Titre: Title:	LiSET: A framework for early-stage life cycle screening of emerging technologies
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Date:	2018
Type:	Article de revue / Journal article
Référence: Citation:	Hung, C. R., Ellingsen, L. A.-W. & Majeau-Bettez, G. (2018). LiSET: A framework for early-stage life cycle screening of emerging technologies. *Journal of Industrial Ecology*. doi:10.1111/jiec.12807

LiSET: a framework for early stage Lifecycle Screening of Emerging Technologies

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Summary

While lifecycle assessment (LCA) is a tool often used to evaluate the environmental impacts of products and technologies, the amount of data required to perform such studies make the evaluation of emerging technologies using the conventional LCA approach challenging. The development paradox is such that the inputs from a comprehensive environmental assessment has the greatest effect early in the development phase, and yet, the data required to perform such an assessment is generally lacking until it is too late. Previous attempts to formalize strategies for performing streamlined or screening LCAs were made in the late 1990s and early 2000s, mostly to rapidly compare the environmental performance of product design candidates. These strategies lack the transparency and consistency required for the environmental screening of large numbers of early-development candidates, for which data is even sparser. We propose the Lifecycle Screening of Emerging Technologies method (LiSET). LiSET is an adaptable screening-to-LCA method that uses the available data to systematically and transparently evaluate the environmental performance of technologies at low readiness levels. Iterations follow technological development and allow a progression to a full LCA if desired. In early iterations, LiSET presents results in a matrix structure combined with a "traffic-light" color grading system. This format inherently communicates the high uncertainty of analysis at this stage and presents numerous environmental aspects assessed. LiSET takes advantage of a decomposition analysis and data not traditionally used in LCAs to gain insight to the lifecycle impacts and ensure that the most environmentally sustainable technologies are adopted.

Keywords: emerging technology; environmental screening; LiSET; lifecycle screening of emerging technologies; matrix LCA; streamlined LCA

Introduction

Aim of study

Lifecycle assessment (LCA) is a standardized method that strives to determine all of the environmental burdens connected to a product or activity. However, capturing all of these environmental flows is very difficult (Rebitzer et al. 2004; Hellweg and Milà i Canals 2014). Although LCA is a powerful tool, it is not without limitations. For instance, the comprehensive nature of an LCA makes it costly and time intensive to perform (Hellweg and Milà i Canals 2014; Graedel et al. 1995; Weitz et al. 1996; Hochschorner and Finnveden 2003; Finnveden et al. 2009). Perhaps more importantly, the standard LCA method also struggles to evaluate technologies at low technological readiness levels (Gavankar et al. 2015). In some cases, there are a multitude of technology candidates at the experimental or laboratory scale, and therefore insufficient data are available to perform an adequate LCA. Furthermore, these data gaps are difficult to readily identify in typical LCA results unless explicitly highlighted by the practitioner.

The abovementioned limitations make LCA unsuitable in early stages of technology development as the necessary information is not usually available (Hetherington et al. 2014). Additionally, the precise quantification of environmental impacts is not the focus in these early phases of development. Rather, it is capturing the relative environmental potential of these developments, and identifying areas of potential concern or dead-end development pathways that is of greatest importance. In these stages of development, there are dozens of potential candidates and there are significant data gaps. What little data that are available may be qualitative, and derived from expert judgment rather than observed values. Such conditions make conventional, full LCAs impossible, and whatever single-score impacts that are extracted from any attempts at a full LCA would be highly under-informed and of limited usefulness due to the quality and quantity of data available for the assessment. However, technology development and design choices made early in the process have a significant effect on the overall environmental performance of the final product (Hetherington et al. 2014). It is therefore during this development phase that the results of an LCA would paradoxically have the greatest influence on the technology (Hellweg and Milà i Canals 2014). Moreover, changes to design or technology selections are significantly less likely to occur later in the development process due to technological lock-in. A systematic framework allowing for an efficient and transparent environmental evaluation of multiple technological candidates early in development would therefore be useful. Such a framework, the Lifecycle Screening of Emerging Technologies (LiSET), is presented here.

Background

In the 1990s, much effort was placed in developing less time- and cost intensive versions of the standard LCA method. In an attempt to address the issues with and develop approaches to reduce the labor and data intensity of the LCA method, the United States Environmental Protection Agency (EPA) hosted a meeting between LCA practitioners from industry, consulting and academia (Curran and Young 1996).

Despite this, there are few universally accepted, systematic means of performing a simplified LCA. While the need for simplified LCA methods was addressed in the 1990s (Graedel et al. 1995; Wenzel et al. 2000; Hunt et al. 1998; Weitz et al. 1996), seemingly little cohesion in this type of assessment remains. Indeed, frameworks designed to assess specific technologies exist (Arena et al. 2013; Tang et al. 2016; Bauer et al. 2008), but development of generic frameworks that can be applied to any emerging technologies seems to have stalled. Two levels of non-full LCAs exist, namely matrix mapping, or screening LCAs, which can be qualitative or semi-quantitative, and streamlined LCAs, which are quantitative (Wenzel 1998).

The environmentally responsible product assessment (ERPA) matrix (Graedel et al. 1995) and the material-energy-chemicals-other (MECO) method (Wenzel 1998; Pommer et al. 2001) are the most prominent semi-quantitative methods for performing a lifecycle screening. While these approaches both provide a fairly comprehensive assessment of early-phase products, they lack flexibility and are subject to arbitrariness (Hochschorner and Finnveden 2003). These approaches also mirror the understanding of and subsequent environmental priorities of their era (i.e., the 1990s). These methods therefore focus on the most visibly apparent aspects of pollution, such as packaging and landfilling (Guinée et al. 2011), rather than the current issues of global warming and biodiversity impacts, among others. Furthermore, the ERPA matrix is limited in its ability to evaluate indirect impacts, such as differences between electricity sources or material production technologies. Additionally, qualitative information has no place in the ERPA matrix, which forces the absence of potentially useful information in an evaluation.

Streamlined LCAs, on the other hand, are fully quantitative, and are therefore preferentially applied to products or technologies with relatively high readiness level rather than those in an early developmental phase. Streamlining approaches usually involve reduced levels of detail or data quality. While more development has occurred in the area of streamlined LCAs than screening LCAs, most of these streamlined LCA approaches seem to entail adopting the strategies developed in the EPA meeting to varying degrees rather than spearheading novel approaches to streamlining. The streamlining strategies developed in the EPA meeting (Curran and Young 1996; Todd and Curran 1999) appear to have been readily adopted (Moberg et al. 2014; Arzoumanidis et al. 2017), yet not further explored or developed. These strategies are:

1. Abandoning, partially or fully, upstream or downstream processes
2. Reducing the number of environmental impacts evaluated
3. Using a threshold value to determine which components are studied
4. Using proxies
5. Mixing qualitative and quantitative data, depending on availability
6. Establishing “zero-tolerance” criteria that when met, discontinues further analysis

These strategies, however, are not all created equal, as some strategies result in vastly different rankings of the evaluated candidates than others (Hunt et al. 1998; Moberg et al. 2014). Moreover, there is no universal guidance as to which of the strategies to apply, nor in what context are they appropriate or to what extent should they be used. For example, strategy 5 does not specify how exactly qualitative and quantitative data could or should be combined in an assessment. The resulting haphazard application and combination of the strategies underpins the subjectivity of current streamlined LCAs. More importantly, the strategies of streamlined LCA are defined very broadly, and when these strategies are applied together, they could essentially yield a zero-information LCA due to the compounding of uncertainties introduced by each strategy. Such an LCA undermines confidence in streamlined LCA results and their ability to guide technology development in a more sustainable direction. It is therefore crucial to accompany streamlining LCAs with a systematic means of communicating assumptions and tracking the evolution of a study through iterations.

This article describes an adaptable screening-to-streamlined-to-full LCA method. This method can be useful in mapping technology candidates in early stages of development, in performing a feasibility assessment of novel technologies, and in pinpointing candidates for further pursuit with relatively little investment in cost and time. While we focus on using the method to inform technology development pathways, the product design process is analogous and therefore similarly applicable.

Proposed new method

In this paper, we propose a formal method for a lifecycle screening framework that should add practical guidance and transparency to strategies of both screening and streamlined LCAs. Unlike previously developed screening and streamlining LCA methods, this method is best suited to the mapping of a large number of candidates at early stages of development. Our LiSET method constitutes the generalization and refinement of an approach developed specifically to screen the literature for nanomaterial candidates with the potential of improving the lifecycle sustainability of traction batteries and fuel cells (Ellingsen et al. 2016). A subsequent application of the method to electrode materials for a rechargeable aluminum battery can be seen in Ellingsen et al. (2018).

The method involves a three-step process to perform relative comparisons between technologies. These three steps can be iterated and refined in a fourth step as the technology develops, and eventually converted to a quantitative analysis in a fifth step (Figure 1). Each step is described in detail later in the text with examples from various sector technologies, but briefly, the process is as follows. First, the technology lifecycle is decomposed into the classic components of impact sources: the amount of inputs and outputs required for fulfilling the designed function and the environmental intensity of these inputs and outputs. Second, the decomposition terms are linked to objective, evaluable lifecycle aspects. Third, quantitative and qualitative data for these aspects are collected and evaluated using a relative scale. The fourth and fifth steps accompany the iterative refinement and transition to a streamlined quantitative LCA comparison, and eventually full-fledged LCA evaluation. After describing the five steps in detail, we close this section with a discussion of transparency matters and approaches to mitigate the subjectivity of the LiSET method.

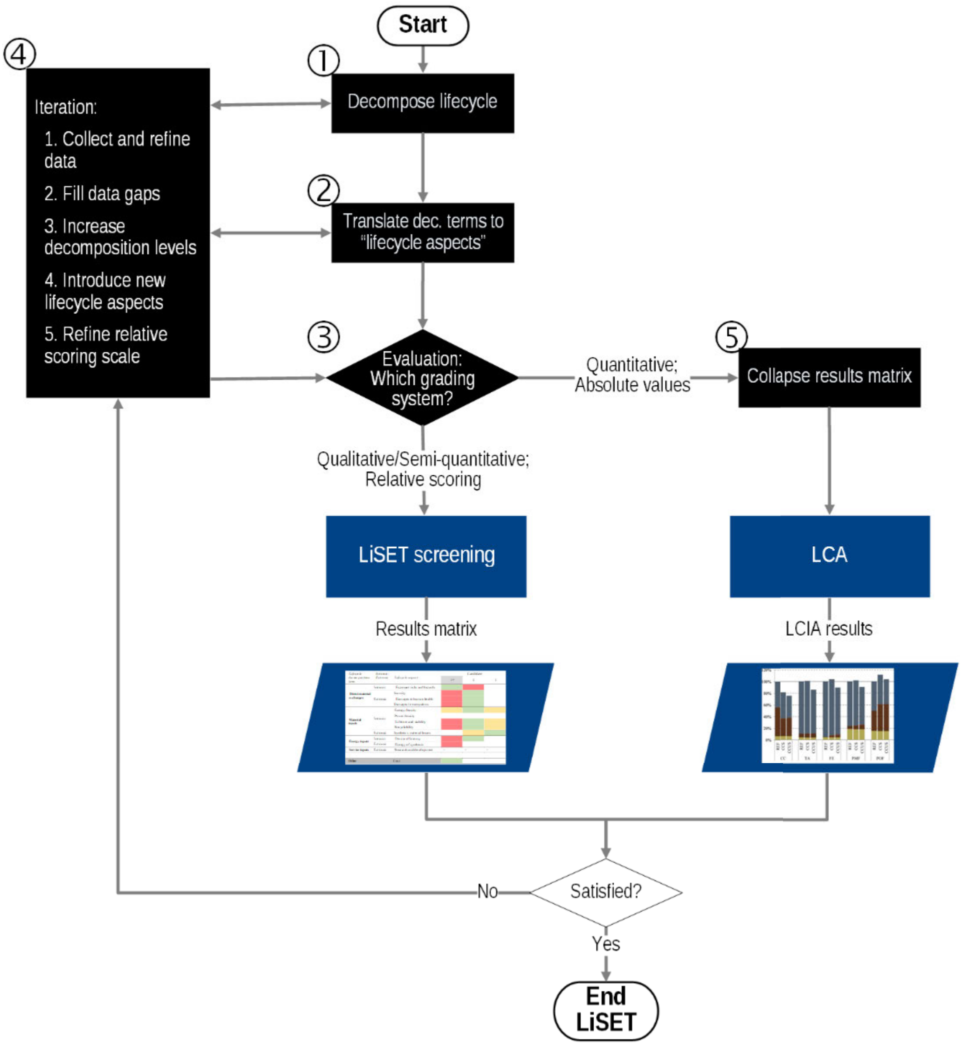

Figure 1 - Workflow for performing LiSET. The numbers indicate the three core steps of the method, with an optional fourth step of iteration and fifth step of transition to quantitative evaluation. Depending on whether a relative scoring or absolute, quantitative results are obtained from the evaluation, a table-based LiSET screening or first-round LCA with collapsed lifecycle impact assessment (LCIA) results.

Decomposition analysis

The basis of LiSET is a decomposition of a technology's lifecycle into a finite number of contributors to environmental impacts that can be identified from first principles. By using this top-down approach, all of the factors influencing environmental impact are explicitly included in the analysis, irrespective of the initial availability of data.

Conceptually, we start decomposing the total lifecycle causal connections by separating direct and embodied impacts (Figure 2, Row I). The former arise from direct exchanges between the technology under evaluation and the environment. These exchanges are those that arise from the technology itself, and are analogous to Scope 1 emissions from the Greenhouse Gas Protocol corporate standard. These direct exchanges might be the water required to irrigate genetically modified crops, the evolution of heat during the operation of a battery, or volatile fumes arising from a 3D printing process. On the other hand, the embodied impacts are mediated through the value chains supplying the technology during manufacturing, operation or disposal of the technology. These embodied impacts are analogous to Scope 2 and 3 emissions. Examples of embodied impacts include the impacts arising from the research and development of the genetically modified crops, of the electricity mix used to charge the battery and the amount of steel (and environmental impacts thereof) used to make the 3D printer. The total environmental impact from the technology is the sum of all direct and embodied impacts.

In the next level (Row II), direct exchanges are categorized as material emissions of pollutants such as carbon dioxide, particulate matter, etc. and energy releases in the form of heat, radiation or even noise. Direct inputs of materials or energy from the environment, otherwise referred to as resource use, to the technology are also considered here. In a similar manner, the impacts from embodied inputs to the technology are categorically decomposed into value chains of material inputs (e.g., metals, chemicals, or water), of energy in the form of electricity or heat requirements, or of non-consumptive inputs, hereafter termed "services" (e.g., person-hours, land-use, transport).

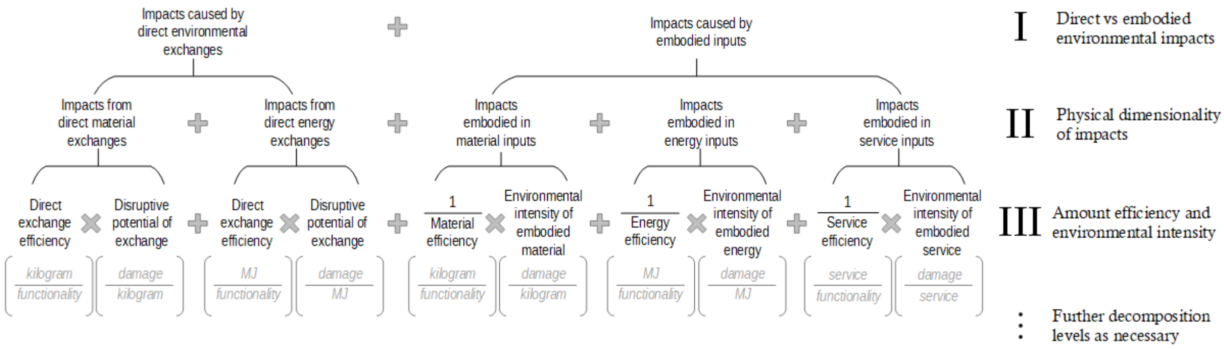

Figure 2 - General decomposition of environmental impacts. Practitioners may choose to decompose further to adapt to the priorities of their analysis, e.g., by distinguishing between individual emission species, midpoint indicators, areas of protection, lifecycle phases, or all of the above.

The impacts arising from each of the terms in Row II are further decomposed as a multiplication of two dimensions: the magnitude of the flow (exchange or input) per unit of delivered functionality, and the specific environmental intensity (damage per unit mass, energy or service) of these flows[1] (Minx et al. 2011) (Row III). That is, impacts arising from direct exchanges are dictated by both the quantity of the emissions per functional unit as well as the disruptive potential (i.e., characterization factor) of the emitted species (Row III, first four terms). Parallels can be drawn to the impacts of embodied emissions (remainder of Row III). Considering both quantity and environmental intensity is particularly important, as technologies demonstrating higher material/energy/service efficiency (i.e., more functionality per mass), often also have the tradeoff of using materials with higher specific environmental intensity (e.g., CO_2 per kg of material) to achieve the increased efficiency.

These first three rows will be the same for all technologies. A decomposition with higher resolution is achieved by extending into more levels. For example, a practitioner may separate inputs from outputs (collectively referred to as “exchanges” in Figure 2).

For example, in a fourth row of decomposition, each of the “environmental intensity” terms in Row III could logically then break down into “greenhouse gas intensity” and “other environmental impacts”. Similarly, the “material efficiency” in Row III might be split into “material requirements for production”, “material requirements during use phase” in Row IV.

One might further distinguish production materials between materials that are incorporated into the technology, "production materials" and materials used in production, but not directly part of the technology, "consumables for production", in Row V. Extending the decomposition analysis retains the complete coverage of lifecycle impacts for the technology candidates while concurrently adding resolution via disaggregation of individual flows. As the decomposition analysis ensures full coverage of all factors leading to environmental impacts, practitioners should strive to also include a comprehensive range of environmental impact types. As an example, this can be done by ensuring that all three areas of protection (human health, ecosystem health, and resource use) are in some way covered by the decomposition terms, even partially.

Lifecycle aspects

The decomposition conceptually splits the lifecycle impact into aggregated decomposition terms. Because decomposition terms conceptually represent multiple flows (e.g., inputs of electricity, heat, etc.), there is a need to translate these decomposition terms into evaluable metrics, or *lifecycle aspects*.

The practitioner selects these lifecycle aspects: physical properties that are proxies used to represent the decomposition terms. The lifecycle aspects should consist of data types that are readily available for many of the technology candidates being evaluated, at the time of the evaluation. Note that several lifecycle aspects may be used concurrently to represent one decomposition term and that these representations should be selected such that all lifecycle phases are considered in the overall evaluation. Furthermore, the aspects are not a "next level" of decomposition, but should rather be thought of as physical manifestations, or overall indicators, of each decomposition term.

During this step, it is important to use a consistent, reasonably transparent and accessible data source across all evaluated technologies. Similarly, with the comparison of several technologies, care should be taken to ensure all candidates are evaluated. The uncertainty involved in early phase assessments mean that the assumptions used in this step have a considerable influence on the results and overall conclusions drawn from the study. Table 1 provides some non-exhaustive, generalized examples of lifecycle aspects that can be used for the different decomposition terms.

It is useful to explicitly identify whether each lifecycle aspect is *intrinsic* or *extrinsic*. *Intrinsic* properties will largely be immutable and are inherent to the technology itself. In contrast, to some extent, *extrinsic* properties depend on the value chain design and can therefore be adjusted by selecting a different value chain. Using energy devices as an example, intrinsic properties include theoretical efficiency, or power density, or the crust concentration of the elements required in the device. In contrast, extrinsic properties for the same devices include transport requirements, or the carbon intensity of the electricity used to assemble the device. Thus, most extrinsic parameters are not affected by the technological choice, and should receive less attention in guiding early technology development. Choices of providers, geographies of production, and other value-chain related considerations are more the focus of technological deployment and scale-up phase.

Using Ellingsen and colleagues (2016) as an example, the lifecycle aspects selected to represent the material efficiency portion of *embodied material inputs* included the battery power density, energy density, material synthesis losses, recyclability, and lifetime and stability. These aspects were selected due to their fitness as representations of the decomposition terms, their relevance to the functionality of the energy device, their roles in contributing to the overall material requirements of the devices, and because these were often the data that were typically published in materials research articles, and therefore available for the lifecycle screening of these early phase developments. Thus, a few data points efficiently serve as indicators for the whole lifecycle phase, and are represented individually, without being aggregated (hidden) in the calculation of a highly uncertain LCA impacts. This feature of LiSET therefore constitutes one of the advantages of this approach: it adapts to available, "non-conventional" data to perform an evaluation of lifecycle impacts.

Table 1 - Examples of lifecycle aspects that could be used to represent the lifecycle decomposition terms (e.g., Row II from Figure 2)

Decomposition terms	**Examples of potential lifecycle aspects**
Direct material exchanges	• Hazard ratings from Material Safety Data Sheets (MSDS) • Characterization factors (mid- or endpoint) • Geological data/criticality evaluations
Direct energy exchanges	• Characterization factors (mid- or endpoint) • Worker guidelines (e.g., for noise)
Value chain material	• Lifetime • Level of design for disposal • Production efficiencies • Maintenance requirements (e.g., spare parts, consumables)
Value chain energy	• Cumulative energy demand • Manufacturing or synthesis energy • Use phase energy requirements
Value chain services	• Transport requirements • Enabled decentralization • Labor • Research and development

An important point to recognize is the treatment of tradeoffs. Few technologies present a true "silver bullet" in terms of environmental impacts. For example, compared to their traditional predecessors, advanced lightweighting materials often provide use-phase gains, or allow for the use of less material in the manufacturing phase. These advanced materials, however, may have higher production impacts than conventional materials via greater energy or material requirements or require more intensive precursors (Luk et al.

2017). These would be covered individually under the separate lifecycle aspects of material efficiency (lightweighting effects) and environmental intensity of materials (resource scarcity) or energy efficiency (production or synthesis energy) such that a complete evaluation of strengths and weaknesses is performed. Cause-and-effect tradeoffs are therefore considered as separate lifecycle aspects as far as possible.

Each lifecycle aspect is graded according to the available data for its evaluation; the data quality, i.e., quantitativeness determines the grading system (Figure 1). For ranking, results are presented in a matrix form similar to the ERPA and MECO approaches where the evaluated candidates are placed across the columns and the different criteria within the lifecycle decomposition terms across the rows (example, Figure 3). Practitioners may opt to include a reference candidate in their evaluation. Such a reference candidate might be, for example, the state-of-the-art technology currently performing the same function. In Ellingsen et al (2016), these were the current state of lithium-ion battery technology, bulk-phase lithium-nickel-cobalt-aluminum oxide as the cathode, and graphite as an anode. However, any grading that occurs is performed on an internal, relative scale. This means that none of the candidates, including this optional reference candidate, acts as a “benchmark”. Such an evaluation scheme ensures that the benefits and disadvantages of every candidate, including the reference candidate, is clearly communicated by being on the same scale. Tradeoffs within each technology are easily identified.

Figure 3 represents a simplified, fictional example of the results after screening two alternatives for an energy device, loosely based on Ellingsen et al (2016). Note that missing data and irrelevant lifecycle aspects are still present in the LiSET matrix, but are represented with blank cells. The advantages of this approach is further discussed below, in *Documentation and transparency.*

Decomposition term	*Intrinsic/ Extrinsic*	*Lifecycle aspect*	Candidate				
			1*	2	3	…	*n*
Direct material exchanges	Intrinsic	Exposure risks and hazards				…	
	Extrinsic	Scarcity				…	
		Damages to human health				…	
		Damages to ecosystems				…	
Material inputs	Intrinsic	Energy density				…	
		Power density				…	
		Lifetime and stability				…	
		Recyclability				…	
	Extrinsic	Synthesis material losses				…	
Energy inputs	Intrinsic	Device efficiency				…	
	Extrinsic	Energy of synthesis	†			…	
Service inputs	Extrinsic	Research and development				…	
Other		Cost	†			…	

Figure 3 - Fictional simplified implementation of early design phase LCA screening for energy devices using "traffic light" grading. Green cells denote a relative strength, red relative weakness, and yellow intermediate characteristics. Blank cells indicate missing information, † indicates data available, but fewer than three candidates have data for the lifecycle aspects, so a three-step grading cannot be made. Candidate 1 represents a reference candidate, e.g., the current state-of-the-art. Practitioners may wish to present additional factors such as costs or ethical considerations that should be considered in the technology's development, as shown here at the end of the table.*

The results table presents the evaluated lifecycle aspects in rows, grouped according to the decomposition term they fall under. Furthermore, the intrinsic and extrinsic nature of each aspect is noted. At the right, technology candidates are placed in columns. The current technology (1*) is also evaluated as a reference candidate.

Making the grade: evaluating the lifecycle aspects

The first thing to note is that the three candidates are graded relative to each other; adding another candidate with values greater or less than the current maximum or minimum, respectively, could change the grading scheme. As this is a mapping, the goal of Figure 3 is not to declare a "winner", but rather to pinpoint areas of concern, strengths, and aspects to consider in future commercialization.

At the coarse end of the grading spectrum, a three-level "traffic light" color system denoted by green (advantageous), yellow (intermediate) and red (poor) may be used. Criteria with insufficient data are left blank, thereby highlighting areas requiring further investigation. Similarly, when fewer than three candidates have data, an internal grading of red-yellow-green cannot be made, but those candidates can be marked with either the data value or a symbol († in Figure 3). This simple, yet intuitive system provides an at-a-glance assessment of technologies both as a whole (i.e., down columns) and with other alternatives (across columns). Furthermore, this system naturally communicates the inherent high uncertainty of the assessment; unlike a scale from 0-10 or 1-100 and so on, there is less than one significant digit of resolution in the three-color scale. As the data become more refined, so does the grading scale (see *Iterative refinement and transition to LCA*).

Concisely representing a wide range of quantitative and qualitative data for multiple technology candidates across a large number of lifecycle assessments presents specific challenges. In a semi-quantitative evaluation, quantitative data can be presented as-is with their actual value, or they can be translated to an evaluation scale. Mixing evaluation systems or presenting large amounts of quantitative results with different units makes a general overview and thereby drawing conclusions difficult. Using a coarse grading system to represent quantitative data also removes the misleading situation where the differences between quantitative results are less than or of similar magnitude to the uncertainty of the results themselves (e.g., removes the apparent superiority of a 96% vs 94% rating, when each of these values has a ±20% uncertainty). We therefore recommend the use of a lowest-common-denominator approach to the graphical representation of the LiSET screening; until all available lifecycle aspects can be expressed on a 1-10 scale, all should be evaluated using the three-color scale.

However, attempting to reduce quantitative data to a coarser (i.e., color) scale raises issues of subjective choices and boundary conditions. Where does one draw the lines between green, yellow and red rankings? As a means of ranking quantitative data in an unbiased manner, a segmentation algorithm should be used to group data. Segmentation algorithms distribute data points into segments or clusters by e.g., minimizing the sum of squares of the distance to the mean within each segment while maximizing the difference between segment means, thus providing groupings without arbitrary thresholds. Jenks natural breaks optimization is an example of such an algorithm (Khan 2012). In cases where the data for a lifecycle aspect spread over multiple orders of magnitude, segmentation should be performed using the log_{10} values to avoid grouping together in the green category small quantities that nonetheless display large relative spread over orders of magnitude. This second approach thus captures relative similarities in order of magnitude, rather than the absolute values of the criterion.

Figure 4 illustrates the advantage of using segmentation algorithms by providing examples of how grouping is affected by different algorithms for two different situations. The first situation (Figure 4a) is a sample group with moderate spread of results (i.e., within one order of magnitude). Examples of lifecycle aspects that would follow this trend could be product lifetimes, or efficiencies. The second situation (Figure 4b) is a sample group with a large spread of results covering several orders of magnitude. Examples of data types demonstrating similar spreads of magnitude include elemental crust concentration (as a fraction), or toxicity characterization factors (measured in, e.g., mg 1,4-dichlorobenzene equivalents). Four algorithms are demonstrated in Figure 4: Jenks optimization on both linear and logarithmic scales, placing equal number of samples in each color grade (tertiles), and groups covering intervals of equal magnitude. In Figure 4a, using Jenks optimization with $\log_{10}$ values is not relevant, due to the single order of magnitude in data spread. Both the tertile and equal interval groupings create grading boundaries between samples with very similar values (candidates 3 and 4 for the former, and 7 and 8 for the latter). With the samples containing large spread, a linear Jenks optimization results in seven orders of magnitude being covered with the green category, while yellow and red categories combined cover only two orders of magnitude. The tertile approach results in the same issue as the first situation, wherein two samples with very similar values are placed in different grading categories (candidates 6 and 7). Finally, using the equal interval approach with large spread results in the lack of samples in the "middle" grade. We provide a thoroughly documented, open-source Python module to facilitate the LiSET clustering analysis and visualization, available at https://github.com/majeau-bettez/LiSET (Majeau-Bettez 2018).

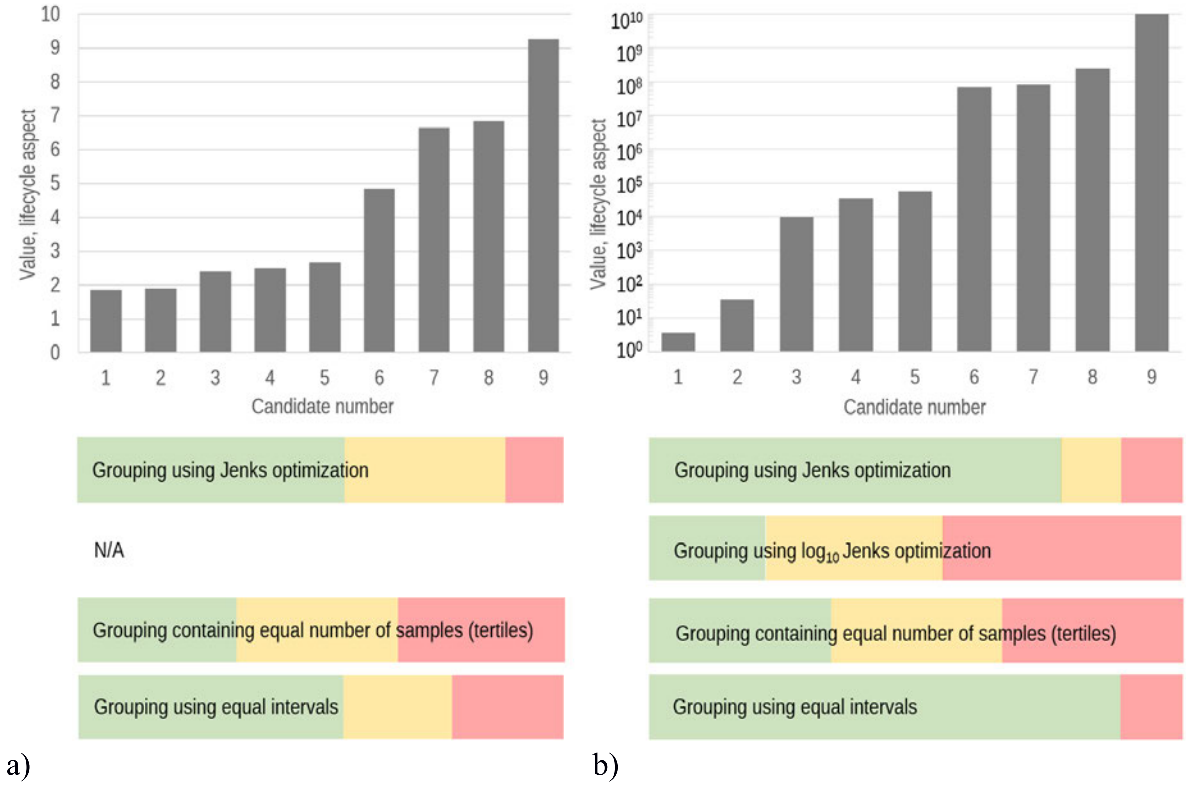

Figure 4 - Illustration of clustering approaches for quantitative data in LiSET. a) Samples with moderate spread (linear scale), b) samples with large relative spread (note the logarithmic scale). The bars indicate the groupings of the samples according to different clustering thresholds: 1) Groups produced using Jenks clustering, 2) Groups produced using Jenks breaks of $\log_{10}$ *values, 3) Groups containing an equal number of samples, 4) Groups using equal interval classification (i.e., intervals of equal magnitude)*

Iterative refinement and transition to LCA

The iterative process in the LiSET framework produces more refined LiSET results, or leads to the conversion to streamlined or full LCA.

Iteration within the LiSET screening with relative scoring

After a first pass through steps 1-3 in Figure 1, what is known about the lifecycle aspects of the different technology candidates is mapped out following a decomposition that, by definition, should cover the candidates' entire lifecycle. The matrix mapping resulting from this initial assessment, however, is not completely filled, has a low resolution, relies on a limited number of lifecycle aspects, and is evaluated following a rough, relative scale. Below, we address these four issues in order to guide iterative data collection efforts (Figure 1Figure 1, step 4.1).

First, the data collection should focus on the ***completeness*** of the screening (Figure 1, step 4.2). Data gaps are clearly identified in the LiSET matrix by blank cells. Practitioners should evaluate the feasibility of obtaining data on lifecycle aspects that represent these ignored parts of the technology candidates' lifecycle, even if these are only an approximation. In other words, this step aims to eliminate *truncation* of the lifecycle system description by filling data gaps early in the technological development and while the LiSET decomposition is still at a low resolution. The practitioners should stop once they evaluate that further data search on the missing aspects of the inventory is proving inefficient.

Second, practitioners should increase the ***resolution*** of the screening (Figure 1, step 4.3) by disaggregating the rows of the LiSET matrix. This disaggregation of the lifecycle description is performed by furthering the decomposition analysis presented in Figure 2. For example, in Figure 2 Row III, the impacts caused by embodied inputs are decomposed so as to single out material requirements per unit of functionality, expressed as (material efficiency)$^{-1}$. The next step would then be to further decompose this material requirement score in terms of the material types that dominate the lifecycle of the different technology candidates, for example, ferrous metals, nickel, other non-ferrous metals, polymers and other materials. As the material requirement term is *multiplied* by another term (i.e., "environmental intensity of material inputs") in Figure 2, any decomposition in the former should be matched by a decomposition of the latter in order to ensure unit consistency. Then, for each new decomposition term, a corresponding lifecycle aspect should be identified and evaluated.

Third, the practitioners should focus on the ***robustness*** of the screening (Figure 1, step 4.4). This is also done by adding new rows to the LiSET matrix, but this time by finding additional lifecycle aspects to further quantify (or serve as additional proxies for) each of the different decomposition terms. For example, in the case of "Material inputs" in Figure 3, multiple lifecycle aspects serve as indicators for this one decomposition term: energy density, power density, and lifetime expectancy of the energy device. Disagreements between different lifecycle aspects of the same decomposition term, or between different data sources, may indicate less robust evaluation. Such data triangulation and validation may, in turn, guide further data collection and disaggregation efforts.

Fourth, the practitioner should strive to increase the ***precision*** of their relative, ranking (Figure 1, step 4.5) As more quantitative data is collected, it should be evaluated whether the level of confidence in the data allows for a refined color-scale, going from a coarse green-yellow-red grading to a more subtle scale, with one significant digit (0-9), or eventually two significant digits (0-100) to reflect an increased confidence in the practitioners' ability to capture finer distinctions between technology candidates.

These four steps should be repeated in short iterations, to follow and accompany the development of the technology candidates. The different iterations of the LiSET matrix should be archived, and the different iteration steps, strategic decisions (e.g., elimination of candidates), and expert judgements should be logged for transparency (Pauliuk et al. 2015). The dynamic evolution of the mapping should serve as a tool for dialogue between LCA practitioners and technology developers.

As the mapping progresses and data collection intensifies, identified “dead-end” candidates are eliminated from the LiSET matrix under subsequent iterations. Candidates demonstrating obvious internal tradeoffs (i.e., strong benefits in some lifecycle aspects, and strong disadvantages in others), however, should not be excluded in the spirit of maintaining objectivity and transparency.

Transition from relative scoring to LCA

One of the shortcomings of previous LCA screening frameworks is the difficulty to “collapse” their mapping into a meaningful indicator of environmental impacts (Graedel et al. 1995; Wenzel 1998). In contrast, LiSET's iterative approach naturally leads to the calculation of lifecycle environmental impacts.

As the LiSET decomposition analysis is refined and more rows are added to the LiSET matrix (Figure 1, step 4.3), the screening increases in resolution until each data point comes to approximate specific product flows, elementary flows, or key parameters. For example, in successive iterations, an analysis may go from using a proxy for “material inputs” to acquiring data on metallic and non-metallic inputs, to eventually knowing the particular requirements of copper, low-alloyed steel, and graphite of a given process.

When practitioners require a lifecycle score (i.e., lifecycle impact assessment results) rather than a mapping, and when the resolution and completeness of the LiSET matrix is deemed sufficient to allow for a first quantitative comparison, the relative scale is dropped, revealing a collection of data with disparate dimensions and units (Figure 1, step 3). The equation of the decomposition analysis (Figure 2), which has grown along with the LiSET matrix through every iteration, directly dictates how these data should be combined to calculate lifecycle scores. That is, which terms should be multiplied and which should be summed.

It should be noted that resulting quantitative scores will represent more or less streamlined LCA results, depending on the level of resolution of the LiSET matrix. The authors should interpret these results with caution, and continue to rely on further LiSET iterations of decomposition and mapping to further transition towards a full-fledged LCA.

The LiSET iteration process only truly ends when the practitioners start to require more extensive connections to LCA unit-process databases such as *ecoinvent*, graphing and contribution analysis capabilities, and detailed uncertainty analyses (e.g., pedigree and Monte Carlo analyses).

Documentation and transparency

LiSET aims to reduce subjectivity and bias by including documentation of all steps, particularly the decomposition analysis.

Current screening, streamlined and full LCA approaches generally ignore missing data altogether when presenting method and results, which presents obvious transparency issues. In contrast, LiSET uses blank spaces to explicitly indicate what data are missing and which decomposition terms have been deemed irrelevant[2]. This treatment of unknowns is unique to any of the screening and streamlining methods in that the status of these are explicitly communicated as unknown or irrelevant. The obvious benefit of this is the systematic and documented approach to omitting aspects, and the communication of this process.

Thus, the presentation of the results matrix such as Figure 3 would be accompanied by the full decomposition analysis and a short description justifying each blank term. Similarly, the data gathered to evaluate each lifecycle aspect and boundary conditions for color groupings should be documented in e.g., a spreadsheet or database structure. This documentation is not only for transparency and quality assurance purposes, but also to facilitate the iteration process. This documentation also ensures that data resolution is not "lost" in the use of simplifying color- or numeric scales. Data uncertainty should be documented by including ranges of published values, triangulation of single lifecycle aspects with other data sources, or quantified uncertainty in such documentation. Once the method has been iterated sufficiently, these data will be readily available to perform more robust uncertainty assessments.

The intended audience for LiSET is researchers working on the technology studied and the agents who play a role in technology adoption. To fully capture the lifecycle perspective of the technology, we envision that the best results would be obtained when a practitioner familiar with LCA principles performs the method in conjunction with those intimately familiar with the technology. However, when technology researchers or product designers are performing the screening themselves, the documentation of all steps makes it easier to consult LCA practitioners and pinpoint missing or weak areas. In other words, rather than offering an oversimplified and under-informed LCA for the uninitiated, the LiSET framework relies on a systematic approach to iteratively explore and map out what is known and not known about the lifecycle aspects of an emerging technology, creating a meeting point and a tool of dialogue for technology developers and LCA experts. The thorough documentation process encourages discussions between screening practitioners, researchers, designers and stakeholders. Such discussions would play a key role in guiding the technology's development and avoiding lock-in effects of suboptimal pathways by identifying dead-end candidates, potential technical and environmental pitfalls at an early phase.

Discussion

The aim of this article was to formalize a lifecycle screening approach suitable for emerging technologies with limited data available for full LCAs. LiSET is suited to both qualitative and quantitative data, and encourages the use of what data is available to assess the environmental characteristics of the technology. Furthermore, evaluations using LiSET may be adapted from an initial screening of technologies to a full LCA through multiple iterations.

In particular, LiSET aims to facilitate screening assessments of very early phase, or emerging, technologies (i.e., lab-scale or design phase). These assessments can be iteratively upgraded, or adapted, with data as the technology develops, thereby providing a systematic, flexible, transparent and objective means of evaluating the environmental aspects of technologies and products. The qualitative and semi-quantitative method described here uses lifecycle principles by considering the manufacturing, use and end-of-life phases of the technology candidates. LiSET also systematically decomposes causal connections that lead to environmental effects. To this end, we distinguish between *intrinsic* and *extrinsic* characteristics. If two technologies demonstrate similar gradings for intrinsic properties, but value chain aspect of one is superior to the other, then it is not undoubtedly the superior technological choice. It is simply the superior choice under the evaluated conditions.

A comparison of LiSET to previously developed methods for screening and streamlining LCAs is provided in the Supporting Information.

A new method for lifecycle screening

While there is certainly high demand for screening and streamlining LCA methods, the development of such approaches has largely stagnated since the 1990s. We introduce LiSET, a method that is intended for screening of technologies in the early design phase, or at low readiness levels.

The color indicators used in early stages of LiSET have several advantages. Firstly, the use of a single scale to communicate all of the criteria considered is an elegant means to harmonize quantitative measurements, qualitative descriptions and estimates. Further, the overview of the results is immediately visually apparent without “translation” to target plots such as that used with ERPA. The strengths and weaknesses of the technologies are individually presented, thus highlighting the tradeoffs, potential hotspots and areas of improvement, both within individual candidates (down columns), and across lifecycle aspects (i.e., rows). The use of a low-resolution three-color scale also conveys the inherent uncertainty in the approach used through avoiding quantitative, finer scales such as scores from 1 to 100 or even 1 to 10, which imply both certainty and resolution that are not possible in an early phase evaluation. With a quick look, stakeholders and designers are able to identify strengths and weaknesses of technology candidates. In addition to this, the representation of insufficient data via a blank space also gives an indication of the data availability without influencing the final evaluation as is the case in some numerical scoring systems. As the technology continues developing, the data continues to “fill out”, certainty increases and the “traffic light” system may eventually be replaced by a number scale, e.g., from 1-10 to indicate greater certainty, and eventually filled out to represent a full LCA.

While LCA aims at providing a comprehensive assessment of multiple environmental impact categories (e.g., acidification, resource depletion, climate change) (Pelton and Smith

2015), LiSET aims to quickly map a large number of technology candidates and pinpoint hotspots of damages to human health, ecosystems, and resource availability. A decomposition analysis ensures that all lifecycle impacts are considered. Lifecycle aspects, used as metrics, are tailored to the specific technologies assessed and the available data. The matrix format for presenting results avoids the communication pitfalls associated with presenting single-score type results at such an early development phase and explicitly includes data gaps.

The iterative nature of LiSET follows and grows with a given technology through its development and maturation. Combined with iterations of the method and prescriptions for objective grading of candidates, the tailored lifecycle aspects allow for a flexible yet objective assessment. The results matrix can be expanded to include more drivers and strategies as the data required for the evaluation of these becomes available. As the technology matures and approaches commercialization, qualitative data may be replaced by quantitative data as greater certainty/knowledge is acquired.

LiSET offers a systematic approach to map the environmental aspects of the technology through its development: from its uncertain, qualitative beginning to the quantitative state of a full LCA. This method is applied as early as possible in the development phase. Early phase assessments allow for the investigation of novel technologies to identify those that are most promising and thereby guide further research directions towards minimizing the environmental impact of new technologies.

Acknowledgments

This research was in part made possible by financing from the Norwegian University of Science and Technology (NTNU), the International Life Cycle Chair (CIRAIG), the European Union's Horizon 2020 research and innovation programme (grant 646286), and the

Norwegian Research Council (grant 255199). The authors thank Anders Hammer Strømman and Rosalie van Zelm for their helpful comments.

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[1] Note that in Figure 2, the environmental intensity of exchanges is referred to as 'disruptive potential' and is different from the term describing the analogous property for embodied inputs ('environmental intensity'). This is because the environmental exchanges refer to individual stressors that have a direct environmental consequence, while the intensity of the embodied inputs may be represented by the overall disruptive potential of processes or process chains, i.e., a combination of exchanges.

[2] The latter would be affected by the nature of the technology, its level of development and the practitioner's understanding of the technology. For example, the environmental intensity of energy inputs to the technology might be left blank because this value is dependent on the energy mix and sources used, but manufacturing or supplier locations might not yet be determined.