the impact of LCA on real estate values, the overall feedback is that the real estate market is not evaluating LCAs significantly yet, but there is anticipation of this changing in the coming years due to regulatory and environmental pressures. Comparing specifically the status quo of the situation with respect to the trade of electrical lighting and the field of façade / daylighting, in some of the countries, the facade sector appears to be more advanced than the lighting sector in terms of LCA application.

The main identified open issues in integrating Life Cycle Assessment (LCA) into building practice include: the need for more accessible LCA tools and databases, increased transparency in LCA methodologies, lack of LCA focus on training architects and engineers, and the complexity of LCA. This specifically has been backed in the survey by a more detailed analysis of existing databases and rating methods for electric lighting and façade and daylighting issues alike, which revealed a lack of data as well as an inconsistency in both the foreground data and the background data (especially concerning lighting product data). There's a need for simpler tools to quantify environmental performance of projects. LCA is currently mostly for specialized professionals, suggesting a need for more widespread education and understanding. The carbon footprint of our lifestyle and housing needs to be better communicated. There's a call for carbon emission limits in building standards, similar to energy consumption limits. Finally, there's a need for clear regulations, incentives for carbon-neutral activities, and better use of recycled materials.

The **review of scientific literature** of 59 relevant research articles can be summarized as follows.

In the field of electric lighting systems, designing lighting products for easy disassembly and reassembly presents a key opportunity to integrate life cycle assessment (LCA) early in the development process. This approach applies not only to the luminaire but also to its individual components, with particular emphasis on the LED driver. A modular driver design allows for the replacement of damaged modules, reducing maintenance time, material use and costs. Similarly, adopting a modular LED luminaire design enables component-level replacement rather than discarding entire units, leading to environmental impact reductions of up to 30 %. Overall, such design strategies optimize material efficiency, improve repairability and extend product lifespan – ultimately lowering raw material consumption and the carbon footprint.

Concerning façade-related systems the review of scientific literature further showed that daylighting and shading systems are less studied in absolute numbers. Studies on shading and daylighting blinds are still very limited.

In general, it was found that simulation-based studies are much more elaborate than real-case studies. The published scientific literature shows also a high number on individual studies available and regularly points out the need for a more integrative approach to better align application and LCA analysis in the different product development stages. Additionally, user behaviour and the effects of lighting on comfort and well-being should not be overlooked. A multi-criteria approach is therefore recommended for conducting comprehensive LCA analyses.

Eco-redesign strategies integrate LCA into design workflows to identify environmental hotspots and optimize material selection and manufacturing processes. Additionally, whole-building LCA is gaining traction, incorporating lighting assessments into BIM workflows and energy modelling tools like EnergyPlus for a holistic environmental evaluation.

Based on the challenges of uncertainties in data and the need for standardized approaches to assess their environmental performance comprehensively, a growing need for accurate LCA data, significant barriers remain: Manufacturers' reluctance to share detailed production data due to intellectual property concerns and competitive pressures limits transparency. Therefore, standardized data collection an advanced databases and closer manufacturer collaboration with environmental analysts can be mentioned as key aspect for improving LCA accuracy in future.

Regardless of lighting scenarios, the use phase has the highest environmental impact, emphasizing the need for efficient planning, energy-conscious operation, and proactive maintenance to sustain performance.

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6 Appendix

Table 2: Databases and content for different countries.

COUNTRY	DATABASE	CONTENT	LUMINAIRE	DATA
AUSTRIA	Baubook	building materials and component	-	GWP, AP, PENRT and other environmental indicators
BELGIUM	TOTEM	building materials and component	-	building: environmental score (This environmental score is obtained by summing up the scores of each indicator (x kg CO_2 equivalent for global warming) multiplied by a specific aggregation factor based on the European PEF (Product Environmental Footprint) weighting method) element: environmental score component: materials
BRAZIL	Sidac EPD Brasil	building materials and component building materials and products	-	CO_2 emission, primary energy demand, average primary energy composition EPD, materials, life, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B6, C1-C4, D
CHINA	CPCD Tiangong	various products and materials processes	1 LED	The carbon footprint of raw material transportation, product transportation, raw materials and accessories production per kilogram of lamps Types and quantities of materials required for different processes
CZECH REPUBLIC	CENIA	building materials and component	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D

DENMARK	Epddanmark	building materials and products	lighting system*1 pillar lamp*4	EPD lighting system: life and the environmental impact of A1-3, B6, C1-4, D stage pillar lamp: weight, life, materials, weight ratio the environmental impact of A1-3, B1-7, C1-4, D stage
FINLAND	co2DATA, RAKENNUSTIETO	building component and products	Luminaire, LED	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
FRANCE	INIES	building component and products	Several interior and exterior lighting systems, plus cables and devices	EPD, materials, life, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
GERMANY	ÖKOBAUDAT	building component and products	1 CFL downlight, lamp*1 LED office luminaire*1 fluorescent lamp socket*2 fluorescent lamp*4	(for luminaire) power, life, weight, the environmental impact of A1-A3 (LED office luminaire contains B6, C1)/C2-C4/D stage

			louvrelight*1 louvrelight integrated into ceiling*3 control gear*2 Diffuser (damp room)*1	
IRELAND	EPD-Ireland	building component and products	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
ITALY	EPD Italy	building component and products	Several interior and exterior luminaire	EPD, weight, materials, the environmental impact of production, distribution, installation, use and maintenance, Eol stage
JAPAN	Japan EPD Program by SuMPO	building materials and component	-	(weight, materials), the GWP of raw material acquisition, production, distribution, use and maintenance, End-of-Life stage
THE NETHERLANDS	MRPI	building component and products	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
NORWAY	EPD-norge	building component and products	Several interior and exterior lighting systems, plus	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B6, C1-C4, D

			cables and devices	
POLAND	ITB	building component and products	Luminaire	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
PORTUGAL	Dap habitat	building component and products	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
SLOVENIA	ZAG	building component and products	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
SPAIN	Opendap	building component and products	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
SWEDEN	Boverket BM	building component and products	-	Generic data, all indicators according EN15804 over life cycle stages A1-A3
USA	Lcacommons eGRID	various materials and processes emissions from electricity generation by state	-	1. input materials and processes, output emission 2. emissions from electricity generation by state
EU	PEP ecopassport	building component	Several interior and exterior lighting systems, plus cables and devices	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D

Table 3: Rating tools for different countries.

COUNTRY	RATING TOOL	CONTENT/METHOD
AUSTRIA	baubook	used to form a whole building life cycle assessment
BELGIUM	TOTEM	build the model by creating your own input data or directly referencing the parameters of the database
BRAZIL	1. sidac 2. CECarbon	Sidac contains both input and output parts, with the input part containing only minimal optional data, the output part is filled manually, which has no impact on the total carbon emission. It has a calculator to quantify the impact of a construction elements such as a wall or roof (based on the materials available in the platform). CECarbon used to calculate carbon emissions for the entire building
CHINA	nenghaobao	each stage or process has been distinguished, it includes a certain number of carbon emission factor database for selection and need to fill in the corresponding basic parameters according to the requirements
DENMARK	lcabyg	enter information about the building parts and possibly the building's energy consumption. The program automatically computes the results in a table and generates figures and a summary report.
GERMANY	Open LCA	fast and reliable calculation of your Sustainability Assessment and/or Life Cycle Assessment; very detailed insights into calculation and analysis results; identify main drivers throughout the life cycle, by process, flow or impact category, visualize results and locate them on a map.
SWEDEN	BM	BM is a tool that calculates the climate impact of a building from construction materials, transportation and processes on site according to LCA methodology defined in EN15804 and EN15974.
THE NETHERLANDS	MRPI, dgbc	(MRPI) need to be registered (dgbc (WEii)) used to calculate energy consumption for the entire building
AMERICA	BEES	used to form a building product life cycle assessment, but there are few options and few variables

Table 4: Databases and content for different countries.

COUNTRY	DATABASE	CONTENT	FACADE	DATA
AUSTRIA	Baubook	building materials and component	Sealants & adhesives*74 Light wells*2 Levelling, levelling and filling compounds (floor)*3 Sealing tapes & thermal bridge breakers*54 Frame*80 Glazing*23 Windows*68 Adhesives & fillers*26 Mounting accessories*5	GWP, AP, PENRT and other environmental indicators

BELGIUM	TOTEM	building materials and component	glass curtain wall*3 external window*17 frame and panel*30 glass*5	building: environmental score (This environmental score is obtained by summing up the scores of each indicator (x Kg CO_2 equivalent for global warming) multiplied by a specific aggregation factor based on the European PEF (Product Environmental Footprint) weighting method) element: environmental score component: materials
BRAZIL	Sidac EPD Brasil	building materials and component building materials and product	Flat glass (3 to 19 mm) and Sun protection glass (4 to 10 mm)	CO_2 emission, primary energy demand, average primary energy composition EPD, materials, life, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B2, C1-C4, D
CHINA	CPCD Tiangong	various products and materials processes	Aluminum-wood composite window*2	Product carbon footprint Types and quantities of materials required for different processes
CZECH REPUBLIC	CENIA	building materials and component	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
DENMARK	Epddanmark	building materials and products	Sun-shading system*1 Window seals Wall panel	EPD Sun-shading system: weight, materials, the environmental impact of and A1-3, C1-4, D stage

			systems Tube cover systems*1	Window seals Wall panel systems Tube cover systems: materials, the environmental impact of A4, A5, B1-7, C1-4, D stage
			Top-guided window*6	Top-guided window: weight, materials, the environmental impact of A1-3, A5, C1-4, D stage
			Windows*8	Windows: weight, materials, the environmental impact of A1-3, (A4, A5), (B1-7), C1-4, D stage
FINLAND	co2DATA RAKENNUSTIETO	building component and products	Windows	Size, weight
FRANCE	INIES	building component and products	Several windows and sun-shading devices	EPD, materials, life, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
GERMANY	ÖKOBAUDAT	building component and products	Window fitting*5 Lock*3 Fastening materials (screws)*2 Window handle*1 Window operator*4	(for facade) Window fitting: weight, materials, the environmental impact of A1-A3, C1, C2, D stage Lock: weight, the environmental impact of A1-A3, (B4, B5), (C1), C2, C3, (C4), D stage Fastening materials(screws): weight, the environmental impact of A1-A3, C1, C2, D stage Window handle: weight, the environmental impact of A1-A3, C2, C3, D stage

			Timber roof window*6 Aluminum windows*5 Plastic windows*8 VELUX modular skylight*2 VELUX PUR roof windows*3	Window operator: weight, the environmental impact of A1-A3, C1-4, D stage Timber roof windows: weight, the environmental impact of every stage Aluminum windows: weight, the environmental impact of every stage Plastic windows: weight, the environmental impact of every stage VELUX modular skylight/VELUX PUR roof windows: weight, the environmental impact of A1-3, C1-4, D stage
IRELAND	EPD-Ireland	building component and products	Windows	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
ITALY	EPD Italy	building component and products	-	EPD, weight, materials, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B7, C1-C4, D
JAPAN	Japan EPD Program by SuMPO	building materials and component	Aluminum windows*2	weight, materials, the GWP of raw material acquisition, distribution, production, use and maintenance, End-of-Life stage
THE NETHERLANDS	MRPI	building component and product	Sunshade	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D

NORWAY	EPD-norge	building component and products	Windows	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B2, B4, C1-C4, D
POLAND	ITB	building component and products	Windows	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
PORTUGAL	Dap habitat	building component and products	/	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
SLOVENIA	ZAG	building component and products	/	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
SPAIN	Opendap	building component and products	Windows	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
SWEDEN	Boverket BM	building component and products	/	Generic data, all indicators according EN15804 over life cycle stages A1-A3
EU	PEP ecopassport	building component	-	EPD, all indicators according EN15804 over all life cycle stages A1-A3, A4, A5, B1-B5, C1-C4, D
UNITED STATES	Lcacommons eGRID	various materials and processes	-	input materials and processes, output emission emissions from electricity generation by state

	emissions from electricity generation by state	

LCA and Lighting in participating countries

This short survey aims at obtaining a first overview on the status of LCA and lighting in participating countries. If you find it helpful to include additional / outside expertise, please consider consulting other experts, e.g., in your faculty. Based on this first overview, we will then later further investigate the topic in ST A with selected guided interviews of professionals especially from the lighting and facade sector.

To make it easier for you, we have compiled two examples for China and Germany, which you find in the Teams folder as well

Thank you for your time and effort!

Country: …
Name: …
University / Institute / Company: …
Date: …

1. General

a) Is LCA (especially GWP indicator) analysis on building level in your country:

Already established? ☐
Partially mandatory (e.g. to get funding)? ☐
Mandatory, i.e. for building permits? ☐

b) Are instruments (databases, rating tools, …) provided for free (by authorities). Please provide a reference

Yes ☐
No ☐

If Yes: please specify (e.g. provide a link):

____

If No: what is the dominant approach in the private sector (if possible include costs, hurdles etc.):

____

c) Is CO_2 priced in your country / market?

____

d) Embodied vs. operational energy: The later often already exists in form of energy ordinances, please specify:

____

e) Global Warming Potential (GWP) only, or also other aspects of ecobalance of relevance?

____

f) Your guess on the impact on real estate value?

____

g) Where are authorities heading, to your believe?

____

h) Do people have experiences / sensitivity to CO_2 and building / building operation?

____

i) What are the main open issues, to your believe?

____

2. Electric Lighting

On industry sector level

…please specify…

On company level

…please specify…

Relevant design processes

…please specify…

3. Façade

On industry sector level

…please specify…

On company level

…please specify…

Relevant design processes

…please specify…

4. Your personal judgement / conclusions for the lighting and façade sector

…please specify…