Summary

This supporting information provides additional details related to the Lifecycle Screening of Emerging Technologies (LiSET) method. The first part addresses some specific issues that might arise in performing a LiSET and the methodological strategies that can be used to handle these issues. The second part provides a detailed discussion relating LiSET to previous screening approaches, namely ERPA, MECO and the streamlining strategies from Curran and Young.

Methodological strategies for handling specific issues

We describe below strategies for handling data conflicts and differing data resolution when performing LiSET. Parentheses indicate for which LiSET step these strategies are relevant.

Note that the not all issues that might arise during a LiSET assessment are covered here or in the main manuscript. Practitioners are encouraged to address these other issues in the LiSET spirit – as objectively as possible and fully documented for transparency.

Dealing with data conflicts: the double bottom line (*Evaluating lifecycle aspects*)

Since the practitioner is left to select physical dimensions to represent the terms in the last decomposition row (e.g., row III in Figure 2 from the main manuscript), several different data types might be suitable to represent the same lifecycle aspect. This opens the possibility of conflicting results for these lifecycle aspects. For example, Ellingsen and colleagues (2016) found that the long-term supply risk evaluations of some elements in literature were in stark opposition to the natural physical abundance of the elements as denoted by their concentration in the Earth's crust. Here, a double bottom line approach was taken to evaluate material scarcity, where thresholds for both supply risk and crust concentration had to be satisfied in order to achieve a certain grading for the material. More specifically, Jenks segmentation is used to objectively grade the candidate values for each of the data types. An overall grading for the decomposition term combines the individual data gradings using a precautionary approach: for a three-level grading system, any red gradings results automatically in a red overall grading. Similarly, both data types must be green in order for an overall green grading. This approach illustrates well the flexibility of the LiSET method to take advantage of alternative or multiple data types to evaluate lifecycle aspects. In other words, collecting indicator data to map out the relative strengths and weaknesses of technologies in terms of broad decomposition terms proves much more flexible than searching for data to use in the computation of an LCA.

Targeting further decomposition (*Iterative refinement*)

Upon iterations of the method, the practitioner should strive to increase the resolution of the screening by increasing the number of decomposition levels (e.g., Figure 2 in the main manuscript). The decomposition analysis should be targeted to maximize the gained insights, and should therefore focus on the most heterogeneous and environmentally significant terms of the lifecycle. In other terms, practitioners should aim to decompose to the point that matches the resolution of the available data. Less significant or less diverse categories may remain aggregated until further iterations, i.e., not all terms must be decomposed to an equal level.

This strategy of combining high- and low-resolution data to efficiently build a complete (step 4.2 in Figure 1 in the main manuscript) yet increasingly detailed (step 4.3 in Figure 1) system description is reminiscent of the combination of LCA processes and input-output (IO) sector data in hybrid LCAs (Suh et al. 2004).

Detailed discussion relating LiSET to ERPA, MECO and Curran and Young

Relation of LiSET to ERPA and MECO

The ERPA method by Graedel (1995) considers five lifecycle phases: premanufacture, product manufacture, product packaging and transport, product use and refurbishment-recycling-disposal. Each phase is evaluated against five areas of environmental concern: material choice, energy use, solid residues, liquid residues, and gaseous residues on a scale ranging from 0 to 4 (highest to lowest environmental impact). The sum of all scores represents the total rating. Further breakdown of the results can be obtained by summing across rows or columns to obtain the relative scores for each lifecycle phase or area of environmental concern, respectively.

The ERPA approach focuses on the environmental preoccupations of industry in the 1990s, namely residues, packaging and transport. In LiSET, we base the analysis on the perspective of production, use, and end-of-life lifecycle phases. Residues, which represent waste in ERPA, are an indication of inefficient resource use and therefore incorporated in the “Material efficiency” lifecycle decomposition term in our method rather than the end-of-life phase. “Material efficiency” thereby captures both reductions in material use via reduced waste and lightweighting or material reductions. The end-of-life aspect of LiSET is rather concerned with recyclability and ease of recycling than with waste. Furthermore, we distinguish between lifecycle aspects that are intrinsic to the technology and those that are characteristic of the supplying value chains (extrinsic). This implicitly communicates to decision makers, design teams and researchers the level of control they have on the environmental impact of the product. The scoring from 0-4 used in ERPA is analogous to our three-color system in that it communicates the inexactitude of the evaluated data types. However, while the scores are summed in the ERPA approach, the decomposition analysis shows that some aspects are multiplicative, and not simply additive (Figure 2, Row III). These multiplicative relationships are internalized in ERPA, which is a less transparent means of presenting the results, and make it difficult to use the data to transition towards a full LCA. Our method improves upon this by keeping the underlying data for these factors separate. Regardless of the grading system chosen in a screening LCA, the issue of establishing the boundaries between scores will be somewhat subjective. The use of segmentation algorithms adds some objectivity to criteria with quantitative data, although subjectivity is an unavoidable issue with qualitative data. Finally, while both ERPA and our approach share the matrix presentation of results, ours is adaptable to progressively quantified matrix results towards a full LCA.

As with the ERPA method, the MECO matrix approach presented by Wenzel (1998) considers each lifecycle phase separately. Environmental impacts are categorized in terms of materials, energy, chemicals and other factors not within these three categories. The difference, however, lies in that MECO is mostly quantitative, and the impacts amongst the different categories become difficult to compare. This is particularly true due to a lack of a unified grading scale across evaluation categories.

MECO lacks a harmonized ranking system as the presented method or ERPA approaches have. Instead, it mixes the qualitative and quantitative data in the presentation of results. The combination of descriptive results for qualitative data and numeric presentation of quantitative data with differing physical units makes it difficult to obtain an overarching assessment of results.

Relation of LiSET to the streamlining strategies in Curran and Young

Curran and Young (1996) describe a number of streamlining strategies ranging from decreasing the comprehensiveness of the study through elimination of included processes or environmental impacts evaluated, to using proxies to mixing quantitative and qualitative data using criteria to discontinue analysis.

Parallels exist between these streamlining strategies and the method presented here. For example, qualitative and quantitative data can be mixed, and some processes might not be evaluated due to missing data. The use of commercial databases and LCA literature to account for damages to human health and ecosystems fall under the strategy of using proxies. While there is no "zero-tolerance" criterion explicitly defined in LiSET, there is an opening for such a threshold, and a related approach is adopted with the "double bottom line". This approach automatically assigns an established grade when certain thresholds are met or failed when evaluating lifecycle aspects.

The streamlining strategies in Curran and Young (1996) differ from the proposed method in how missing data are handled, and the data types used. For the former, most of the streamlining strategies relate to the subjective removal of aspects to study. Without a formalized approach to perform such removals, the risk of omitting significant contributors to lifecycle impacts becomes real; when performing a streamlined LCA, the quantity and intensity of the process must either be modelled together, or not at all. In an early phase, the production location is likely undetermined. As a result, the intensity of the electricity used in manufacturing is unknown. In such cases, using the streamlining strategies from Curran and Young (1996) means that an assumption must be made about likely production locations in order to model the impacts from manufacturing electricity. The other option in this situation is to omit the manufacturing electricity use altogether. With our method, the decomposition analysis separates the amount of energy required and the environmental intensity of the energy mix or fuel. This removes the need to make assumptions that introduce larger uncertainty into the results while making the results more comprehensive than with the streamlining approach. In addition, our approach, rather than merely omitting the decomposition terms that are missing data, uses blank cells in the results tables to transparently communicate data shortcomings. This approach avoids apparent bias that missing data could introduce with single-score results, and clearly communicates what data are missing, in contrast to streamlining strategies. LiSET thereby provides a more systematic and transparent approach to handling missing data and streamlining traditional LCAs.

LiSET also has an advantage in its flexibility with regards to data types. While the streamlining strategies generally require the same type of input data as conventional LCAs, the proposed method avoids the exclusion of candidates due to the lack of such data by adapting to and allowing data beyond the conventional physical input and output information used in process LCAs. This makes the pool of available data much wider and avoids the outright omission of potential impact sources. Furthermore, the presented method provides a smooth means to harmonize the representation of qualitative and quantitative data using a color scale-based evaluation scheme.

Supplementary information references

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