TYPE Editorial
PUBLISHED 09 May 2023
DOI 10.3389/fclim.2023.1204840

OPEN ACCESS

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RECEIVED 12 April 2023
ACCEPTED 24 April 2023
PUBLISHED 09 May 2023

CITATION
Sick V, Armstrong K and Moni S (2023) Editorial: Harmonizing life cycle analysis (LCA) and techno-economic analysis (TEA) guidelines: a common framework for consistent conduct and transparent reporting of carbon dioxide removal and CCU technology appraisal. *Front. Clim.* 5:1204840.
doi: 10.3389/fclim.2023.1204840

Editorial: Harmonizing life cycle analysis (LCA) and techno-economic analysis (TEA) guidelines: a common framework for consistent conduct and transparent reporting of carbon dioxide removal and CCU technology appraisal

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KEYWORDS

carbon dioxide capture and utilization (CCU), life cycle assessment (LCA), techno-economic assessment (TEA), emerging technologies, terminology, technology adoption, low technology readiness level

Editorial on the Research Topic
Harmonizing life cycle analysis (LCA) and techno-economic analysis (TEA) guidelines: a common framework for consistent conduct and transparent reporting of carbon dioxide removal and CCU technology appraisal

Stabilizing the climate will require significant efforts to curb greenhouse gas emissions, manage emissions that cannot be avoided, and remove as many legacy emissions as possible [i.e., carbon dioxide (International Energy Agency, 2020; Author Collective, 2022)]. In that context, negative emissions technologies will take CO_2 from the air (Direct Air Capture) or the water (Direct Ocean Capture) and permanently remove it (Roger et al., 2021) either by sequestering the CO_2 underground or converting it to so-called Track 1 materials (Sick et al., 2021) that have lifetimes of >100 years. Shorter-lived products that decompose back into CO_2 in <100 years are categorized as Track 2 materials and will at best be carbon neutral. A carbon neutral status can also be achieved if captured CO_2 from fossil-based point sources is sequestered or used to create Track 1 materials. Conversion of CO_2 from fossil-based sources to any Track 2 material and subsequent decomposition would add new fossil-based carbon to the atmosphere, constituting an ultimately undesirable process. The overall carbon footprint of a process or product will depend on many factors associated with the carbon production, use, and disposal phases.

Thorough and transparent life cycle assessments (LCA) and techno-economic assessments (TEA) are critical for determining the environmental and economic risks and opportunities of a technology or product before industrial deployment is pursued. It is also critical that the assessments be consistently applied, enabling direct comparison of technologies, products, and production pathways to select the best possible outcomes. Though ISO standards for LCA exist, none are available for TEA. While ISO standards are a starting point, they leave room for methodological decisions; for example, how to handle multi-functionality in CO_2 conversion processes. Several efforts have produced suitable guidelines for LCA and/or TEA (Zimmermann et al., 2018; Arno et al., 2020; Langhorst et al., 2022; National Energy Technology Laboratory, n.d.; Argonne National Laboratory, n.d.; National Renewable Energy Laboratory, n.d.) for CO_2 capture, utilization, and sequestration (CCUS); the International CCU Assessment Harmonization Group was formed to coordinate work and guidelines to harmonize guidance where possible and define and illustrate where and why differences remain (Sick et al., 2019). The AssessCCUS website (Global CO2 Initiative, n.d.) integrates diverse resources to expedite the discovery process and enable rapid centralized access: *AssessCCUS: An Integrated Approach for Aggregating Resources to Enable Techno-Economic and Life Cycle Assessment of Carbon Management Technologies* (Faber, Mangin et al.).

Considerable confusion about technical terms related to carbon capture, utilization, and sequestration exists, leading to misconceptions, inadvertent greenwashing, and more (Faber and Sick, 2022). *Why Terminology Matters for Successful Rollout of Carbon Dioxide Utilization Technologies* discusses the need to clearly define terminology to prevent problems related to wrongly used technical terms (Olfe-Kräutlein et al.). A prominent example is the frequent use of "CCUS" when the efforts considered only include CO_2 sequestration to manage captured CO_2. These ambiguities may create problems regarding policy making, funding proposals, and, especially, public discourse. Acronyms and technical abbreviations are the chief cause of potential misunderstandings and should be avoided whenever possible or else include a brief explanation. Consistent and precise use of terminology will facilitate transparent dialogue concerning CO_2 capture and utilization in the future.

LCA and TEA can be powerful tools to guide research and decisions about scale-up, and, ultimately, deployment of technologies. However, the lower the technology readiness level (TRL) the less accurate the assessments will be. *Life-Cycle and Techno-Economic Assessment of Early-Stage Carbon Capture and Utilization Technologies—A Discussion of Current Challenges and Best Practices* (Zimmermann et al.) presents current challenges related to the interplay of LCA, TEA, and TRL and shows best practices for assessing early-stage climate change mitigation technologies using carbon capture and utilization (CCU). Methodological challenges are highlighted for practitioners when adapting the goal and scope, identifying benchmark technologies, creating a comprehensive inventory, comparing early stage to commercial stage, and ensuring clarity of recommendations for decision-making under high uncertainty.

Comparisons of emerging CCU technologies to incumbent technologies are necessary to support developers and help policymakers design appropriate long-term incentives to mitigate climate change through the deployment of CCU. These comparisons can be misleading, as emerging technologies typically experience a drastic increase in performance and decrease in cost and greenhouse gas emissions as they transition from research to mass market deployment due to various forms of learning. The effects of cumulative learning can be quantitatively described using technology learning curves (TLCs). TLC approaches have been developed for various technologies, but a harmonized methodology for using TLCs in TEA and LCA for CCU is required. *Adapting Technology Learning Curves for Prospective Techno-Economic and Life Cycle Assessments of Emerging Carbon Capture and Utilization Pathways* (Faber, Ruttinger et al.) describes a methodology that incorporates TLCs into TEA and LCA to forecast the environmental and economic performance of emerging CCU technologies.

LCA and TEA focus on environmental and economic factors but do not directly incorporate other stakeholder needs and values. The technology performance level (TPL) combined indicator provides a comprehensive and holistic assessment of an emerging technology's potential, which is described by its techno-economic performance, environmental impacts, social impacts, safety considerations, market and deployment opportunities, use integration impacts, and general risks. *Adapting the Technology Performance Level Integrated Assessment Framework to Low-TRL Technologies Within the Carbon Capture, Utilization, and Storage Industry, Part I* (Mendoza et al.) demonstrates how stakeholder needs and values can be incorporated, how LCA and TEA metrics can be balanced, and how other dimensions can be integrated into a single metric that measures a technology's potential.

Emerging technologies typically require significant policy support to enter markets. Approaches to achieve that goal usually differ regionally and are pertinent to CCU as well, as discussed in *Committed to implementing CCU? A comparison of the policy mix in the US and the EU* (Thielges et al.). Here, a cross-regional comparison of policy mixes is used to formulate policy recommendations to improve policy mixes for CCU. A clearer strategic commitment to CCU, its incorporation into green public procurement guidelines and across different funding schemes for a sustainable energy transition, and ambitious new targets for renewable electricity and green hydrogen are recommended to help develop the policy mixes further to provide a supportive framework for CCU.

Author contributions

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

Acknowledgments

VS acknowledges support from the Global CO_2 Initiative. KA is grateful to the Unilever Safety and Environmental Assurance Centre, Environmental Sustainability team for review, and comments. SM is grateful to Timothy Skone, Michelle Krynock, and the U.S. Department of Energy National Energy Technology Laboratory (NETL) LCA Team.

Conflict of interest

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