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Life cycle assessment of emerging technologies

Evaluation techniques at different stages of market and technical maturity

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Abstract

Life cycle assessment (LCA) analysts are increasingly being asked to conduct life cycle-based systems level analysis at the earliest stages of technology development. While early assessments provide the greatest opportunity to influence design and ultimately environmental performance, it is the stage with the least available data, greatest uncertainty, and a paucity of analytic tools for addressing these challenges. While the fundamental approach to conducting an LCA of emerging technologies is akin to that of LCA of existing technologies, emerging technologies pose additional challenges. In this paper, we present a broad set of market and technology characteristics that typically influence an LCA of emerging technologies and identify questions that researchers must address to account for the most important aspects of the systems they are studying. The paper presents: (a) guidance to identify the specific technology characteristics and dynamic market context that are most relevant and unique to a particular study, (b) an overview of the challenges faced by early stage assessments that are unique because of these conditions, (c) questions that researchers should ask themselves for such a study to be conducted, and (d) illustrative examples from the transportation sector to demonstrate the factors to consider when conducting LCAs of emerging technologies. The paper is intended to be used as an organizing platform to synthesize existing methods, procedures and insights and guide researchers, analysts and technology developer to better recognize key study design elements and to manage expectations of study outcomes.

KEYWORDS
early stage technology assessment, environmental impacts, industrial ecology, life cycle assessment (LCA), research and development (R&D), unintended consequences

1 | INTRODUCTION

While environmental impacts were once considered an afterthought in the development of new technologies, a series of adverse surprises have resulted in a more proactive approach to evaluating the impacts of new and emerging technologies prior to commercialization at scale (Fisher, Mahajan, & Mitcham, 2006). The spectrum of emerging technologies ranges from products or processes that are innovative and potentially disruptive, to the next generation of popular products incorporating marginal changes to incumbent technologies. Although it has been widely recognized that the greatest potential to steer technology towards environmentally preferable outcomes exists at the *earliest* stages of technology development (Collingridge, 1980), this stage also coincides with the least available data, greatest uncertainty, and a paucity of analytic tools for addressing these challenges (Hetherington, Borrion, Griffiths, & McManus, 2014). Since publication of the seminal "Strategies for Manufacturing" (Frosch & Gallopoulos, 1989), the material life cycle has been identified as the appropriate perspective for study of the environmental consequences of technology. Analysts are now increasingly being asked to conduct life cycle-based systems level analysis at the *earliest* stages of technology development prior to or during a technology's emergence into a market (Wender et al., 2014a).

While the fundamental approach to conducting life cycle assessment (LCA) of emerging technologies is akin to that of LCA of existing technologies, emerging technologies pose additional and unique challenges for the analyst. Challenges associated with LCAs of emerging technologies include issues related to lack of data, scale-up, a lack (in some cases) of incumbents against which to compare, and uncertainty with respect to both how the emerging technology will be deployed as well as the market conditions into which the technology will be deployed (Hetherington et al., 2014; Moni, Mahmud, High, & Carbajales-Dale, 2019). An early stage assessment can help set targets for technology development, influence design and ensure that environmental goals of innovation are achieved (Moni et al., 2019). Several funding agencies now require technology developers to report LCA results of emerging technologies (e.g., US DOE, 2012, 2014, 2016a, 2016b, 2017; see additional explanation in Moni et al. (2019) and use it to track progress throughout the funding cycle (EC, 2018, 2019). Despite the growing use of LCA at these early stages, there is a lack of a systematic guidance for LCA analysts to address the particular challenges of emerging technologies (e.g., Wender et al., 2014b). Specifically, there remains confusion about how LCA can (or should) be used at different stages of technology development and market adoption. Critically important research questions include:

- When is it useful to conduct an LCA and what questions can it reasonably answer at different stages of development and commercialization?
- What aspects of the technology/adoption context need the most careful consideration?
- With what other tools or techniques can/should the LCA be coupled to maximize their utility?

Industry uses tools for technology assessment throughout the innovation cycle, including techno-economic assessment and stage gate evaluation (Grönlund, Sjödin, & Frishammar, 2010). Techno-economic assessment does not have a standardized framework, with techniques that are often company-specific and used for internal strategic development and therefore, tend not to be transparent. Stage gate evaluation does not typically take the full life cycle environmental consequences into account. Assessment typically rests on characteristics such as strategic fit, expected financial returns, and competitive landscape.

The literature on LCA of emerging technologies includes many case studies, variously using terms such as prospective (Mendoza Beltran et al., 2018; Cooper & Gutowski, 2018; Raugei & Winfield, 2019; Sathre et al., 2014; Wender & Seager, 2011), early stage (Cramer, 2000; Hetherington et al., 2014; Hung, Ellingsen, & Majeau-Bettez, 2018), ex ante (Hesser, 2015; Villares, Işıldar, Van der Giesen, & Guinée, 2017; Zhou et al., 2012), anticipatory (Gifford, Chester, Hristovski, & Westerhoff, 2016; Kendall & Yuan, 2013; Mattick, Landis, Allenby, & Genovese, 2015; Ravikumar, Seager, Cucurachi, Prado, & Mutel, 2018; Tsang, Philippot, Aymonier, & Sonnemann, 2016; Wender et al., 2014b; Wender, Foley, Guston, Seager, & Wiek, 2012), explorative (Steubing, Mutel, Suter, & Hellweg, 2016), and scenario-based (Arvidsson et al., 2017) LCA. The diversity of terms mirrors the wide range of available methods and disparate language employed across the LCA community. In some cases, different terms refer to similar approaches, and in others the same term is interpreted differently by different research groups. Guinée, Cucurachi, Henriksson, and Heijungs (2018) provide an excellent overview of the various definitions and use of acronyms in LCA.

In addition to confusion in terminology, the procedures and tools employed to assess emerging technologies have yet to be well-defined or systematized, with no clear guidelines as to what methods are available, applicable or appropriate. While some authors review and provide recommendations based on specific cases, for example, in drop-in fuels (synthetic substitutes to petroleum-derived fuels that do not require any changes to engine or fuel infrastructure: for example, Cuéllar-Franca & Azapagic, 2015; Van der Giesen, Kleijn, & Kramer, 2014; Von Der Assen, Voll, Peters, & Bardow, 2014), nanomaterials (e.g., Gavankar, Anderson, & Keller, 2015; Gavankar, Suh, & Keller, 2015; Khanna, Bakshi, & Lee, 2008; Piccinno, Hischier, Seeger, & Som, 2018; Simon, Bachtin, Kiliç, Amor, & Weil, 2016; Wender & Seager, 2011), and photovoltaics (e.g., Jungbluth, Bauer, Dones, & Frischknecht, 2005; Ravikumar et al., 2018; Wender et al., 2014b), there is a need for additional cross-case analysis to provide more generalized guidance (Miller & Keoleian, 2015; Wender et al., 2014a). The discussion is further complicated by the diversity with respect to objectives of the analysis and methods to employ, for example, related to the use of attributional versus consequential LCA (ALCA vs. CLCA; Earles & Halog, 2011; Plevin, Delucchi, & Creutzig, 2014; Suh & Yang, 2014; Zamagni, Guinée, Heijungs, Masoni, & Raggi, 2012). There is much debate about the different applications and implications associated with ALCA and CLCA approaches. We are not trying to advance that discussion here, but we do describe conditions under which modeling of system-wide market-based effects are most needed. We also note the conditions that should lead an analyst to pay closer attention to technology versus market drivers of uncertainties during goal and scope definition and LCA result interpretation. To address the methodological challenges of conducting LCAs in the context of emerging technologies, we argue below that one must first identify key characteristics of the technology, with special consideration given to whether the LCA result is likely to be driven by the parameters of the technology itself, the characteristics of the surrounding context ("market") into which it is adopted, or a combination of both.

Several recent studies have addressed the procedure of LCA for early stage technologies (Arvidsson et al., 2017; Cooper & Gutowski, 2018; Hetherington et al., 2014; Moni et al., 2019; Sharp & Miller, 2016; Villares et al., 2017). Villares et al. (2017) reflect on the usefulness of ex ante LCA through application to a case study of metal recovery from e-waste and propose a set of procedures that consider the characteristics of the technology and market system in which the technology might penetrate. Both Cooper and Gutowski (2018) and Sharp and Miller (2016) propose connecting LCA techniques with diffusion of innovations methods such as Bass modeling and product cannibalization analysis to better represent realistic implementation conditions for the emerging technology. Another recent contribution, Arvidsson et al. (2017) conduct a review of existing LCAs of emerging technologies in the areas of nanomaterials, biomaterials, and energy technologies and make recommendations about the use of predictive scenarios and scenario ranges. Moni et al. (2019) argue that methodological advances beyond LCA approaches typically employed to characterize commercial technologies are required for evaluating emerging technologies. They provide recommendations about techniques to employ at various stages of commercialization of an emerging technology. Generally, these publications have focused on situations where LCA is applied to emerging technologies deployed in mature markets. This literature does not include the distinction between technology and market factors or the identification of the characteristics of emerging technologies and emerging markets that may influence how an LCA of an emerging technology could/should be conducted. This paper is a first step to advance the dialogue and offer guidance for the community through providing a cross-case reflection on both technology and market uncertainties faced by analysts.

This paper is a synthesis of ideas and insights generated by leading researchers on this topic at a workshop on LCA of emerging technologies held in Banff, Canada, hosted by the University of Calgary, as well as special sessions and research workshops as part of the International Symposium on Sustainable Systems and Technology (ISSST) and American Center for Life Cycle Assessment (ACLCA) conferences (details of each conference session are provided in Supporting Information). The purpose of the paper is to start the discussion on this issue, call for a research network to further discuss these challenges, and enable the development of new analytical tools to assess emerging technologies in a consistent and robust way. This paper is intended to:

1. be used as an organizing platform to aid in moving the research community from a set of ad-hoc processes to organizing and synthesizing existing methods, procedures and insights,
2. aid LCA researchers/analysts in characterizing emerging technologies, identifying critical uncertainties that these technologies face, and providing guidance on overcoming common challenges that arise in their analysis, and
3. guide LCA researchers/analysts and technology developers to better understand key study design elements and to manage expectations of study outcomes.

In this paper, we identify a broad set of technology characteristics and market conditions affecting the deployment and future performance of emerging technologies and pose questions that researchers should consider to identify the most important aspects of the systems they are studying. The structure of the paper is as follows: first we provide guidance to identify the technology characteristics and dynamic market context that are relevant and unique to their study. Second, we describe the challenges faced by assessments that are distinctive because of these technology characteristics and dynamic market context. Finally, we pose questions that researchers should ask themselves and the stakeholders (including decision makers) calling for such a study to be conducted, along with illustrative examples from the transportation sector to further delineate our definitions and provide specific examples for conducting LCA on these technologies.

2 | IDENTIFYING TECHNOLOGY CHARACTERISTICS AND DYNAMIC MARKET CONTEXT RELATED TO THE STUDY

Traditionally, the technology assessment literature applies metrics such as Technology Readiness Level (TRL; Mankins, 2009) and Manufacturing Readiness Level (MRL; GAO, 2010) to describe the maturity of a technology and its associated production infrastructure, where the lowest levels are representative of fundamental lab-based research and development and the highest, of proven full-scale commercialized technology. However, the markets into which technologies are deployed may also be characterized by different levels of maturity. Markets comprise the context into which a technology is deployed; the diffusion of technology is reflected via transactions in the market. Markets have a size (e.g., number of passenger vehicles sold per year or passenger-miles driven), a composition (e.g., market share of different technologies), and are affected by consumer behavior/use patterns (e.g., private vehicles vs. shared). Within the market, factors such as availability of material and energy supplies, supporting infrastructure, relevant policy and legislation, and consumer behavior influence technology adoption that are important attributes when modeling

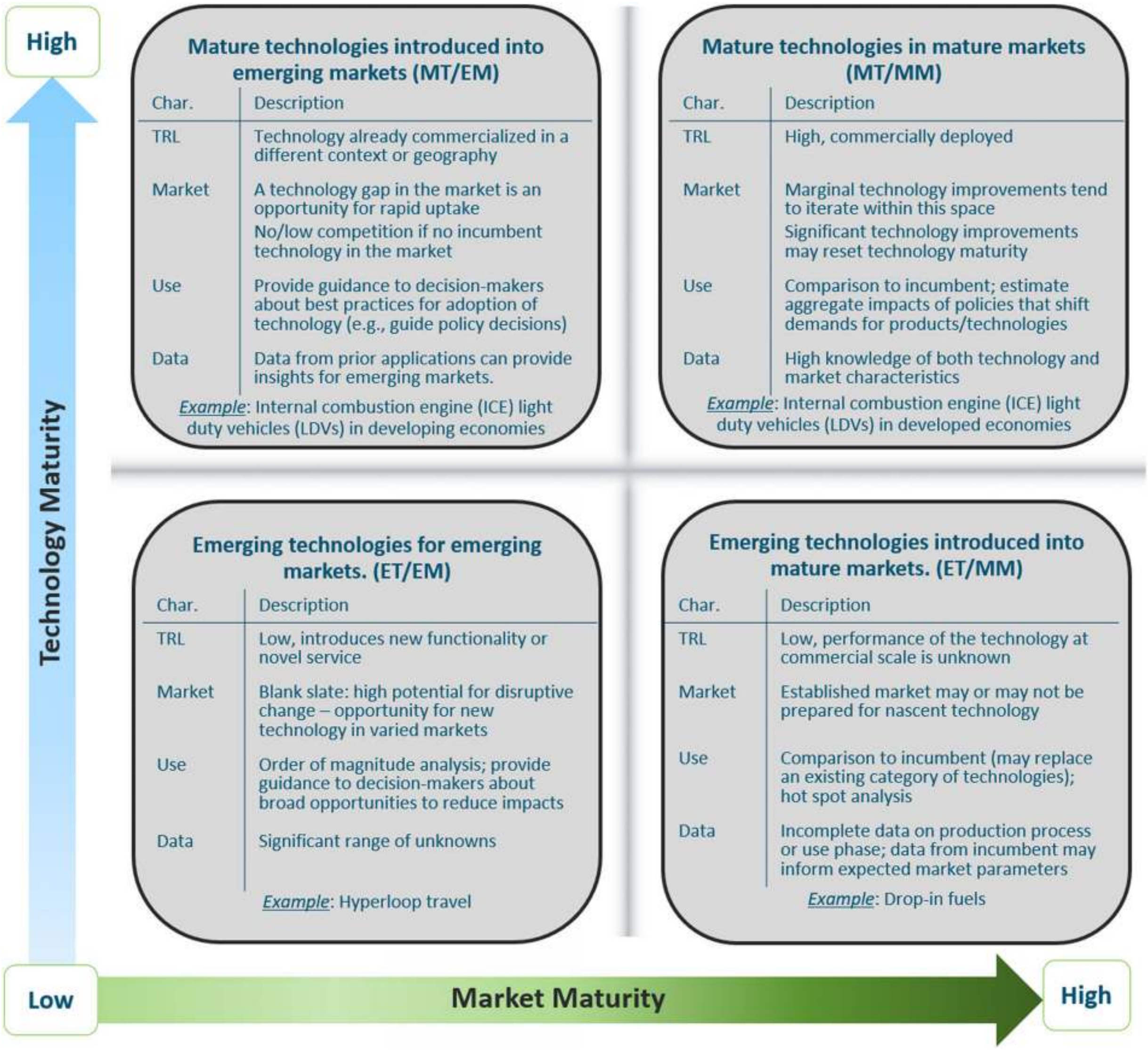

FIGURE 1 Proposed technology and market maturity quadrants. The purpose of the figure is to help an analyst situate themselves in a quadrant that will then lead to posing specific questions that affect choices at the goal and scope definition stage as well as selection of methods to employ in their study. Inside the quadrants are descriptions of the characteristics (char.) that would help an analyst fit their study into a quadrant. Use refers to the common types of decisions being informed using LCA; other uses may still be applicable

how a technology will perform. The nature of the market and its associated adoption patterns and resulting consumer behavior can have a strong influence on LCA results, which makes it an important aspect to consider in evaluation of emerging technologies.

The analytical tools required to characterize expected life cycle environmental impacts of products at different stages of technology and market maturity will vary. While technology maturity and market maturity are spectrums, we use the terms emerging and mature for the purposes of this paper we use the terms emerging and mature to frame the discussion and articulate distinguishing aspects across the spectrum. Notable characteristics of technologies that fall within the four quadrants of technological and market maturity are shown in Figure 1. We consider emerging technologies to be those that are not produced at full-scale or –rates. We also distinguish between specific technologies/products (e.g., a Ford F150 vehicle) and the general technology category within which that technology exists (e.g., light-duty internal combustion engine, ICE, vehicles). In the context of LCA, most "emerging technologies" are composed of multiple discrete technologies. For example, a battery electric vehicle (BEV) is composed of battery, drivetrain, and sensing technologies, each with their corresponding supply chains and level of maturity. Thus, a technology may be emerging either because it depends on a novel component, or a novel combination or architecture of existing discrete technologies. Likewise, a technology is in an emerging market if it provides a novel service, or if it requires substantial market changes (e.g., infrastructure investments) before it can be deployed at scale.

Consideration of technology and market factors starts at the goal and scope phase of LCA where it is essential to establish the position of a technology within the matrix in Figure 1 (alternate framings of the quadrant system presented in Figure 1 can be found in Supporting Information). Figure 1 also presents some of the characteristics of each technology/market maturity quadrant to assist the researcher/analyst orient their study within this context. It is critical at this stage to determine the developmental direction the LCA is intended to support. For example, LCA research informing materials scientists of the potential environmental consequences of a new catalyst might be motivated by an opportunity to accelerate the maturation of the technology towards environmentally preferable formulations. By contrast, an LCA that examines the consequences of expanding production and recovery operations in the catalyst's materials supply chain might guide market maturation.

The International Organization for Standardization (ISO) standards for LCA (ISO 14040/14044, ISO, 2006) provide broad guidance for analysts at each stage in an LCA, including goal and scope definition. We believe that the ISO standards fully apply to LCA of emerging technologies but that they require additional considerations that may be intuitive to seasoned analysts but are not explicit in the ISO standards. For example, ISO provides general guidance that sensitivity and uncertainty should be incorporated into LCAs but no specific recommendations for how to conduct these analyses or communicate the results (Gregory, Noshadravan, Olivetti, & Kirchain, 2016).

3 | CONSIDERING TECHNOLOGICAL AND MARKET UNCERTAINTIES

Accounting for uncertainty is critical in LCAs of both commercial technologies (discussed in Gregory et al., 2016; Igos, Benetto, Meyer, Baustert, & Othoniel, 2019; Mendoza Beltran et al., 2018; Lloyd and Ries, 2007) as well as emerging technologies. Some studies (Lacirignola, Blanc, Girard, Pérez-López, & Blanc, 2016; Ravikumar et al., 2018) have proposed new methods for accounting for uncertainty in LCA of emerging technologies using sensitivity analyses to aid in identifying key parameters affecting a technology's environmental impacts. Integrated Assessment Models have been used to develop future demand scenarios to account for market conditions surrounding demand for current technologies (Mendoza Beltran et al., 2018) or deployment of emerging technologies (Cucurachi, Borgonovo, & Heijungs, 2016; Steubing, Reinhard, Zah, & Ludwig, 2011). Others have employed consequential modeling approaches to assess the net environmental effects of future increases in demand for a product such as renewable fuels (Reinhard & Zah, 2009; Reinhard & Zah, 2008). Scenarios are employed to account for uncertainty with respect to how technologies will be deployed and perform in the future (e.g., Cucurachi, Van der Giesen, & Guinée, 1998; Steubing et al., 2016; Valsasina et al., 2017).

Identifying the parameters that may have the greatest influence on future environmental impacts when the technology is at full-scale can help focus LCA data collection efforts to reduce uncertainty around those parameters and enable early design decisions that will lead to preferable outcomes (Hetherington et al., 2014). Figure S1 in Supporting Information characterizes uncertainty in parameters associated with both technical and market maturity that occur within the overall system. The uncertainties associated with the technology can be classified into two major types; technological uncertainty and market uncertainty (see Figure S1 and additional discussion in Supporting Information).

Importantly, these two uncertainty classifications are interdependent. There can be significant overlap between factors that contribute to both technological and market uncertainty, as anticipated user behavior will impact technological design and vice versa (see Figure S1 in Supporting Information). The technology factors that tend not to overlap with market are often associated with material extraction and manufacturing phases of a product life cycle.

4 | CHARACTERISTICS AND LCA CHALLENGES FOR THE FOUR MATURITY QUADRANTS WITH ILLUSTRATIVE EXAMPLES FROM THE TRANSPORTATION SECTOR

This section contains an overview of the characteristics of each quadrant presented in Figure 1, and the types of LCA methods that would typically be employed in each quadrant. We present an illustrative example for each technology–market quadrant (following the convention described in Figure 1: MT, mature technology; ET, emerging technology; MM, mature market; EM, emerging market). The purpose is to further delineate our definitions of the market and technology axes and provide specific examples for conducting LCA on these types of technologies. Each of the illustrative examples is related to the transportation sector to show how new advances within a similar category of technologies might need different considerations in conducting an LCA. However, the discussion is applicable to a broad set of technologies.

As with any LCA, the perspective (e.g., car owner, vehicle manufacturer, city transportation planner, transportation policy initiative) and purpose of an LCA of an emerging technology is critical and should guide the goal and scope definition of the study. For example, a policymaker will be more likely to require an LCA to be extended to include system-wide impacts (e.g., market effects), whereas a technology (e.g., vehicle) developer may be interested in a neatly bounded attributional LCA.

Figure 2 depicts the relative magnitudes of uncertainties (represented by the size of the sphere) associated with technological and market factors and their evolution as technologies and markets mature, applied to illustrative examples from the transportation sector. The path a technology might take as it migrates toward maturity depends on the technology and the market context. For example, a technology could move from ET/EM to MT/MM in incremental and equal steps. Another technology might have a breakthrough that results in a jump from ET/EM to MT/EM and then more slowly progress to MT/MM. As design decisions are made, or as additional data becomes available over time, uncertainty is typically reduced. A design parameter that exists at the technology–market interface (where technology and market spheres overlap) is not necessarily more or less

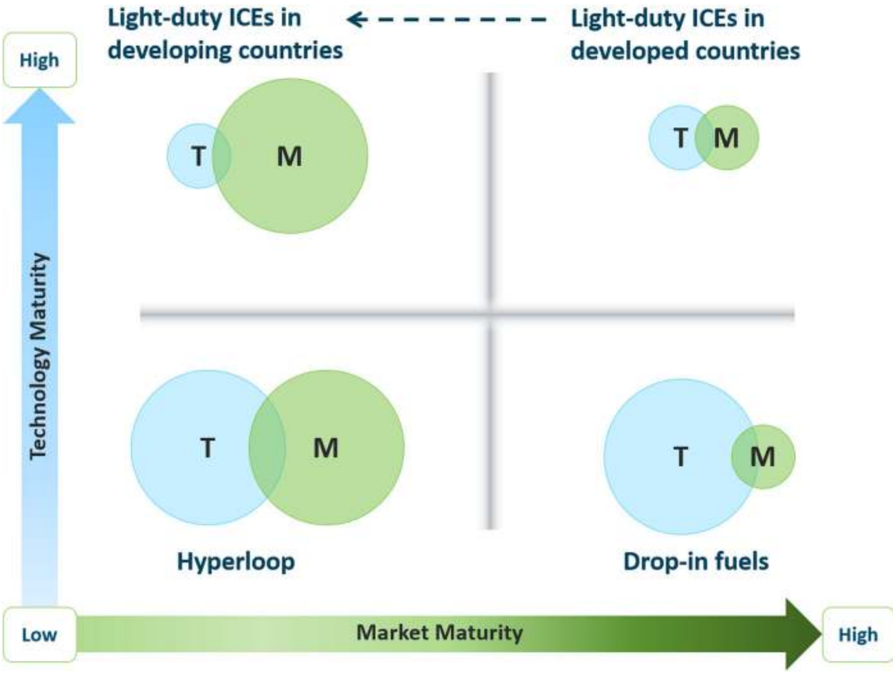

FIGURE 2 Relative magnitudes of uncertainties (represented by bubble size) associated with technology and market maturation and changes in uncertainty as technologies move between quadrants. For example, light-duty vehicles (e.g., a Ford F150 pickup truck) are a mature technology in a mature market but are continually incrementally improved (e.g., material changes to individual technologies that increase energy efficiency by a few percentage points) in the MT/MM quadrant. As established light-duty ICEs are deployed in new markets the market uncertainty grows even though the technology is mature (ET/MM quadrant). Potentially disruptive technologies where very little is known about the technology and market starts with high degrees of uncertainty on both axes, such as Hyperloop technology (ET/EM quadrant). An emerging technology that can be a direct substitute for an existing technology with an established market begins with high uncertainty about the technology but less about the market, such as drop-in fuels (ET/MM quadrant)

important than a parameter contained entirely within either the technological or market sphere (see discussion in Supporting Information about parameters that exist in the overlap between technological and market spheres). However, a parameter that sits in the overlapping space might suggest a need to take into account considerations of technology and market in a way that might not be necessary if it sits only within one sphere. For example, a technology design parameter influencing consumer behavior (technology–market interface) might require treatment of technology uncertainty as well as market behavior and use.

4.1 | Mature technologies in mature markets (MT/MM)

This quadrant represents the most common application of LCA, in which a technology with a high TRL and MRL is deployed into a well-established market. Examples might include an analysis of a model "refresh" for an existing light-duty vehicle, comparison of manufacturing choices, or any relatively marginal change to an established product. There is relatively low uncertainty surrounding the context of the product, as assumptions surrounding its production and use can be inferred from existing and historic observations.

Within this quadrant, LCAs

- Typically assess incremental improvements to the incumbent technology and their effects on and within the specific technology pathway.
- Are often used for environmental verification or certification, to promote a product over its competitors, continuous improvement or in the implementation of a regulatory scheme (e.g., low carbon fuel standard).
- Explore disruptors that might displace the incumbent technology. While the disruptor technology sits in a different quadrant, the incumbent technology is often an important comparator. The primary challenge in this context is typically lack of access to data (e.g., due to its proprietary nature), rather than lack of data itself.

4.1.1 | Techniques used/guidance

In this quadrant, the typical tools used and guidance provided for LCA (e.g., process-based LCA) are generally sufficient to provide a thorough analysis without being supplemented with additional tools (e.g., learning curve models). There is a wide literature on best practices for LCA that are applicable to this quadrant (Curran, 2013; Curren, Mann, & Norris, 2005; EPA, 2008; Finnveden et al., 2009; Hauschild et al., 2008; Suh & Huppes, 2005; Weidema, 2001; Weidema, Wenzel, Petersen, & Hansen, 2004). The ISO standards (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006; ISO, 2006) were developed predominantly when products and systems in this quadrant were the most widely used applications of LCA methods, prior to significant interest in developing LCA for technologies at an early stage. Most of the LCAs that account for system-wide market effects to date have been undertaken in this quadrant, focusing on the wider implications of a change in technology on the broader system (e.g., Earles & Halog, 2011; Kätelhön, Bardow, & Suh, 2016; Schmidt & Weidema, 2008; Searchinger et al., 2008; Smeets et al., 2014; Whitefoot et al., 2011).

LCA of mature technologies in mature markets can benefit from foundational work and vetted data sets. Often, in this quadrant LCAs can employ existing models or update existing models to account for incremental changes to a technology or market effects. Direct and indirect market consequences can present a greater challenge than the technology assessment component in this quadrant. For example, the increased sales of light-duty trucks in the United States observed over the last five years could change course if there is a sustained increase in the cost of transportation fuels. Alternatively, sales could increase if the regulatory structure for emissions and fuel economy is curtailed through policy changes. These market effects would not change LCA results on a functional unit basis but may impact aggregate environmental impacts from use of the technology. That is, as consumer use patterns change due to exogenous forces (in this case, due to changes in demand).

4.2 | Emerging technologies in mature markets (ET/MM)

This quadrant represents cases where a technology with a low to moderate TRL is expected to penetrate a mature market in the future and compete against an incumbent technology. Technologies in this quadrant are not yet commercialized but their commercialization is not anticipated to change the incumbent infrastructure and market sufficiently to consider the market new or emerging.

Within this quadrant, LCAs

- Typically compare the expected environmental performance of the emerging technology with that of the incumbent.
- Face unique challenges in that comparisons may be skewed in favor of the established (better-optimized) technology or, in contrast, in favor of the emerging technology if potentially overly optimistic assumptions regarding the eventual production and performance of the emerging technology are employed.
- Often require extrapolating lab or pilot-scale data to full-scale production of the emerging technology. The potential for rapid evolution of the emerging technology makes medium- to long-term analysis particularly problematic, as product evolution both depends on, and drives, product development (e.g., learning-by-doing).

4.2.1 | Techniques used/guidance

In this quadrant tools such as techno-economic assessment and process-design techniques can be used to predict potential performance of the technology at commercial scale (ANL/NREL/PNNL, 2013; Morrow, Shehabi, & Smith, 2015; NREL, 2013). Resulting values of technical performance parameters (e.g., fuel inputs, product yields) can then be used to inform the development of the LCA.

As an example, the technology to convert alternative feedstocks such as CO_2 or cellulosic biomass to drop-in fuels is emerging but once introduced to the market, the resulting fuels will likely be distributed using existing networks and used in existing vehicles driven on existing road networks to deliver a comparable service (i.e., personal or commercial transport). Studies in this area (Von Der Assen et al., 2014; Cuéllar-Franca & Azapagic, 2015; Van der Giesen et al., 2014) have predominantly taken an attributional LCA approach focused on the upstream (conversion) processes to identify hot spots and opportunities to minimize the impacts in the upstream stages (Finkbeiner et al., 2006). These assessments are also compared to an incumbent pathway to understand the potential benefits and tradeoffs of the new technology (Van der Giesen et al., 2014). These assessments should also consider several issues, including supply chain impacts, existing and potential infrastructure requirements, current and future grid mix, marginal emissions, conversion efficiencies and incumbent technologies (e.g., conventional fuels) that will change over time.

Incorporation of other methods into an LCA can also be helpful in this quadrant. Models to scale-up emerging technologies have been proposed in the literature (e.g., Piccinno, Hischier, Seeger, & Som, 2016; Simon et al., 2016) as well as several case studies (e.g., Caduff, Huijbregts, Koehler, Althaus, & Hellweg, 2014; Piccinno et al., 2018; Shibasaki, Fischer, & Barthel, 2007; Walczak, Hutchins, & Dornfeld, 2014). Thermodynamic modeling to estimate the distance from the technologies' respective physical efficiency limits (and thus potential for improvement), use of learning or experience curves to project product improvement, or development of causal scenarios of potential process improvements can also be helpful. Break-even analysis could help to define thresholds of performance required for the technologies to be competitive economically and/or environmentally.

While most studies in the quadrant have historically excluded market consequences and focused on technology improvement, we argue that broader, system-wide analysis that incorporates some market aspects can be helpful despite the uncertainty. Principles of diffusion of innovation are well-established and were largely developed for technologies within this quadrant and they can be integrated into LCA (Cooper & Gutowski, 2018; Sharp & Miller, 2016). In practice, defining realistic deployment and technological diffusion parameters can be difficult. Uncertainty quantification in this quadrant is important both in the context of understanding baseline technological performance, but also performance under different levels of market penetration and methods of assessment.

4.3 | Mature technologies in emerging markets [MT/EM]

This quadrant contains existing commercialized technologies being deployed in new contexts. These technologies could either be entering a new geographic region or being used for a new purpose in a different market sector than originally designed. These technologies introduce new functions, providing previously unavailable services rather than directly competing with an incumbent, though there may be competition among technologies or services (e.g., light-duty ICE competing with public transport).

Common examples of mature technologies deployed in emerging markets occur as developing countries adopt mature technologies from developed countries, such as civil infrastructure (e.g., electric grids, road networks, sanitation systems, refrigeration, passenger vehicles). This quadrant also includes expansion of technologies within developed economies (e.g., deployment of light rail in regions lacking public transit), deployment of existing technologies using new business models (e.g., ride-sharing programs), and transitioning from one market sector to another (e.g., commercializing GPS from niche applications to a broad consumer base).

Within this quadrant, LCAs

- Tend to be exploratory rather than comparative. The LCA may include multiple plausible scenarios to understand the range of potential impacts (Pesonen et al., 2000).
- Relate more strongly to assessing how a market will respond to the introduction of a new technology; often used to guide policy related to adoption practices.
- Are affected by assumptions regarding use phase inventories (e.g., operational efficiencies associated with different use patterns).
- Possess uncertainties related to social acceptance of the technology and potential leap frogging (i.e., the creation of a more advanced or deliberately/logically designed system in a new context than in the original one), how the technology will be deployed, by which users, and at what scale. Adoption patterns and user interactions are likely to differ from prior experience due to the new social context and associated infrastructure.

4.3.1 | Techniques used/guidance

LCAs in this quadrant generally focus on technology adoption scenarios for strategic planning and policy development. The life cycle environmental attributes of the mature technology are often considered with as inputs to a broader scenario analysis model or partial life cycle data considered (e.g., production and use inventory data only). Evaluation of mature technologies in emerging markets with LCA is a relatively new application today when compared to product-based LCAs. In this quadrant, methods are being explored to integrate agent-based models with LCA to estimate how a mature technology may evolve in an emerging market (Alfaro, Sharp, & Miller, 2010; Davis, Nikolíc, & Dijkema, 2009; Florent & Enrico, 2015; Hu, 2009; Miller, Moysey, Sharp, & Alfaro, 2013), as well as limited exploration of Bayesian and/or Markov methods to evaluate system-wide effects of the deployment of these technologies and development of a new market (Miller et al., 2013). These tools typically focus on conditions of deployment, often aided by the development of multiple representative narrative scenarios rather than employment of formal uncertainty quantification techniques.

An example of a system in this quadrant is the market penetration of light-duty ICEs in developing countries. Vehicle ownership rates in sub-Saharan Africa are among the lowest in the world, yet are expected to increase as income levels rise (Dargay & Gately, 1999). Many LCAs have quantified associated materials and energy use of the technology by itself or as an incumbent technology for a comparison with emerging design, fuel, and engine options (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013; Kaniut, Cetiner, & Franzeck, 1997; MacLean & Lave, 1998, 2003; Mendoza Beltran et al., 2018; Sullivan & Cobas-Flores, 2001). A common metric for measuring life cycle performance of the automobile is kg CO_2eq/passenger-mile (or km). In mature markets, this value can be estimated reasonably well, given available data on manufacturing, fuel economy ranges, fuel type, passenger occupancy, and distance per vehicle. In countries where vehicles are scarce and fuel is costly and/or difficult to obtain, it is expected that vehicle occupancy is likely to be higher, although an individual's wealth appears to have a major effect on overall carpooling behavior (Mitullah & Vanderschuren, 2017). Similarly, fuel consumption will change with respect to infrastructure design and quality. Poor roads and areas of high congestion due to infrastructure designs or policies that incentivize personal vehicles rather than public transportation will increase fuel consumption per kilometer. Therefore, the kg CO_2-eq/passenger-mile associated with the same vehicle may be different in emerging markets due to differences in usage patterns. As the market matures and more information is obtained, uncertainty in these parameters is reduced. Similarly, proactive policies that are based on insights from an LCA's improvement analysis can help shape usage patterns to reduce the environmental impact associated with increased introduction of light-duty ICEs into the region.

4.4 | Emerging technologies in emerging markets (ET/EM)

This quadrant represents "blank slate" technologies, which are both low TRL/MRL and introduce novel functionality into an existing market or to create new markets. This quadrant is the most likely to contain truly disruptive technologies that have the potential to transform important aspects of society. Historical examples include the assembly line production processes that enabled mass production of the Ford Model T, thus transforming personal mobility; and new information and communication technologies that enabled the internet as a new way to transfer information, thereby transforming broad sectors from banking to entertainment. Modern-day examples include development of autonomous vehicles, commercial space travel, and gene-editing capabilities, each with consequences yet to be realized.

Within this quadrant, LCAs

- Often do not have a clear incumbent technology.
- Face the challenge of many unknowns (both known and unknown), including the potential for wide-scale unexpected consequences (i.e., "unknown unknowns").
- Combine the challenges posed by the previous two quadrants: lack of data surrounding the production process and parameters of use, low knowledge of the potential disruptions that will occur within the broader system, and potential for rapid evolution of the technology itself and the indirect effects it will have on society.
- Are most useful when an exploratory analysis is conducted to understand a range of plausible outcomes and when the limitations are appropriately acknowledged (see Figure S2 of Supporting Information).

4.4.1 | Techniques used/guidance

The evaluation in this quadrant will be more exploratory and scenarios will likely be broader in nature by incorporating a larger range of possible future conditions than in other quadrants. Emphasis should be placed on novel interpretation and presentation techniques to ensure that stakeholders appreciate the degrees of uncertainty, as well as the value of inconclusive but directional insights, to aid in technology development and to highlight potential unintended consequences. Simplified LCA or screening approaches may be more appropriate in this quadrant (e.g., Hung, Ellingsen, & Majeau-Bettez, 2018; Hur et al., 2005; Marco, Ferruccio, Michele, Faraldi, & Polverini, 2007). It is imperative that the analyst communicate that the set of preliminary configurations and conditions selected for the analysis likely do not reflect the full set of potential conditions and applications for that technology (Tuomisto & Teixeira De Mattos, 2011).

An example concept in this quadrant is the Hyperloop. An evacuated tube houses a pod in which passengers or goods can be transported. The technology offers the potential for lower cost, faster speeds and higher efficiencies. However, the environmental impacts and potential unintended consequences are not clear. We consider the nature of the Hyperloop technology so disruptive that the potential demand, if successful, is very different than that of high-speed rail or transport generally, including air and automotive transport. Hyperloop technology could evolve such that there are iterations on the technology which improves performance, tests the concepts and the technology moves towards maturity while the market drivers and potential uses remain uncertain (or the technology remains too costly to be deployed in a market). Alternatively, the market for the technology becomes more clear (reduced uncertainty in the market) while the technology remains uncertain. Or, both the technology and market emerge and evolve in step such that both the technology and market maturity increase and the uncertainty in both domains is reduced.

Analysis of the environmental impacts for Hyperloop could be split into two essentially independent activities. The first attributional LCA activity would focus on the technology itself, performing a bounding analysis and attempting to generate estimates of the material and energy requirements for the technology by asking questions such as those related to technical parameters (e.g., pipeline diameter, thickness, pressure), materials that would satisfy strength requirements, energy required for propulsion, and so forth. This would allow for the construction of an inventory of the energy and material interventions that the technology would cause. The second (preliminary, including market dynamics) LCA could involve scenario generation for potential demand. Part of this might involve estimating which current travel mode (or modes) Hyperloop might replace and to what extent, as well as whether rebound effects would affect the net environmental impacts from deploying this technology.

This LCA approach may help identify preferable scenarios and design pathways that seem to lead to more favorable environmental outcomes. Nevertheless, it is important to acknowledge the difficulty in adequately anticipating unexpected outcomes or even assessing the level of uncertainty.

4.5 | Questions to drive the goal and scope definition for the LCA of emerging technologies

The above discussion highlights some of the challenges an analyst faces when performing LCA of emerging systems in each technology/market maturity quadrant. Several approaches can inform LCAs of technologies and of the wider systems in which they potentially sit and influence, including: learning curves, technical potential studies, engineering studies, techno-economic modeling, scenario development, partial and general equilibrium economic modeling, integrated assessment models, and so forth. Common to all emerging systems (i.e., whether due to technological or market immaturity) is the requirement for the LCA analyst to work in a relatively data poor environment, often with ill-defined systems,

TABLE 1 Questions to pose during goal and scope definition when conducting LCA of emerging technologies

Technology factors	Market factors
Interaction with technological system • Does the innovation fit within an existing technological system (e.g., a new part), or is it an entirely new system? • Does it require/allow changes to the rest of the system (e.g., vehicle light weighting allows for powertrain resizing) • Is the technology standalone or does it require changes to background infrastructure (e.g., electric vehicle changing infrastructure)? → See additional "market" questions Functional materials (e.g., rare-earth metals for EV batteries) • Are there resource criticality impacts or supply limitations? • What are the supply chains and LCA impacts associated with these materials? • Do novel materials (e.g., nanometals) introduce new environmental concerns, and how might these be quantified? Commercialization pathway • What are current commercial or lab scale material and energy requirements? • What scale is considered and what scaling rules apply (e.g., improved heat transfer at scale for a chemical process)? • What future process efficiency improvements can be expected? Over what time horizon? • Are there thermodynamic limits to process improvement? Production and use characteristics • The product's functional unit(s)? • Underlying manufacturing technology (e.g., thermochemical vs. biochemical routes)? • Facility design (e.g., purpose-built vs. assembly line; batch vs. flow reactor)? • What are the direct process emissions and production process inputs (e.g., energy needs)? • What is the expected efficiency and/or emissions in use phase? • Expected product lifetime? • What co-products are produced? • Other characteristics that affect end use (e.g., electric vehicle range and charging time)?	Service offered by the technology • Does the technology offer a new service or change to existing services? • For general use technologies (e.g., internet), what use cases are considered (e.g., entertainment? online commerce? telecommunication?) Background systems • Policies and regulations? • Characteristics of supporting infrastructure (e.g., Emission intensity of the average or marginal electric grid, existing road networks, and fuel distribution systems)? Consumer behavior • How will the technology be used (e.g., will autonomous vehicles be shared, or individually owned?) • How will the technology affect existing consumption patterns (e.g., direct rebound effect (Sorrell, Dimitropoulos, & Sommerville, 2009), mix of products consumed, characteristics of those products)? • What incumbent product (if any) will be displaced? • What supporting technologies may be encouraged/enabled? • User interactions? Market dynamics • Indirect rebound effects (e.g., income rebound, indirect fuel use effect) and other market-mediated effects (e.g., indirect land use change, learning-by-doing, spillover effects to other regions or technologies)? Interference or effects of other incumbent technologies (e.g., uptake of drop-in fuels may prolong use of ICEVs and make electric vehicles less competitive in the near term)? Adoption patterns and characteristics of adoption regions: • Speed of adoption, diffusion effects? • Location of potentially impacted systems (e.g., is there a sensitive ecosystem nearby? is there a large population center that will experience changes in air quality)? • Heterogeneity of local background systems? • Local climate? • Cultural and social preferences affecting adoption patterns and use? Internal consistency • What is the time frame and geography of analysis? • Is evolution of background and foreground systems consistent (e.g., greening of electric grid alongside improvement of the technology within future scenarios)? • Does the background system respond to the rollout of the technology (e.g., do electric vehicles play a role in grid storage? Is additional electricity demand accounted for?)

Technology and market columns correspond approximately to questions/uncertainties/drivers that fall respectively within the technology and market bubbles of Figure 2.

resulting in increased uncertainty relative to studies that focus on established products. It is therefore incumbent upon the analyst to clearly define the system and scope of analysis, specify and reference all underlying data sources and their overarching assumptions, and to communicate results with care. Though good practice for all LCA studies, it is especially important within emerging systems to define internally consistent scenarios with clear and consistent temporal and geographic boundaries, scale of production (both production plant size and net scale of overall technology deployment), and so on.

Predicting future adoption patterns and technical performance of an emerging technology in an LCA adds a level of uncertainty not encountered in LCAs of commercial products and requires the analyst to make assumptions that may impact the results of the LCA significantly, by an order of magnitude or more. The analyst should specify what dimensions of the system are being considered, and recognize the limitations of the analysis, which by necessity cannot provide comprehensive treatment of all potentially relevant factors. For emerging technologies, it is important to specify details of the technology itself: what is it made from, how is it made, what are its end-use characteristics, and how it integrates into existing technological systems. Within emerging markets, a wide range of factors related to consumer behavior, background systems, and broader system interactions will all influence the eventual environmental impact of the technology as it is deployed. In either case, the analyst can choose either to specify a specific set of conditions (i.e., assumptions about the technology and how it is deployed) or to scope out and compare a range of future technology and/or market scenarios.

Examples of relevant factors that can be broadly characterized as technology or market factors are shown in Table 1. A recently published framework (Miller & Keoleian, 2015) categorized ten major factors commonly considered in LCA of emerging technologies, depending on what questions the study is attempting to address, broadly classifying these factors as intrinsic, indirect, and external to the system being studied. We include those factors from Miller and Keoleian (2015) in Table 1 but clarify how each factor is relevant in the context of technology or market development. While no individual study can comprehensively address all major considerations of an emerging technology, the goal is to provide researchers/analysts with a partial checklist of factors to consider when determining the goal and scope of an LCA on emerging systems. Returning to Figure 2, the relative size of the technology and market bubbles provide guidance regarding which column of Table 1 requires greater focus within the LCA study. Due to the overlapping and interactive nature of these factors, even the smaller bubble (e.g., a mature market) will always require some consideration. The examples provided in Table 1 are a demonstrative set of questions to help the analyst prepare for their analysis. It is a starting point for structuring the goal and scope stage of the LCA and could be expanded and further refined in future work.

Returning to the example of drop-in fuels produced from CO_2, where the technology is placed in the ET/MM quadrant, the LCA of this technology is focused on the technology factors column as the market for drop-in fuels is already mature. The functional materials and commercialization pathway factors are identified as the most important because they focus on the upstream stage of the process (e.g., the range of methods for producing drop-in fuels, supply chain impacts) rather than downstream aspects that are less relevant as drop-in fuels are direct replacements to the incumbent (e.g., petroleum-derived gasoline). As such, the analyst could focus on addressing the questions posed in the table that are related to functional materials and the commercialization pathway. These questions lead to choices about boundaries and methods in the goal and scope definition to account for the most critical factors in early-stage LCAs of this technology. For the case of drop-in fuels, due to their low TRL, the analyst should focus on choosing appropriate methods for technology scale-up and accounting for associated uncertainties.

It is also important to emphasize in this context the importance of a broader multidisciplinary systems analysis approach that combines the insights from, for example, techno-economic assessment (e.g., Sakti, Michalek, Fuchs, & Whitacre, 2015; Verma, Raj, Kumar, Ghandehariun, & Kumar, 2015), market assessment (e.g., Kihm and Trommer, 2014), systems modeling (e.g., Krey, 2014), behavioral characterization (Huijts et al., 2012), and expert elicitation (Morgan, 2014) to inform the environmental life cycle study design. While motivated by the environmental LCA perspective for the evaluation of emerging technologies, this approach has applicability to the broader technology evaluation community and could be applied to techno-economic assessments or market assessments as well as impacts related to each pillar of the classic triple bottom line (economic, social and environmental; Elkington, 1998; *The Economist*, 2009).

5 | CONCLUSIONS

This paper contributes a dialogue that is designed to aid researchers/analysts in considering the specific technology characteristics and dynamic market context that affect the technology they wish to assess. This, in addition to the goal of their study, will help to direct the questions that can be asked to define the types of tools and techniques that can be applied and the specific challenges that should be addressed. The potential issues associated with emerging technologies and the use of technologies in emerging markets can be significant and need to be addressed as we develop systems and technologies and integrate them into society. In general, emerging systems require a nuanced treatment of uncertainty that provides probabilistic distributions where feasible, while acknowledging that often only ranges and bounds are possible. In all cases, the analyst should be clear about objectives of the analysis, circumstances in which it is applicable, and which conclusions can be drawn as opposed to which questions remain unexplored or which results are too uncertain to provide answers.

The importance of understanding both the level of technology maturity and the level of maturity of the market into which the technology will be deployed are critical defining factors of the emerging technology assessments. These guide study design, boundary selection, stakeholder expectations and ultimately the selection of appropriate analytical techniques from the broad array available. Illustrative examples are used to highlight key challenges and commonalities involved in assessing technologies at different stages of technology and market maturities. LCA has proven to be an important part of technology evaluation in today's society. The need for clear guidance and realistic approaches (expectations) for LCAs of emerging technologies is needed to guide both decision-makers and analysts to ensure the questions of interest: (a) consider both technology and market factors, (b) focus on the key factors and model aspects of importance, and (c) provide the knowledge to improve decision-making through life cycle-based systems analysis.

This paper is intended to be a starting point for these discussions and a call for the formation of a research network to systematically address the methodological challenges described in this paper. The research network will focus on developing more structured guidance documents to support researchers in obtaining relevant data, selecting appropriate tools for their analyses, and managing assessments as technologies transition between quadrants. Activities that the network intends to undertake in the near term include continuing to convene workshops/special sessions at conferences, engaging stakeholders external to the LCA community, and arranging graduate exchanges or residences to facilitate knowledge exchange within the network. Example topics that the research network plans to address include: (a) techniques within LCA to scale-up results from lab tests to project performance at commercialization, (b) integration of LCA and techno-economic analysis communities/methods, (c) integration of LCA with economic models, and (d) adaptation of LCA methods to improve decision support.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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