Controversy and consensus: common ground and best practices for life cycle assessment of emerging technologies

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Abstract

The past decade has seen a surge in public and private interest in the application of life cycle assessment (LCA), further accelerated by the emergence of new policies and disclosure practices explicitly mandating LCA. Simultaneously, the magnitude and diversity of stakeholder groups affected by LCA and LCA-based decision making have expanded rapidly. These shifts have brought about a renewed sense of urgency in conducting LCA faster, more accurately, and (often) earlier in the technology development cycle when products and materials can be more easily replaced, modified, or optimized. However, this increased demand for LCA of emerging technologies has revealed several crucial yet unsettled areas of debate regarding best practices for assessing sustainability at early stages of technology development. In this paper, we explore six such controversial topics: (1) appropriate use of LCA, (2) uncertainty assessment, (3) comparison with incumbents, (4) adopting standards, (5) system scale-up, and (6) stakeholder engagement. These topics encompass key issues vigorously debated during a series of workshop-style discussions convened by the LCA of Emerging Technologies Research Network (currently hosted by ACLCA). In this paper, we present the main points of support and opposition for a declarative resolution representing each topic, along with points of consensus, held amongst our research network of LCA practitioners and experts. These debates and associated open questions are intended to build awareness amongst practitioners and decision-makers of the common challenges associated with assessing emerging technologies, while fostering evidence-based and context-informed discussions that are both transparent and impactful for the broader community.

Introduction

One of the leading challenges in the field of life cycle assessment (LCA) is the creation, adaptation, and application of techniques to assess emerging technologies early in their development cycle. While LCA has the potential to offer impactful insights if done as a proactive technology assessment of emerging technologies, existing LCA guidance, frameworks, and tools are not necessarily designed to support LCA of emerging technologies (Bergerson et al., 2020; Moni et al., 2019). We define the term 'emerging technologies' as it is used in Bergerson et al., referring to general technology categories within which specific technologies and products exist but are not produced at full scale or rates. This disconnect motivates the development of new technical methods like uncertainty or scale-up frameworks. It also highlights the urgent need to build consensus such as when LCA is appropriate, how to effectively engage stakeholders— and communication strategies to aid broad audiences in how to interpret LCA results and understand their limitations.

Here, we build upon our 2020 paper that explored the shift from reactive to proactive assessment strategies as a result of a deepening recognition of the significance of environmental considerations in the development of emerging technologies (Bergerson et al., 2020). The 2020 paper notes the lack of systematic guidance for analysts and discusses the unique challenges posed by emerging technologies, including data scarcity, uncertainties (e.g., unknowns in possible industrial scale-up), a potential lack of incumbents and competitors for comparison, and uncertainty regarding deployment and market conditions. The paper concludes with a synthesis of insights from leading researchers, and a call to action including a foundation for further dialogue, research network development, and the creation of analytical tools to assess emerging technologies consistently and robustly. Researchers in the LCA of Emerging Technologies Research Network (currently hosted by the ACLCA at www.aclca.org) have been meeting regularly since 2017 to discuss the latest issues confronting practitioners of emerging technology LCA. As we endeavored to follow our own suggestion to "systematically address the methodological challenges" (Bergerson et al., 2020) described in our first paper, we encountered several fundamental disagreements about challenges and solutions we were attempting to address. Recognizing an impasse, we decided to summarize our discussions and debates rather than attempting to directly resolve our differences. We aim to inform the broader community of LCA practitioners, researchers, and any stakeholders that may interact with LCA.

Healthy debate is a cornerstone of academic progress. By its nature, LCA requires considerable reliance on modeling, assumptions and normative choices around system boundaries, scenarios, impact accounting and more. Even among mature systems and contexts such as biofuels and approaches to biogenic carbon accounting (e.g., Mayer et al., 2020), environmental or human health impacts of microplastics (e.g., Jiao et al., 2024), and sources of uncertainty or uncertainty analysis methods (e.g., Matlock et al., 2022), arguments and response commentaries persist. The debate also extends to LCA methods, from the (in)validity (e.g., Plevin et al., 2014) or usefulness (e.g., Suh & Yang, 2014) of attributional LCA, to the spectrum between consequential and attributional approaches (e.g., Suh & Yang, 2014; Yang, 2016), to challenges (e.g., DeCicco, 2012; DeCicco & Krishnan, 2015) and defenses (e.g., De Kleine, Anderson, et al., 2017; De Kleine, Wallington, et al., 2017) of the use of LCA. A final example is the debate about the accuracy of hybrid LCA (Pomponi & Lenzen, 2018) versus process LCA (Yang et al., 2017). These debates helpfully challenge conventional wisdom and highlight both advantages and limitations as well as implicit and explicit assumptions embedded in different approaches. They serve as a valuable entry point for junior researchers and as an opportunity for experienced researchers to sharpen their perspectives.

In this paper, we highlight several controversial topics, within the scope of LCA of emerging technologies, that have arisen during a series of workshop-style discussions held at meetings of the International Symposium on Sustainable Systems and Technology (ISSST) and the American Center for Life Cycle Assessment (ACLCA). The structure of this paper draws inspiration from the tradition

of Faraday Discussions and the corresponding journal published by the Royal Society of Chemistry. Faraday Discussions papers are intended to document conference discussions and debates on rapidly evolving current and emerging topics, traditionally in the field of physical chemistry. We present the disparate perspectives within our group for each controversial topic to raise awareness of key issues that should be considered in LCA of emerging technologies—including areas where judgment calls may need to be made by individual practitioners and clearly communicated, and areas where common ground and consistent guidance across a broader swath of the LCA community may be possible. These topics include the appropriate use of LCA, uncertainty, comparisons, standardization, scale-up and stakeholder engagement, as summarized in Figure 1. For each topic we present two divergent views, structured as support/opposition for a specific resolution and then discuss aspects of the topic that the group of authors agreed on. This is followed by a discussion of the implications of these debates, what they mean for the field moving forward, and what can or should be done to either resolve disagreements or develop alternative paths forward.

This paper also serves as a pulse-check on the status of LCA of emerging technologies in 2024 and aims to highlight opportunities for advancing the field, especially in an environment of increasing reliance on LCA in decision-making processes by regulatory bodies, funding agencies, and private entities. The intended audience of this paper is broad. We aim to alert technology developers about the need to consider the issues discussed here as they apply LCA and interpret and incorporate results. We also hope to inform policy makers, funding agencies and investors to ensure that LCA studies are used and interpreted correctly to inform their investment decisions. Lastly, we provide more detailed guidance to LCA practitioners to build awareness of the common challenges associated with assessing emerging technologies and facilitate discussion about how to navigate them.



Figure 1. Overview of the controversial topics addressed in this paper. Note that numbers correspond to sections in the paper, but the process flow is not linear; rather, each topic should be assessed and addressed iteratively throughout various stages of the LCA process.

Debate Topic 1: Appropriate use of LCA

The first controversial topic involves the fundamental dilemma of whether and how to apply LCA to emerging technologies. On the one hand, LCA can have the greatest potential influence on achieving sustainability goals and avoiding negative environmental consequences when implemented at the earliest stage of technology development (Tischner & Charter, 2001). We do not want to delay preliminary assessment so long as useful insights from LCA are only available after all primary design decisions have been made and impacts are "baked into" the technology, a situation often referred to as "technology lock-in." On the other hand, LCA should be applied at a point in a technology's development process at which potential environmental impacts can be meaningfully determined; namely, uncertainty about future development decisions should not be so great as to undermine any sense of robustness in the evaluation. Given this requirement, one might assume that LCA is not appropriate until a technology is close to or at commercialization. There is a delicate balance between "too early" and "too late." The strong opinions on either side of this debate highlight the need for a strategic approach and communication plan that optimizes the timing of LCA to maximize its benefits in guiding technology development while maintaining a level of reliability or robustness required by the decisions that the study is meant to inform. Figure 2 summarizes the trajectory of technology development on the x-axis (from concept to commercial) along with the prevalence of use and usefulness of LCA considerations and types of LCA for each stage of development.



Figure 2. Appropriate uses of LCA as a technology emerges and scales. Across technology development stages (increasing TRL – technology readiness level), the prevalence of use and usefulness of different types of LCA and life cycle thinking approaches are highlighted (Note: these are representative approaches and are not intended to be comprehensive). As indicated with hashed shading, there is an opportunity to expand and improve the methods that could be applied mid-development where more data becomes available, and more clarity emerges about the conditions in which the technology might be deployed. At the same time, the potential for both design and technology "lock-in" starts to increase as the degrees of freedom about the technology reduce. Note: this figure is not a robust quantification; rather, the shapes and heights of the curves are qualitative and are intended as schematic.

Many definitions, models, and approaches to LCA of emerging technologies exist throughout the literature (Guinée et al., 2018). However, there is a lack of unified methods and consensus in the field (Grimaldi, 2020). A variety of frameworks have been proposed ranging from simplified, screeninglevel risk assessment metrics to detailed, ISO-compliant prospective or anticipatory LCA. For example, Buyle et al. (2019) conduct a review of the literature on early-stage or "ex ante" LCA and classify activities as proposed conceptual frameworks, new procedural actions, and/or data collection methods that span multiple technology readiness levels (TRLs) while accounting for technological learning and technology diffusion. Particularly at the earliest TRL stages, researchers have cautioned that LCAs may be inappropriate or impractical (Grimaldi, 2020), and screening-level risk assessment frameworks have been proposed instead. For example, the Emerging Materials Risk Analysis (EMRA) framework of Horgan et al. (2022) uses a risk matrix approach to compare alternative materials or different production routes by assessing both the consequence of impact and probability of impact occurring. Putsche et al. (2023) propose the use of "stoplight diagrams" to assess predominant contributors, supply chain considerations, and environmental and social justice concerns at each early TRL stage ranging from TRL 1 (e.g., concept) to TRL 4 (lab prototype and validation). Data from such early-stage screening assessments can be incorporated into LCAs as technologies advance, but care must be taken to emphasize the nature and magnitude of uncertainty in these methods and what this means for appropriate use of such an analysis.

Resolution

LCA can be appropriate and helpful at any point across the technology development process.

Support for resolution

Even in cases where conclusive insights about the prospects of a technology are challenging, LCA can be used to support a gap analysis, revealing the unknowns about a technology, the data and expertise needed to assess its performance at the current stage of development, as well as how this performance might change as it approaches deployment. LCA can be used to facilitate environmentally informed decision-making and research priorities by identifying "hotspots" (key processes that lead to highest impacts) in the technology itself or across its potential future supply chain. While a comprehensive LCA of an emerging technology may not be possible due to missing and/or poor-guality data, the core concepts of life cycle thinking remain valuable as long as the limitations of analysis and appropriate use of findings are communicated effectively as per ISO 14040 series guidelines. There are also techniques that can be used to mitigate the challenges with data scarcity and quality. For example, projections, scenario analyses, scale-up methods, and incorporating proxy data from technologies with similar characteristics can be used to fill data gaps in modeling efforts until more accurate data becomes available (Gavankar et al., 2015; Piccinno et al., 2016; Weyand et al., 2023). This is also a potential area of growth for the field of LCA of emerging technologies where new techniques can be developed or adapted from other fields to enhance the ability to generate helpful insights even in the face of data scarcity and quality (e.g., screening-level risk assessment metrics) (Horgan et al., 2022; National Research Council, 2009).

Opposition to resolution

While it is promising that LCA is being requested more frequently, more broadly, and earlier in the development of new technologies, conducting an LCA without robust data and without the ability to project a technology's potential future performance can lead to negative unintended consequences. LCA is commonly used as a buzzword in funding proposals but inappropriate applications of the method can result in an analysis that does not meet minimum criteria needed to be considered a "good" or "robust" LCA (Brandão et al., 2024; Rebitzer & Schäfer, 2009). Failing to disclose deficiencies in LCAs of emerging technologies can result in misinformation, poor characterization, misleading conclusions, incomparable results, and suboptimal decision-making, all of which can harm the field's reputation and undermine public trust in LCAs.

The types of consequences that could arise include:

- 1. Impacts can be over- or underestimated due to a lack of parameter bounds. Not considering uncertainty in a systematic way can lead to a false sense of *certainty* in LCA impact estimates, which can be risky for decision support. (See Debate Topic 2 in the following section for additional discussion on this subject.)
- 2. Misinterpretations may occur because LCA findings can vary significantly based on underlying assumptions. For emerging technologies, these assumptions tend to be more numerous and have greater consequences if compared to alternatives (e.g., other data-poor emerging technologies) and other studies (e.g., data-rich and optimized incumbent processes). Comparative assessments can be valuable for target setting but possibly not appropriate for direct comparisons with existing technologies.
- 3. LCA can be ineffective if it does not account for possible alternative processes, especially if emerging technology processes change. For example, new technology categories may be prematurely dismissed if all potential development options are not considered.

Common Ground

Life cycle thinking can be a powerful starting point to inform decisions about emerging technologies. However, life cycle thinking is not the same as a comprehensive LCA where uncertainties associated with a commercialized technology have largely been resolved. It is critical to clarify this when communicating life cycle results of any sort. Observing ISO 14040 series guidelines, emphasizing consistency, completeness, sensitivity, and logical conclusions aligned with the study's goal and scope are important starting points. LCA is also most useful when methods, data, and assumptions are transparently described. For emerging technologies, both LCA and technology expertise are necessary. This ensures that the technology's nuances and disproportionately high uncertainty with respect to function, performance and comparison systems are properly treated and communicated consistent with the intended use of the LCA.

ISO 14040 series guidance on how to conduct "good LCAs" needs even more emphasis for LCA of an emerging technology, and potentially supplemental guidance specific to LCA of an emerging technology. This includes careful attention to the goal and scope definition, clear function(s) and functional unit(s) that are possible, and transparent communication of limitations and findings. For example, ISO 14040 series guidance suggests that the decision being informed should be clearly stated as part of the goal and scope and then revisited for consistency at the interpretation stage. Following such guidance is even more critical and challenging for an emerging technology, where multiple possible functional units, uncertainty around technology use and performance, etc., are the norm. ISO 14040 series does not provide guidance about how to determine whether the study itself can support the decision maker in confidently making the decision that they laid out in the goal and scope. Guidance on how to determine this "threshold" and evidence for whether the analysis meets this threshold alongside the results can improve the appropriate interpretation of the results when they are presented to the decision maker.

Other communication strategies could include developing classifications of LCA at different levels of rigor similar to those implemented in some techno-economic assessment categorizations (Bredehoeft et al., 2020). In this recommended practice, different maturity levels relative to the completion status of the project and end use of the estimate are associated with specific methodologies and expected accuracy confidence intervals. Defining various "tiers" of LCA accounting for the differing stages of emerging technology, methodologies, and uncertainties can provide practitioners with clearer points of comparison when appropriately applying LCA.

Debate Topic 2: Uncertainty

Uncertainty in LCA is deep and widespread, even for mature technologies (Heijungs, 2024; Igos et al., 2019). Challenges surrounding uncertainty in LCA are magnified when applying LCA to low TRL emerging technologies. There is little historic data on which to draw, the final performance of the foreground system under study is largely unknown, and the background system into which it will be deployed is speculative. In addition to the uncertainties that LCA generally contends with (e.g., temporal and geographic variability), new types of uncertainty are introduced in LCAs for low-TRL technologies, most notably scenario uncertainty (due to unknown future external factors), parameter uncertainty (due to technology development options), and model uncertainty (due to subjective modelling choices) (Blanco et al., 2020). Another framing of the source of uncertainties that dominate the LCA at different stages of technology development include process, scaling, and market uncertainties, as presented in Figure 3.



Figure 3. Uncertainty considerations and uncertainty assessment methods for LCA of emerging technologies (across TRL – technology readiness level). The top figure highlights examples of uncertainty methods loosely ordered by sophistication and technology stage at which they can be applied. The bottom figure showcases (1) non-exhaustive examples of prominent uncertainty types and (2) the prevalence of complete or sophisticated uncertainty assessment, both varying across technology development stages. At the earliest development stages, uncertainties are high and very basic uncertainty methods tend to be applied. As the technology develops, scaling uncertainty often becomes prominent. As the technology gets closer to commercialization, the more comprehensively the uncertainties can be characterized and quantified. At the same time, the potential for both design and technology "lock-in" starts to increase as the degrees of freedom about the technology reduces (Gavankar et al., 2015), Note: this figure is not a robust quantification; rather, the shapes and heights of the curves are qualitative and are intended as schematic.

Methodological and conceptual frameworks have been proposed to characterize and address uncertainties in emerging technologies (Blanco et al., 2020). Since uncertainties can propagate from data gaps in LCI databases, Grimaldi (2020) proposes a framework for early-stage LCA in process chemistry based on an "optimization loop" to reduce uncertainties in LCI and benchmark performance compared to incumbents, cautioning against LCA at TRL stages of 3 or earlier due to intractable and inconsistent uncertainties. To specifically address background system evolution and enable robust comparisons, Douziech et al. (2023) expand on the open-source *lca_algebraic* library to combine parameterized LCIs of foreground and background systems via publicly available models and datasets. Other studies address specific economic or political factors leading to LCI uncertainties, such as the influence of an early-stage technology's adoption price (Miller et al., 2020) or different climate mitigation targets (Sacchi et al., 2022) on prospective LCI databases.

There remains a lack of consensus on best practices for addressing LCA uncertainty for technology in early stages. This has led to a paradoxical bifurcation of the LCA community, with some arguing that the pervasive uncertainty requires increasingly sophisticated methods (e.g., Monte Carlo simulation), while others respond that the uncertainty itself is so profound such that these methods are not appropriate.

Resolution

Given the higher degree of uncertainty, LCA of emerging technologies requires the application of more sophisticated uncertainty assessment compared to the LCA of conventional technologies.

Support for Resolution

Uncertainty is present at all stages of technology development, whether we acknowledge it or not (Gavankar et al., 2015). Conducting a structured uncertainty assessment (e.g., generating a probability distribution of LCA results), even if somewhat arbitrary, reinforces to the reader that the results are uncertain rather than presenting point estimates that imply a certainty that could lead to incorrect interpretations. Simply put: if an LCA practitioner does not believe that a point estimate can stand alone as a single "best guess" or central case, then it shouldn't be presented as such. Uncertainty assessment using a formal method such as Monte Carlo simulation allows the LCA practitioner to quantify (in a systematic way) the degree and nature of uncertainty and implications for the ultimate performance of the technology.

The ability to speak in terms of confidence intervals is a useful way to succinctly capture and quantify the magnitude of uncertainty. It can also be a key tool for decision making such as when evaluating the likelihood of meeting certain thresholds for performance. For example, at the very lowest TRL levels, first principles calculations combined with order of magnitude estimates can help identify theoretical upper and lower limits to physical and chemical parameters that can inform performance and life cycle inventories. While simple ranges or bounding scenarios can also capture optimistic and pessimistic outcomes, the use of probabilistic methods enables tighter and arguably more realistic bounds on the results than artificially setting all parameters at their best/worst values and examining edge cases through parametric sensitivity approaches that involve potentially arbitrary combinations of high/low across multiple inputs.

Uncertainty assessment can enable a more holistic, global picture of sensitivity to modeled input parameters and facilitate the identification of robust technology options (i.e., those that perform well across a wide number of model iterations), which is likely to be a key consideration in a world of deep uncertainty. An example, proposed by Blanco et al. (2020), is a probabilistic scenario model combined with global sensitivity analysis for LCA models of emerging technologies. Such approaches can be used for managing many degrees of freedom while filtering out the modeling decisions that have negligible impact on the distribution of impact score, despite their uncertainties.

Opposition to Resolution

The very data gaps that cause uncertainty in the model also prevent the determination of a robust and well justified characterization of the nature and magnitude of uncertainty across the life cycle. There is thus a risk that in aiming to prevent overconfidence in the point estimate, a detailed uncertainty assessment can mislead the reader/decision maker due to over-confidence implied by the final probability distribution. Rather, it should be acknowledged and communicated up front that these models can provide tendencies rather than truths (even those presented as probabilities).

For early-stage technologies, the key question is often not how well we expect the technology to perform, but rather does it have the *potential* to outperform the incumbent; or what choices in the technology's development are likely to drive its environmental performance. These are questions which may be fundamentally better served with simple bounding exercises or scenario analysis to highlight the conditions under which it does/does not perform well. For example, Saltelli et al. (2013, 2020) propose sensitivity auditing for environmental modeling, essentially a checklist that enables practitioners to highlight and explore assumptions, check for inappropriate use of models that can come from over-interpreting results, and confirm that the correct questions are being asked.

Probabilistic models are best suited to capture parametric uncertainties (i.e., known unknowns), which may pale in comparison to the uncertainty in model structure (e.g., function the technology serves, future projections, scale-up from laboratory data) that frequently dominate emerging technologies. When it comes to emerging technologies, we are often navigating in the realm of "unknown unknowns" —a domain where the future is unpredictable and uncertainties are not just unknown but also unquantifiable. This additional layer of uncertainty introduces profound complexities in quantifying future uncertainties, making it challenging to apply traditional LCA methods effectively. Thus, *qualified* point estimates (informed by bounding exercises or scenario analysis) may instead be more helpful (Villares et al., 2016).

A final argument against more sophisticated uncertainty assessment is less theoretical and more practical—cost. Early-stage researchers and project developers may enthusiastically perform or request an LCA on a proposed technology. The complexity of uncertainty analysis when they are struggling to understand scale-up parameters and other basic assumptions may be cost-prohibitive. Such a requirement or recommendation may be too high of a burden, while offering few benefits in terms of actionable insight. A more qualitative approach to uncertainty may be more feasible and useful at such an early stage.

Common Ground

Uncertainty is inherent in all LCAs—even for mature technologies—and requires careful treatment, particularly when applied to emerging technologies where deep uncertainties exist about the emerging technology and its potential impacts. When presenting LCA results, regardless of the approach taken to treat uncertainty (i.e., use of Monte Carlo simulation versus order of magnitude or bounding analyses), discussion should focus on factors driving environmental impacts or hot-spot type analyses rather than a focus on the absolute or precise quantitative results. Further, clear and effective communication of the limitations of the study given the early stage of the technology can prevent the study audience from misinterpreting either point estimate results or probability distributions as an absolute prediction of the future environmental performance of the technology. Effective communication of uncertainty should include consideration of explicit reporting, contextualization, scenario crafting, the use of straightforward language, and visual aids in the interpretation stage of the study.

Debate Topic 3: Comparison with incumbent

LCA is increasingly being used in the context of technology advancement decisions, both in public and private sectors (Jegen, 2024). Often, these decisions are informed by comparisons of the technology in question to a benchmark, baseline, or incumbent technology. In this context, "incumbent" is used to refer to an appropriate comparator or dominant alternative (e.g., the technology that has the greatest market share and is the target of being offset by the emerging technology, if it exists). Emerging technologies present a set of unique challenges for application of LCA, particularly when conducting a comparative LCA. When defining the comparison system, it is often difficult to identify the appropriate comparison technology and use scenario(s). ISO 14040 series does not provide specific guidance on how to select the appropriate comparison in general, which is particularly challenging for emerging technology comparisons where there are likely a variety of potential incumbent and potential future competing technologies. There are some guidelines that have been published for application to specific use cases (e.g., Langhorst et al., 2022; Skone et al., 2022); however, consensus on best practices has not been attempted to date (Blanco et al., 2020; Douziech et al., 2023; Grimaldi, 2020).



Figure 4. Challenges and opportunities of making comparisons with an incumbent as a new technology develops (across TRL – technology readiness level). Here, "incumbent" is an appropriate comparator or dominant alternative (e.g., the technology that has the

market share that is trying to be offset by the emerging technology, if it exists). As the technology develops, the uncertainties associated with the performance of an emerging technology as well as the appropriate comparator improve and, therefore, the benefits of and confidence in comparisons increase. At the same time, the potential for both design and technology "lock-in" starts to increase as the degrees of freedom about the technology are reduced. The bubbles at the top of the figure suggest some considerations as an appropriate incumbent is identified and assessed, as well as while interpreting any LCA results or studies. The bottom figure highlights how selecting an incumbent comparator is particularly challenging at very low TRL for a variety of reasons; for example, since scaling a new technology takes time, the comparator will also evolve over that time interval such that its future performance is uncertain. Note: this figure is not a robust quantification; rather, the shapes and heights of the curves are qualitative and are intended as schematic.

Commercial deployment of emerging technologies is, by definition, at some point in the future. The function of the emerging technology and, thus, the appropriate comparison technologies, may be uncertain. Furthermore, the current mix of comparison technologies may not be reflective of a future world in which the emerging technology would deploy. Comparisons based on present day incumbents may be misleading. For example, the benefits of the emerging technology might be understated if the potential for the emerging technology to improve over time is not considered. Additionally, the technologies being compared will likely be at different scales (pre-commercial emerging technology vs. commercial incumbent) as well as different stages of maturity. This introduces potential methodological differences in how the LCA is carried out as well as differing levels of uncertainty on the key assumptions. Further, the comparison could be based on a mix of technologies providing the same function or some subset of that mix (e.g., marginal cost, best-inclass environmental performance). For many emerging technologies, the function may evolve over time, necessitating an update to the comparison technology selection and thereby the LCA comparison over time. Figure 4 summarizes how the confidence in selecting a comparator and the value of the comparison change as the emerging technology develops over time.

Resolution

We should evaluate emerging technologies in comparison to incumbent technology reference systems.

Support for Resolution

LCA results that focus on relative differences between alternatives can be meaningful even when uncertainty is high. For example, identifying hotspots is valuable when conducting an LCA of a system in isolation; however, it does not provide sufficient information to benchmark or measure progress in a future deployment scenario in the way that a comparison does. As noted above, one argument for implementing LCA early in the development cycle is that it is more cost-effective to make changes compared to a mature system (Cucurachi et al., 2018). Without effective benchmarking in the form of comparison, it is difficult to assess improvements throughout the development cycle.

There is also value in comparison of multiple variations of a proposed technology. For example, developers may be evaluating a variety of potential options within a given technology space, and consistent benchmarking facilitates more useful comparisons within variants. Comparative LCA can also be useful when evaluating multiple potential functions of an emerging technology relative to a variety of different potential end uses and associated incumbent technologies. The results provide decision makers with the full context of potential impacts to allow the assessment of potential trade-offs in impacts between the systems.

Opposition to Resolution

At early stages of technology development, the availability of data to perform LCA of emerging technologies is limited. The end uses of an emerging technology might not be specific or fully developed at early stages, which makes it very challenging to define a functional unit. Similarly, the utility of co-products, end-of-life or feasibility of recycling, or reuse of materials might not be

understood. All of these issues create challenges in selecting functionally equivalent benchmark(s) for comparison.

ISO 14040 series does not require a comparison in the context of an LCA. ISO 14040 series requires that if a comparison is done, it is done consistently in terms of "functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment (4.2.3.7)." Any inconsistencies among the systems relative to these attributes should be noted in the LCA report. ISO 14040 series also requires a critical review for comparative results intended for public disclosure. However, the standard does not offer more specific guidance on comparison system selection criteria.

While some guidelines are available (e.g., Langhorst et al., 2022; Skone et al., 2022), the comparison system selection process is nuanced. For example, a clear definition and justification of what is meant by marginal technology, market average, or best in class is often missing in LCA studies. An emerging technology can appear as "better" or "worse" depending on the comparison system (e.g., marginal technology versus average of alternative technologies) and degree of optimism surrounding future performance improvements. Such incomparable or inconsistent results may confuse the LCA audience and could mislead investment or policy decisions. This ambiguity also leads to the potential for those conducting the LCA to introduce bias into the analysis (e.g., "cherry pick" the emerging technology data and/or comparator to favor the outcome they are marketing).

Common Ground

Comparing LCA results of emerging technologies with appropriate comparison systems at early stages of development can provide useful insights and support technology developers in setting priority areas to improve the overall competitiveness of the emerging technology. However, careful interpretation of the results, and corresponding uncertainty should be exercised when making decisions. Performance targets can likewise be set based on comparison to incumbent systems while avoiding claims of preferability based on current or expected performance. A final "go" or "noao" decision by technology developers, funding agencies or investors might not be advisable until data completeness and uncertainty analysis provide sufficient justification. The threshold for what is needed to make such decisions is subjective and must be determined by the decision maker (not the LCA practitioner). As technologies advance through the development cycle, technology developers need to respond to the changes in data availability and market trends to justify the validity of the comparison systems selection and identify when updates to the LCA are necessary. Finally, although comparison with benchmarks can be useful at early stages of technology development, care must be taken to select proper benchmarks by considering the TRL of the emerging technology, functional equivalency or substitutability of emerging technology, changes in the comparison system over time, and associated uncertainties. These choices and their justifications should be included in the documentation of any LCA but are particularly important for LCAs of emerging technologies.

Debate Topic 4: Standardization

Global standards provide guidance on the practice of environmental LCA as part of the ISO 14000 series of International Standards on Environmental Management, including 14040 (Life Cycle Assessment – Principles and Framework) and 14044 (Life Cycle Assessment – Requirements and Guidelines). An assertion of an "ISO-compliant" LCA creates the perception of a gold standard for environmental assessment of a product, process, or service and that comparability across studies is assured. However, even an ISO-compliant LCA allows broad latitude in how an LCA is conducted including modeling assumptions, data, and uncertainty assessment techniques employed.

Consider, for example, the following guidance on data collection for LCA (excerpted from ISO 14044):

"Data selected for an LCA depend on the goal and scope of the study. Such data may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, all data may include a mixture of measured, calculated or estimated data." (ISO 14044 (2006): Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2006).

Plainly, the practitioner is given broad discretion in selecting appropriate data while acting in good faith to follow the standard. The result is that practitioner choices can have an enormous impact on results. If one analyst chooses to measure elementary flows onsite at a manufacturing facility, while a second analyst chooses to calculate the same flows from first principles or utilize proxy data from the literature, it would be much more surprising for the results to agree than for them to diverge. As elaborated in ISO 14040,

"there is no single method for conducting LCA. Organizations have the flexibility to implement LCA as established in this International Standard, in accordance with the intended application and the requirements of the organization." (ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework, 2006)

While methodological flexibility is an important element of application-agnostic standards, a clear disadvantage is that assertions of compliance with relevant ISO 14040 series guidelines may suggest a level of harmonization and comparability across LCA studies that may not be appropriate. Furthermore, even the flexible framework of the ISO 14040 series can be challenging to apply to low-TRL technologies because so many aspects of the methodology were devised with mature and existent products in mind (Bergerson et al., 2020). Explicit standardization of LCA of emerging technologies could provide new opportunities but comes with challenges and risks. Indeed, pockets of standardization have already begun to emerge, particularly in reference to regulations (e.g., from the California Air Resources Board (2020) or Inflation Reduction Act (Cheng et al., 2023)), industry consortia (Langhorst et al., 2022), industry-specific product category rules (The PCR | EPD International, n.d.), and guidelines from funding bodies (Skone et al., 2022). While no standard can capture every aspect of the LCA process, and none is a perfect substitute for analyst judgment across all contexts, these efforts nevertheless could achieve a level of consistency and comparability within their specific domain (e.g., goal and scope of a specific funding call). At the same time, politicization and bias have been identified with standardization (e.g., Blind & von Laer, 2022) in terms of representation on committees, etc.



Considerations to design, apply & interpret standards Product: Role of **Design:** How to balance **Regulation: Type:** Is it a Scope: TRL: Are standards How Should generic vs prescriptive for reporting flexibility vs standard. productstandards should consistency certification, or procedure differ by TRL? specific standards be? across studies? guideline? analysis? standards? Increasing "lock-in" and data quantity/quality High **Representative approaches** Conventional methods Emerging interventions, & knowledge methods, knowledge Guidance from **Degree of** ISO 14040 series confidence Reliance on is applicable standards can in **Development** of mask true statement uncertainty new emerging tech Industry-specific standards could be standards exist (e.g., PCRs, useful CCU, PVPŠ Low

Concept Technology stage (Increasing TRL) Commercial

Figure 5. Standardization options for LCA of emerging technologies (across TRL – technology readiness level). Across technology development stages, as well as across industries, specific characteristics and methods that are and can be standardized differ. Similarly, standardization brings about unique advantages and disadvantages at various stages and fields. The top of this figure highlights key questions LCA practitioners and stakeholders should be considering when developing, using, and interpreting standards. The bottom of the figure represents qualitative considerations as a function of TRL, and existing and proposed standards and guidelines are also highlighted. We highlight several example standards: PCRs - Product Category Rules (BS EN 15804, 2021) (available for many product categories); CCU – Carbon Capture and Utilization (Langhorst et al., 2022); and PVPS - Photovoltaic Power System Program (Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity 3rd Edition, 2017). It is important to note that these are representative approaches and existing examples and are not intended to be comprehensive. The hashed shading represents the specific opportunity highlighted in this paper to expand and improve standards during the mid-development period. Note: this figure is not a robust quantification; rather, the shapes and heights of the curves are qualitative and are intended as schematic.

Resolution

We should develop standards for conducting LCA of emerging technologies.

Support for Resolution

Standards provide explicit guidance for methodological steps, definitions, and assumptions that might otherwise be left to the judgment of individual practitioners. In some cases (e.g., whether specific scale-up activities should be incorporated), practices may be accepted as norms within a community but not clearly spelled out, which can lead to misinterpretations in the absence of a

foundational standard that documents the shared understandings. In other cases, practitioners may disagree on best practices; or a novel application that resists assessment with standard techniques may inspire the development of an entirely new method. Lack of consensus across the community can result in an unfortunate "wild west" where such a broad range of methods are in active use that each study stands alone as an independent and noncomparable assessment. This situation is uncomfortably close to the current reality of LCA for emerging technologies, and standardization to enable consistency and comparability of studies is needed to address this problem.

LCA techniques are known to be difficult to apply to emerging technologies, in part because the methods for estimating elementary flows are not obvious when inputs and outputs cannot be physically measured as in a commercial system. Level-setting through standardization would increase the transparency, comprehensibility, and reliability of emerging technology LCAs by explicitly laying out the appropriate techniques that should be used in different cases. Standardization could also facilitate LCA education and training for novice analysts, researchers, product engineering and design teams, funders, and other decision-makers that play a role in early-stage technology development.

Opposition to Resolution

LCA guidelines that are confusing, noncomprehensive or contradictory can be worse than having no guidelines at all. It is extremely difficult to develop harmonized standards that offer sufficient guidance to be useful, while avoiding constraints that inadvertently exclude certain industries or use cases. Consensus-building around standards is similarly challenging, and sometimes impossible—particularly when stakeholders come from different technical communities and may have opposing views. Prescriptive standardization can limit expert discretion in making necessary adjustments to methods when the need arises. For emerging technologies, overly constrained guidance can be particularly problematic because application novelty is the rule, rather than the exception. Even when LCA techniques are methodologically appropriate, assertions of compliance with an accepted standard may instill overconfidence in study results. Standardization might improve the consistency and harmonization of study results in some ways, but standards can also be exploited through bias in selection of (allowable) assumptions that favor desired outcomes. When results of an LCA are certified as compliant with an accepted standard, bias may not be evident to decision-makers who trust in the standard or might not fully appreciate what being "compliant" means.

Equally problematic is that standards may provide a certain level of consistency, but with no guarantee of increased accuracy. Many choices made within LCA require iterative judgment calls (e.g., setting system boundaries to balance data needs and workload against capturing the most relevant impacts), context-specific choices (e.g., setting a functional unit based on a specific potential use case), assumptions around supply chains (e.g., input sourcing or end-of-life treatment options, which may differ across production environments), and arbitrary choices for handling multifunctionality (e.g., co-product allocation). While a single set of rules (e.g., energy-based allocation) guarantees consistency, logical context may dictate alternate choices—or else sensitivity analysis may be needed to evaluate whether alternate choices (e.g., system expansion, financial-based allocation) might produce different but potentially equally (or more) valid results.

Common Ground

In the case of emerging technologies, reporting a standard set of key information may be most helpful. Important items of emphasis include the TRL of the technology and whether the inventory represents the technology "as is" (at its current state of development) or if some modification of data has been conducted to model the technology "as might be" at commercialization (and whether these modifications represent central, optimistic or pessimistic cases). Clarity is also needed regarding assumptions around the future conditions (e.g., background systems) into which the technology may be deployed, which may include internally consistent standard scenarios and

standardized conclusion language such as those proposed by Sacchi et al. (2022). If standardization does occur, it could generally be tailored to specific industries or use cases. As shown in Figure 5, examples for existing products are Product Category Rules (PCR) (*BS EN 15804*, 2021; *ISO 14025*, 2006; *ISO 21930*, 2017) for standardizing the creation of Environmental Product Declarations (EPD) by constraining them to a "group of products that can fulfil equivalent functions" (*ISO 14025*, 2006). The IEA Task 12 for PV systems published guidelines for the LCA of photovoltaic systems (*Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity 3rd Edition*, 2017). An example in the emerging technology domain would be the Global CO₂ Initiative guidelines for TEA and LCA for carbon capture and utilization (CCU) systems (Langhorst et al., 2022). Some funding agencies have used standardized models or tools to accompany calls for proposals (e.g., the REMADE Institute n.d.), which helps to enable comparison of results across teams that submit proposals.

When standardization is employed, it should not come at the expense of flexibility to explore how different analytical decisions may influence the results. For example, guidelines that set a required baseline for consistency ("must" statements) are generally well complemented with flexibility to conduct alternate versions of the analysis ("may" statements), or even requirements to test key assumptions embedded in the standard. Standardization of background LCI datasets for future scenarios (e.g., NREL's Standard Scenarios (Gagnon et al., 2024)) would be a helpful addition for consequential modeling generally, beyond LCA for emerging technologies.

Debate Topic 5: Scale-up

Envisioning how a technology might change as it moves through development stages and, in turn, how (or whether) to incorporate these changes in an LCA remains an unresolved issue in the LCA community. Tsoy et al. (2020) define "upscaling methods" as procedures "that project how a new technology currently available at a lower TRL may look and function at a higher TRL." ISO 14040 series does not explicitly recommend use of a scale-up framework; however, as an example of inconsistency (ISO 14044: B.3.4 Consistency check), the guideline lists differences in technology coverage (i.e., comparison of LCA results based on experimental process (Option A) with existing large-scale technology (Option B)). This has inspired multiple calls to better characterize scaling effects and to develop methods for scaling LCA results in a rational, data-driven way.

This has been an active area of research in the LCA community over the past few years in particular. For example, Tsoy et al. (2020) reviews upscaling methods for early-stage ex-ante LCAs, categorizing methods into process simulations, manual calculations, molecular structure models, and use of proxies. Van Der Hulst (2020) proposes a prospective LCA procedure to assess future impacts based on mechanisms from technology development phases (i.e., process changes, size scaling effects, and process synergies) and industrial development phases (i.e., industrial learning and external developments), calling for creation of open-source databases with process-specific upscaling data. Weyand et al. (2023) introduced "UpFunMatLCA," a systematic and structured framework to account for likely future development and best-case upscaling scenarios of emerging functional materials ("lab to fab"). Upscaling mechanisms defined by Weyend at al. (2023) include process learning (technological learning, size scaling, and industrial learning), material learning (new systems or architectures, material substitutions, optimization of materials), and external developments (e.g., background system learning), with the ultimate goal of integrating scaling scenarios into prospective LCAs. These learning mechanisms are depicted in Figure 6. Erakca et al. (2024) identify 14 systematic scaling methods from a review of 78 studies, creating a tool to help modelers select the most suitable method given their context and specifications. Researchers have also proposed a number of sector-specific frameworks. For example, Shibasaki et al. (2007) and Piccinno et al. (2016, 2018) each propose frameworks for upscaling chemical processes. Figure 6

provides examples of the types of methods that are typically being applied, their prevalence of use and where emerging methods are being presented in this literature.

Despite this rich discussion and groundwork for how to incorporate the various aspects of change from early TRL to deployment, the community lacks consensus around when and how to apply such methods in an LCA. At early stages of development, only lab-, bench-, and/or pilot-scale processes are available for an emerging technology. Typically, lab- or bench-scale processes are highly inefficient in terms of materials and energy consumption and may not well represent the corresponding processes or equipment that would be deployed at industrial scale (Cucurachi & Blanco, 2022; Moni et al., 2019). LCA results based on lab- or bench-scale processes can therefore provide only limited insights into the future performance of the emerging technology at industrial scale. Not considering the likely future performance of an emerging technology at a higher TRL, particularly when comparing with an existing industrial-scale benchmark technology, can lead to unfair and/or misleading comparisons.



Figure 6. Scale-up methods and considerations of systems in LCA (across TRL – technology readiness level). In LCA for emerging technologies, it is important to assess and project how a technology might change as a function of development stage. The lower portion of the figure shows example techniques that can be used to envision the changes that are possible as the technology approaches commercialization. The top portion of the figure presents examples of technology characteristics that could change throughout the development and deployment process, which can each be assessed using different scale-up models from the literature, and is adapted from van der Hulst, et al. (2020) and Weyand, et al. (2023). Note: this figure is not a robust quantification; rather, the shapes and heights of the curves are qualitative and are intended as schematic.

Despite the growing body of literature on the importance of suitable scale-up assumptions, barriers that make it challenging to consistently utilize the existing scale-up frameworks for LCA of emerging technologies remain. The remaining barriers include the lack of consistent scale-up frameworks across different industrial sectors, sparse availability of scale-up factors for specific unit operations (especially for new technology unit processes), challenges associated with modeling the impact of technology learning curves on future performance of emerging technologies, and uncertainty associated with scale-up models and assumptions. Therefore, questions about whether and how we should use scale-up frameworks when performing LCA of emerging technologies remain in the community. Is it worth the cost of the complexities and uncertainties associated with scale-up frameworks to produce (potentially) better future estimates, or are these estimates so weakened by the necessary assumptions that they are not useful?

Resolution:

We should scale-up data from technologies at low TRL to project how they might perform at higher TRL.

Support for Resolution

Depending on the stage of technology development (e.g., lab-, bench-, pilot-, or industrial- scale), LCA results differ in several important ways: technical differences (e.g., differences in unit processes or process equipment); differences in material and energy efficiency (which might be measurable, accurate, and stable only after the technology reaches a certain maturity level); differences in resource utilization (such as waste heat recovery or material recycling); and differences related to technology development learning curves and learning-by-doing. Divergence of LCA results based on technology scale can become more pronounced in comparative LCAs, where the environmental performance of technologies under development might be compared with commercial-scale technologies that have already been in operation, sometimes for years or decades. Since lab-scale processes typically involve equipment and systems that differ from those used at industrial scale, LCA results based on inventory datasets collected at low TRLs must be scaled-up to provide more appropriate or plausible comparison with existing alternatives (or alternatives at different TRLs). For some cases, these scale-up frameworks might have limited applications, and there are uncertainties involved in the scale-up modeling. However, the application of scale-up frameworks enables the LCA practitioner to generate an initial estimate (either as a point or a range) about the potential future impact of emerging technologies. When appropriately bounded by uncertainty estimates, scaled results can help the LCA practitioner communicate key results to technology stakeholders in meaningful terms, and can provide important insights to technology developers while they are still able to make changes (i.e., early during the technology development process). Including potential changes due to scale-up in an LCA can inform research by highlighting where research and development efforts could be prioritized to maximize environmental performance and ensure competitiveness with incumbent technologies.

Opposition to Resolution

Very limited data and guidance is available about how emerging technologies scale. At early development stages, the function(s) of an emerging technology may not be clearly specified (if at all), and the availability of relevant data to construct an upscaling framework will likely be limited. It may not yet be clear how the technology will be scaled, how learning mechanisms will affect the performance of the technology, and what other (yet unknown) processes may become necessary to achieve full functionality, safety, regulatory compliance, and other requirements at commercial scale. Scale-up is complex and non-linear, and any upscaling framework will depend on assumptions (Pizzol et al., 2021). Rather than providing helpful and robust insights, such an exercise could

introduce more uncertainties than it resolves. At very early stages, simpler methods such as using empirical data (if available), data from simulation tools, inputs from experts/vendors, or proxies from literature could be used in place of more elaborate modeling frameworks. Avoiding upscaling at early stages would keep the LCA process manageable in scope and could be updated later in the technology development process once higher quality data are available to estimate environmental impact at the industrial scale.

Common Ground

Although there is no single, consistent framework available for scale-up modeling, different approaches (e.g., engineering-based frameworks, scaling laws based on empirical data, or combinations of different methods with scenario analysis) for scale-up techniques continue to be developed for LCA of emerging technologies. If undertaken, they should be performed with diligence and assumptions should be made clear to the intended audience of the LCA study. Developing more consistent and comprehensive methods and guidance to assist LCA practitioners in considering all aspects of technology scaling has the potential to better guide technology developers beyond simply assessing an early-stage technology in isolation. Assessing scale-up scenarios early on could reveal scaling-related impact hotspots, guide R&D priorities, and, if acted upon before technology lock-in, accelerate the process of scaling technology in an environmentally informed way. An open-source, public data repository with results from LCA studies and process-specific upscaling inventory data for different technologies could provide valuable examples and proxy scaling trajectories for a range of similar technologies, helping to address the data paucity barriers researchers face today in applying scale-up methods (Tsoy et al., 2020; Van Der Hulst et al., 2020). Moreover, user-friendly workflows to perform such analyses consistently would help accelerate the accessibility and adoption of upscaling frameworks by LCA practitioners.

Debate Topic 6: Stakeholder Engagement

Often, LCA of emerging technologies are conducted to inform decisions that are urgent and present high stakes for society (Ravetz and Funtowicz, 2015). However, input from affected community stakeholders is not often directly integrated into the LCA process, leading to a lack of consideration (or uninformed assumptions) about the priorities of these communities in terms of environmental and social benefits and harms. Ideally, analysis under these conditions would involve an "extended peer community" participating in stakeholder and community engagement, with transparent opportunities for public participation in high-stakes LCA. Stakeholders may include policy makers, subject matter experts, industry partners, users or consumers of a technology or product, impacted community members, and the public. Engagement can take different forms and serve different purposes including informing, consulting, involving, collaborating and empowering (Kujala et al., 2022). Stakeholder engagement is not explicitly mentioned in the ISO 14040 series guidelines, and its role in LCA is not settled despite calls to include it in "anticipatory LCA" of emerging technologies to foster "responsible research and innovation" (Wender et al., 2014). The ISO 14040 series guidelines do include a requirement for expert review (if comparative assertions are intended to be presented to the public), which provides one opportunity to engage stakeholders (ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework, 2006, p. 207; ISO 14044 (2006): Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2006). Within the broader context of energy systems modeling, frameworks for good practice have been developed to "integrate more diverse perspectives on possible and preferred futures into the modelling process" (McGookin et al., 2024).



Examples of stakeholder roles & contributions



Figure 7. Stakeholder Engagement in LCA. Key groups of stakeholders at different stages of development can play unique roles in interfacing with the LCA process. The involvement of four key groups are represented schematically with curves encompassing various technology readiness levels (TRLs), ranging from scientists and engineers at early stages to international (int'l), analysts at mid-stages, and environmental NGOs at later stages. Our consensus is that community members can be engaged throughout the technology development process, which can iteratively inform LCAs throughout. The shading represents where engagement can be improved in the future. Effective stakeholder engagement—rooted in collaboration and empowerment—can positively impact early stage LCA in myriad ways such as informing relevant topics, improving quality assurance of the results, and facilitating better dialogue across the range of stakeholders potentially interested in an emerging technology. Note: this figure is not a robust quantification; rather, the shapes and heights of the curves are qualitative and are intended as schematic.

Resolution

A broad range of stakeholders should be engaged in the LCA of an emerging technology early and iteratively as the technology develops.

Support for Resolution

Stakeholders bring diverse perspectives that can provide value not only in the design process for the LCA but also throughout the LCA (Ravetz & Funtowicz, 2015), as summarized in Figure 7. Here, we focus on two key types of stakeholders: members of society (e.g., workers, local communities, value chain actors - UNEP, 2020) that may be impacted by new technologies and subject matter experts.

Stakeholders can contribute data in areas difficult to measure by traditional inventories and can provide context for assumptions and study insights. This is especially important for emerging technologies because, unlike commercially deployed technologies that have entered public awareness, there may be no deep knowledge or history of community concerns for an emerging technology. By engaging stakeholders in the LCA scoping phase, their perspectives and concerns can be used to inform assumptions, scenarios, system boundaries and impact categories. For example, stakeholders may reveal a concern about local air quality as being a higher priority than climate impacts when considering a transition from natural gas to biomass as a fuel (Pitre et al., 2024), thereby broadening the scope of a study but making it more informative. On the other hand, stakeholders could help focus the study on a more limited set of metrics (avoiding potentially unnecessary costs) that would have been incurred if the impacts of concern are unknown. Stakeholders can even help to inform which technologies are developed or what targets of performance should be achieved early in the process before technology lock-in has occurred.

The inclusion of stakeholders in LCA at early stages of development has implications for environmental justice and social impact (Cowell et al., 2002; Mathe, 2014). Exclusion of their perspectives gives priority to the perspectives of study commissioners, technology developers and technical analysts who may have blind spots. Stakeholder inclusion can help the practice of LCA become more "locally attuned and responsive" and promote environmental justice. Input from stakeholders can help build confidence in LCA models and insights as well as inform key assumptions and future scenarios (Sleep et al., 2021).

Subject matter experts in particular may be versed in the underlying scientific relationships that drive key performance characteristics as well as key contextual information such as regulations, natural resources, infrastructure, supply chains, human capital, and public support/perception that can shape the development of a technology. They can provide advice on scoping decisions such as supply chains or proxy assumptions. They may also have an informed sense of possible functional units, scaling pathways and feasibility of use cases that the LCA practitioner may not be familiar with. Subject matter experts may also be cognizant of current trends that might not yet be presented in the literature (Verdolini et al., 2018). As in the case of critical review, subject matter experts can provide quality control, identifying when the easiest or most tractable choice might not be appropriate. For example, a recent study employing stakeholder engagement showed the need for more localized assumptions for indirect emissions, rather than an average from a different geographic region (Sleep et al., 2021).

It is easy to question whether the LCA analyst is equipped and should try to engage stakeholders, especially when resources are limited. However, especially for emerging technology areas, a single study may turn out to be a benchmark used by many and could influence policy, funding and technology development decisions, so engaging stakeholders from the outset is important.

Opposition to Resolution

While most practitioners recognize the value of engaging stakeholders in LCA of emerging technologies, the challenges in doing so often outweigh the potential benefits. Other than critical review, stakeholder engagement is not explicitly included in the ISO 14040 series guidelines for LCA. This means the methods of engaging with stakeholders are still not well defined, leading to methodological gaps and inconsistencies. Especially considering the lack of formal guidance, LCA practitioners may simply not have the background to perform meaningful stakeholder engagement; attempts to do so may even cause unintended stakeholder concerns, annoyance, and delays in completing the LCA projects (Cowell et al., 2002). Even identifying who the community stakeholders may be for an early tech with uncertain future use-case is difficult.

Identification of stakeholders and definition of their roles is a key challenge. It is not possible to consult all possibly affected people, and it is very difficult to make unbiased decisions regarding

which voices matter and can reasonably be consulted. Establishing relationships with stakeholders takes time and may not always be possible, especially within the study time/scope. There are also social justice issues if the consultation creates a burden on the stakeholders, and consultation alone might not be sufficient. For example, divergent views and values across stakeholder groups might impede useful insights about realistic deployment pathways and require co-creation activities rather than simply "consulting" each group. Resources to create a just and effective engagement process for stakeholders may not be available at early development stages and without appropriate care and attention may lead to tokenism and extractivism. Identifying subject matter experts is also challenging. Many emerging technologies may not have a sufficient pool of experts to engage with. Even those with technology developers that may have sufficient knowledge to be helpful may have concerns related to confidentiality and protection of their intellectual property, and thus omit or abstract important information.

Funders for LCA studies focused on emerging technologies may not be convinced of the importance of stakeholder engagement. They may be unwilling to support a project that incorporates it. Confidentiality concerns about a new technology or the possibility of criticism and negative impact on public image (whether warranted or not) could exacerbate this. Further, stakeholder engagement may not be necessary. For example, if the scope of the study is exploratory (e.g., a hotspot analysis of GHG emissions) and intended to provide input to the data needs for a more detailed assessment, the value of stakeholder input might be low. For this purpose, LCAs with proper communication of all the assumptions and limitations might be sufficient.

Common Ground

Stakeholder engagement can provide important insights into the ambitions and concerns of the local community, geographical and policy considerations, market trends, consumer behavior, and material and energy resources. Subject matter experts can share their learnings from experience with similar technologies, which can inform the development of LCA specifications for emerging technologies. However, care must be taken to prioritize available resources and ensure that any stakeholder engagement is conducted earnestly and rigorously. The type and extent of stakeholder engagement should be based on the key purpose or goal of the LCA. For emerging technologies, even if not a full-scale LCA, several scenarios can be developed in collaboration with communities, technology developers, and LCA practitioners. As mentioned, there is still a lack of standardization surrounding stakeholder engagement in LCA. The LCA community would be well-served to explore this area further given the potential benefits to produce more accurate LCAs that better inform decision-makers.

Discussion

This study critically examines controversial topics surrounding the application of LCA to emerging technologies. We review six key methodological debates within the LCA field:

- 1. Appropriate use of LCA: how can LCA methods be selected and communicated to reflect the unique characteristics of emerging technologies to ensure that the results are interpreted appropriately?
- 2. Uncertainty assessment: how can uncertainty in LCA be quantified and managed in the context of emerging technologies with limited data?
- **3. Comparison with incumbent**: what are the best practices for conducting comparative LCAs that fairly evaluate emerging technologies?

- **4. Standardization**: what are the gaps in current LCA standards, and how can they be revised/augmented to accommodate the evolving nature of early-stage technologies?
- **5. Scale-up**: what are the most effective ways to assess the potential future environmental impact of emerging technologies in a hypothetical commercial setting?
- 6. Stakeholder engagement: how can technology experts, society and LCA practitioners collaborate more effectively to improve LCA practices for emerging technologies?

This paper uses these questions as a launching point to address some of the complexities associated with LCA of new and evolving technologies. In Table 1, we summarize outcomes of the discussions of our research network. Within the LCA community, particularly in the context of emerging technologies, there is an ongoing discourse and examination of methodological development. The focus is on addressing scale-up challenges, managing uncertainties, and refining comparative analysis approaches. The community is actively seeking effective collaboration among various stakeholders, including technology developers and practitioners, to enhance LCA methods for these new technologies. This phase is marked by a shared recognition of the unique complexities inherent in assessing environmental impacts of emerging technologies.

Both consensus and disagreement arose in our research network's discussion of these six main topics. Consensus is found in recognizing the importance of life cycle thinking as a foundation for decision-making, the need for transparent communication of LCA limitations, and the value of understanding technology nuances and uncertainties. However, there is significant disagreement on when and how to apply LCA in the technology development process, the challenges of scaling up and comparing emerging technologies, and the handling of uncertainties and standardization issues. These divergences highlight the need for ongoing discussion and methodological development in the field of LCA.

We agree that when dealing with the results of an LCA for an emerging technology amidst significant uncertainties, the approach and communication strategy need to be carefully considered. LCA results should be seen as provisional insights to guide further research and development rather than as conclusive predictions. They can identify potential environmental hotspots and areas where improvement is needed or where further investigation is required. We strongly recommend avoiding overconfidence in study results by communicating results in a manner that clearly outlines the assumptions made, the uncertainties involved, and the potential limitations of the study. Practitioners should present scenarios or ranges of possible outcomes, explaining how different assumptions might lead to different outcomes. The approach and interpretation of the results should be consistent with the decision that the LCA is meant to inform. Poorly communicated or misinterpreted LCA results can lead to risks of misguided decisions or public misconceptions. However, if communicated effectively, these results can act as a crucial guide for improvements in sustainability. They can inform stakeholders about potential environmental impacts and guide technology developers toward more sustainable design, funding and policy choices.

While debates about these six topics will likely persist, this paper serves as an update on the current state of LCA in the emerging technology context, as well as a guide for stakeholders navigating intricacies and uncertainties inherent in evaluating these emerging technologies. As technologies continue to evolve, so must our practices and our discussions. By continuing to address the uncertainties and challenges outlined here, LCA practitioners can ensure that their work remains a vital resource in shaping the technology decisions of the future.

Debate Topic	Open questions	Key challenges and takeaways	Recommendations for practitioners	Next steps in the field
Appropriate use of LCA	 How early is "too early" to use LCA? How should type of LCA and level of robustness be determined and communicated? 	 Life cycle thinking ≠ robust LCA. Clarity is critical when communicating any life cycle results. As TRL increases, a trade-off exists between an increasing availability of information and increasing technology lock-in and impacts. Failing to disclose deficiencies and limitations in LCAs of emerging technologies can result in misinformation and harm the field's reputation. 	 Determine and clearly communicate the robustness of the LCA (i.e., whether and how the study can support the decision given the purpose noted in the goal and scope). Contextualize conclusions (i.e., "X is true only under these assumptions") and avoid making recommendations beyond what the data can meaningfully support. Clearly communicate intended use and limitations of the LCA to avoid misinterpretation. 	 Better characterize "types" of LCAs. Develop and deploy early-stage life cycle thinking tools for emerging technologies that can later be expanded into a robust LCA. Develop guidance to determine the type of LCA and how it affects the robustness of the results. Develop consistent language around the strength of conclusions.
Uncertainty assessment	 At which TRL should uncertainties begin to be assessed? Which methods are appropriate at each TRL? How should results be communicated to avoid misinterpretations? 	 Uncertainty is intrinsic to LCA, and even more pronounced for emerging technologies due to data gaps etc. Effective communication of uncertainty is crucial (e.g., explicit reporting, contextualization, scenario development, and visual aids). LCA methods need to adapt to the dynamic nature of emerging technologies. 	 Adopt transparent and comprehensive uncertainty reporting. Utilize sophisticated probabilistic methods with caution. Bounding estimates and performance thresholds or breakeven analyses are often useful. Enhance communication strategies. Focus on drivers of environmental performance rather than absolute quantitative results. 	 Develop guidance on communication of uncertainty. Continue to explore other methods to characterize, quantify and propagate uncertainty in LCA, especially in the data poor context of emerging technologies.

Table 1. Summary of topic questions, key challenges and takeaways, recommendations for practitioners, and next steps in the field.

Comparison with incumbent	 Should comparisons be made at low TRL? If so, how should an appropriate comparator be determined? How to account for scaling dynamics and uncertainty? 	 LCA of new technologies is often conducted with the intention of comparison with an incumbent. No consensus exists on what constitutes an appropriate comparator or how to reconcile differences between technologies (e.g., early stage vs. commercially deployed). 	 When making a comparison, consider: purpose of the LCA, the use of one incumbent, or a mix, possible biases in data sources and modeling choices, other functions (and associated incumbents) and potential future incumbents at commercialization. Communicate how future technology performance and background systems are modeled. 	 Develop guidance specific to emerging technologies including: when a comparison is appropriate, how to characterize appropriate incumbent, how to deal with the uncertainties introduced by forecasting future performance and what the future incumbent will be.
Standardization	 How could/should additional standards play in assessing emerging technologies? How to develop fit- for-purpose standards? 	 Standardizing LCA of emerging technologies offers opportunities and risks (e.g., reduce ad hoc nature of current method decisions, overconfidence in accuracy and comparability). Not clear what could/should be standardized (e.g., assumptions, study, practitioner) and tech. 	 Make as much use of the existing ISO 14040 series guidance as possible. In the absence of additional guidance specifically related to emerging technologies, focus on transparency in reporting to clearly define all assumptions and known limitations in the interpretation of results. 	 Further discuss as a community what could or should be standardized as well as alternative guidance opportunities. Continue development of standard sets of narratively consistent future scenarios
Scale-up	 Should methods be developed and applied to envision future performance of low TRL technologies? If so, what methods and types 	 ISO 14040 series does not provide guidance on how to make fair comparisons between technologies at different levels of development. TRL of technology, scaling method applied, 	 When making a comparison, consider the development stages of each technology system and whether such a comparison is appropriate. Consider how the technology could change from the current stage to deployment at commercial 	 Develop guidance on what to consider in scaling and how to present results of scaling activities. Review current frameworks for scaling and expand as needed to fill gaps.

	of learning should be considered?	 and comparator selected can change conclusions. Goals of a meaningful comparison between technologies at different TRL must be balanced with risks of uncertainty in such comparisons. 	 scale and the types of learning involved in these changes. Explain assumptions and provide evidence that the framework is appropriate for the technology assessed. 	 Develop an open- source, publicly accessible database with process-specific upscaling inventory data for different technologies and markets at different levels of development.
Stakeholder engagement	 Should we include stakeholders in LCA of emerging technologies? If so, which stakeholders? 	 "Engagement" is not explicitly in ISO 14040 series, and its importance in LCA is not settled. Despite concerns on when and how to engage stakeholders, diverse perspectives can provide value not only in design of the LCA but also throughout the study. 	 Explore the role that stakeholders could and should play in LCA of emerging technology. Ensure consultation (if relevant/planned) occurs prior to associated technology lock-in. Examine potential for analyst blind spots and biases; avoid value judgments masquerading as expertise. 	 Develop guidance on the risks and benefits of including stakeholders for each type of LCA. Systematically analyze case studies that have engaged stakeholders and their outcomes. Clarify the appropriate degree of stakeholder engagement (i.e., informing to empowering).

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CRediT Statement

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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