Data Driven Sustainability for Mechanical and Electrical Products in Buildings

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ABSTRACT

Most mechanical & electrical (M&E) equipment industries have been slow to adopt sustainability approaches beyond energy efficiency, such as materiality, circularity principles, or embodied carbon reporting. Additionally, whole building life cycle assessment (LCA) practitioners have identified large gaps in information for M&E products with operational-use-phase components (e.g., lighting). Filling these data gaps requires an understanding of the sustainability impacts of M&E products across impact categories and the entire product life cycle, including raw material extraction, manufacturing, use, transport, and end-of-life. Developing scalable and standardized methods is crucial to enabling the broad adoption of sustainability approaches by product manufacturers and M&E industries and enables comparison of sustainability impacts across products. This paper highlights recent work developing tools to complete LCAs more quickly and effectively for the lighting industry. Electrical product manufacturers face many roadblocks when completing an LCA, including complexity in the process and lack of information on the environmental impact of small electronic components. This paper describes these roadblocks and presents methods to overcome them in the lighting industry and opportunities to expand these methods to other M&E products. This paper is intended to be a reference for building researchers, designers, engineers, contractors, and manufacturers eager to promote whole building sustainability. Through standardized reporting, component-level data, regional comparability, and stakeholder collaboration, together we can build and enjoy a more sustainable future.

Introduction

In the face of irreversible and catastrophic climate change, the global community, through the Paris Climate Accord, has committed to limiting the rise in the average global temperature to 2°C above pre-industrial levels. Achieving this goal necessitates a significant reduction in greenhouse gas (GHG) emissions, the primary driver of global warming and its associated impacts. The building industry is both resource- and energy-intensive, consuming over 60% of the world's raw materials and 40% of its energy supply (Al-Ghamdi and Bilec 2017; Yang et al. 2022; Mastrucci et al. 2017). As a result of these factors, the building industry contributes over 30% of the global GHG emissions (Yang et al. 2022). Thus, there is significant opportunity for designers, architects, and decision-makers to support the goals of the Paris

Climate Accord by actively promoting measures to reduce the environmental impact and enhance sustainability in the building industry.

Many ratings, certifications, and corporate pledges have emerged to provide guidance and transparency surrounding sustainability in the building industry. Among these, the environmental product declaration (EPD), which is a regulated and standardized document using life cycle assessments (LCAs) to provide concise summaries of a product's environmental impact, stands out (WH 2021; Yarmuth 2022). Despite the standardization and overall widespread use of these methodologies, many industries are struggling to provide the comprehensive data necessary to develop EPDs. One example is the mechanical & electrical (M&E) sector within the building industry. These struggles are especially evident for products that have a significant operational use phase, such as lighting. The residential and commercial sectors rely heavily on electricity to meet energy needs, with building-related use-phase activities such as heating, cooling, ventilation (HVAC), lighting, and appliance usage accounting for 62.9% and 66.9% of their respective energy consumption. (USEPA 2024). The commercial end-use sector, which was estimated to contribute 15.8% of U.S. GHG emissions in 2022, faces numerous challenges that prevent EPD development, including complex supply chains, a lack of industry guidelines, and quickly evolving technologies which have hindered the development of scalable methods (USEPA 2024).

In this research, Pacific Northwest National Laboratory (PNNL) led a collaborative initiative, focusing on lighting as the inaugural M&E industry product type for investigation. The initiative involved LCA experts and lighting manufacturers with the primary goal of streamlining and simplifying the LCA data collection process for lighting manufacturers to support the development of transparent and comparable EPDs. Through their ongoing work, the PNNL team aims to establish clearer procedures for LCA data collection that can be adopted by other M&E industries to facilitate the development of more EPDs and enable whole building life cycle sustainability.

The Role of Life Cycle Assessment and Environmental Product Declarations in Sustainability

When designing or specifying a material, product, or project, it is important to consider its impacts comprehensively. LCA provides a comprehensive assessment in two main ways (see Figure 1): by considering the environmental impacts associated with all stages of the material, product, or project's life cycle and by investigating across a variety of categories (Niederl-Schmidinger and Narodoslawsky 2008). Assessing the environmental impacts associated with all stages of the material, product, or project's life cycle, from raw material extraction through production, use, and end-of-life disposal or recycling enables decision-makers to pinpoint impact hotspots across the life cycle for targeted reductions. By evaluating a variety of categories, such as GHG emissions, water use, energy consumption, air and water pollution, land use, and toxicity, LCA considers impacts to human health, ecosystem quality, and resource depletion. Capturing a broad range of environmental impacts enables decision-makers to identify tradeoffs between different impacts and helps prevent shifting burdens from one impact to another. Impact hotspots identified through the LCA can be mitigated by swapping or improving materials, processes, or transportation distances. For example, high GHG emissions from production and transportation of a steel component could be addressed by reducing transportation distances or shifting to lower emission transportation, swapping to a material with identical function but lower emissions, or offsetting those emissions by reducing emissions in other phases of the product life cycle. Such efforts across an industry will trigger free market competition, reducing impact hotspots and improving environmental impact portfolios across the board. Together, by assessing across the entire life cycle and across multiple impact categories, LCA provides a holistic view that empowers decision-makers to make informed choices to mitigate the environmental impacts of the material, product, or project.

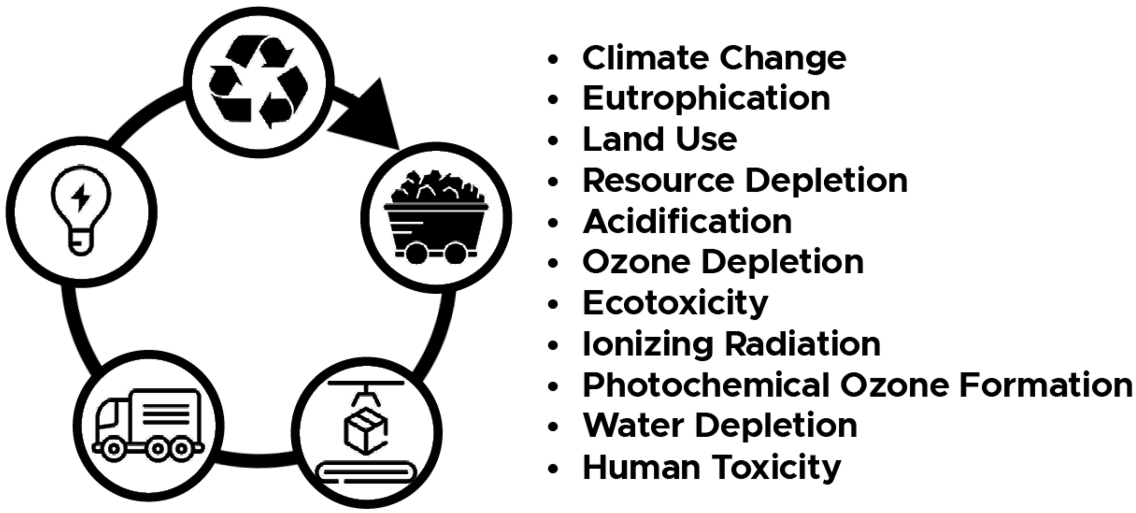

Figure 1. LCA provides a comprehensive assessment by considering the environmental impacts associated with all stages of the material, product, or project life cycle and by investigating environmental impact across a variety of categories. *Source*: Hickcox, PNNL.

EPDs are comprehensive, independently verified reports that use LCA methodology to communicate details on the environmental performance of a product over its entire life cycle, including life cycle impacts, emissions, and resource consumption (OCLCA 2024). The requirements for EPD development are stated by the product category rules (PCRs) relevant to the product of interest. PCRs provide the guidelines and requirements for conducting an LCA on a specific product, including defining the system boundaries, functional unit, and impact categories of interest, to ensure that products with similar functions are assessed in the same way, enabling comparison of EPDs in the same category. (Anderson 2024; OCLCA 2024; Noel 2013; Yarmuth 2022; Feng, Sadiq, and Hewage 2022; ACLCA 2022a; Mills 2023)

How LCA Benefits Society

Using LCA approaches allows for the identification of impact "hotspots" in a product's life cycle. Hotspots are life cycle phases with a greater magnitude of impacts compared to other stages or impact categories with large impacts compared to other categories. For example, the material extraction phase in a specific product's life cycle could produce the greatest human health impacts when compared to the transport, manufacturing, use, and end-of-life phases. Identifying and understanding the impact hotspots in a product's life cycle can help decision-makers prioritize interventions to minimize impacts and avoid unintended consequences.

Understanding and minimizing environmental, social, and economic impacts, especially on communities that have been historically overburdened by impacts or left out of decision-making processes, is crucial to developing a more just society. The concept of cosmopolitan justice, which integrates life cycle thinking with the energy justice framework, aims to consider impacts on historically marginalized or underrepresented communities across all life cycle stages (Heffron and McCauley 2018; Maier, Mueller, and Yan 2018). Achieving a holistic view of a product's life cycle impacts requires consideration of impacts, both positive and negative, across multiple categories such as human health, safety, and economy. For example, it is important to consider the economic benefits of a life cycle stage for workers while also considering the impacts on worker safety. The social life cycle assessment (S-LCA) methodology emerges as another valuable tool for assessing the social implications of a product's life cycle. S-LCA considers impact categories that center around identifying and managing impacts on people, with subcategories focusing on workers, local community, value chain actors, consumers, society, and children. By integrating S-LCA into sustainability evaluations, decision-makers can broaden their comprehension of the social ramifications of a product's life cycle (Benoît Norris et al. 2020).

Understanding where activities and impacts occur and what communities are being exposed to the ramifications is critical to minimizing damage to historically marginalized or underrepresented communities. Teams can begin considering regional and social implications by exploring questions like "where is a product's manufacturing facility sited?" "Where are the materials extracted?" "Where is the waste being disposed and processed?" and "Who lives and works nearby?" Census demographic data and stakeholder engagement can be used to determine what communities live closest to each life cycle stage and what impacts they are facing throughout a product's life cycle. As M&E industries continue to set new goals to reduce climate change impacts and to promote equity and justice across product life cycles, holistic approaches that consider the environmental, social, and economic impacts are key to avoiding unintended consequences and ensuring that the most vulnerable communities do not continue to bear the weight of negative life cycle impacts.

Life Cycle Assessment Gaps and Opportunities

Over recent decades, a growing movement has emerged to reduce the significant environmental impacts associated with the building industry. This movement has led many organizations (e.g., MEP 2040, AIA 2040, Mindful Materials) and legislative bodies (e.g., LEED, WELL, Federal Buy Clean Initiative) to prioritize sustainability. In response, many engineers, designers, architects, and builders or contractors have started to incorporate material transparency reports, such as EPDs, into their practice. While EPDs offer valuable insights and represent progress toward sustainable buildings, they are not without flaws. According to informal feedback from several industry partners, there is a significant gap in the standardization of reports and availability of component-level data, especially within the M&E systems, as well as incompatibility across regions, all of which are exacerbated by barriers to stakeholder collaboration.

Standardized Reporting

Presently, EPDs do not adhere to any standardized formatting, and information and data are presented in varying layouts and structures. This lack of uniformity hampers practitioners' ability to compare similar products effectively and obtain insights into industry averages. It also makes updating the life cycle inventory (LCI) arduous, costly, and time-consuming when there are technological advancements, process changes, or material alterations. Without such standardization, the efficacy and validity of the reported information are at risk.

Component-Level Data

There is a notable deficiency in data at the component level, particularly within the M&E industries. The root cause lies in the manufacturers' mandate to identify all inputs and outputs of the materials and processes associated with their product. This requirement poses a considerable challenge for manufacturers, particularly because many M&E products comprise a multitude of sub-components. Often, these sub-components lack accurate or available EPDs, further exacerbating the difficulty in obtaining comprehensive component-level data. As a result, the absence of detailed data at the component level hampers the ability to accurately assess and report the environmental impacts of M&E systems. Without robust data on individual components, the overall sustainability performance of M&E systems remains inadequately quantified and understood, hindering efforts to enhance environmental stewardship in the built environment.

Regional Comparability

Building systems, especially M&E products, are seldom confined to a single geographic location, necessitating assessments that consider regional variations. Recognizing regional differences in energy sources and manufacturing practices is vital for accurate environmental impact evaluations. However, existing EPD methodologies lack the capability to adjust reported impacts based on geographical factors, specifically between European and U.S. regions. This is particularly crucial considering the widespread distribution of many M&E products and related reporting guidelines, which currently compels practitioners to undergo expensive, labor-intensive evaluations of their systems to account for regional differences.

Stakeholder Collaboration

Finally, although many manufacturers express a desire to collaborate and furnish comprehensive, accurate data, doing so poses a specific challenge. Numerous products, processes, and materials are typically developed under proprietary conditions and safeguarded as trade secrets. Consequently, there is a risk of inadvertent disclosure or exposure under the existing EPD methodology. Therefore, it is imperative that all EPD methods foster an environment conducive to open and transparent communication among stakeholders. This involves identifying common goals, providing effective training and resources, promoting data sharing and collaboration, and establishing feedback mechanisms. These efforts are integral to enhancing stakeholder collaboration in the whole building life cycle assessment (WBLCA) process.

Life Cycle Inventory Data collection workbook

In recent years, PNNL has collaborated extensively with U.S. manufacturers and international stakeholders to address the shortcomings in EPDs by redefining the standard PCRs for lighting fixtures and luminaires. This collaboration has created a precise, unified, and transparent LCI Data collection workbook ("LCI workbook") that aligns with various international and open standards governing LCA, EPD, and PCR and includes all data linkages required for comprehensive impact category reporting. The PNNL LCI workbook stands apart from other LCA tools because it adheres to the American Center for Life Cycle Assessment (ACLCA) 2022 PCR Open Standard Tiers and is designed to meet anticipated Federal Buy Clean regulations (ACLCA 2022b).

Luminaire Life Cycle Inventory Workbook Case Study

In 2022, sustainability engineering and lighting experts at PNNL spearheaded a collaboration with key stakeholders in the lighting industry. This involved partnering with two North American lighting manufacturers of different sizes, along with the GreenLight Alliance through their LCA Incubator initiative. The primary goal was to address existing barriers that hinder lighting manufacturers from creating high-quality, publicly accessible life cycle impact assessments (LCIAs), see Figure 2 for relationship between LCIs and LCIAs. The result of this collaboration was the development of a versatile yet comprehensive workbook that begins to standardize the reporting of impact potentials resulting from the luminaire life cycle, accounting down to the component level, while accommodating regional variations. This tool empowers practitioners to report life cycle environmental information consistently and accurately across the industry.

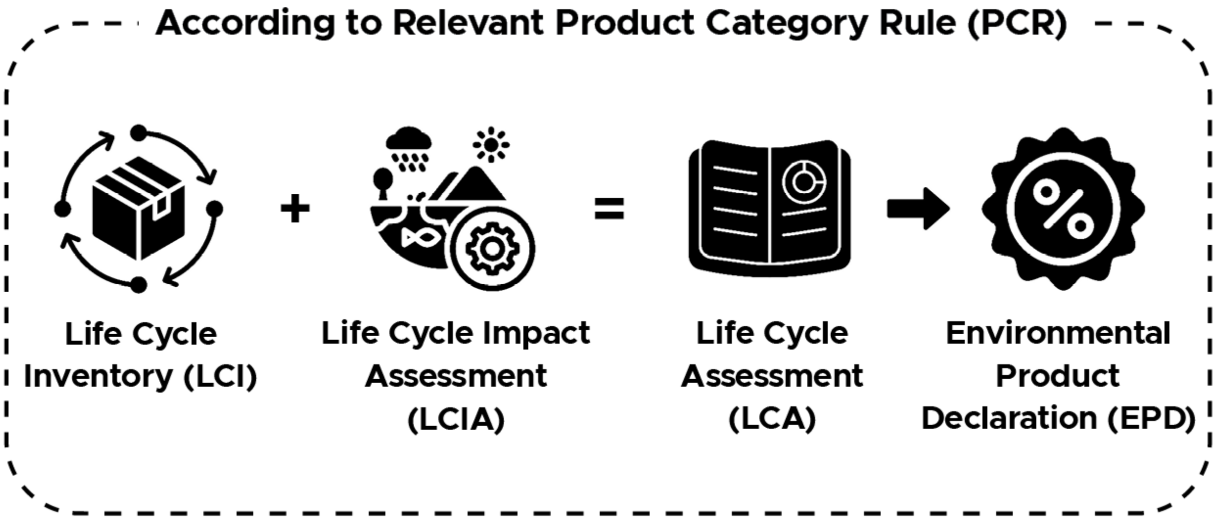

Figure 2. Relationship between LCI, LCIA, LCA, EPD, and PCR. *Source:* Hickcox, PNNL.

Resulting from this first-of-its-kind collaboration, PNNL released an Excel-based open-model linked LCI workbook via GitHub to automate, standardize, and expand LCA/EPD use in the lighting industry (PNNL 2023). The intent of this proof-of-concept effort was to establish the foundations of a framework for standardizing the collection of LCI data within the lighting industry, with an initial focus on the luminaires product category. The standardized and automated LCI workbook was specifically designed to facilitate the development of clear and uniform EPDs for easy comparison. Furthermore, to ensure widespread adoption this workbook was vetted for its functionality and relevance through stakeholder collaborations. The tool was also intended to be a preliminary draft for potential inclusion in a new North American PCR dedicated to luminaires.

For the luminaire LCI workbook to be standardized, comprehensive, versatile, and automated, PNNL developed well-labeled, highlighted, and documented optional workflows to lead the user through the process (Figure 3). The workbook was designed to allow for various levels of data input resolution while still enabling the highest of quality results to be assessed and reported. The output of the workbook can be uploaded into openLCA via a SQL script. openLCA is a widely used open-source software that has been developed in collaboration with government agencies. While the current version of the lighting LCI workbook is built on an Excel-based platform accessible to all, next steps include publishing future iterations on a web-based platform for universal accessibility.

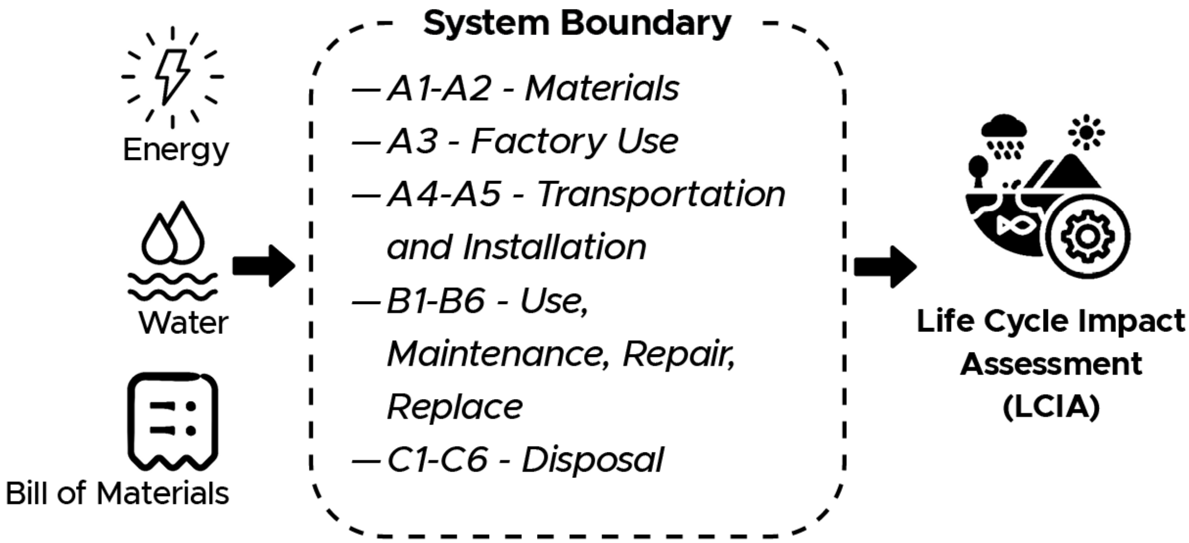

Figure 3. Example inputs used in the PNNL-developed Life Cycle Inventory Workbook (PNNL 2023). *Source:* Hickcox, PNNL.

Continuing with stakeholder engagement, following the release of the LCI workbook, PNNL surveyed 14 users of the lighting industry workbook to better understand the positive aspects of the tool as well as any challenges the users may have encountered. The survey data revealed positive sentiments toward the model-linked LCI workbook, highlighting its potential to enhance the compilation of environmental declarations for sustainable public procurement. Overall, respondents anticipated that the LCI workbook would likely increase organizational participation in standardized environmental labeling, component and material transparency, and sustainable public procurement programs. Of note, most respondents reported the workbook reduced the time required to compile LCI data for LCA/EPD studies and declarations. Participants also indicated the LCI workbook improved the accuracy and consistency of the lighting-related inventory data, helping to enhance transparency in environmental labeling and procurement processes. Respondents also noted the workbook's user-friendly interface and flexibility to accommodate diverse luminaire configurations, a wide variety of component and material options, and global supply chain nuances, and felt that the workbook would integrate well with existing environmental labeling systems.

Despite the overall positive perception, a minority of participants found room for improvement in the LCI workbook's user-friendliness and flexibility, suggesting enhancements to the labeling, instructions, and flow of the interface and identifying system components/configurations in need of additional customizations. Two respondents expressed concerns with the workbook's potential to identify areas for environmental improvement. As the LCI workbook itself does not proceed to LCIA, which calculates the suite of environmental impact category results, but rather accumulates and links the process reference flow data for LCIA in another system, this highlights the need for improved clarity on the tool's functionality and its role in streamlining the LCI stage of the LCA/EPD process. Finally, while the majority agreed on the potential for cost savings by using the LCI workbook, some participants expressed less confidence. As the LCI workbook methodology continues to iterate and improve, some team goals include (1) further understanding and resolving user and stakeholder concerns and challenges; (2) bolstering what all respondents recognized as the workbook's potential to streamline, automate, and standardize lighting industry LCI data collection using a versatile, vetted, and open-access workbook; and (3) enabling efficiencies and potential cost savings when completing the LCA/EPD process.

LED Power Supply Component LCI Pilot Study

As the team of lighting manufacturers, designers, and sustainability researchers was developing and vetting the lighting LCI workbook, it became evident that there is a substantial gap in background manufacturing processes and materials for light-emitting diode (LED) power supply (driver) components. Luminaire manufacturers have faced significant obstacles in obtaining data on LED power supply manufacturing, material, and supply chain because of historically limited transparency in the industry. Accurate data on power supply inventory is essential for a comprehensive LCA of LEDs and luminaires as LCA results for other electronic equipment and systems vary greatly depending on the manufacturing, materials, and supply chains. Furthermore, power supplies are vital not only to proper luminaire assessments, but also for most electrical loads in modern buildings. The PNNL sustainability engineering and lighting team expanded the collaboration to include a multinational power supply manufacturer to improve industry access to LCI data and LCA results for power supplies. A LCI data collection pilot study ensued to provide recommendations for enhancing LCA and EPD development among power supply and luminaire manufacturers.

The power supply manufacturer supplied crucial LCI data related to one of their power supplies, facilitating a comparison of their environmental impacts against five life cycle processes used as proxies for power supplies in luminaire-level LCAs. Those datasets were chosen because they represented possible proxy datasets for power supplies that could be used when collecting LCI data on luminaire systems. Results demonstrated that accurate LCI data for power supplies may be crucial for representative LCAs reporting on power supplies, complete luminaire systems, as well as whole building microgrids. Figure 4 shows how differing power supply LCI flows can affect results for complete luminaire systems. Despite being only one component of the luminaire system, varying power supply datasets can skew results of a luminaire LCA by up to 20% in some impact categories.

Additionally, the findings indicated that using generic electrical processes as a proxy for accurate LCI data on power supply could significantly skew results, by more than an order of magnitude in some categories, resulting in an average difference of 20% for the luminaire results.

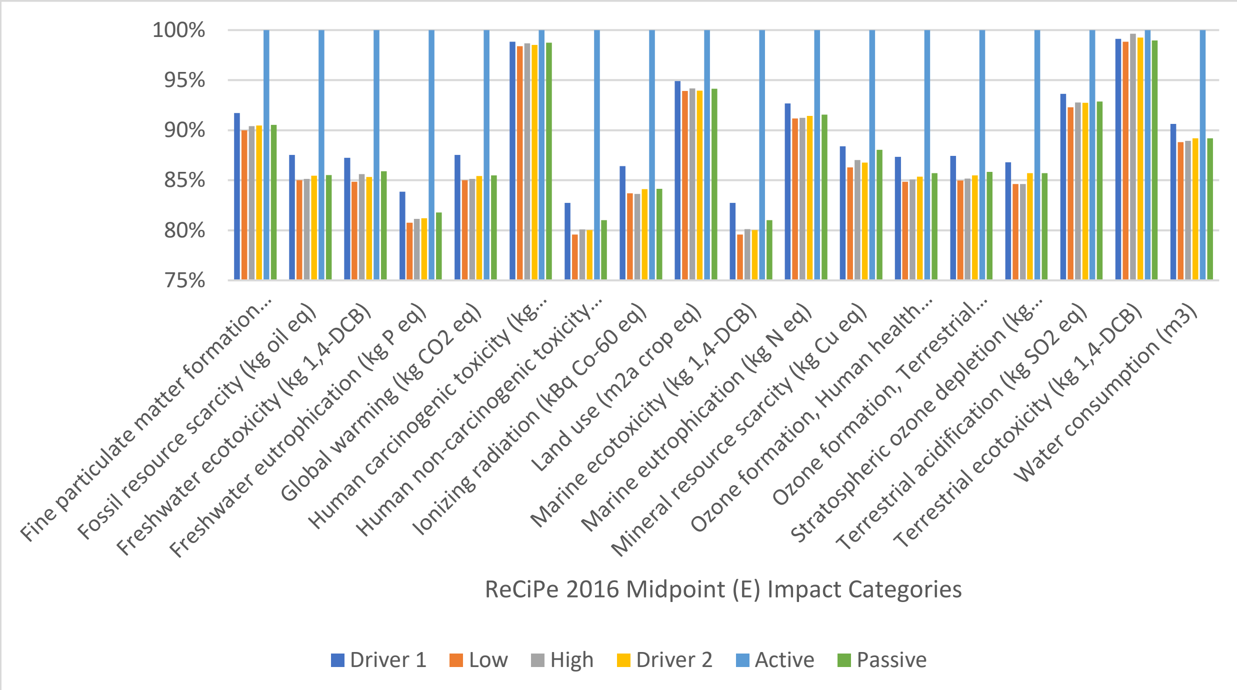

Figure 4. Environmental impact results for luminaires with either a driver or proxies. Results are normalized to the proxy: 'active' driver (PNNL 2023).

Findings from this pilot study of LED power supply component LCI include recommendations for manufacturers of luminaires, or other M&E products, to collect detailed information about power supply components; use standardized methodologies for data collection; consider regional variations in manufacturing processes and energy sources; provide clear documentation on methodologies, assumptions, and data sources, regularly updating LCI workbooks and guidance to reflect technological and material changes; and foster increased collaboration among stakeholders in the LCI data collection process.

The Future of Sustainability for Mechanical and Electrical Products

Impact Categories of Interest

In addition to energy efficiency, which has historically dominated the focus of sustainability in M&E, there is a critical need to broaden the array of impact categories. These include, but are not limited to, materiality, circularity principles, embodied carbon, water usage, air quality, biodiversity, human health, and social equity.

Materiality includes the environmental and social impacts associated with the extraction, processing, and transportation of raw materials used in M&E products (KPMG 2014). Assessing materiality involves considering factors such as resource depletion, ecosystem impacts, and labor practices throughout the supply chain. Circularity principles focus on the ability of M&E products to be reduced, reused, recycled, or repurposed at the end of their life cycle, thereby minimizing waste and resource consumption (EMF 2024). This involves evaluating factors such as product design for disassembly, material recyclability, and availability of recycling infrastructure (Hickcox and Smith 2022). Water usage is another critical impact category, particularly in regions facing water scarcity or pollution challenges. Assessing the water footprint of M&E products involves assessing water consumption during manufacturing, operation, and maintenance, as well as potential impacts on local water resources. Air quality considerations involve both indoor and outdoor air pollution associated with M&E products. These include emissions of volatile organic compounds, particulate matter, and other pollutants that can affect human health and environmental quality.

Product Category Gaps

A barrier to enhancing sustainability within M&E is the lack of comprehensive data across various product categories. LCA practitioners conducting WBLCAs have identified substantial deficiencies in available information, posing challenges for decision-makers striving to assess the sustainability performance of M&E products. These deficiencies include incomplete data on environmental footprints across the life cycle, poor supply chain transparency, and a lack of assessment in key impact categories beyond energy efficiency. Additionally, there are often insufficient data on product performance and challenges in standardization and comparability, hindering accurate sustainability assessments.

To address the deficiencies in data within M&E, establishing industry-wide standards for data collection and reporting specifically for North America is a necessity. Confidential and secure data sharing should also be enabled and incentivized among manufacturers, researchers, and industry stakeholders to enhance the availability, reliability, and accuracy of information, which will promote more representative and useful sustainability assessments and informed decision-making processes.

Data Transparency

LCI data typically comes from either primary or secondary sources. Primary data is "directly measured or collected data representative of activities at a specific facility or set of facilities," whereas secondary data are "data that is not directly collected, measured, or estimated, but rather sourced from a third-party life-cycle-inventory database" (Allacker et al. 2014). To maintain the public trust and validity of reported impacts, LCA data must be both accurate and transparent. This transparency is typically achieved through primary data as it can be validated at the source. Alternatively, secondary data is frequently plagued with issues of transparency, with an estimated 65% of all secondary data missing information regarding their sources and or accompanying information (Wu and Wang 2022). Thus, a strong focus on data transparency must be maintained, especially as LCA data moves toward the use of open-source data platforms (i.e., Federal LCA Commons). This will enable future LCA studies to maintain an equal level of validity, transparency, and above all reproducibility.

Innovative/Disruptive Technological Development

Technological development is pivotal in propelling sustainability within M&E, as evidenced by the emergence of energy-efficient HVAC systems and intelligent lighting controls.

These innovative solutions have been instrumental in diminishing the environmental impact of M&E products and systems. Disruptive technologies, such as additive manufacturing and advanced materials, are also revolutionizing design and production methods by placing sustainability at the forefront of innovation.

Informing Decision-Makers:

To effectively inform decision-makers within the M&E industry, concerted efforts are needed to enhance data accessibility, promote education and training, and develop decision support tools. Initiatives should focus on improving data transparency and accessibility by establishing platforms or databases where comprehensive information on the environmental and social impacts of M&E products is readily available.

Education and training programs should also be developed to enhance decision-makers' understanding of sustainability concepts and the implications of their decisions on environmental and social sustainability. These programs could take the form of workshops, seminars, online courses, and certifications tailored to the needs of decision-makers in the M&E industry.

Conclusion

LCAs provide decision-makers with critical insights into product sustainability by quantifying certain impact categories (e.g., carbon emissions, energy consumption, resource utilization) across a product's entire life cycle. However, many M&E product manufacturers face challenges to conducting LCAs because of data deficiencies and a lack of standardization in the data collection process. To address these barriers, PNNL has focused on developing tools and methodologies aimed at streamlining the LCA process within the M&E sector. These resources enable M&E manufacturers to gauge the environmental impacts of their products, identify impact hotspots, and make more environmentally and socially responsible decisions. PNNL intends to continue extending these approaches to encompass other M&E product categories to build a data-driven, sustainable future.

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