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EDITORIAL

Life cycle assessment in the context of decarbonization and carbon neutrality

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) emphasizes the need to immediately tackle climate change by significantly reducing greenhouse gas (GHG) emissions and capping global warming at 1.5 °C above pre-industrial levels (IPCC, 2022). In the Paris Agreement, most countries committed themselves to achieve GHG neutrality by 2050 to tackle the global impacts of climate change (United Nations Framework Convention on Climate Change, 2022). These commitments are not only being addressed on a country level, but also broken down to industrial sectors and companies and their products, leading to an increase in carbon neutrality labels and claims. To achieve carbon neutrality, most scientists advocate for the "mitigation-over-compensation" hierarchy, which prioritizes mitigation through the avoidance and reduction of GHG emissions and the replacement of carbon-intensive activities, but also recognizes the necessity of offsetting to compensate for emissions that cannot be mitigated.

Carbon neutrality refers to a condition where the carbon dioxide emissions generated by the actions of an product, company, city, or country are balanced out or offset by measures that reduce or remove an equivalent amount of GHG from the atmosphere, resulting in a net-zero carbon footprint (Finkbeiner and Bach 2021; Science Based Targets initiative, 2021). The terms climate neutral/neutrality and carbon neutral/neutrality are not used consistent by various initiatives and stakeholders (Kaskeala 2022). In the following, these terms are used interchangeably, referring to balancing out all GHG emissions and not only carbon dioxide emissions.

Several sectors contribute to global GHG emissions. The energy sector is the largest contributor accounting for around 73% of global GHG emissions in 2019 due to burning of fossil fuels to generate electricity and heat. In the transportation sector around 15% of global GHG occur, emissions primarily coming from the burning of gasoline and diesel fuel in passenger cars, trucks, and busses. Emissions from aviation and shipping also add to the sector's greenhouse gas footprint. The agriculture sector contributes with 13% with the largest source being enteric fermentation from livestock. Further, manure management, the use of synthetic fertilizers, and rice cultivation lead to emission. The cement as well as iron and steel industry are both responsible for around 7% of GHG emissions (IPPC, 2018, 2021, 2022).

To achieve climate neutrality and mitigate risk of climate change, both political and technological measures are essential for implementation of decarbonization strategies. Policy creates the necessary conditions to support the transition to a low-carbon economy, while technology provides the means to reduce greenhouse gas emissions. This can be achieved through a range of measures, including transitioning to renewable energy sources, the use of electric vehicles, biofuels and hydrogen fuel cells in the transport sector, development of high-capacity batteries, precision farming techniques and use of alternative protein sources in the agricultural sector, as well as development of low-carbon cement and direct reduced iron for the industry sector (IPCC, 2022).

However, decarbonization faces several challenges, for example, costs when transitioning to low-carbon technologies and infrastructure, the development of necessary infrastructure, strong political will and commitment from governments and other actors, technological limitations in certain sectors such as aviation and heavy industry as well as public support and engagement. For effective implementation, a life cycle perspective serves as the foundation for calculating carbon footprints, identifying carbon-intensive stages of a product's life and opportunities for reduction and is therefore an essential component of any comprehensive decarbonization

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strategy, as it helps to prevent double-counting, carbon leakage, problem-shifting, and green-washing.

As pointed out by Finkbeiner and Bach (2021), there are still several methodological challenges which need to be resolved for assessing decarbonization strategies including accounting of renewable energy, biogenic carbon, so-called green suppliers, avoided emissions, and end of life allocation procedures. Additionally, offsetting faces its own challenges due to low quality often leading to an overestimation of carbon credits (West et al. 2020; York 2012).

The *International Journal of Life Cycle Assessment* is the journal for publishing methodological aspects as well as novel case studies regarding decarbonization measures and strategies. This special issue aims at furthering the understanding and deepening the topic of decarbonization and carbon neutrality by addressing approaches for more consistent assessment of GHG, addressing measures and strategies to avoid, replace, and reduce emissions as well as how to deal with offsetting.

2 Scope of this special issue

This SI focusing on the issue of decarbonization and carbon neutrality was developed as these topics are seen as major trends in the next years. Therefore, an opportunity exists to incorporate life cycle thinking and approaches into organizational and decision-making contexts of carbon neutrality as highlighted by Finkbeiner and Bach (2021).

The goal of the SI was to encourage a more proactive role of the LCA community in the carbon neutrality and decarbonization debate and to inspire further research efforts to tackle unresolved accounting challenges. Thus, the SI demonstrates its potential to serve as an appropriate platform for presenting current research regarding decarbonization contributing to global climate goals and climate neutrality.

3 Overview of the papers included in this special issue

The SI has attracted the interest and attention of the scientific community worldwide, with a collection of 13 papers accepted between 2021 and 2023. Authors come from all over the world, including Argentina, Austria, China, Finland, France, Germany, Norway, Spain, Sweden, Thailand, and the USA; from a variety of different research institutes reflecting the multidisciplinary aspects necessary to explore this complex topic of carbon neutrality and decarbonization.

In the following, the contributions to this SI are introduced. The authors addressed the challenges of consistent GHG accounting and assessment ("Sect. 3.1"), mitigation options in several sectors including the building, transport, and agricultural sector ("Sect. 3.2") as well as challenges related to emission offsetting ("Sect. 3.3").

3.1 Consistent GHG accounting and assessment

Consistent GHG accounting is essential for mitigating climate change by identifying contributions of sectors and activities, to set emissions reduction targets and track progress towards meeting those targets as well as implementing effective mitigation strategies. Consistent accounting also allows for identifying best practices and driving innovations. Further, ensuring accountability and building trust among stakeholders can only be achieved by precise and transparent determination of emissions reduction goals. Three papers address aspects of consistent GHG accounting and assessment.

The paper by de Bortoli et al. (2023) titled *Planning sustainable carbon neutrality pathways: accounting challenges experienced by organizations and solutions from industrial ecology* explores the challenges faced by organizations in accounting for GHG emissions and sustainability aspects when planning a transition towards carbon neutrality. The authors propose a "Measure-Reduce-Neutralize-Control" sequence and discuss accounting challenges, potential solutions, and the role of the community for harmonization of standards, tools, and databases.

The paper by Holzapfel et al. (2023) titled *Electricity accounting in life cycle assessment: the challenge of double counting* identifies challenges and proposes solutions for double counting of electricity from specific energy sources in life cycle assessment and greenhouse gas accounting, particularly with the parallel application of location-based and market-based methods. The study recommends consistent electricity accounting rules to avoid double counting and under- and overestimations of environmental impacts.

The paper by Ventura (2022) titled *Conceptual issue of the dynamic GWP indicator and solution* proposes a new indicator for the dynamic assessment of global warming potential that considers the total impact of all flows and sets the time of observation duration based on the life cycle duration and time horizon of impact. It can therefore account for delayed emissions compared to static LCA and can be applied in regulations. Further, the author states that overestimation of possible beneficial effects of temporary carbon storage in the construction sector as a whole has to be avoided.

3.2 Mitigation measures

Mitigation measures are implemented to reduce GHG emissions. They can be technical, political, or based on behavioral changes. Without mitigation measures in all sectors, GHG will continue to rise and the global climate goal of

1.5 °C cannot be reached. Within this SI, nine papers address mitigation measures for the sectors building, transport, and agricultural.

The following five papers address potential mitigation measures to reduce GHG emissions of the building sector. The paper by Cordoba and Irassar (2023) titled *Carbon footprint of reinforced concretes columns with and without supplementary cementitious materials* examines the carbon footprint of reinforced concrete columns and explores the impact of replacing Portland cement with supplementary cementitious materials (SCM) and increasing the steel cross-section. The study finds that higher-strength concretes lead to lower carbon footprints, and increasing the steel section reduces the volume of materials and carbon footprint. However, SCM replacement may increase the material volume and carbon footprint at another point in the life cycle.

The paper by Massana et al. (2023) titled *Environmental assessment of a new building envelope material derived from urban agriculture wastes: the case of the tomato plants stems* presents a preliminary analysis of using an infill wall component (envelope material) produced employing tomato plant stems (UA waste) for buildings sited in the proximity of the production facility. The potential of this material in fixing carbon emissions for a long time has been shown but needs to be discussed in a broader context.

The paper by Scherz et al. (2022) titled *Strategies to improve building environmental and economic performance: an exploratory study on 37 residential building scenarios* conducted an analysis of a residential building in Austria to identify ways to minimize GHG emissions and costs considering 37 different scenarios with different construction materials, insulation materials, and technical building equipment. Results indicate that improving the energetic standard of buildings can reduce environmental impacts by 25% but comes with higher construction costs over 50 years. Thus, it is important to conduct eco-efficiency assessments during the design process to ensure cost-optimal environmental improvements for buildings.

The paper by Scherz et al. (2023) titled *Transition of the procurement process to Paris-compatible buildings: consideration of environmental life cycle costing in tendering and award decisions* proposes a procurement process that reduces GHG emissions by considering embodied and operational emissions. A theoretical process model was developed and validated through environmental life cycle costing on a single-family house case study. They found that awarding contracts based on life cycle costing can significantly reduction GHG emissions. Further reductions can be achieved with a GHG emission bonus/malus system.

The paper by Kiss and Szalay (2022) titled *Sensitivity of buildings' carbon footprint to electricity decarbonization: a life cycle–based multi-objective optimization approach* examines how changes in electricity mix impacts GHG emissions. Multi-objective optimization was used to minimize global warming potential and costs. According to the results, optimizing the building envelope can improve the design by an average of 18% in terms of life cycle GHG compared to typical new designs, given the current electricity mix. The study also shows that considering the impact of electricity is crucial in building design optimization.

The following two papers address mitigation measures for the transport sector, including changes in fuel use, logistic management, and materials for infrastructure. The transport sector is responsible for around 16% of global GHG emissions, with the road sub-sector having the highest contribution with 12%.

The paper by Xue et al. (2022) titled *Assessing decarbonization pathways of China's heavy-duty trucks in a well-to-wheels perspective* evaluates different measures that can be taken to reduce the carbon footprint of China's heavy-duty truck (HDT) sector. A dynamic model is used to project GHG of the HDT fleet from 2020 to 2050. The study concludes that a mix of powertrain technologies, energy sources, and logistical solutions will be necessary for a sustainable low carbon transition, requiring a more comprehensive regulatory framework to promote innovation.

The paper by AzariJafari et al. (2023) titled *Solutions to achieve carbon–neutral mixtures for the U.S. pavement network* assesses the feasibility of achieving carbon–neutral asphalt and concrete mixtures for the US pavement network by 2050 using various GHG mitigation solutions. By applying data science approaches, and a dynamic material flow analysis and life cycle assessment models, the embodied carbon attributed to the pavement network could be determined. The results suggest that multiple solutions such as type of binders, reclaimed asphalt pavement, and carbon capture and utilization technologies must be applied together, and a 100% renewable electricity supply is required to achieve carbon neutrality.

The agricultural sector with around 20% global emissions is one of the hardest to mitigate due to large number of small farmers worldwide, the strong link between agricultural practices and behavioral activity, and the lack of implementable technologies for certain aspects such as livestock management. The paper by Moungsree et al. (2022) titled *Carbon footprint and life cycle costing of maize production in Thailand with temporal and geographical resolutions* estimated greenhouse gas emissions and life cycle costing associated with maize production during different cropping seasons in Thailand. The study found that total GHG emissions from maize production were on average 429 ± 27 kg CO2-eq/ton grain, with the highest emissions occurring during the dry season.

3.3 Offsetting

In the last step of each carbon neutrality strategy, the non-abatable emissions are offset following the mitigation over compensation hierarchy. Offsetting projects have been criticized regarding their quality (e.g., Arendt et al. (2021) and Kaskeala (2022)) but are a necessary step towards climate neutrality. Two papers address the issue of offsetting.

The paper by Helppi et al. (2023) titled *Review of carbon emissions offsetting guidelines using instructional criteria* evaluates seven carbon offsetting guidelines for corporations and finds that none of them provides sufficient instructions for appropriate emissions offsetting. This creates uncertainty and hinders successful offsetting. The study recommends developing better guidance and standardizing the practice to reduce uncertainty and improve the effectiveness of carbon offsetting.

The paper by Zakrisson et al. (2023) titled *Climate impact of bioenergy with or without carbon dioxide removal: influence of functional unit and parameter variability* compares climate impacts of three bioenergy systems (biochar, BECCS, and CHP) using a parameterized life cycle inventory model and different functional units. The results showed that the CDR systems had lower climate impacts than the reference system, but the preferable system varied depending on the functional unit and energy background system. The study recommends using multiple functional units and performing sensitivity analysis.

4 Conclusions

The SI has collected a variety of relevant studies regarding decarbonization and carbon neutrality. Thus, the SI plays a role in contributing of filling the scientific voids by providing scientifically sound solutions for implementing carbon neutrality principles. This SI further contributes to raising awareness to the topic of measuring GHG emissions, decarbonization measures as well as climate neutrality. The overview of the papers revealed that several technological and political measures are available for decarbonizing the various sectors, especially the building and transport sector. Further, challenges as well as first ideas are presented to reach carbon neutrality including consistent emission accounting. Finally, the significance response of this SI proves that the LCA community is doing important research on the topic of climate neutrality and decarbonization.

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Declarations

Conflict of interest There are no conflicts of interest to be declared.

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