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Editorial: Early-stage quantitative sustainability assessment: Approaches for policy, processes and materials

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Editorial on the Research Topic
Early-stage quantitative sustainability assessment: Approaches for policy, processes and materials

Quantitative sustainability assessment methods, such as life cycle assessment (LCA) evaluate the potential impacts of products, processes and services. ISO standards and further technical guidelines such as, e.g., PEF[1] or EPD[2] related category rule documents provide guidance to practitioners on carrying out LCA studies on existing products, processes and services, which are retrospective (*ex-post*) in nature.

A key limitation of quantitative sustainability assessment lies in its prospective (*ex-ante*) application, i.e., in the analysis of new products, technologies, and projects at low technology readiness levels (TRL). At the early development stages, the potential to improve environmental performance is the greatest, while the organizational effort and the financial cost to change the course of a project might still be relatively low. However, the lack of direct information and the uncertainty in forecasting technology development and market evolution makes this kind of anticipatory studies particularly challenging.

In recent years, the research community has started a fruitful discussion on the methodological advances required by an *ex-ante* and *anticipatory* application of quantitative sustainability assessment (Wender et al., 2014; Cucurachi et al., 2018; Ravikumar et al., 2018; Buyle et al., 2019; Bergerson et al., 2020; Adrianto et al., 2021). The 5 articles that form this

1 Product Environmental Footprint: LCA-based method introduced in the EU by the Recommendation 2013/179/EC to regulate the calculation, assessment, third party validation and communication to all stakeholders of the environmental impacts of products and services.

2 Environmental Product Declaration: statement that quantifies the environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function, as defined by ISO 14025.

Research Topic continue this discussion by offering methodological contributions on the development of prospective assessment frameworks.

Main differences of a prospective LCA compared to its retrospective counterpart are the inclusion of future time considerations in the choice of emerging technological options, the projection of background systems, and the upscaling of foreground systems (Arvidsson et al., 2018). The work by Lai et al. exemplifies approaches to address those three aspects with reference to the assessment of alternative technology pathways to sustainable aviation fuels (SAF) in Sweden. The selection of alternative feedstocks for SAF was performed by applying a socio-technical system (STS) approach. The STS model traces the interdependencies between feedstocks, markets, and institutions in order to systematically identify relevant feedstock types for SAF by considering constraints to supply, the competition in the demand of feedstocks by different markets, and trends in availability of certain feedstocks owing to policy changes. Advanced biofuels obtained from forest residues and black liquor, and e-fuels derived from green hydrogen and biomass-enhanced CO_2 capture were recognized as potential SAF feedstocks in the Swedish context. A filter based on TRL and economic considerations allowed screening of the technological options for the production of biofuels and e-fuels down to a selected number of processes, which were modeled prospectively using the upscaling framework proposed by Tsoy et al. (2020). Future background systems were modeled by adapting the approach by Steubing and de Koning (2021), i.e., by modifying the Ecoinvent database with information from integrated assessment modeling (IAM) scenarios.

Ventura discusses the prospective application of LCA at a more fundamental level, focusing on the broader issue of transition. Her article describes a novel conceptual framework, called transition LCA (Tr-LCA). Tr-LCA aims at studying transition scenarios for entire geographical contexts, rather than focusing on single products or organizations. As such, a methodological implication is that, differently from conventional LCAs, in Tr-LCA multiple functional units can be included and they can vary, as a consequence of the deep structural changes to the economy that transitions might realize. The modeling of substitution is another crucial aspect. Ventura extensively discusses integration with material flow analysis as a way to solve this issue at the level of the broad system boundaries of Tr-LCA.

Key for prospective LCA is its use as decision-support tool and, thus, its inclusion into multi-criteria decision-making frameworks. The most simple and widespread decision-support framework is the combination of LCA and techno-economic analysis (TEA). However, the lack of dedicated tools makes early-stage assessments a daunting task for technologists and practitioners. Faber et al. address this issue in the context of carbon capture and utilization (CCU), by presenting a series of ready-to-use, customizable, spreadsheet-based templates for the LCA/TEA of high-priority CCU pathways such as direct air capture, concrete/aggregates carbonation, chemical synthesis, and algae products. This streamlined approach enables an accelerated and standardized screening of CCU pathways, by providing reliable, order-of-magnitude estimates that allow discarding the less promising options and limiting the number of alternatives for which performing a comprehensive assessment.

Another relevant area for early-stage LCA together with decarbonization technologies is the transition toward circular economy (CE). Maximizing recirculation of materials does not necessarily result in a greater sustainability. Thus, solid assessment is needed to certify the soundness of CE projects (Blum et al., 2020). Küpfer et al. touch upon this relevant issue with reference to the building sector. They propose a decision-making framework for reuse of structural components in new construction projects. The proposed approach identifies the optimal rate of reused components by generating design alternatives and evaluating them on a combination of criteria, including environmental (LCA), economic and technical (procurement risk and project complexity) considerations.

More generally, the analysis of "end-of-life" scenarios is particularly critical in the context of novel products and emerging technologies, as very limited or no data are available on the potential impacts (see, e.g., the issues of microplastics and nanomaterials, or the dismantling of PV modules). Atabay et al. propose a top-down approach for the accounting of cradle-to-grave impacts of plastics based on the economic input-output life cycle assessment (EIO-LCA) method. The proposed model, named "Polluter Pays LCA", aims at covering all the direct and indirect impacts of the plastics value chain, taking a monetization approach akin to life cycle costing with social perspective and including in the system boundaries also the negative externalities in terms of additional burdens to the healthcare and social assistance sector. The mechanism considered to account for the damages of plastics EoL on human health combines emission factors of different toxic compounds from plastic waste management scenarios with a simplified quantification of the effect of micro-plastics (MPs) in enhancing the bioaccumulation of polycyclic aromatic compounds.

The body of work presented in this Research Topic testifies the extensive and prolific activity currently devoted by the scientific community toward early-stage sustainability assessment. By proposing innovative frameworks and informative case studies, articles in this collection contribute to the ongoing development of quantitative methods for the anticipatory analysis of the impacts of emerging technologies and provide suggestions for future work.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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