Exergy-Based LCA of Buildings: Bridging Gaps Through Enriched Material Databases

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Abstract

Exergy-based life cycle assessment (Ex-LCA) extends conventional LCA by incorporating the second law of thermodynamics, capturing both the quantity and quality of resource use. However, its application in building analysis is constrained by inconsistent and incomplete data on material exergies. This paper discusses the methodological origins of these discrepancies and proposes a framework for enriching material databases through multi-source reconciliation, reference environment harmonization, and uncertainty quantification. By integrating the approach within existing LCA workflows and aligning it with standards, the study aims at enhancing data reliability and comparability. The resulting framework enables more rigorous, exergy-informed sustainability assessments across building life cycles.

Introduction

Life cycle assessment (LCA) is a standardized methodology for quantifying the environmental impacts of products or systems across their entire life cycle, from raw material extraction through production, use, end-of-life treatment, and disposal. Standardized under ISO 14040/44 (International Organization for Standardization, 2006a, 2006b), LCA typically evaluates impacts in categories such as global warming potential, resource depletion, and acidification, often relying on energy content as a proxy for resource use (M. Nwodo & Anumba, 2021). Exergy-based LCA extends this by incorporating the second law of thermodynamics, measuring the maximum useful work obtainable from a system as it reaches equilibrium with its environment. Exergy distinguishes between energy forms based on quality; high-grade electricity carries more exergy than low-grade heat, thus revealing inefficiencies invisible in first-law analyses.

In building contexts, exergy-based LCA addresses three key impact categories: material consumption, energy consumption, and emissions arising from both. Exergy consumption of materials quantifies the thermodynamic potential embedded in structural elements like concrete and steel during extraction and processing. Resource exergy consumption of energy evaluates fuels and electricity used in manufacturing and operations, accounting for conversion losses. Exergy of emissions expresses the work potential still contained in pollutants, treating them as degraded resources whose abatement reflects their remaining usefulness (Michalakakis et al., 2021).

The exergy of materials, calculated as cumulative exergy demand, arises from standard chemical reactions to form the material from reference substances and all upstream exergy invested into their production. For construction staples, it is calculated via elemental composition using models like Szargut's reference environment (Szargut, 2005). Among the three categories, exergy of energy consumption is the best documented, with robust inventories in tools like Ecoinvent for fuels and grids, enabling precise operational assessments (Koroneos et al., 2012). In contrast, material exergies and those tied to emissions from material and energy processes remain underexplored, suffering from sparse data and methodological inconsistencies. Further diligence is required to aggregate reliable values, as current gaps hinder holistic building sustainability evaluations (Ari, 2011).

Challenge

The practical application of exergy-based LCA in buildings is limited by a lack of standardized data on the exergy of construction materials, compounded by discrepancies across available sources. Several reviews underscore this issue: while energy inventories are mature, material exergy databases are fragmented,

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with values for elements like steel varying from 22 to 34 MJ/kg depending on alloy specifics, reference states, and inclusion of process exergies (Ari, 2011), (M. Nwodo & Anumba, 2021), (Koroneos et al., 2012). Concrete shows analogous spreads (0.54-1.7 MJ/kg), driven by cement-to-aggregate ratios and clinker production assumptions not uniformly documented (M. Nwodo & Anumba, 2021), (Koroneos et al., 2012).

These inconsistencies trace to methodological divergences. Standard chemical exergy tables, such as those from Szargut's, provide elemental baselines but require aggregation for composites, introducing errors when sources diverge on reference environments (Szargut, 2005). Studies applying exergy-based LCA to buildings report variance in embodied exergy totals due to such inputs, eroding result comparability. Global reviews further highlight underrepresentation of regional materials, exacerbating biases in international assessments (Ari, 2011). Handbook analyses confirm that neglecting physical exergy components or recycling credits amplifies these gaps (Kotas, 1985), (Lizarraga & Picallo-Perez, 2019).

Without unified repositories, exergy-based LCA cannot reliably inform design choices or certifications.

Discussion

Addressing the data challenges in exergy-based LCA demands a multifaceted strategy focused on standardization, aggregation, and validation processes. Key aspects warrant development: First, methods should support multiple, well-documented reference environments, since exergy is inherently state-dependent and rigid reliance on one global model risks misrepresenting regional and sector-specific conditions. Practitioners can still use one model as a common baseline, but any adaptations for local relevance should be explicitly justified and transparently documented.

Secondly, multi-source data compilation is essential. Inventories should be developed by cross-referencing elemental exergies from validated tables (e.g., Szargut's) (Szargut, 2005) with compound-level studies, weighting by recency and peer-review status. For discrepant values, either (a) statistical reconciliation can be employed or (b) values can be recalculated by breaking down compounds into elemental compositions and re-deriving exergies to systematically recheck existing sources.

Enrichment protocols should leverage proxies for data voids: decompose materials into elements and sum standard molar exergies, validating results against benchmarks such as component or assembly case studies. Collaborative platforms, similar to ecoinvent's structure, could host community-updated exergy libraries that explicitly incorporate recycling loops and other circularity features.

Comprehensive system coverage is critical. For material exergies, calculations should use detailed inventory data on constituent substances and production processes, ensuring complete coverage of upstream and life cycle stages. For the exergy of emissions, substance-level emission data should be accounted for prior to characterization, enabling precise exergy calculations for individual emissions before aggregation, and capturing downstream effects that manifest as negative environmental impacts, such as climate change. In this way, material exergy reflects not only the embedded work potential of emission elements but also the environmental impacts they impose.

Fifth, uncertainty quantification must become routine. Categorize sources by pedigree (e.g., lab-measured vs. modeled) and propagate errors using Monte Carlo approaches in LCA software, ensuring exergy inputs reflect real-world variability (M. Nwodo & Anumba, 2021). For emissions exergy, extend abatement models to include dispersion potentials, bridging the gap with energy-focused inventories.

Sixth, integration workflows are critical: embed enriched data in open LCA tools, running sensitivity tests to assess impacts on building totals (e.g., 15% embodied exergy shift from steel harmonization). Theoretical development involves hybrid metrics, exergy per functional unit (m^2 floor area), to compare renovations vs. new builds, critiquing potential energy-LCA's underestimation of material dominance.

Finally, institutional aspects require attention: advocate for exergy inclusion in standards like EN 15978 (European Committee for Standardization, 2011), with guidelines mandating checklist adherence (standardize, compile, quantify, reconcile, validate). Pilot applications in German contexts (e.g., KfW 40+ renovations) can demonstrate feasibility, fostering adoption. This holistic development, processual, statistical, and collaborative, transforms exergy-LCA from niche to mainstream, resolving literature contradictions through rigorous, evidence-based evolution.

Conclusion

Exergy-based LCA contributes to sustainability accounting by providing a thermodynamically solid framework that considers both the quality and quantity of resources, enabling comprehensive, physically grounded assessments of embedded materials, use-phase processes, and emissions. By addressing data gaps through the proposed processes, standardization, multi-source reconciliation, uncertainty handling, and validation, this approach enhances authenticity and reproducibility, supporting the development of single-indicator metrics for design optimization and policy formulation.

These guidelines pave the way for broader adoption, supporting certifications like DGNB by delivering consistent exergy inventories that outperform energy proxies in revealing true sustainability trade-offs. Ultimately, they promote a paradigm shift toward exergy-informed practices, fostering resource-efficient construction and progress in global sustainability goals.

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